USERS MANUAL FOR PRECO-2006:

EXCITON MODEL PREEQUILIBRIUM NUCLEAR REACTION CODE WITH DIRECT REACTIONS

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Abstract

PRECO-2006 is a two-component exciton model code for the calculation of double differential cross sections of light particle nuclear reactions. The code, written in FORTRAN-77, runs on a PC and calculates the emission of particles up to mass four, including separate subroutines for nucleon transfer processes, knockout and inelastic scattering involving complex particles, and collective state excitation (both discrete and giant resonance states). Emission of a second nucleon at either the preequilibrium or equilibrium phase of the reaction is allowed following neutron or proton emission. Available options include collective or ordinary pairing corrections, isospin conservation, and shell structure effects. Output of both the energy differential and double differential cross sections is available, along with an option to print out the cross sections going into specific final nuclides. A recommended set of global input parameters is provided. The most significant improvements relative to PRECO-2000 are in the description of reactions with complex particles in the entrance and/or exit channel.

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1. Introduction

The exciton model, first proposed by Griffin [GR66], is a simple statistical model which describes the equilibration of the composite nucleus in light particle induced reactions and calculates the energy spectra for the emission of light particles. It takes an independent-particle view of the nucleus and neglects all angular momentum effects. Over the years it has, however, proven to be an extremely useful model, and one which is quite adaptable to the inclusion of additional physics. Thus the effects of the pairing interaction, shell structure, and isospin are all now considered. Double differential cross sections are obtained from global empirical systematics describing the variation of the energy differential cross section with emission angle.

In the basic exciton model, the nucleus is assumed to have equally spaced single particle states, and the states of the nucleus as a whole are described in terms of the numbers of particle and hole degrees of freedom they contain. The interactions which cause transitions from one class of states to another are assumed to be two-body, residual, and energy conserving. Particle emission rates are calculated from microscopic reversibility. In the two-component model, proton and neutron degrees of freedom are treated separately. This is necessary for a reasonable treatment of pairing, shell structure, and isospin.

PRECO refers to a family of FORTRAN computer codes of increasing sophistication and accuracy, designed to calculate the energy spectra of particles emitted in nuclear reactions within the framework of the exciton model. The early codes (dating back to around 1970) used the one-component model where no distinction is made between proton and neutron degrees of freedom. PRECO-D (and later PRECO-D2 [KA85a]) extended this formalism by dividing the preequilibrium cross section into its multi-step direct (MSD) and multi-step compound (MSC) parts for the early study of angular distributions. The MSD component is assumed to have forward-peaked angular distributions, while the MSC part has angular distributions symmetric around 90 degrees in the center of mass. However, these studies indicated that most angular distributions can be reasonably well described

using the preequilibrium and equilibrium cross sections to approximate the MSD and MSC contributions, respectively. Thus in PRECO-E, released in 1991 [KA91], the MSD/MSC division was abandoned in favor of moving to a two-component version of the exciton model. The two-component version has continued to be used in PRECO-2000 and now in PRECO-2006.

The approach taken in the development of the exciton model and the PRECO code system has been largely phenomenological, relying on data from the literature (a) to guide the choice between alternative formulations of various effects, (b) to indicate the mathematical forms and parameter dependences of other effects, and (c) to provide values for model parameters that cannot be obtained from independent sources. The physics currently included in the PRECO-2006 is:

- Closed form calculations for the equilibration process, allowing for exciton scattering interactions as well as the creation of particle-hole pairs.
- Two-component state densities (neutron and proton degrees of freedom are distinguishable) and transition rates derived in the equi-spacing model.
- Shell structure effects included in the state densities.
- Two options for including pairing corrections in the state densities.
- An option for isospin conservation in the preequilibrium phase of the reaction with a variable amount of conservation at equilibrium; including *new* default conditions for determining the extent of isospin conservation in a given reaction.
- Finite well depth corrections to the state densities.
- An option for shallower well depths to account for surface localization of the initial target-projectile interaction, including *revised* default options.
- Preequilibrium and equilibrium emission of a second nucleon following neutron or proton emission during exciton model equilibration or (*new*) in direct nucleon stripping with a complex projectile.
- A simple approximation to account for γ-ray competition with secondary evaporation.
- A subroutine for semi-empirical treatment of direct nucleon transfer reactions (*significantly revised* since PRECO-2000).

- Subroutines for inelastic and knockout processes involving cluster degrees of freedom (*slightly revised* since PRECO-2000).
- A subroutine for excitation of both spectroscopic and giant resonance collective excitations as well as a crude estimate of elastic scattering.
- Empirical systematics for the angular dependence of the double differential cross sections (*revised* for incident neutrons)..

In addition, a fairly robust set of global input parameters for (nucleon,nucleon) or (N,N) reactions has been developed through a methodical benchmarking process using experimental spectra from the literature. This has been extended to reactions that emit complex particles. Finally, arrays of residual nucleus cross sections can be requested. These can include only the contributions from preequilibrium emission, if they are to be passed on to larger Hauser-Feshbach codes that use PRECO as a preequilibrium module, or they can include the total production cross sections for different product nuclides.

Much additional work remains to be done. This includes addressing open questions of physics for (N,N) reactions at incident energies significantly above 60 MeV as well as re-examining complex-particle-induced reactions with the addition of a projectile breakup model. Still, enough improvements have been made since PRECO-2000 that a new release of the code is being provided for the benefit of users.

This users manual describes in some detail the physics expressed in the code. This is especially beneficial since the model has developed over a long series of papers, and it is not possible in a journal article to gather all the details together in one place. The manual also describes the structure of the code, the needed input quantities, the available output options, and a suggested set of global input parameters. The appendices contain a list of variables, as well as sample input and output files. The FORTRAN files of the code are available in electronic format, as are the sample input and output files.

2. Two-Component Particle-Hole State Densities

The basic building blocks of all exciton model calculations are the state densities for the various classes of particle-hole configurations in the composite and residual nuclei. They are used to derive the transition rates for the residual interactions which take the system from one class of states to another. In addition, the state densities for the composite and residual states feature prominantly in the , and the residual state densities are used in the phenomenological model for direct transfer reactions.

2.1. Fundamental Parameters

The states in a given nucleus are designated by the four indices p_π, h_π, p_ν, and h_ν, where the symbols p and h denote particle and hole *degrees of freedom*, respectively, and the subscripts π and ν refer to protons and neutrons, respectively. These four parameters are related to the parameters in the one-component model through the relations $p = p_\pi + p_\nu$ and $h = h_\pi + h_\nu$. They can also be combined to give the total number, n, of excitons (degrees of freedom) $n = p + h = p_\pi + h_\pi + p_\nu + h_\nu = n_\pi + n_\nu$.

Particles and holes are determined relative to the Fermi level, half way between the last filled and first vacant single particle states when the nucleus is in its ground state. Thus the total number of proton particles *must* equal the total number of proton holes and similarly for neutrons. However, not all of the particles and holes will necessarily be degrees of freedom. As the Fermi level moves up or down with the absorption and emission of particles, particles and holes may be formed adjacent to the Fermi level. These are termed 'passive' since they have no permutable excitation energy and are thus not degrees of freedom. They do, however, influence the energy requirements for the configuration based on the Pauli exclusion principle.

The composite nucleus is assumed to be formed in a unique particle-hole configuration which is currently taken to consist of the projectile nucleons as particle degrees of freedom and no hole degrees of freedom. Thus it is denoted by $(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a, 0, N_a, 0)$, where the subscript a refers to the projectile. Other assumptions would need to be programmed in.

The particle-hole differences are assumed to remain constant throughout the equilibration process so that in the composite nucleus $p_\pi - h_\pi = Z_a$, $p_\nu - h_\nu = N_a$, and thus $p - h = A_a$ where A_a is the projectile mass number. These conditions will not always be true, particularly close to equilibrium, but they seem adequate for closed form preequilibrium calculations. In the residual nuclei (which are also the composite nuclei for subsequent or secondary particle emission), the differences are normally given by $p_\pi - h_\pi = Z_a - Z_b$, $p_\nu - h_\nu = N_a - N_b$, and $p - h = A_a - A_b$ where the subscript b refers to the emitted particle. Because of these relations, once the projectile has been specified, the quantities p and p_π are adequate to label states in the composite nucleus, and once the ejectile has also been specified, they are adequate to label states in the residual nucleus. These then are the labels used in the code and in many places in this manual.

In the two-component model, there are two sets of equally spaced single particle states, one for protons and one for neutrons. They are specified by the single particle state densities $g_{\pi 0}$ and $g_{\nu 0}$, respectively, given in units of states/MeV. Together these combine to form the single particle state density from the one-component model, $g_0 = g_{\pi 0} + g_{\nu 0}$. The single particle state densities are determined by the Z and N of the nucleus under consideration and are often taken to be proportional to these quantities. This is the default option in PRECO where

$$g_{\pi 0} = Z/K_g \tag{2.1}$$

$$g_{\nu 0} = N/K_g \tag{2.2}$$

and the normalization parameter is read in but defaults to $K_g = 15$ MeV. In PRECO-2000, separate normalization factors for the proton and neutron single particle state densities were read in, but they are almost always equal, so only a single normalization is used here.

The final parameter needed to describe the states of the system is the excitation energy, E, of the nucleus.

2.2. Basic State Density Formula

In the two-component exciton model, the basic state density formula is due to Williams [WI71] and is given by

$$\omega_{\rm ESM}(p,p_\pi,E) = \frac{(g_{\pi 0})^{n_\pi}\ (g_{\nu 0})^{n_\nu}\ \ [E - A(p,p_\pi,E)]^{n-1}}{p_\pi!\ h_\pi!\ p_\nu!\ h_\nu!\ \ (n-1)!} \tag{2.3}$$

where $A(p,p_\pi,E)$ is the Pauli correction function and is here given by

$$\begin{aligned} A(p,p_\pi,E) = E_{\rm th}(p,p_\pi) &- \frac{p_\pi^2 + h_\pi^2 + n_\pi}{4g_{\pi 0}} - \frac{p_\nu^2 + h_\nu^2 + n_\nu}{4g_{\nu 0}} \\ &+ \frac{\left[\left(p_\pi - \frac{2}{m}\right)\left(p_\pi - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(p_\pi - \frac{1}{2})}{g_{\pi 0}G_\pi(p,p_\pi,E)} \\ &+ \frac{\left[\left(h_\pi - \frac{2}{m}\right)\left(h_\pi - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(h_\pi - \frac{1}{2})}{g_{\pi 0}G_\pi(p,p_\pi,E)} \\ &+ \frac{\left[\left(p_\nu - \frac{2}{m}\right)\left(p_\nu - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(p_\nu - \frac{1}{2})}{g_{\nu 0}G_\nu(p,p_\pi,E)} \\ &+ \frac{\left[\left(h_\nu - \frac{2}{m}\right)\left(h_\nu - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(h_\nu - \frac{1}{2})}{g_{\nu 0}G_\nu(p,p_\pi,E)}. \end{aligned} \tag{2.4}$$

This form, unlike the one proposed by Williams, is symmetric in particle and hole degrees of freedom and contains four extra energy-dependent terms. Here $E_{\rm th}$ is the threshold energy for the configuration. In the equi-spacing model (ESM) it is given by

$$E_{\rm th}^{\rm ESM}(p,p_\pi) = \frac{q_\pi^2}{g_{\pi 0}} + \frac{q_\nu^2}{g_{\nu 0}} \tag{2.5}$$

where $q_\pi = \max(p_\pi, h_\pi)$ and similarly for q_ν. The use of the q's means that the threshold energy includes the requirements of any passive particles and holes adjacent to the Fermi level.

The last four terms in Eq. (2.4) were determined empirically to give improved agreement with exact state densities in the ESM near the threshold energy [KA95]. The quantity m is the number of active exciton classes. There are four possible "classes" of excitons (proton particle, proton hole, neutron particle, and neutron hole degrees of freedom), and those that have at least one exciton are called active classes. The functions in the denominators of these terms have the form

$$G_\pi(p,p_\pi,E) = 9.35 + \frac{(5.7 - 0.6m)\, m g_{\pi 0}\, [E - E_{\rm th}(p,p_\pi)]}{n} \tag{2.6}$$

and similarly for G_ν. Finally, Θ is the Heaviside function which is unity for a positive argument and zero for a negative one. The arguments of the Heaviside functions cause the last terms to be included only for active exciton classes. Pairing, shell structure and isospin conservation all modify $E_{\rm th}$, as discussed later.

The state densities of Eq. (2.3) were derived for an infinitely deep potential well and are multiplied by a correction factor, $f_{\rm fwd}(n,h,V)$, which accounts for the effects of the finite depth V of the potential well in limiting the excitation energy that can be carried by a hole degree of freedom. The well depth is measured relative to the Fermi level. When all the interactions occur inside the main volume of the nucleus, then $f_{\rm fwd}(n,h,V)$ has the approximate form

$$f_{\rm fwd}(n,h,E,V) = 1 + \sum_{i=1}^{h} (-1)^i \binom{h}{i} \left(\frac{E-iV}{E}\right)^{n-1} \Theta(E-iV) \tag{2.7}$$

The full well depth is taken to be $V = V_0 = 38$ MeV by default. In the main reaction calculations, Eq. (2.7) is used and finite well depth corrections are applied only for states with $h = 1$ or 2, formed in either the first or second pair creation interaction. For direct nucleon transfer reactions, however, values of h up to 6 may be needed when multi-nucleon pickup occurs and the simultaneous excitation of additional particle-hole pairs is allowed, so the most general form of the finite well depth correction is given here.

2.3. Surface Effects

There is evidence that the initial interaction between a projectile and a target nucleon is frequently localized near the nuclear surface. When this happens, the local well depth is less than the central depth V_0. In this case, the finite well depth correction is averaged over a range of depths centered about the average effective value, V_1, whenever the average is not too close to one of the physical limits. (Here the subscript 1 refers to the well depth at the location of the first interaction.) This average is denoted $\langle f_{\rm fwd}(n,h,E,V_0,V_1)\rangle$. In PRECO the averaging is carried out whenever V_i is in the range 0.5 MeV $\leq V_1 \leq (V_0 - 0.5$ MeV). The assumed distribution or weighting function is [KA85]

$$\begin{aligned}\phi(V,V_i) &= \left[1+\exp\left(\frac{V-V_1}{w}\right)\right]^{-1}\left[1+\exp\left(\frac{V_1-V}{w}\right)\right]^{-1} \\ &= \left[2+\exp\left(\frac{V-V_1}{w}\right)+\exp\left(\frac{V_1-V}{w}\right)\right]^{-1}\end{aligned} \tag{2.8}$$

with

$$w = V_i \left(V_0 - V_i\right) / 2V_0. \tag{2.9}$$

In practice it is typically calculated in nine steps, each of width w. Figure 2.1 shows the functional dependences of w and ϕ.

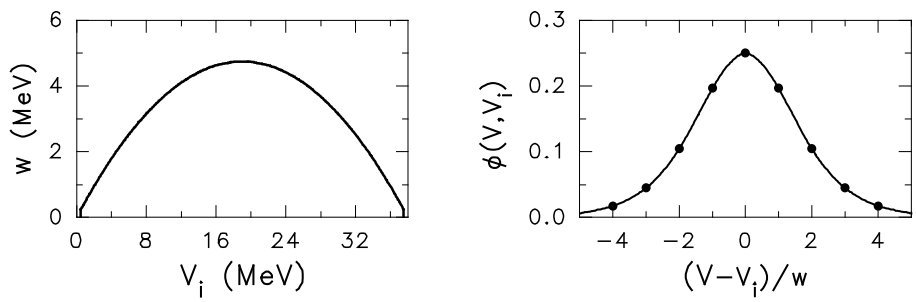

Figure 2.1: *The functional dependences of the averaging function $\phi(V, V_i)$ and its width w. The points in the plot of ϕ show the centers of the averaging bins. This figure is from* [KA00].

A set of simple systematics to describe surface localization of the initial interaction was first included in PRECO-E and was revised in PRECO-2000 following the results of [KA00]. For PRECO-2006 the values for incident neutrons have been further revised, as in [KA04], and are different depending on whether the projectile interacts first with a neutron or a proton. All the values of V_1 were determined empirically from a study of nucleon induced reactions at incident energies up to 100 MeV and on a broad range of targets. They indicate a marked difference in the amount of surface localization for incident protons and neutrons, at least up to 26 MeV, and are parameterized as

$$V_{1\mathrm{p}}(E_{a\mathrm{L}}) = 17 \text{ MeV} \tag{2.10}$$

$$V_{1,\mathrm{nn}}(E_{a\mathrm{L}}) = 7 \text{ MeV} \tag{2.11a}$$

$$V_{1,\mathrm{np}}(E_{a\mathrm{L}}) = \min\left(7 \text{ MeV} + 5.2\, E_{a\mathrm{L}} \left[\frac{N-Z}{A}\right]^2, V_0\right). \tag{2.11b}$$

where $E_{a\mathrm{L}}$ is the laboratory energy of the projectile. The results of these equations are shown in Figs. 2.2 and 2.3.

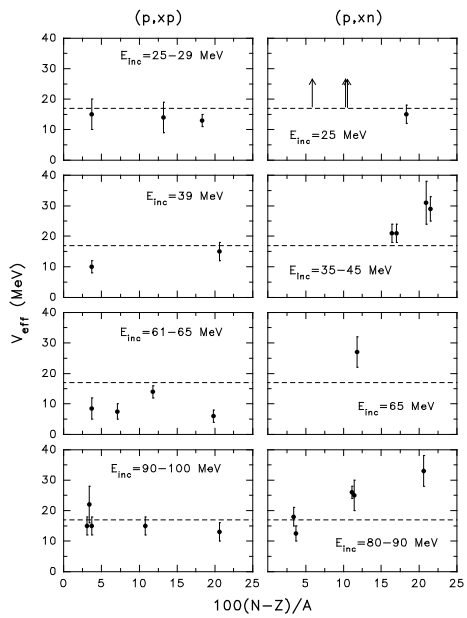

Figure 2.2: *Values of the average effective potential well depth at the point of the first target-projectile interaction for incident protons as determined from the spectral shape of inclusive energy spectra. The results for different incident laboratory energies are shown as a function of the neutron excess of the nucleus. The points show the values determined from energy spectra in the literature, and the dashed lines show the adopted value given in Eq. (2.10). This figure is taken from [KA04].*

Here additional work is clearly needed. First, a form for Eq. (2.11b) that goes smoothly to the limit $V_{\text{eff}} = V_0$ would be desireable. Next, Fig. 2.2 shows that, at some point, it may be appropriate to study additional (p,xn) spectra and introduce the same sort of dependence of the effective well depth on A and E for the pn interaction as is used for incident neutrons with the np interaction. Further, for both nucleon projectiles, the relationship between the apparent effective well depth in the inelastic channel and the normalization of the model for collective excitations needs to be further examined. These two effects are difficult to untangle and may yet imply that the effective well depths inferred from the exchange channels should also be used for the pp and nn interactions. This behavior may mirror the transition from a surface-dominant to volume-dominant imaginary optical model potential as the excitation energy increases [KO04].

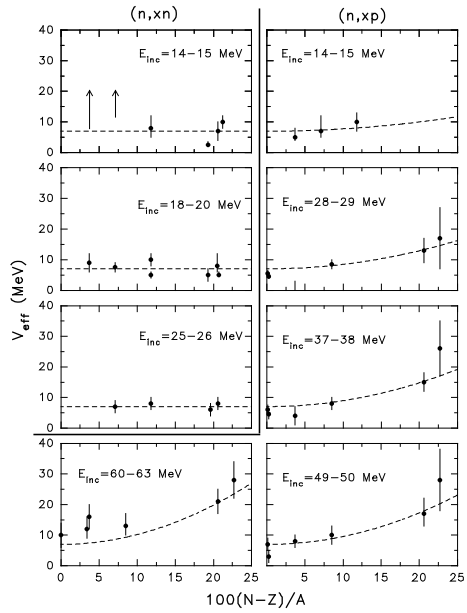

Figure 2.3: *Average effective well depth in the region of the first neutron-target interaction as determined from the spectral shape of inclusive energy spectra. The dashed curves show the adopted systematics of Eqs. (2.11a) and (2.11b). This figure is taken from [KA04].*

Surface localization has not been directly studied for complex projectiles, but approximate information has been inferred from the study of nucleon transfer reactions with complex projectiles [KA05]. The values of V_1 are assumed to depend on the projectile charge so that

$$V_{1\mathrm{d}}(E_{a\mathrm{L}}) = V_{1\mathrm{t}}(E_{a\mathrm{L}}) = V_{1\mathrm{p}}(E_{a\mathrm{L}}) = 17 \text{ MeV} \tag{2.12a}$$

$$V_{1\mathrm{He-3}}(E_{a\mathrm{L}}) = V_{1\alpha}(E_{a\mathrm{L}}) = 25 \text{ MeV}. \tag{2.12b}$$

In PRECO-2000, a value of 17 MeV was used for all complex projectiles. The value of V_2 for all projectiles is taken to be the central well depth, V_0. These parameterizations are the default in PRECO-2006, though values of V_0, $V_{1,\mathrm{an}}$, and $V_{1,\mathrm{ap}}$ can also be read in, where the subscript a denotes the projectile.

2.4. Pairing Correlations

There is as yet no concensus as to the most appropriate method for including the effects of the pairing interaction in exciton model particle-hole state densities. As a result, several options are provided. Basically, if pairing corrections are desired, they may be either an energy shift that is the same for all excitation energies and all configurations in a given nucleus that have both proton and neutron excitons, or they may be based on a simplified model for collective pairing [FU84, KA87]. In most calculations, the choice between these options makes no practical difference in the results.

In either case the important parameters are the ground state pairing condensation energies $C_{\pi 0}$ and $C_{\nu 0}$ for protons and neutrons, respectively. Typically the same values are used in the equilibrium part of the calculations, but different values can be read in. The condensation energies default to values representing the smooth trend of the Gilbert and Cameron [GI65] values. In PRECO the condensation energies are taken to be zero for odd values of Z or N, and positive for even values. They thus represent the energy by which the ground state configuration is lowered by the pairing interaction. Separate energy shifts are applied for shell structure effects as described below. Thus so-called back-shifted corrections, which typically contain both pairing and shell contributions, should not be used.

The constant pairing correction option is based on the implicit assumption that all pairing correlations are washed out at finite excitation energy. The threshold energy of a configuration thus becomes

$$E_{\rm th}^{\rm pair}(p,p_\pi) = E_{\rm th}^{\rm ESM}(p,p_\pi) + C_{\pi 0}(Z)\,\Theta\left(n_\pi - \frac{1}{2}\right) + C_{\nu 0}(N)\,\Theta\left(n_\nu - \frac{1}{2}\right) \quad (2.13)$$

where the Heaviside functions mean that if n_π (n_ν) is zero then $C_{\pi 0}$ ($C_{\nu 0}$) is not subtracted. This is similar to what is often done in the total level densities used in evaporation calculations, except that the Heaviside functions are not needed.

For pairing corrections in the simplified collective model, it is convenient to work with the gap parameters, Δ. These are related to the condensation energies through the relation

$$C_{\pi 0} = \frac{g_{\pi 0}\,(\Delta_{\pi 0})^2}{4} \quad (2.14)$$

and the analogous expression for $C_{\nu 0}$. Using these quantities, the results of [KA87]

give the collective pairing threshold energy for protons as

$$E^{\rm coll}_{{\rm th},\pi}(p,p_\pi,E) = g_{\pi 0}\frac{[\Delta_{\pi 0}(Z)]^2 - [\Delta_\pi(p,p_\pi,E,Z)]^2}{4} + q_\pi\left(\left[\frac{q_\pi}{g_{\pi 0}}\right]^2 + [\Delta_\pi(p,p_\pi,E,Z)]^2\right)^{1/2} \tag{2.15}$$

with a similar expression for neutrons so that

$$E^{\rm coll}_{\rm th}(p,p_\pi,E) = E^{\rm coll}_{{\rm th},\pi}(p,p_\pi,E)\,\Theta\left(n_\pi - \frac{1}{2}\right) + E^{\rm coll}_{{\rm th},\nu}(p,p_\pi,E)\,\Theta\left(n_\nu - \frac{1}{2}\right). \tag{2.16}$$

Strictly speaking, Eq. (2.15) gives the threshold energy for the indicated proton configuration that is associated with the gap parameter Δ_π evaluated at excitation energy E. Thus it has an excitation energy dependence. It is not the *physical* threshold energy for the indicated exciton configuration but is the appropriate "threshold" energy correction to include in the state density formula.

The configuration dependent gap parameters, Δ_π and Δ_ν, are evaluated as in [KA87] except that the role of the passive particles and holes is taken into account by using the gap parameters for the *target* nucleus in the reaction (or more generally for the nucleus with $Z-p_\pi+h_\pi$ protons and $N-p_\nu+h_\nu$ neutrons). Thus

$$\Delta_\pi(p,p_\pi,E,Z) = \Theta(E_\pi - E_{\pi,{\rm phase}})\,\Delta_{\pi 0}(Z_{\rm tar}) \times\left[0.996 - 1.76\left(\frac{n_\pi}{n_{\pi {\rm c}}}\right)^{1.60}\left(\frac{E_\pi}{C_{\pi 0}(Z_{\rm tar})}\right)^{-0.68}\right] \tag{2.17}$$

where the critical exciton number for protons, $n_{\pi {\rm c}}$, is

$$n_{\pi {\rm c}} = 0.792\ g_{\pi 0}\ \Delta_{\pi 0}(Z_{\rm tar}). \tag{2.18}$$

For most states, the excitation energy, E_π, carried by the proton degrees of freedom is assumed to be

$$E_\pi = \frac{n_\pi}{n}\ E, \tag{2.19}$$

while for simple states where finite well depth corrections are calculated it is approximately

$$E_\pi = \frac{E}{n}\left[p_\pi\frac{f_{\rm fwd}(n,h,E,V)}{f_{\rm fwd}(n+1,h,E,V)} + h_\pi\left(\frac{n}{h} - \frac{p}{h}\,\frac{f_{\rm fwd}(n,h,E,V)}{f_{\rm fwd}(n+1,h,E,V)}\right)\right]. \tag{2.20}$$

For $n_\pi/n_{\pi\mathrm{c}} > 0.446$, the quantity $E_{\pi,\mathrm{phase}}$ is the energy of the superconducting/normal phase transition. For $n_\pi/n_{\pi\mathrm{c}} < 0.446$, there is no such phase transition and $E_{\pi,\mathrm{phase}}$ takes on the value of the *physical* threshold energy for the configuration. The appropriate expressions are

$$E_{\pi,\mathrm{phase}} = \begin{cases} C_\pi(Z_{\mathrm{tar}}) \left[3.23\,(n_\pi/n_{\pi\mathrm{c}}) - 1.57\,(n_\pi/n_{\pi\mathrm{c}})^2\right] & \text{for } n_\pi/n_{\pi\mathrm{c}} < 0.446 \\ C_\pi(Z_{\mathrm{tar}}) \left[0.716 + 2.44\,(n_\pi/n_{\pi\mathrm{c}})^{2.17}\right] & \text{for } n_\pi/n_{\pi\mathrm{c}} > 0.446. \end{cases} \tag{2.21}$$

Above $E_{\pi,\mathrm{phase}}$, Δ_π is given by Eq. (2.17), while below $E_{\pi,\mathrm{phase}}$ it is taken to be zero (though technically Δ_π is not defined below the threshold energy).

If both Δ_π and Δ_ν are zero, then Eq. (2.16) reduces to Eq. (2.13), while if both $\Delta_{\pi 0}$ and $\Delta_{\nu 0}$ are also zero then the corresponding C's are zero and Eq. (2.13) reduces to the usual ESM threshold energy.

2.5. Shell Structure Corrections

The shell corrections in PRECO-2006 are unchanged from those in PRECO-2000 and are calculated in the shell-shifted equi-spacing model or S^2-ESM using the formalism of [KA95]. In this model, whenever a shell closure is to be taken into account, a shell gap is introduced into the ESM set of single particle states at the appropriate position relative to the Fermi energy, as shown in Fig. 2.4. The single particle states that would normally fall inside the gap are shifted in energy, with half of them being piled up in a degenerate level below the gap and half piled up above the gap. The threshold energy for the affected type of nucleons is then reevaluated in the shell-shifted scheme, and average effective single particle state densities are calculated for particles and holes of this type. In practice, the full S^2-ESM state densities are used only for a closed-shell configuration. As N or Z moves away from a shell closure, the shell effects are assumed to wash out gradually, so that weighted averages of the shell-corrected and ESM values for the threshold energy and for the single particle state densities are used.

The new parameters that must be specified are the magic numbers, Z_{mag} and N_{mag}, (only the one closest to the Fermi level is considered) and the widths of the shell gaps, D_π and D_ν. It is also useful for the discussion below to define several derivative variables. The ensuing discussion is given in terms of the proton variables. The corresponding neutron variables simply have the subscript π replaced

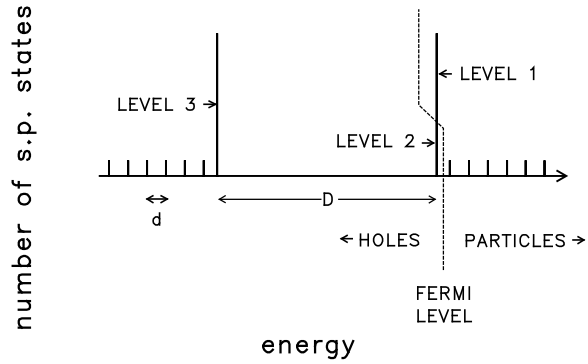

Figure 2.4: *Schematic diagram of the single particle states in the shell-shifted equi-spacing model. The full vertical lines show the single particle states, D is the width of the shell gap, and $d = 1/g_0$ is the single particle spacing in the ESM. The dotted line shows the position of the Fermi level for N or Z just above a magic number. It divides the degenerate level above the gap into two parts, one accessible to the particle degrees of freedom and the other accessible to the holes. For a closed shell configuration, the Fermi level would be in the middle of the gap. This figure is taken from [KA95].*

by ν and the quantity Z replaced by N. The first such variable is

$$I_\pi = |Z - Z_{\text{mag}}| \tag{2.22}$$

which indicates how close to the closed shell the current nucleus is. The quantity

$$M_\pi = \text{integer}\left(\frac{D_\pi + d_\pi}{2d_\pi}\right) \tag{2.23}$$

gives the degeneracy of the piled up levels at the top and bottom of the gap, where $d_\pi = 1/g_{\pi 0}$ is the ESM level spacing. Finally, when $I_\pi > M_\pi$, the Fermi level is outside the gap and its degenerate levels. In this case it is useful to define

$$\alpha_\pi = \min(q_\pi, |I_\pi - M_\pi|) \tag{2.24}$$

which determines how many ESM states between the gap and the Fermi level enter into the calculation of the configuration's threshold energy.

The basic state density formula in the S^2-ESM is the same as the usual ESM formula of Eq. (2.3) except that configuration-dependent single particle state densities are used. The new formula is

$$\omega_{S^2-\mathrm{ESM}}(p,p_\pi,E) = \frac{[g_\pi(p,p_\pi,E)]^{p_\pi}\left[g_{(\pi)}(p,p_\pi,E)\right]^{h_\pi}}{p_\pi!\;h_\pi!}\;\frac{[g_\nu(p,p_\pi,E)]^{p_\nu}\left[g_{(\nu)}(p,p_\pi,E)\right]^{h_\nu}}{p_\nu!\;h_\nu!} \times \frac{[E-A(p,p_\pi,E)]^{n-1}}{(n-1)!} \tag{2.25}$$

where subscripts in parentheses refer to hole degrees of freedom.

2.5.1. The Pauli correction function

The Pauli correction function has the same form as previously, in Eq. (2.4), but here the threshold energy of the shell-shifted configuration is used. It is given by

$$E_{\mathrm{th}}^{S^2-\mathrm{ESM}}(p,p_\pi) = E_{\mathrm{th},\pi}^{S^2-\mathrm{ESM}}(p,p_\pi) + E_{\mathrm{th},\nu}^{S^2-\mathrm{ESM}}(p,p_\pi) \tag{2.26}$$

where the proton part has the form

$$\begin{aligned} E_{\mathrm{th},\pi}^{S^2-\mathrm{ESM}}(p,p_\pi) = &\left\{(q_\pi - |M_\pi - I_\pi|)\,\frac{2M_\pi\,d_\pi - D_\pi}{2}\right. \\ &\left. + (q_\pi - |M_\pi - I_\pi|)^2\,\frac{d_\pi}{2}\right\}\Theta\left(q_\pi - |M_\pi - I_\pi| - \frac{1}{2}\right) \\ &+ \left\{(q_\pi - (M_\pi + I_\pi))\,\frac{2M_\pi\,d_\pi - D_\pi}{2}\right. \\ &\left. + (q_\pi - (M_\pi + I_\pi))^2\,\frac{d_\pi}{2}\right\}\Theta\left(q_\pi - (M_\pi + I_\pi) - \frac{1}{2}\right) \\ &+ (q_\pi - I_\pi)\,D_\pi\,\Theta\left(q_\pi - I_\pi - \frac{1}{2}\right) + \alpha_\pi(2q_\pi - \alpha_\pi)d_\pi\,\Theta\left(I_\pi - M_\pi - \frac{1}{2}\right) \end{aligned} \tag{2.27}$$

and the neutron form is analogous. The inclusion of the $-\frac{1}{2}$ in the Heaviside function avoids the ambiguity if the argument is zero.

2.5.2. Effective single particle state densities

The effective single particle state densities were chosen to reproduce the exact-counting state densities in the S^2-ESM as faithfully as possible. The scheme

is described in [KA95], where comparisons between calculated and exact state densities in the S^2-ESM are given. The work was approached in a step-wise fashion. First the closed-shell configurations were studied, beginning with state densities with only one active class of excitons and moving up to those with multiple classes. Then various near-shell cases were examined, again beginning with only one active exciton class. This required modifications to the closed-shell prescription whenever excitons are excited across the shell gap with increasing excitation energy. Final adjustments to the scheme were made to account for what were termed 'highly constrained' cases: those in which all or all but one or two excitons are located between the Fermi level and a shell gap at threshold. The resulting scheme was tested on so called 'mixed' cases where the shell structure is different in the proton and neutron single particle states. No closed form equations were found that could describe the behavior of the effective single particle state densities, but a methodology or algorithm was arrived at.

The basic algorithm chosen for the effective single particle (s.p.) states for a single class i of excitons is

$$\begin{aligned} g_i^{\mathrm{S}^2-\mathrm{ESM}}(p, p_\pi, E) &= g_{i0} \frac{\text{avg. number of s.p. states accessible, } \mathrm{S}^2-\mathrm{ESM}}{\text{avg. number of s.p. states accessible, ESM}} \\ &= g_{i0} \frac{N_{\mathrm{sh},i}}{N_{\mathrm{ESM},i}}. \end{aligned} \tag{2.28}$$

The denominator is easily evaluated as

$$N_{\mathrm{ESM},i} = n_i + \frac{g_{i0}\, E_x(p, p_\pi)}{n-1} \tag{2.29}$$

where n_i is the number of excitons (p_π, h_π, p_ν, or h_ν) in class i (and thus the number of s.p. states accessible to the class at threshold), and $E_x = E - E_{\mathrm{th}}^{\mathrm{S}^2-\mathrm{ESM}}$ is the energy above configuration threshold in the S^2-ESM. The first term counts the single particle states occupied at threshold, while the second is the average number of additional states accessible at energy E. The denominator $n-1$ was determined empirically. The second term also occurs in the numerator of Eq. (2.28) so that it is convenient to define it as

$$N_{\mathrm{E}i}(p, p_\pi) = \frac{g_{i0}\, E_x(p, p_\pi)}{n-1} \tag{2.30}$$

which is the same for particle and hole degrees of freedom.

The results for the numerator in Eq. (2.28) are more complicated. In the rest of this section they are given for the proton single particle states while similar results apply for the neutron single particle states. It is assumed that $Z \geq Z_{\rm mag}$ (and, when the proton results depend on both configurations, that $N \geq N_{\rm mag}$). If $Z < Z_{\rm mag}$ (or $N < N_{\rm mag}$) then the roles of proton (neutron) particles and holes are reversed. For the two classes of proton excitons, the numerator of Eq. (2.28) is

$$N_{{\rm sh},\pi} = N_{{\rm th},\pi} + C_{1\pi}(E) + N_{{\rm E}\pi}(p, p_\pi) - \Delta N_a - \Delta N_b, \tag{2.31a}$$

$$N_{{\rm sh},(\pi)} = N_{{\rm th},(\pi)} + C_{2\pi}(E) + C_{3\pi}(E) + N_{{\rm E}\pi}(p, p_\pi) - \Delta N_a - \Delta N_b. \tag{2.31b}$$

Here the $N_{{\rm th},i}$ give the number of non-degenerate single particle states accessible at threshold, the $C_{j\pi}$ give the contributions from the corresponding degenerate levels using the numbering shown in Fig. 2.4 on page 19, and the ΔN give corrections to $N_{\rm E}$ when excitons are excited across a shell gap. The quantity ΔN_a seems to reflect the excitation energy tied up in exciting *both* neutrons and protons across shell gaps, while the physical origin of ΔN_b is less clear though it may relate to some interplay between combinatorials in degenerate levels 2 and 3. The forms of the different contributions to Eq. (2.31) are discussed below.

2.5.3. Contributions from the degenerate levels

The $C_{j\pi}$ values are calculated by taking account of the average number of excitons in the jth proton degenerate level at a given excitation energy. If there are $M_{j\pi}$ single particle states in this level and an average of $\mu_{j\pi}$ proton degrees of freedom in it, then the average effective number of accessible single particle states is

$$C_{j\pi}(E) = \begin{cases} M_{j\pi} & \text{for } 0 < \mu_{j\pi}(E) \leq 1 \\ \mu_{j\pi}(E)\binom{M_{j\pi}}{\mu_{j\pi}(E)}^{1/\mu_{j\pi}(E)} & \text{for } 1 < \mu_{j\pi}(E) \leq M_{j\pi}. \end{cases} \tag{2.32}$$

Because the average occupation numbers, $\mu_{j\pi}$, are often non-integers, the factorials in the binomial are evaluated using Sterlings approximation with a correction factor that is important for low x

$$x! \cong \sqrt{2\pi x}\,\left(\frac{x}{e}\right)^x \left[1 + \frac{1}{12x}\right]. \tag{2.33}$$

Earlier versions of PRECO used a denominator of $12x - 1$ in the correction term, but the present form is slightly more accurate. The occupation numbers, $\mu_{j\pi}$,

are estimated by making the following assumptions that tend to produce larger contributions from the degenerate levels:

- As the excitation energy increases, the occupation of a degenerate level tends toward $M_j/2$ to the extent possible while still leaving at least one exciton in the corresponding class to carry random amounts of excitation energy. This maximizes the value of the binomial in Eq. (2.32).

- If there are not enough excitons in the class to maximize both levels 2 and 3 when both are active, then level 3 is preferentially maximized at higher energies since it is higher in excitation and has the larger degeneracy.

- Initially it is assumed that $|\mu_j(E) - \mu_j(E_{\rm th})|$ is the maximum possible (until the desired limit is reached) based on the average share of $E_x(p, p_\pi)$ that would be ascribed to the excitons in the 'source' states. Normally for excitons of class i this would be $n_i E_x(p, p_\pi)/n$. In the near-shell case where cross-gap excitations are possible, the number of excitons, $\Delta_{g\pi}$ and/or $\Delta_{g\nu}$, excited across the gap is first calculated using this energy. Then the emptying of levels 1 and 3 (which entail no further gap crossings) is calculated using $E_x - \Delta_{g\pi} D_\pi - \Delta_{g\nu} D_\nu$ in place of E_x and $n_{\rm f} + \Delta_{g\pi} + \Delta_{g\nu}$ in place of n to determine the average energy available to the source excitons. Here $n_{\rm f}$ is the number of excitons that are 'free' (*i.e.* not constrained to lie between the Fermi level and a shell gap) at configuration threshold.

- For protons when $Z > Z_{\rm mag}$, if $h_\pi > Z - Z_{\rm mag}$, then level 2 is maximally occupied at threshold and there are excitons above the gap which would tend to block cross gap transitions. In this case $\Delta_{g\pi}$ is reduced by a factor of $\max(1 - |Z - Z_{\rm mag}|\, d_\pi/D_\pi, 0.5)$. The limitation of this reduction factor to a value of 0.5 has not been tested. A similar reduction applies for $p_\pi > |Z - Z_{\rm mag}|$ when $Z < Z_{\rm mag}$, and analogous results apply for the neutron single particle states.

- If levels 1 and/or 3 are overpopulated at threshold relative to their limiting value and if the limiting value is less than $M_j/2$, then depopulation is slowed by a factor of 0.75 unless this is the only active class of excitons.

The estimates of $C_{1\pi}$ and $C_{3\pi}$ from Eq. (2.32) are also reduced if there are less than two excitons in the pertinent class that are above the shell gap. Physically this reduction comes from the fact that at least one exciton in the class should be available to carry a random amount of the available excitation energy.

2.5.4. Corrections to N_E due to excitations across a shell gap

The ΔN quantities in Eq. (2.31) are evaluated empirically and both of them include contributions from both proton and neutron gap crossings so that

$$\Delta N_a = \left(h_\pi \Delta N_{a\pi} + h_\nu \Delta N_{a\nu}\right)/n \tag{2.34}$$

and similarly for ΔN_b. [Here it is assumed that $N \geq N_{\rm mag}$. Otherwise p_ν would be used instead of h_ν. Similar considerations apply for proton degrees of freedom.] Both ΔN_a and ΔN_b are zero unless the nucleus has a near-shell configuration for either protons or neutrons or both. The reason is that excitons are not excited across a shell gap in closed-shell or no-shell configurations. Evaluating the four quantities $\Delta N_{a\pi}$, $\Delta N_{a\nu}$, $\Delta N_{b\pi}$, and $\Delta N_{b\nu}$ is fairly complicated, and the considerations will again be discussed in terms of the proton single particle states.

Given the fact that $\Delta N_{a\pi}$ and $\Delta N_{a\nu}$ reflect the excitation energy tied up in gap crossings, they tend to increase linearly with E_x in each of several energy domains. For $\Delta N_{a\pi}$, the initial slope is determined by $h_{\pi\rm f}$, the number of "free" proton holes at threshold. The slope decreases in each succeeding energy domain until a limiting value of $\Delta N_{a\pi} = D_\pi h_{\pi\rm tr}/h_\pi$ is reached, where $h_{\pi\rm tr}$ is the number of proton holes "trapped" between the Fermi level and a shell gap at threshold. This limit is reduced if $2h_{\pi\rm tr} + h_{\nu\rm tr} > 3$ and at least one other class of excitons has free excitons at threshold (*i.e.* if $n_{\rm f} > h_{\pi\rm f}$).

As already mentioned, the physical origin of ΔN_b is not entirely clear. For $h_{\pi\rm f} < M_{3\pi} - 1$, the proton part, $\Delta N_{b\pi}$, is positive at low E_x and decreases to zero, while for $h_{\pi\rm f} \geq M_{3\pi} - 1$ it is negative and proportional to E_x with a limiting value of -1. This contribution is reduced by the same factor as $\Delta N_{a\pi}$ and under the same conditions.

The quantities ΔN_a and ΔN_b have to be evaluated separately since ΔN_a is used by itself in evaluating state densities for the constrained cases discussed next.

2.5.5. Constrained cases

The above prescriptions for $N_{\rm sh,(\pi)}$ are modified for cases that are "highly constrained"; that is when most or all of the excitons are trapped. It is these modifications that reproduce most of the sharp jumps and plateaus seen at low excitation energies in the exact counting S^2-ESM state densities for these configurations. There are two types of constraints. The first applies only to the single class of excitons being considered and occurs when all of its excitons are trapped at the

current excitation energy. The other type relates to the configuration as a whole and occurs for proton holes if the following three conditions are fulfilled:

- $h_{\pi\mathrm{f}} \leq 1$ and $h_{\nu\mathrm{f}} \leq 1$,
- $p_\pi + p_\nu = 0$ (*i.e.* no excitons in the unconstrained classes), and
- $\{h_{\pi\mathrm{f}} + \text{integer}\left[\left(E_x \pm d_\pi/2\right)/D_\pi\right]\} < \min(2m, h_\pi + 1 - h_{\nu\mathrm{f}})$ where the plus sign applies for $h_{\pi\mathrm{f}} = h_{\nu\mathrm{f}} = 1$, and the minus sign applies otherwise.

Here, as in Sect. 2.2 on page 11, m is the number of active exciton classes. The three conditions show that both types of constraints disappear as the excitation energy increases and more excitons can be excited across the shell gaps so that $h_{\pi\mathrm{f}}$ and $h_{\nu\mathrm{f}}$ both increase.

The constraints act differently when E_x is within half a single particle spacing of an integer multiple (including zero) of D_π/d_π than elsewhere. They affect virtually all of the terms in Eq. (2.31b). In the extreme case where there are no free excitons at threshold, they set the state density to zero between the configuration ground state energy and the energy required to excite the first exciton across a shell gap. Clearly this is the physical result since there are no free excitons to carry the excitation energy.

2.5.6. Washing out of shell effects

The above shell corrections are derived assuming that the shell gaps are as distinct and effective in near-shell nuclei as in closed-shell configurations. It has been shown [KA95a, KA99], however, that improved agreement with experiment can be obtained if the shell effects are assumed to wash out or lose their effectiveness as N or Z moves away from a magic number. In particular, the results of [KA99] suggest that the range over which this washout occurs is about D/d or roughly twice the degeneracy of the piled up levels at the top and bottom of the gap. In general, the range of mass numbers over which the shell effects wash out is given as $f_{\mathrm{shell}}D/(2d)$, so that the indicated value of f_{shell} is 2. Other values can be read in.

The quantity calculated is the fraction of the shell effects remaining, and it is calculated separately for the proton and neutron shell effects of the particular nucleus in question. Both linear and square root dependences were investigated

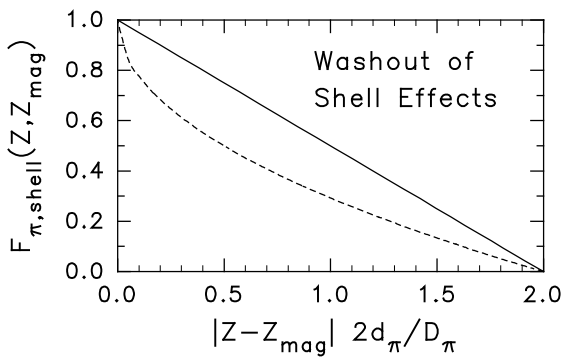

Figure 2.5: *The washout of proton shell effects as the Z of the nucleus moves away from the closed shell value of Z_{mag}. The solid line shows the linear washout currently used in preequilibrium calculations, while the dashed curve shows the more rapid square root washout of Eq. (2.35) which has been retained for the equilibrium calculations.*

phenomenologically. The square root dependence, which for protons has the form

$$F_{\pi,\mathrm{shell}} = 1 - \left(\frac{|Z - Z_{\mathrm{mag}}|}{f_{\mathrm{shell}} D_\pi/(2d_\pi)} \right)^{1/2}, \tag{2.35}$$

was indicated in [KA99] as being most suitable for the equilibrium components (discussed later) and was adopted for the preequilibrium components as well, but more recent work [KA06], in which extra residual configurations were included in the exciton model calculations, indicate a slower linear dependence for the preequilibrium calculations. For protons the fraction of the shell effects remaining then has the form

$$F_{\pi,\mathrm{shell}} = 1 - \frac{|Z - Z_{\mathrm{mag}}|}{f_{\mathrm{shell}} D_\pi/(2d_\pi)}. \tag{2.36}$$

The reason that a more rapid washout is needed at equilibrium is that the S^2-ESM values are all calculated for a closed-shell configuration so that the washout factor must account not only for the disappearance of the shell structure in the single particle states but also for the difference between the actual N or Z and the corresponding closed-shell values. The values of $F_{\pi,\mathrm{shell}}$ obtained with both the linear and square root washout factors are shown in Fig. 2.5.

The shell corrected values of the threshold energy and the neutron and proton single particle state densities are now all given by a weighted average between the

ESM and S^2-ESM values. Thus

$$E_{\rm th}^{\rm shell}(p,p_\pi) = F_{\pi,\rm shell}\, E_{{\rm th},\pi}^{\rm S^2-ESM}(p,p_\pi) + (1-F_{\pi,\rm shell})\, E_{{\rm th},\pi}^{\rm ESM}(p,p_\pi)$$
$$+\; F_{\nu,\rm shell}\, E_{{\rm th},\nu}^{\rm S^2-ESM}(p,p_\pi) + (1-F_{\nu,\rm shell})\, E_{{\rm th},\nu}^{\rm ESM}(p,p_\pi) \qquad (2.37)$$

and

$$g_i(p,p_\pi,E) = F_{i,\rm shell}\, g_i^{\rm S^2-ESM}(p,p_\pi,E) + (1-F_{i,\rm shell})\, g_{i0} \qquad (2.38)$$

where i is π, (π), ν,or (ν), though the washout factor is the same for particle and hole degrees of freedom.

2.6. States with Good Isospin

The gradual mixing of isospin is not explicitly handled in PRECO, but calculations can be run assuming either complete mixing or complete conservation of the isospin quantum number during the preequilibrium part of the calculations. If it is conserved during the preequilibrium part, then the amount of mixing to be assumed at equilibrium is also needed as input. For isospin conserved calculations, state densities for particle-hole configurations with good isospin are needed. These have been taken from [KA93] and involve two changes to the usual ESM state density: the threshold energy is increased by the symmetry energy requirements, and a correction factor, $f_{\rm iso}(p,p_\pi,T,T_{\rm z})$, is included. Here T is the isospin quantum number of the states and $T_z = (N-Z)/2$ is its z-component. The situation is far more complicated than for total state densities because, as shown in Fig. 2.6, there are three different types of isospin flip transitions (that convert a neutron into a proton or *vice versa*) and these do not always conserve the particle-hole quantum numbers in the two-component exciton model, though they do in the one-component model.

The threshold in the equi-spacing model with isospin conservation is now

$$E_{\rm th}^{\rm ESM}(p,p_\pi,T,T_{\rm z}) = E_{\rm th}^{\rm ESM}(p,p_\pi) + E_{\rm sym}(T,T_z). \qquad (2.39)$$

A similar adjustment is made in the threshold energies evaluated in the shell-shifted ESM or when pairing corrections are included.

The correction function $f_{\rm iso}(p,p_\pi,T,T_z)$ has a different form for each allowed value of $T-T_z$. In calculations for light particle reactions, at most three isospin values need to be considered in a given nucleus: $T=|T_z|$, $|T_z|+1$, and $|T_z|+2$. The corresponding correction functions are given in terms of the ground state

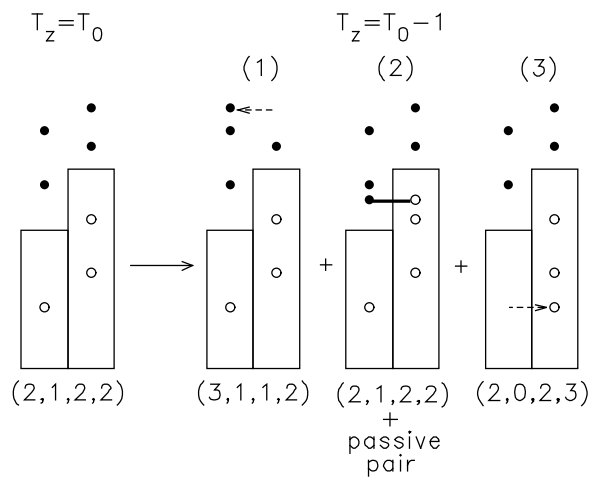

Figure 2.6: *Schematic representation of the components in the $T_z = T_0 - 1$ isobaric analog of a $(p_\pi, h_\pi, p_\nu, h_\nu) = (2, 1, 2, 2)$, $T = T_0$ configuration in a $T_z = T_0$ nucleus. The blocks indicate single particle states occupied in the ground state of this nucleus, with energy increasing in the vertical direction. The excited particles are denoted as solid circles above the blocks and the excited holes as open circles inside the blocks. This figure is taken from Ref. [KA93].*

isospin of the target nucleus, which is denoted as T_e. The use of the target value automatically corrects for the presence of passive particles and holes. The actual forms of these equations are quite complex, but can be simplified somewhat by defining additional quantities.

The first such quantity gives the effective excitation energies, E_i, for states with isospin $T = |T_z| + i$

$$E_i = E - E_{\text{sym}}\left(|T_z| + i, T_z\right). \tag{2.40}$$

The remaining quantities are related to the relative probabilities of the three possible types of isospin flip, shown in Fig. 2.6. Assuming that $N > Z$, the relative weights for the three types of isospin flips are approximately p_ν, $B(p_\pi, h_\nu, E_i)$, and h_π, respectively. The quantity B has a value of $2(T_e + i)$ (the number of neutrons in the neutron excess region) corrected for the number of proton particle and neutron hole degrees of freedom which will, on average, fall in that region and

thus block the potential isospin flips. It has the form

$$B(p_\pi, h_\nu, E_i) = 2(T_e + i) - (p_\pi + h_\nu) f_2(p, p_\pi, E_i) + \frac{p_\pi h_\nu}{2T_e} \left[f_2(p, p_\pi, E_i) \right]^2 \quad (2.41)$$

where

$$f_2(p, p_\pi, E_i) = 1 - \left[\frac{E_i - A(p, p_\pi) - 2(T_e + i)/g_a}{E_i - A(p, p_\pi)} \right]^{n-1} . \quad (2.42)$$

The quantity f_2 represents the fraction of the n excitons in the full configuration with an excitation energy between zero and $2(T_e + i)/g_a$. Proton particle and neutron hole degrees of freedom in this energy range will be located in the single particles states in the neutron excess region. Here g_a is the average single particle state density, $g_a = (g_{\pi 0} + g_{\nu 0})/2$. The total number of isospin flip possibilities in the nucleus where T is the ground state isospin is thus

$$C(p_\pi, h_\pi, p_\nu, h_\nu, E_i) = B(p_\pi, h_\nu, E_i) + p_\nu + h_\pi \quad (2.43)$$

where for clarity the particle-hole labels are given explicitly in this and the following equations. The weighting factors for the different types of single isospin flips are thus

$$X_1(p_\pi, h_\pi, p_\nu, h_\nu, E_1) = \frac{p_\nu}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_1)} \quad (2.44a)$$

$$X_2(p_\pi, h_\pi, p_\nu, h_\nu, E_1) = \frac{B(p_\pi, h_\nu, E_1)}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_1)} \quad (2.44b)$$

$$X_3(p_\pi, h_\pi, p_\nu, h_\nu, E_1) = \frac{h_\pi}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_1)} \quad (2.44c)$$

and those for double isospin flips are

$$X_{11}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{p_\nu}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{p_\nu - 1}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45a}$$

$$X_{12}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{p_\nu}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{B(p_\pi, h_\nu, E_2)}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45b}$$

$$X_{13}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{p_\nu}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{h_\pi}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45c}$$

$$X_{22}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{B(p_\pi, h_\nu, E_2)}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{B(p_\pi, h_\nu, E_2) - 1}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45d}$$

$$X_{23}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{B(p_\pi, h_\nu, E_2)}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{h_\pi}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45e}$$

$$X_{33}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = \frac{h_\pi}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \frac{h_\pi - 1}{C(p_\pi, h_\pi, p_\nu, h_\nu, E_2) - 1} \tag{2.45f}$$

$$X_{ij}(p_\pi, h_\pi, p_\nu, h_\nu, E_2) = X_{ji}(p_\pi, h_\pi, p_\nu, h_\nu, E_2). \tag{2.45g}$$

Finally there are three Y functions, corresponding to the three types of isospin flips:

$$Y_1(p_\pi, h_\pi, p_\nu, h_\nu, E_i) = \frac{p_\pi + 1}{p_\nu + h_\pi + 2(T_e + i)} \frac{g_{\nu 0}}{g_{\pi 0}} \tag{2.46a}$$

$$Y_2(p_\pi, h_\pi, p_\nu, h_\nu, E_i) = \frac{B(p_\pi, h_\nu, E_i)}{p_\nu + h_\pi + 2(T_e + i)} \frac{(p_\pi + 1)(h_\nu + 1)n(n+1)}{g_{\pi 0}\ g_{\nu 0}\ \left[E - A(\text{main})\right]^2} \tag{2.46b}$$

$$Y_3(p_\pi, h_\pi, p_\nu, h_\nu, E_i) = \frac{h_\nu + 1}{p_\nu + h_\pi + 2(T_e + i)} \frac{g_{\pi 0}}{g_{\nu 0}}, \tag{2.46c}$$

where $A(\text{main})$ is the ESM Pauli correction for the main configuration whose T-dependent state density is being calculated.

Using these factors, the approximate expressions for the isospin dependent state density correction functions are given in terms of a variety of T-mixed state densities. These are all evaluated in PRECO using pure ESM state densities with no pairing, shell structure or finite well depth corrections. The form of the correction factor f_{iso}, depends on the value of $T - T_z$ and increases in complexity as this

value increases. For the ground state isospin it has the form

$$f_{\rm iso}(p_\pi,h_\pi,p_\nu,h_\nu,E,T_z,T_z) = 1 - \Big[Y_1(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_1) \\ +Y_2(p_\pi-1,h_\pi,p_\nu,h_\nu-1,E_1) + Y_3(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_1)\Big] \\ \times \frac{\omega(p_\pi,h_\pi,p_\nu,h_\nu,E_1)}{\omega(p_\pi,h_\pi,p_\nu,h_\nu,E)} \tag{2.47}$$

while for the two higher isospins it becomes

$$f_{\rm iso}(p_\pi,h_\pi,p_\nu,h_\nu,E,T_z+1,T_z) = \omega(p_\pi,h_\pi,p_\nu,h_\nu,E_1)^{-1} \\ \times \Big[X_1(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_1)\ \omega(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_1) \\ + X_2(p_\pi,h_\pi,p_\nu,h_\nu,E_1)\ \omega(p_\pi,h_\pi,p_\nu,h_\nu,E_1) \\ +X_3(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_1)\ \omega(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_1)\Big] \\ -\Big\{X_1(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_1)\frac{p_\pi}{p_\nu+1}\frac{g_{\nu0}}{g_{\pi0}}\Big[Y_1(p_\pi-2,h_\pi,p_\nu+2,h_\nu,E_2) \\ +Y_2(p_\pi-2,h_\pi,p_\nu+1,h_\nu-1,E_2) + Y_3(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_2)\Big] \\ + X_2(p_\pi,h_\pi,p_\nu,h_\nu,E_1)\Big[Y_1(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_2) \\ +Y_2(p_\pi-1,h_\pi,p_\nu,h_\nu-1,E_2) + Y_3(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_2)\Big] \\ + X_3(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_1)\frac{h_\nu}{h_\pi+1}\frac{g_{\pi0}}{g_{\nu0}}\Big[Y_1(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_2) \\ +Y_2(p_\pi-1,h_\pi+1,p_\nu,h_\nu-2,E_2) + Y_3(p_\pi,h_\pi+2,p_\nu,h_\nu-2,E_2)\Big]\Big\} \\ \times \frac{\omega(p_\pi,h_\pi,p_\nu,h_\nu,E_2)}{\omega(p_\pi,h_\pi,p_\nu,h_\nu,E_1)}, \tag{2.48}$$

and

$$
\begin{aligned}
&f_{\rm iso}(p_\pi,h_\pi,p_\nu,h_\nu,E,T_z+2,T_z)=\omega(p_\pi,h_\pi,p_\nu,h_\nu,E_2)^{-1}\\
&\quad\times\Big[X_{11}(p_\pi-2,h_\pi,p_\nu+2,h_\nu,E_2)\;\omega(p_\pi-2,h_\pi,p_\nu+2,h_\nu,E_2)\\
&\qquad+2X_{12}(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_2)\;\omega(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_2)\\
&\qquad+2X_{13}(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_2)\;\omega(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_2)\\
&\qquad+X_{22}(p_\pi,h_\pi,p_\nu,h_\nu,E_2)\;\omega(p_\pi,h_\pi,p_\nu,h_\nu,E_2)\\
&\qquad+2X_{23}(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_2)\;\omega(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_2)\\
&\qquad+\;X_{33}(p_\pi,h_\pi+2,p_\nu,h_\nu-2,E_2)\;\omega(p_\pi,h_\pi+2,p_\nu,h_\nu-2,E_2)\Big]\\
&-\Bigg\{X_{11}(p_\pi-2,h_\pi,p_\nu+2,h_\nu,E_2)\frac{p_\pi\,(p_\pi-1)}{(p_\nu+1)(p_\nu+2)}\left(\frac{g_{\nu0}}{g_{\pi0}}\right)^2\\
&\qquad+\Big[Y_1(p_\pi-3,h_\pi,p_\nu+3,h_\nu,E_3)\\
&\qquad+Y_2(p_\pi-3,h_\pi,p_\nu+2,h_\nu-1,E_3)+Y_3(p_\pi-2,h_\pi+1,p_\nu+2,h_\nu-1,E_3)\Big]\\
&\quad+2X_{12}(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_2)\frac{p_\pi}{p_\nu+1}\,\frac{g_{\nu0}}{g_{\pi0}}\Big[Y_1(p_\pi-2,h_\pi,p_\nu+2,h_\nu,E_3)\\
&\qquad+Y_2(p_\pi-2,h_\pi,p_\nu+1,h_\nu-1,E_3)+Y_3(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_3)\Big]\\
&\quad+2X_{13}(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_2)\frac{p_\pi}{p_\nu+1}\,\frac{h_\nu}{h_\pi+1}\\
&\qquad\Big[Y_1(p_\pi-2,h_\pi+1,p_\nu+2,h_\nu-1,E_3)\\
&\qquad+Y_2(p_\pi-2,h_\pi+1,p_\nu+1,h_\nu-2,E_3)+Y_3(p_\pi-1,h_\pi+2,p_\nu+1,h_\nu-2,E_3)\Big]\\
&\quad+X_{22}(p_\pi,h_\pi,p_\nu,h_\nu,E_2)\Big[Y_1(p_\pi-1,h_\pi,p_\nu+1,h_\nu,E_3)\\
&\qquad+Y_2(p_\pi-1,h_\pi,p_\nu,h_\nu-1,E_3)+Y_3(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_3)\Big]\\
&\quad+2X_{23}(p_\pi,h_\pi+1,p_\nu,h_\nu-1,E_2)\frac{h_\nu}{h_\pi+1}\,\frac{g_{\pi0}}{g_{\nu0}}\Big[Y_1(p_\pi-1,h_\pi+1,p_\nu+1,h_\nu-1,E_3)\\
&\qquad+Y_2(p_\pi-1,h_\pi+1,p_\nu,h_\nu-2,E_3)+Y_3(p_\pi,h_\pi+2,p_\nu,h_\nu-2,E_3)\Big]
\end{aligned}
$$

$$+ X_{33}(p_\pi, h_\pi + 2, p_\nu, h_\nu - 2, E_2) \frac{h_\nu\,(h_\nu - 1)}{(h_\pi + 1)(h_\pi + 2)} \left(\frac{g_{\pi 0}}{g_{\nu 0}}\right)^2$$

$$\Big[Y_1(p_\pi - 1, h_\pi + 2, p_\nu + 1, h_\nu - 2, E_3)$$

$$+ Y_2(p_\pi - 1, h_\pi + 2, p_\nu, h_\nu - 3, E_3) + Y_3(p_\pi, h_\pi + 3, p_\nu, h_\nu - 3, E_3) \Big] \Big\}$$

$$\times \frac{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E_3)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E_2)} \tag{2.49}$$

Equations (2.47) through (2.49) are valid for reactions in which the nuclei have $N > Z$. For systems with a proton excess or $Z > N$, the roles of the proton and neutron degrees of freedom are reversed.

The symmetry energies are calculated internally using the symmetry energy terms from the Meyers and Swiatecki mass formula [MY66] so that

$$E_{\rm sym}(T, T_z) = \left[\frac{112 \text{ MeV}}{A} - \frac{133 \text{ MeV}}{A^{4/3}}\right] \left(T^2 - T_z^2\right), \tag{2.50}$$

$$E_{\rm sym}(T_z + 1, T_z) = \left[\frac{112 \text{ MeV}}{A} - \frac{133 \text{ MeV}}{A^{4/3}}\right] (2\,|T_z| + 1) \tag{2.51}$$

It is also possible to "comment out" the FORTRAN statements for the second term in square brackets so as to use only the volume surface energy term, but this is usually not indicated. An option in earlier versions of PRECO to allow the symmetry energies to be read in was deleted in PRECO-2000.

2.7. Complete State Density Formula

The modifications to the ESM two-component state densities which account for surface effects, pairing (simple or collective), shell structure, and isospin can be combined to produce the comprehensive formula

$$\omega\,(p, p_\pi, E, T) = \frac{[g_\pi(p, p_\pi, E)]^{p_\pi} \left[g_{(\pi)}(p, p_\pi, E)\right]^{h_\pi}}{p_\pi!\; h_\pi!} \; \frac{[g_\nu(p, p_\pi, E)]^{p_\nu} \left[g_{(\nu)}(p, p_\pi, E)\right]^{h_\nu}}{p_\nu!\; h_\nu!}$$

$$\times \frac{[E - A(p, p_\pi, E, T)]^{n-1}}{(n-1)!} \langle f_{\rm fwd}(n, h, E, V_0, V_i)\rangle \;\; f_{\rm iso}(p, p_\pi, E, T, T_z) \tag{2.52}$$

Here if isospin is mixed, the T label is omitted and $f_{\rm iso}$ is set equal to unity. If more than two interactions have occurred (generally if $h > 2$) then $f_{\rm fwd}$ is set

equal to unity, and if $V_i \cong V_0$ then no average of $f_{\rm fwd}$ is needed and the function is simply given by Eq. (2.7). The Pauli correction function is given by

$$\begin{aligned} A(p,p_\pi,E,T) = E_{\rm th}(p,p_\pi,T) &- \frac{p_\pi^2+h_\pi^2+n_\pi}{4g_{\pi 0}} - \frac{p_\nu^2+h_\nu^2+n_\nu}{4g_{\nu 0}} \\ &+ \frac{\left[\left(p_\pi - \frac{2}{m}\right)\left(p_\pi - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(p_\pi - \frac{1}{2})}{g_{\pi 0}G_\pi(p,p_\pi,E)} \\ &+ \frac{\left[\left(h_\pi - \frac{2}{m}\right)\left(h_\pi - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(h_\pi - \frac{1}{2})}{g_{\pi 0}G_\pi(p,p_\pi,E)} \\ &+ \frac{\left[\left(p_\nu - \frac{2}{m}\right)\left(p_\nu - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(p_\nu - \frac{1}{2})}{g_{\nu 0}G_\nu(p,p_\pi,E)} \\ &+ \frac{\left[\left(h_\nu - \frac{2}{m}\right)\left(h_\nu - \frac{3}{m}\right) + \frac{1}{m}\right]\Theta(h_\nu - \frac{1}{2})}{g_{\nu 0}G_\nu(p,p_\pi,E)}. \end{aligned} \tag{2.53}$$

which is identical to Eq. (2.4) except for the isospin label. The overall threshold energy is

$$E_{\rm th}(p,p_\pi,E,T) = E_{\rm th}^{\rm shell}(p,p_\pi) + E_{\rm th}^{\rm coll}(p,p_\pi,E) + E_{\rm sym}(T,T_z) - E_{\rm th}^{\rm ESM}(p,p_\pi) \tag{2.54}$$

Here the shell corrected threshold energy is given by Eqs. (2.37), (2.36) and (2.27) and reduces to the ESM result if no shell closures are present. Likewise the collective pairing threshold is given by Eqs. (2.15) and (2.16). It is replaced by the normal pairing-corrected ESM threshold of Eq. (2.13) if collective pairing is not used, and either of these results reduces to the simple ESM threshold energy if the condensation energies are both zero. Since two complete threshold energies are thus added, the equi-spacing model result of Eq. (2.5) must be subtracted.

Implicit in Eq. (2.54) is the assumption that shell, pairing, and isospin effects operate independently of one another. This is not correct but is the best one can do at present in a simple model.

3. The Two-Component Exciton Model

Once the particle-hole state densities are in hand, they can be used to derive as well as the rates for the internal transitions that carry the nucleus from one particle-hole configuration to another. The latter are used to describe the equilibration process, while the former are needed to compute the energy spectra of the emitted particles.

3.1. Internal Transition Rates

The interactions which carry the system from one class of particle-hole configuration to another are assumed to be energy-conserving and two-body in nature. Thus the possible transitions involve the creation of a particle-hole pair, the annihilation of a particle-hole pair, or the conversion of a proton pair into a neutron pair or *vice versa*. The rates for these are derived assuming that the main part of the two-body interactions between constituent nucleons in the composite system has already gone into generating the potential well in which the single particle states exist. Thus the interactions causing energy equilibration are residual, and the rates can be derived from time-dependent perturbation theory using the standard relationship $\lambda = (2\pi/\hbar)\,|M|^2\,\omega(\text{accessible})$, where $|M|^2$ is the mean square matrix element for the residual interaction and is multiplied by the average density of final states accessible from a given initial state.

In practice, for the simple, few-exciton states that are responsible for most of the preequilibrium particle emission, pair creation interactions dominate. Exciton exchange is slower and can be treated approximately, while pair annihilation is still slower and can be ignored. Thus calculations in PRECO are done in closed form, considering only pair creation and pair exchange interactions. The four

rates that are needed are

$\lambda_{\pi+}(p, p_\pi, E, T)$	creation of a proton particle-hole pair
$\lambda_{\nu+}(p, p_\pi, E, T)$	creation of a neutron particle-hole pair
$\lambda_{\pi\nu}(p, p_\pi, E, T)$	conversion of a proton pair into a neutron pair
$\lambda_{\nu\pi}(p, p_\pi, E, T)$	conversion of a neutron pair into a proton pair

The pair creation rates, in turn, each have separate components depending on the nature of the initiating exciton.

3.1.1. The mean square matrix elements

The mean square matrix elements used in the exciton model need to be regarded as effective as well as residual in nature. Since the whole approach of the model is phenomenological, the values of the mean square matrix elements may compensate for approximations in other parts of the calculation, and they will be coupled to the values chosen for other model parameters. Thus, for instance, moving from a one-component to a two-component version of the model required a renormalization of the matrix elements by roughly a factor of 8/3 [KA86].

In the two-component exciton model it is necessary to allow for different mean square matrix elements depending on the nature of the two interacting particles. Thus there are really three quantities that need to be considered, $|M_{\pi\pi}|^2$, $|M_{\nu\nu}|^2$, and $|M_{\pi\nu}|^2 = |M_{\nu\pi}|^2$, where the subscripts π and ν again refer to proton and neutron degrees of freedom. Each of these matrix elements is assumed to have the same functional form but a separate normalization constant. The form used in PRECO-2006 has been modified from that cited in the literature. The most recent literature form is [KA05]

$$|M_{ij}|^2 = K_{ij}\ A_a\, A^{-3} \left(\frac{E}{3A_a} + 20.9 \right)^{-3}, \tag{3.1}$$

where A_a is the mass number of the projectile. Except for the initial factor of A_a (which was introduced since PRECO-2000), this form was established for incident nucleon energies up to around 65 MeV. It works reasonably well at 90 MeV and, with the factor of A_a, for equivalent $E_{\rm inc}/A_a$ values for complex projectiles, but the energy dependence may need to be modified at higher energies. In particular, it has been suggested [KO04] that an asymptotic value may be reached at high bombarding energies.

What has been done differently in PRECO-2006 is to replace the A^{-3} dependence in Eq. (3.1) with a $g_0^{-3} = (A/K_g)^{-3}$ dependence, where K_g is the normalization constant for the single particle state density and defaults to $K_g = 15$ MeV. This value of g_0 in terms of K_g is used, even if other single particle state densities are read in and used in calculating the state densities. The new formula for the mean square matrix elements is thus

$$|M_{ij}|^2 = K_{ij}\ A_a\, g_0^{-3} \left(\frac{E}{3A_a} + 20.9 \right)^{-3}, \tag{3.2}$$

where the K_{ij} values will now, obviously, be different. This change was made to reduce the strong coupling between the needed values of K_g and the matrix element normalizations, K_{ij}. The coupling was due in large measure to the three single-particle-state-density factors appearing in the expression for the pair creation rates given below. Two of those factors come from the state density ratio in the first line of Eq. (3.3) and the analogous expression for $\lambda_{\nu+}$. In addition, the new values of K_{ij} have the more natural units of MeV^2, rather than MeV^5 as with the previous formulation. Some coupling between K_g and the K_{ij} remains, because the single particle state densities appear in the and because particle emission competes with the creation of particle-hole pairs. It is the balance between particle emission and pair creation that largely determines the size needed for the $|M_{ij}|^2$.

The normalization constants K_{ij} are read in at the beginning of each input batch file but default to $K_{\pi\pi} : K_{\pi\nu} : K_{\nu\nu} = 2200 : 900 : 900$ MeV^2. These values correspond generally to the values [KA06] of $K_{\pi\pi} : K_{\pi\nu} : K_{\nu\nu} = 7.5 \times 10^6 : 3.0 \times 10^6 : 3.0 \times 10^6$ which, in turn were revised after the release of PRECO-2000 to reflect changes made in the emission rates discussed below. Their overall size is now much less strongly coupled to the size of $g_{\pi 0}$ and $g_{\nu 0}$.

3.1.2. The transition rates

The densities of the accessible final states which are needed to complete the transition rate expressions are derived from the basic ESM two-component state densities given by Eq. (2.3). The corrections for shell structure, pairing, the finite well depth, and isospin conservation are then added in a manner consistent with the physics of the derivation and in a manner that preserves the steady state condition at the equilibrium limit. The transition rates are given here assuming that the configuration label (p, p_π) is again a shorthand for $(p_\pi, h_\pi, p_\nu, h_\nu)$ and refers to

the starting configuration in the interaction. Full configuration designations are sometimes used in the body of the equations for clarity.

The resulting transition rate for creating a proton particle-hole pair is

$$\begin{aligned}\lambda_{\pi+}(p,p_\pi,E,T) = \frac{2\pi}{\hbar}\,\frac{(p_\pi+1)(h_\pi+1)}{2}\,\frac{\omega(p_\pi+1,h_\pi+1,p_\nu,h_\nu,E,T)}{\omega(p_\pi,h_\pi,p_\nu,h_\nu,E,T)} \\ \times\Big\{|M_{\pi\pi}|^2\Big(p_\pi\,g_\pi(p,p_\pi,E)+h_\pi\,g_{(\pi)}(p,p_\pi,E)\Big) \\ +2\,|M_{\pi\nu}|^2\Big(p_\nu\,g_\nu(p,p_\pi,E)+h_\nu\,g_{(\nu)}(p,p_\pi,E)\Big)\Big\} \\ \times\langle f_{\rm fwd}(n,h,E,V_0,V_i)\rangle\;f_{\rm iso}(p_\pi,h_\pi,p_\nu,h_\nu,E,T) \qquad (3.3)\end{aligned}$$

with an analogous expression for $\lambda_{\nu+}$ but with the π and ν subscripts interchanged in the body of the equation. The rate for converting a proton pair into a neutron pair is

$$\begin{aligned}\lambda_{\pi\nu}(p,p_\pi,E,T) = \frac{2\pi}{\hbar}\,|M_{\pi\nu}|^2\,\frac{p_\pi\,h_\pi}{n}\,g_\nu(p,p_\pi-1,E)\,g_{(\nu)}(p,p_\pi-1,E) \\ \times\left(\frac{g_\nu(p,p_\pi-1,E)}{g_\nu(p,p_\pi,E)}\right)^{p_\nu}\left(\frac{g_{(\nu)}(p,p_\pi-1,E)}{g_{(\nu)}(p,p_\pi,E)}\right)^{h_\nu}\left(\frac{g_\pi(p,p_\pi-1,E)}{g_\pi(p,p_\pi,E)}\right)^{p_\pi-1} \\ \times\left(\frac{g_{(\pi)}(p,p_\pi-1,E)}{g_{(\pi)}(p,p_\pi,E)}\right)^{h_\pi-1}\left(\frac{E-A_{\pi\nu}(p,p_\pi,E,T)}{E-A(p,p_\pi,E,T)}\right)^{n-1} \\ \times\Big\{2\Big[E-A_{\pi\nu}(p,p_\pi,E,T)\Big]-n\Big|A(p,p_\pi,E,T)-A(p,p_\pi-1,E,T)\Big|\Big\} \\ \times\langle f_{\rm fwd}(n,h,E,V_0,V_i)\rangle\;f_{\rm iso}(p,p_\pi-1,E,T) \qquad (3.4)\end{aligned}$$

where $(p,p_\pi-1,E)$ is shorthand for the final state designation of $(p_\pi-1,h_\pi-1,p_\nu+1,h_\nu+1,E)$ and

$$\begin{aligned}A_{\pi\nu}(p,p_\pi,E,T) = \\ \max\Big(A(p_\pi,h_\pi,p_\nu,h_\nu,E,T),A(p_\pi-1,h_\pi-1,p_\nu+1,h_\nu+1,E,T)\Big). \qquad (3.5)\end{aligned}$$

Again, there is an analogous expression for $\lambda_{\nu\pi}$ but with the π and ν subscripts interchanged, with $(p,p_\pi+1,E)$ being the shorthand for the final state designation of $(p_\pi+1,h_\pi+1,p_\nu-1,h_\nu-1,E)$, and with

$$\begin{aligned}A_{\nu\pi}(p,p_\pi,E,T) = \\ \max\Big(A(p_\pi,h_\pi,p_\nu,h_\nu,E,T),A(p_\pi+1,h_\pi+1,p_\nu-1,h_\nu-1,E,T)\Big). \qquad (3.6)\end{aligned}$$

The above transition rates are all in the form where isospin is assumed to be a good quantum number. For the isospin mixed case, the T label is dropped and the function $f_{\rm iso}$ is omitted.

3.2. Particle Emission Rates

The rate for emitting particles of type b and channel energy ε from a particular class of states is derived from microscopic reversibility. In the isospin mixed case it has the form

$$W_b(p, p_\pi, E, \varepsilon) = \frac{2s_b + 1}{\pi^2\,\hbar^3}\,\mu_b\,\varepsilon\,\sigma_b(\varepsilon)\,\frac{\omega(p_\pi - Z_b, h_\pi, p_\nu - N_b, h_\nu, U)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E)} \tag{3.7}$$

where Z_b and N_b are the proton and neutron number of the emitted particle, s_b is its spin, and μ_b is its reduced mass. The quantity $\sigma_b(\varepsilon)$ is the total reaction cross section for the inverse of the exit channel process (*i.e.* absorption of a particle of type b on the residual nucleus), and U is the excitation energy in the residual nucleus. The residual excitation energy is given by $U = E - \varepsilon - B_b$ where B_b is the binding energy of the emitted particle in the emitting nucleus. The inverse reaction cross section may be either read in or calculated using an empirical approximation to the optical model reaction cross sections.

This is the result used in previous two-component versions of PRECO, but recent work [KA06] has included one significant modification. Because the Fermi level moves down during particle emission, in going from the emitting nucleus to the residual nucleus, there are final states that can physically be populated but that are not included in the usual residual state density $\omega(p_\pi - Z_b, h_\pi, p_\nu - N_b, h_\nu, U)$. Therefore, these extra configurations need to be added. They occur when $Z_a < Z_b$ and/or $N_a < N_b$ for primary particle emission. (The extra configurations are not included for secondary emission.) Thus the emission rate now uses an effective residual nucleus state density and becomes

$$W_b(p, p_\pi, E, \varepsilon) = \frac{2s_b + 1}{\pi^2\,\hbar^3}\,\mu_b\,\varepsilon\,\sigma_b(\varepsilon)\,\frac{\omega_{\rm eff}(p_\pi - Z_b, h_\pi, p_\nu - N_b, h_\nu, U)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E)} \tag{3.8}$$

where

$$\omega_{\rm eff}(p_\pi - Z_b, h_\nu, p_\nu - N_b, h_\nu, U) = \sum_{i=i_{\rm min}}^{h_\pi} \sum_{j=j_{\rm min}}^{h_\nu} \omega(p_\pi - Z_b, i, p_\nu - N_b, j, U) \tag{3.9}$$

and where $i_{\min} = \min(p_\pi - Z_b, h_\pi)$ and $j_{\min} = \min(p_\nu - N_b, h_\nu)$. This reverts to the normal state density expression when $p_\pi - Z_b \geqslant h_\pi$ and $p_\nu - N_b \geqslant h_\nu$, or equivalently (since $h_\pi = p_\pi - Z_a$ and $h_\nu = p_\nu - N_a$) when $Z_a \geqslant Z_b$ and $N_a \geqslant N_b$, as noted above. Thus, for instance, the added states occur for (n,p) and (p,n) reactions but not for nucleon inelastic scattering. The added states are most important when the main state density has a large shell or pairing correction that vanishes or is much smaller in the auxilliary configurations.

When isospin is conserved in the composite nucleus, then the emission rate becomes

$$W_b(p, p_\pi, E, \varepsilon, T) = \frac{2s_b + 1}{\pi^2 \hbar^3} \mu_b \, \varepsilon \, \sigma_b(\varepsilon) \times \sum_{T_B} [C_b(T, T_B)]^2 \frac{\omega_{\text{eff}}(p_\pi - Z_b, h_\pi, p_\nu - N_b, h_\nu, U, T_B)}{\omega(p_\pi, h_\pi, p_\nu, h_\nu, E, T)} \tag{3.10}$$

where T_B is the isospin quantum number in the residual nucleus B, and $C_b(T, T_B)$ is the isospin coupling Clebsch-Gordan coefficient in the exit channel. The sum extends over all allowed isospins in the residual nucleus. For emission of particles up through mass four, either one or two residual isospin values are allowed from each composite nucleus isospin. The allowed isospins and all of the Clebsch-Gordan coefficients are evaluated internally in the program.

3.3. Closed Form Reaction Equations

A set of closed form equations [KA86] is used to calculate the average amount of time spent by an equilibrating nucleus in each of the particle-hole configurations considered. The system is assumed to be formed in the initial configuration

$$(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a, 0, N_a, 0) \tag{3.11}$$

where the projectile nucleons are the particle degrees of freedom. It then equilibrates mainly through a series of pair creation interactions. At most one exciton scattering interaction of the type given by $\lambda_{\pi\nu}$ or $\lambda_{\nu\pi}$ is allowed between pair creations. Particle emission is assumed to begin only after creation of the first particle-hole pair, and this creation may, in fact, happen as the projectile enters the target. For nucleon emission, this is the obvious physical assumption, since emission prior to the first interaction can only lead to elastic scattering. For complex particle projectiles, it is possible that the projectile "dissolves" into its

constituent nucleons before exciting the target, so that emission of particles with a lower mass number than the projectile could be possible prior to the first pair excitation. The question of whether particle emission should begin before or after the first pair creation interaction for complex projectiles is a subject for future study, after a projectile breakup model is included, as discussed in [KA05]. Regardless of when the first emission is allowed to occur, the equilibration should be started with the configuration of Eq. (3.11) so that the initial interaction will excite proton and neutron pairs in the right relative proportions.

In this section, the excitation energy and (when they apply) isospin labels are omitted from most of the variables for the sake of simplicity.

In order to formulate the closed form reaction equations, it is useful to define two sets of lifetimes for the various classes of states. They are characterized by the relations

$$\tau(p,p_\pi) = \Bigg[\lambda_{\pi+}(p,p_\pi) + \lambda_{\nu+}(p,p_\pi) + \lambda_{\pi\nu}(p,p_\pi) + \lambda_{\nu\pi}(p,p_\pi) + \sum_b \int W_b(p,p_\pi,E,\varepsilon)d\varepsilon\Bigg]^{-1} \tag{3.12}$$

which includes the effects of the exciton scattering interactions and

$$\tau'(p,p_\pi) = \left[\lambda_{\pi+}(p,p_\pi) + \lambda_{\nu+}(p,p_\pi) + \sum_b \int W_b(p,p_\pi,E,\varepsilon)d\varepsilon\right]^{-1} \tag{3.13}$$

which does not. In both cases the emission rates of all six light ejectile types (n, p, d, t, ^{3}He and α) are included in the sum over b. These lifetimes, in turn, are used to convert the internal transition rates into their corresponding branching ratios

$$\Gamma_{\pi+}(p,p_\pi) = \lambda_{\pi+}(p,p_\pi)\tau(p,p_\pi), \tag{3.14a}$$
$$\Gamma_{\nu+}(p,p_\pi) = \lambda_{\nu+}(p,p_\pi)\tau(p,p_\pi), \tag{3.14b}$$
$$\Gamma_{\pi\nu}(p,p_\pi) = \lambda_{\pi\nu}(p,p_\pi)\tau(p,p_\pi), \tag{3.14c}$$
$$\Gamma_{\nu\pi}(p,p_\pi) = \lambda_{\nu\pi}(p,p_\pi)\tau(p,p_\pi), \tag{3.14d}$$

and to define the factor

$$L(p,p_\pi) = \tau'(p,p_\pi)/\tau(p,p_\pi) \tag{3.15}$$

which is used to correct for higher (*i.e.* second or third) order exchange processes.

The evolution of the composite nucleus toward equilibrium is described in terms of two strength functions: $P_1(p, p_\pi)$ which represents the strength populating states in the specified class *directly* through pair creation from simpler states, and $P_2(p, p_\pi)$ which gives the *total* strength passing through this class of states after considering pair exchange. Thus P_2 will generally be greater than P_1.

The closed form reaction calculations are started with

$$P_2(A_a, p_\pi) = \begin{cases} 1 & \text{for } p_\pi = Z_a \\ 0 & \text{otherwise} \end{cases} \tag{3.16}$$

corresponding to the initial conditions of Eq. (3.11). The strengths for higher values of p are found through the recursion relations

$$P_1(p, p_\pi) = P_2(p-1, p_\pi-1)\,\Gamma_{\pi+}(p-1, p_\pi-1) + P_2(p-1, p_\pi)\,\Gamma_{\nu+}(p-1, p_\pi) \tag{3.17}$$

and

$$P_2(p, p_\pi) = P_1(p, p_\pi) + L(p, p_\pi)\Big[P_1(p, p_\pi - 1)\,\Gamma_{\nu\pi}(p, p_\pi - 1) + P_1(p, p_\pi + 1)\,\Gamma_{\pi\nu}(p, p_\pi + 1)\Big]. \tag{3.18}$$

Finally, the average amount of time spent in each class of configuration during the preequilibrium phase of the reaction is given by

$$\mathcal{S}_{\rm pre}(p, p_\pi) = P_2(p, p_\pi)\,\tau(p, p_\pi), \tag{3.19}$$

and the energy differential preequilibrium cross section for the reaction (a,b) is

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon_a}\right]_{\rm pre} = \sigma_{a,{\rm pre}}(\varepsilon_a) \sum_p \sum_{p_\pi} \mathcal{S}_{\rm pre}(p, p_\pi)\, W_b(p, p_\pi, E, \varepsilon). \tag{3.20}$$

Here $\sigma_{a,{\rm pre}}$ is the cross section σ_a for forming the composite nucleus reduced by whatever cross section goes into direct reaction mechanisms not included in the exciton model. The quantity σ_a is evaluated at the incident channel energy ε_a in the same way as the total reaction cross sections in the exit channels are evaluated. The direct reaction cross sections are discussed in Chapter 4. When isospin is assumed to be conserved, separate calculations are done for each composite isospin, T, that is allowed (either one or two values) and the results are added. In this case the result of Eq. (3.20) is applied to each T and is multiplied by the entrance

channel isospin coupling Clebsch-Gordan coefficient. The overall preequilibrium cross section thus becomes

$$\begin{aligned}\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon_a}\right]_{\text{pre}} &= \sum_T \left[\frac{d\sigma_{a,b}(\varepsilon,T)}{d\varepsilon_a}\right]_{\text{pre}} \\ &= \sigma_a(\varepsilon_a) \sum_T \left[C_a(T,T_A)\right]^2 \\ &\quad \times \sum_p \sum_{p_\pi} \mathcal{S}_{\text{pre}}(p,p_\pi,T)\, W_b(p,p_\pi,E,\varepsilon,T). \end{aligned} \tag{3.21}$$

In either case, the sum over p begins with $p = A_a + 1$ and continues until one of the following three conditions is met:

- p reaches the most probable value at equilibrium,
- p reaches the maximum value dimensioned for (currently 12), or
- the initial strength has all gone into particle emission.

At that point, any remaining strength is handled using equilibrium model calculations.

3.4. Secondary Preequilibrium Emission

At sufficiently high excitation energies, emission of a second particle during the preequilibrium phase of the reaction can make a noticeable contribution to the inclusive energy spectra. This possibility was added in PRECO-2000 [KA95b]. The physics of the addition is quite straightforward, but it significantly expands the required computation time. Currently secondary emission is only considered for nucleons and only following primary emission of a nucleon, even though primary emission of particles up through mass four (α-particles) is always calculated. The reasons for these restrictions are:

- Primary preequilibrium emission of complex particles is generally weaker than that of nucleons, with much of their cross section coming from other mechanisms such as direct nucleon transfer. Thus their secondary emission should also be weak, even following primary nucleon emission. This inherent weakness is due in part to the higher binding energies of the complex

particles (except α-particles) in the emitting nucleus and to the fact that particle emission reduces the exciton number in the residual nucleus by A_b units so that as A_b increases, the residual states have fewer excitons and their state densities are generally smaller.

- Primary emission of complex particles removes particle degrees of freedom, leaving the residual nucleus with a higher proportion of hole degrees of freedom. For states with a given number of excitons, this reduces the probability of all secondary particle emission and particularly of secondary complex particle emission. The effect again increases with A_b.

Thus while there is no conceptual reasons why a broader treatment of secondary emission could not be considered, neither is there any obvious reason to include it, and it would significantly increase the computation time.

For each nucleon type and emission energy from primary preequilibrium emission, a new set of closed form reaction calculations is done that is analogous to the primary reaction calculations except that, because of the lower excitation energies, the maximum value for which p is dimensioned is decreased from 12 to 8. The flow of strength from the primary to the secondary emission calculations is shown in a simplified schematic in Fig. 3.1. Secondary emission following each type and energy of primary nucleon begins with the strength in the residual particle-hole configurations produced by emission from the simplest possible states. These residual configurations will have A_a particle and 1 hole degrees of freedom corresponding to $n_0 = A_a + 2$ in the initial composite nucleus. At each successive stage in the equilibration chain, the residual strength following primary emission of particles of the same type and energy from states with the current number of hole degrees of freedom is added in. Finally, any residual strength from primary preequilibrium nucleon emission that does not undergo secondary preequilibrium emission is made available (along with residual strength from primary evaporation) for secondary equilibrium emission.

The lines in Fig. 3.1 that go from `target+projectile` to one of the residual nuclei represent strength from direct nucleon transfer reactions with complex particle projectiles (d, t, He-3 or α). In PRECO-2006 this cross section is also allowed to enter the secondary equilibration cascades. Most of the strength will go into configurations with $n = p = A_a - 1$, but small amounts of strength will also go to states with one or even two additional particle-hole pairs, as discussed in Sec. 4.1.1, below. It is possible that, once projectile breakup is included in the code, it will be desireable to allow preequilibrium exciton model emission for projectiles

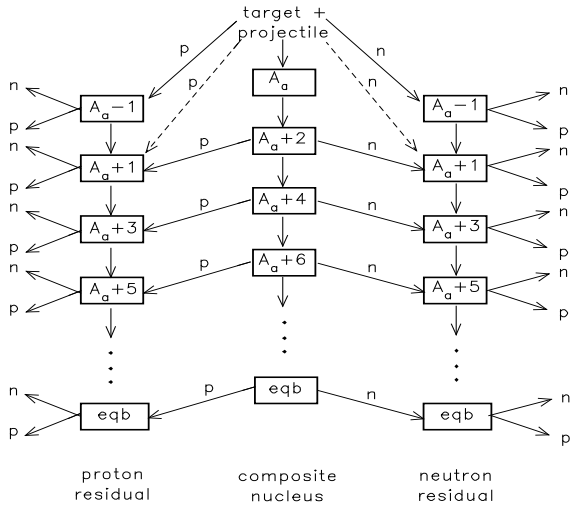

Figure 3.1: *Simplified schematic diagram of the flow of reaction strength into secondary particle emssion during the preequilibrium phase of a reaction. The boxes represent classes of states with different total numbers of excitons, the vertical lines represent interactions which create a particle-hole pair, while diagonal arrows labeled n or p represent particle emission. All of the arrows between boxes represent processes calculated in PRECO, while the arrows from the label "target+projectile" represent direct nucleon transfer. In reality, of course, each box in the figure is really made up of a number of boxes corresponding to different distributions of the constituent excitons into proton and neutron degrees of freedom.*

with $A_a > 1$ to begin in configurations with $n = p = A_a$. For nucleon projectiles, such emission is not possible, because the residual nucleus would have no degrees of freedom to carry the remaining excitation energy.

When calculation of secondary emission is requested in the code, the binding energies for the secondary protons and neutrons are read in, and the total reaction cross sections in the exit channels are recalculated for the appropriate nuclei. In addition, the shell, pairing and isospin corrections are also reevaluated.

4. Other Reaction Calculations

For a complete description of particle emission in a nuclear reaction, a number of other reaction mechanisms need to be considered in addition to the exciton model preequilibrium emission. Early in a reaction, there are various direct reaction mechanisms that are not included in the exciton model. These include direct nucleon transfer (stripping, pickup and exchange), inelastic scattering or knockout processes involving cluster degrees of freedom, and excitation of strong collective states (both spectroscopic and giant resonance). Direct breakup of complex projectiles can also be important for a wide variety of incident energies. Finally, at higher incident energies, quasi-free scattering of incident nucleons should be considered. At the other end of the reaction, it is necessary to treat particle evaporation from both the initial composite nucleus and from the residual nuclei formed in primary emission, once these nuclei have reached statistical equilibrium. In addition, both γ-ray emission and nuclear fission can sometimes compete with equilibrium emission. All of these mechanisms are discussed in this chapter and most are included in PRECO-2006.

4.1. Direct Reaction Mechanisms

While some types of direct particle emission are calculated within the framework of the exciton model, a number of other important mechanisms are not. Several of these are calculated separately through a series of small, largely phenomenological models, and their cross section is removed from the entrance channel cross section that is available for primary preequilibrium emission. Two others still need to be added.

The mini-models employed here for nucleon transfer reactions and for knockout and inelastic scattering involving cluster degrees of freedom should be used with caution for complex projectiles, especially for the loosely bound projectiles d, t and ^{3}He. While the models have been modified somewhat since PRECO-2000, projectile breakup is not yet included in the code and indications are that it may have an

impact on the initial configuration to be used in the exciton model, as well as on the description of nucleon transfer and cluster knockout [KA05]. Once projectile breakup is included, it may be desireable to allow particle emission for complex particle induced reactions to begin from the initial states with $(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a, 0, N_a, 0)$.

4.1.1. Nucleon transfer processes

The calculation of nucleon transfer processes is carried out in the subroutine NUTRA, which was revised for PRECO-2000 and has been significantly revised again for PRECO-2006 based on the analysis of additional data [KA05]. Nucleon transfer includes direct pickup or stripping of up to three nucleons if the projectile and emitted particle have different mass numbers. It also includes nucleon exhange reactions for inelastic scattering of all light projectiles and for the (t,^{3}He) and (^{3}He,t) charge exchange reactions. [In PRECO-2000, nucleon exchange was not considered for incident nucleons or α-particles.] For the inelastic processes, contributions from both proton and neutron exchange are considered.

For the reaction A(a,b)B, the general formula for the nucleon transfer energy differential cross section is

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon}\right]_{\rm NT} = \frac{2s_b+1}{2s_a+1}\,\frac{A_b}{A_a}\,\varepsilon\,\sigma_b(\varepsilon)\,K_{\alpha,p}\left(\frac{A_a}{E_a+V_a}\right)^{2n}\left(\frac{C_a}{A_B}\right)^{n} \times \mathcal{N}_a \sum_{p_\pi}\left(\frac{2Z_A}{A_A}\right)^{2(Z_a+2)h_\pi+2p_\nu} \omega_{\rm NT}(p_\pi, h_\pi, p_\nu, h_\nu, U). \qquad (4.1)$$

Here the inverse cross section σ_b is the same as the one appearing in the exciton model emission rates. The quantity E_a is the incident energy in the laboratory system, while V_a is currently set at $V_a = 12.5A_a$ MeV which is roughly the average potential drop seen by the projectile between infinity and the Fermi level. In addition, the normalization constants are

$$C_a = \begin{cases} 5500\ \text{MeV}^2 & \text{for incident n} \\ 3800\ \text{MeV}^2 & \text{for charged projectiles} \end{cases}, \qquad (4.2)$$

$$\mathcal{N}_a = \begin{cases} (80A_a\,\varepsilon_a)^{-1} & \text{for pickup} \\ (580\ \text{MeV}^{1/2}\,A_a\sqrt{\varepsilon_a})^{-1} & \text{for stripping} \\ (1160\ \text{MeV}^{1/2}\,A_a\sqrt{\varepsilon_a})^{-1} & \text{for exchange} \end{cases}. \qquad (4.3)$$

The quantity $K_{\alpha,p}$ is an enhancement factor for (α,N) and (N,α) reactions, where N is a nucleon. It is not applied to the inelastic exchange channels for these

projectiles, and the (α,α') data at incident energies of 35 to 59 MeV will not accomodate it. It has a value of 12 but vanishes for (α,N) reactions when the incident energy is much larger than the internal binding energy of the α-particle. Thus it is given by

$$K_{\alpha,p} = \begin{cases} 12 & \text{for } (N,\alpha) \\ 12 & \text{for } (\alpha,N) \text{ and } \varepsilon_a < 20 \\ 12 - 11(\varepsilon_a - 20 \text{ MeV})/\varepsilon_a & \text{for } (\alpha,N) \text{ and } \varepsilon_a > 20 \\ 1 & \text{otherwise,} \end{cases} . \tag{4.4}$$

The final nucleus state density, $\omega_{\rm NT}(p_\pi, h_\pi, p_\nu, h_\nu, U)$ [or $\omega_{\rm NT}(p_\pi, h_\pi, p_\nu, h_\nu, U, T)$ when isospin is conserved], contains contributions from the main configuration and from two kinds of related configurations. The main particle-hole configuration is the one designated by the labels p_π, h_π, p_ν, and h_ν, and it is determined by the transferred nucleons. Stripped nucleons become particle degrees of freedom and picked up nucleons leave hole degrees of freedom behind. The main configuration is augmented by allowing for the excitation of anywhere from one to three additional particle-hole pairs. Thus the effective residual state density becomes

$$\omega_{\rm NT}(p_\pi, h_\pi, p_\nu, h_\nu, U) = \sum_{i=0}^{3} \sum_{j=0}^{3-i} (X_{\rm NT})^{i+j}\, \omega(p_\pi + i, h_\pi + i, p_\nu + j, h_\nu + j, U). \tag{4.5}$$

Here the factor $X_{\rm NT}$ represents the probability of exciting each additional pair and is given by

$$X_{\rm NT} = \left(\frac{E_a}{A_a}\right)^{1/2} \frac{7}{V_1\, A_A^2} \left(p_\pi^2 + 1.5 h_\pi^2 + p_\nu^2 + h_\nu^2\right), \tag{4.6}$$

where V_1 is the well depth used for the simplest states in the exciton model calculations. The form of $X_{\rm NT}$ is empirical and has been modified since the release of PRECO-2000, based on the analysis of additional data. It suggests that proton pickup is more effective at exciting extra particle-hole pairs than is proton stripping or neutron transfer.

The state density for the main configuration is also augmented by allowing transfer of nucleons at the Fermi level. These additional state densities are simply

added in, so that Eq. (4.5) becomes

$$\omega_{\rm NT}(p_\pi,h_\pi,p_\nu,h_\nu,U) = \sum_{i=0}^{3}\sum_{j=0}^{3-i}(X_{\rm NT})^{i+j}\,\omega(p_\pi+i,h_\pi+i,p_\nu+j,h_\nu+j,U)$$
$$+\sum_{i=0}^{p_\pi}\sum_{j=0}^{h_\pi}\sum_{k=0}^{p_\nu}\sum_{l=0}^{h_\nu}\omega(p_\pi-i,h_\pi-j,p_\nu-k,h_\nu-l,U)\,\Theta\left(i+j+k+l-\frac{1}{2}\right). \tag{4.7}$$

Here the Heaviside function keeps the main configuration from being added in a second time. These last added configurations are not employed in inelastic channels because they should be automatically included in the main configuration whenever $p_\pi = h_\pi$ and $p_\nu = h_\nu$. For stripping, pickup, and charge exchange reactions, either p_π or h_π will be zero and either p_ν or h_ν will be zero, so the extra configurations need to be added manually.

The finite well depth corrections in the state densities of Eq. (4.7) are made assuming a well depth of

$$V = \begin{cases} V_1(2Z/A) & \text{if } n_\pi = 0 \\ V_1 & \text{otherwise,} \end{cases} \tag{4.8}$$

where V_1 is again the well depth used for the simplest states in the exciton model calculations. The sum over p_π in Eq. (4.1) is needed only for exchange reactions in inelastic scattering. In this case $p_\pi = 0$ or 1 depending on whether a pair of neutrons or of protons is exchanged.

When isospin is conserved in a calculation, then Eq. (4.1) is modified by including the isospin coupling coefficients in both the entrance and exit channels of the reaction, and a sum over final state isospins is needed. Thus the result is

$$\left[\frac{d\sigma_{a,b}(\varepsilon,T)}{d\varepsilon}\right]_{\rm NT} = [C_a(T,T_A)]^2\,\frac{2s_b+1}{2s_a+1}\,\frac{A_b}{A_a}\,\varepsilon\,\sigma_b(\varepsilon)\,K_{\alpha,p}\left(\frac{A_a}{E_a+V_a}\right)^{2n}\left(\frac{C_a}{A_B}\right)^{n}$$
$$\times\,\mathcal{N}_a\sum_{T_B}[C_b(T,T_B)]^2\sum_{p_\pi}\left(\frac{2Z_A}{A_A}\right)^{2(Z_a+2)h_\pi+2p_\nu}\omega_{\rm NT}(p_\pi,h_\pi,p_\nu,h_\nu,U,T_B), \tag{4.9}$$

and again the results for the possible composite nucleus isospins (if two are allowed) are added. The normal exciton model particle-hole state density expression, including pairing and shell corrections, is used for all of the state densities in

Eq. (4.7). The only difference is that a well depth V determined by V_1 is used no matter how many hole degrees of freedom there are. The corresponding isospin dependent state densities are used in Eq. (4.9).

4.1.2. Knockout and inelastic processes with cluster degrees of freedom

Knockout and inelastic processes involving cluster (multi-particle) degrees of freedom are treated in the subroutines KNOCK and INEL which are unchanged from PRECO-2000 except for the overall normalization factor. This was changed from 1/12 to 1/14.

In this type of mechanism, a complex projectile is assumed to retain its own cluster identity while exciting a proton, neutron or α-cluster particle-hole pair in the target. Either of the resulting particle degrees of freedom in this composite state can be emitted, and their relative probabilities are determined by phase space considerations. Nucleon pair excitation by a nucleon projectile is already considered in the exciton model, so only α-cluster excitation is considered here for incident neutrons and protons.

For the reaction A(a,b)B, the basic equation for the energy differential cross section for knockout reactions is

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon}\right]_{\mathrm{KO}} = \frac{\sigma_a(\varepsilon_a)}{14}\,(2s_b+1)\,A_b\,\varepsilon\,\sigma_b(\varepsilon) \times \frac{\mathcal{P}_b\,g_a\,g_b\,[U - A_{\mathrm{KO}}(p_a,h_b)]}{\sum_{c=a,b}(2s_c+1)\,A_c\,\langle\sigma_c\rangle\,(\varepsilon_{\mathrm{m}}+2B_{\mathrm{coul},c})(\varepsilon_{\mathrm{m}}-B_{\mathrm{coul},c})^2\,g_a\,g_b^2/6g_c} \tag{4.10}$$

where $\mathcal{P}_b$ is the probability of exciting a b-type particle-hole pair, ε_{m} is the maximum emission energy, and $B_{\mathrm{coul},c}$ is the Coulomb barrier for a particle of type c. The quantity $\sigma_a(\varepsilon_a)$ is the entrance channel total reaction cross section evaluated at the incident energy, while $\langle\sigma_c\rangle$ is the inverse cross section in the channel where a particle of type c is emitted averaged over emission energy from $B_{\mathrm{coul},c}$ to the maximum allowed. The final state contains an a-type particle and a b-type hole, and the Pauli correction factor is calculated in the simplest equi-spacing model, neglecting the energy dependent terms, so that

$$A_{\mathrm{KO}}(p_a,h_b) = \frac{1}{2g_a} + \frac{1}{2g_b}. \tag{4.11}$$

For inelastic scattering, the final state consists of a particle and hole of the same type, and for this kind of state the Pauli correction function is zero. Thus

the equation for the cross section becomes

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon}\right]_{\rm IN} = \frac{\sigma_a(\varepsilon_a)}{14}\,(2s_a+1)\,A_a\,\varepsilon\,\sigma_a(\varepsilon)$$
$$\times \sum_{i=n,p,\alpha} \frac{\mathcal{P}_i\,g_i^2\,U}{\sum_{c=a,i}(2s_c+1)\,A_a\,\langle\sigma_c\rangle\,(\varepsilon_{\rm m}+2B_{{\rm coul},c})(\varepsilon_{\rm m}-B_{{\rm coul},c})^2\,g_a\,g_i^2/6g_c} \quad (4.12)$$

for complex projectiles and

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon}\right]_{\rm IN} = \frac{\sigma_a(\varepsilon_a)}{14}\,(2s_a+1)\,A_a\,\varepsilon\,\sigma_a(\varepsilon)$$
$$\times \frac{\mathcal{P}_\alpha\,g_\alpha^2\,U}{\sum_{c=a,\alpha}(2s_c+1)\,A_a\,\langle\sigma_c\rangle\,(\varepsilon_{\rm m}+2B_{{\rm coul},c})(\varepsilon_{\rm m}-B_{{\rm coul},c})^2\,g_a\,g_\alpha^2/6g_c} \quad (4.13)$$

for nucleon projectiles.

Because of the uncertainty of how to treat pairing, isospin, or shell structure for cluster degrees of freedom, none of those effects are considered in this part of the calculations. However, whenever an isospin conserved calculation is being run, the entrance channel Clebsch-Gordan coefficients are multiplied into Eqs. (4.10), (4.12), and (4.13). For similar reasons, finite well depth effects and any surface peaking of the initial interaction are not included. On the other hand, the most important of the components calculated in this model turn out to be inelastic scattering of complex projectiles via nucleon pair excitation. These processes produce residual states with a nucleon particle-hole pair and should have finite well depth correction factors like those of the one particle - one hole states in the exciton model. The implementation and effects of using such a correction will be investigated as part of ongoing work on complex particle induced reactions.

In evaluating the single particle state densities for the cluster degrees of freedom, it is assumed that all of the nucleons of a cluster are in correlated orbits, each holding a maximum of two protons and two neutrons. In addition, it should be recognized that a cluster of A_b nucleons will carry A_b times the energy of a nucleon in one of these orbits. Since the single particle state densities are the number of cluster states per unit of energy *carried by the cluster*, they are (the subscript h denotes ^{3}He clusters)

$$g_d = (g_{\pi 0}+g_{\nu 0})/4 \;=\; (A/52)\ {\rm MeV}^{-1} \quad (4.14a)$$
$$g_t = g_h \;=\; (g_{\pi 0}+g_{\nu 0})/12 \;=\; (A/156)\ {\rm MeV}^{-1} \quad (4.14b)$$
$$g_\alpha = (g_{\pi 0}+g_{\nu 0})/16 \;=\; (A/208)\ {\rm MeV}^{-1} \quad (4.14c)$$

where the proton and neutron single particle state densities are assumed to be

$$g_{\pi 0} = (Z/13)\ \mathrm{MeV}^{-1} \tag{4.15a}$$

$$g_{\nu 0} = (N/13)\ \mathrm{MeV}^{-1}. \tag{4.15b}$$

This normalization for $g_{\pi 0}$ and $g_{\nu 0}$ is the former default for the exciton model and affects only the size of the Pauli correction functions since it otherwise cancels out in the emission cross section calculations.

The probabilities for exciting the different kinds of particle-hole pairs are taken to be

$$\mathcal{P}_{\mathrm{n}} = \frac{N_A - \phi Z_A}{A_A - 2\phi Z_A + \phi Z_A/2} \cong \frac{N_A}{A_A} \tag{4.16a}$$

$$\mathcal{P}_{\mathrm{p}} = \frac{Z_A - \phi Z_A}{A_A - 2\phi Z_A + \phi Z_A/2} \cong \frac{Z_A}{A_A} \tag{4.16b}$$

$$\mathcal{P}_{\alpha} = \frac{\phi Z_A/2}{A_A - 2\phi Z_A + \phi Z_A/2} \cong \frac{\phi Z_A}{2A_A}. \tag{4.16c}$$

Here ϕ is the fraction of the time that four nucleons in correlated orbits will "look like" an α-cluster or, alternatively, the fraction of the possible α-clusters that will, on average, exist at any given time. It has been assumed that $N \geq Z$ so that a maximum of $Z/2$ α-clusters is possible. The approximate expressions (the ones actually used in the code) are obtained assuming that $\phi \ll 1$. The exact size and systematics of ϕ are not well known. Here the values obtained from (p,α) and (n,α) reactions [BO74, MI75, MI77] by neglecting pickup are renormalized and parameterized to give

$$\phi = \begin{cases} 0.08 & \text{for } N_A \leq 116 \\ 0.02 + 0.06(126 - N_A)/10 & \text{for } 116 < N_A < 126 \\ 0.02 + 0.06(N_A - 126)/3 & \text{for } 126 \leq N_A < 129 \\ 0.08 & \text{for } 129 \leq N_A \end{cases} . \tag{4.17}$$

While this model is used for all projectile types and is physically reasonable for incident nucleons and α-particles, it is unclear whether it makes sense to use it for incident deuterons or even tritons and ^{3}He, which are more loosely bound and for which the nucleon emission spectra exhibit prominent break-up peaks. This is an area for further investigation once projectile break-up is included in the model calculations.

4.1.3. Excitation of strong collective states

The excitation of strong spectroscopic collective states forms a prominent feature of inelastic scattering spectra. In PRECO it is included using the simple model of Kalka *et al* [KA89] which has been reformulated [KA00] in terms of the energies of the incoming and outgoing particles and where the entrance and exit channel penetrability factors are evaluated in terms of the ratio between the total reaction cross sections and the corresponding geometric cross sections. The resulting expression for the energy differential cross section for a collective state of multipolarity λ is

$$\left[\frac{d\sigma_{a,a'}(\varepsilon_i,\varepsilon_f)}{d\varepsilon_f}\right]_{\mathrm{COL}} = \frac{2m}{9A_a\hbar^2}\,\frac{\varepsilon_f^{1/2}}{\varepsilon_i^{3/2}}\,\frac{\beta_\lambda^2}{2\lambda+1}\,V_{\mathrm{R}}^2\,R^4\,\frac{\sigma_i(\varepsilon_i)}{\sigma_{i,\mathrm{geom}}(\varepsilon_i)}\,\frac{\sigma_f(\varepsilon_f)}{\sigma_{f,\mathrm{geom}}(\varepsilon_f)}\mathcal{P}(E,E_\lambda,w) \tag{4.18}$$

where E_λ and β_λ are the excitation energy and deformation parameter of the collective state, and ε_i and ε_f are the center-of-mass energies of the initial and final particles. The quantity m is the nucleon mass, A_a is the projectile mass number, R is the nuclear radius, and V_{R} is the real optical model potential well depth. Values of $V_{\mathrm{R}} = 50$ MeV and $R = 1.23 \times A^{1/3}$ are used, and the geometrical cross sections are evaluated as described in Sect. 6.2.1 on page 83. The function $\mathcal{P}(E_\lambda, w)$ is a Gaussian line-shape function centered at E_λ and with a variable width parameter w:

$$\mathcal{P}(E,E_\lambda,w) = \frac{1}{\sqrt{2\pi}w}\exp\left[-\frac{(E-E_\lambda)^2}{2\,w^2}\right]. \tag{4.19}$$

Here $E = \varepsilon_i - \varepsilon_f$ is the excitation energy in the final nucleus. The width of the Gaussian accounts for the experimental energy resolution and any inherent spreading of the collective strength. Eq. (4.18) is applied separately to as many individual resonances as are specified on input. The total number of collective states which can be considered is currently limited to 10 by the dimension statements. This number includes both spectroscopic and giant resonance states (see Sect. 4.1.4), as well as the elastic peak (see Sect. 4.1.5) if it is to be estimated.

The spectroscopic collective states which are considered represent 2+, 3−, and sometimes 4+ strength. A list of possible values for E_λ and β_λ is included as Table 6.4 (page 89) in the chapter on recommended input parameters. The collective state parameters for even-even nuclei are typically those of the lowest states of the correct spin and parity. The decision about whether or not to include

a 4+ excitation was, where possible, resolved empirically by looking at inelastic scattering data. In addition, data for a few nuclei indicate that a higher energy state of the same spin and parity actually carried more of the collective strength than the lowest state, and the higher state was substituted. Sometimes two or more states are strong and should be included in the calculations. For odd-A targets the collective state parameters were typically taken to be the average for the neighboring even-even nuclei. For targets that are one unit removed in N or Z from a closed-shell configuration, the values for the closed-shell nucleus are recommended. In addition, a few empirical adjustments have been made, most noteably for ^{27}Al. The collective state width parameter w must be adjusted depending on the energy resolution of the experiments being described and/or the spacing of the emission energy grid used in the calculations.

4.1.4. Excitation of giant resonance states

The other type of collective state which can be excited is giant resonance (GR) states. These are handled using the previously described model for the spectroscopic collective states, summarized in Eq. (4.18). The four lowest energy isoscaler resonances have been considered, though obviously others could be included. For these states it is usually adequate to assume that the resonance energy is a smooth function of the mass number of the nucleus and that its inherent width is either constant or also a smooth function of A. The deformation parameter of a GR state is determined from the appropriate energy-weighted sum rule after subtracting contributions from the strong spectroscopic collective states. The GR line shapes are assumed to be Gaussian with a width parameter, w, that is the usual full width at half maximum (FWHM) divided by 2.35. (A Lorentzian shape

$$\mathcal{P}_{\mathrm{Lor}}(E, E_\lambda, \Gamma) = \frac{2}{\pi\Gamma} \frac{\Gamma^2\, E^2}{\left(E^2 - E_\lambda^2\right)^2 + \Gamma^2\, E^2} \tag{4.20}$$

with a FWHM of Γ is also available.) A set of prescriptions for these parameters was arrived at in [KA00] and is summarized in Sect. 6.3.2 on page 91. It is discussed briefly here.

The energy-weighted sum rules for determining the GR widths are frequently evaluated for a uniform mass distribution of radius R, giving the results

$$S_\ell = \sum_i E_{\ell,i} \cdot \beta_{\ell,i}^2 = \frac{2\pi\hbar^2}{3AmR^2}\, \ell(2\ell+1) = 57.5 A^{-5/3}\, \ell(2\ell+1)\ \mathrm{MeV} \tag{4.21}$$

for $\ell \geq 2$, and

$$S_0 = \sum_i E_{0,i} \cdot \beta_{0,i}^2 = \frac{5\hbar^2}{6AmR^2} = 23A^{-5/3} \text{ MeV} \tag{4.22}$$

for $\ell = 0$. Here m is the nucleon mass, and the radius has been taken to be $R = 1.23A^{1/3}$ fm.

The first GR state, the one that is lowest in energy, is the low energy octopole resonance or LEOR which consists of $1\hbar\omega$ $3-$ transitions. Its excitation energy is approximately $E_{\text{LEOR}} = 31A^{-1/3}$ MeV and its FWHM is taken to be $\Gamma_{\text{LEOR}} = 5$ MeV, corresponding to a Gaussian width parameter of $w_{\text{LEOR}} = 2.1$ MeV. It and the spectroscopic $3-$ states exhaust about 30% of the $\ell = 3$ sum rule strength, with the rest going into the $3\hbar\omega$ $3-$ transitions making up the high energy octopole resonance.

The GR state which is next lowest in energy is the giant quadrupole resonance or GQR. Its excitation energy is approximately $E_{\text{GQR}} = 65A^{-1/3}$ MeV and its width is about $\Gamma_{\text{GQR}} = 85A^{-2/3}$ MeV (or $w_{\text{GQR}} = 36A^{-2/3}$ MeV). The GQR plus the spectroscopic $2+$ collective states should exhaust the $\ell = 2$ sum rule strength.

The giant monopole resonance or GMR is weak and its parameters are somewhat uncertain. Reference [KA00] suggests a linear mass dependence for its excitation energy of $E_{\text{GMR}} = (18.7 - A/40)$ MeV and a width of $\Gamma_{\text{GMR}} = 3$ MeV. The GMR should exhaust the $\ell = 0$ energy-weighted sum rule. It is very weak and usually does not need to be included in reaction calculations.

Finally the high energy octopole resonance or HEOR has an average excitation energy of about $E_{\text{HEOR}} = 115A^{-1/3}$ MeV and a width of about $\Gamma_{\text{HEOR}} = (9.3 - A/48)$ MeV [or $w_{\text{HEOR}} = (4.0 - A/113)$ MeV]. As mentioned above, it exhausts the remaining roughly 70% of the $\ell = 3$ sum rule strength.

The contributions of these giant resonance states to inelastic scattering spectra are typically not large but can be noticeable, particularly for deformed, heavy nuclei where the spectroscopic collective states lie quite close to the ground state and do not use up much of the sum rule strengths.

4.1.5. Elastic scattering

In the event that a very rough estimate of the elastic scattering cross section is needed, it can be obtained by entering the elastic peak as if it were a strong collective state. In this case, the parameter values should be set at $\lambda = 0$ and $E_\lambda = 0$, while β_λ is generated in PRECO and can be arbitrary in the input.

Two different mechanisms can contribute to elastic scattering: nuclear and Coulomb processes. The nuclear processes can be described using the collective state model formula of Eq. (4.18) and a deformation parameter of $\beta_\lambda = 1.5\ (1 + Z_a/A_a^2) \cdot A_A^{-1/3}$ where the subscripts a and A refer to the projectile and target, respectively. For charged particles, Coulomb scattering can also contribute. Here the elastic cross section is given by

$$\sigma_{a,a}(\varepsilon_i)_{\mathrm{EL,Coul}} = K_{\mathrm{Coul}}\,\frac{Z_a^2\,Z_A^2}{\varepsilon_i^2} \tag{4.23}$$

$$\left[\frac{d\sigma_{a,a}(\varepsilon_i,\varepsilon_f)}{d\varepsilon_f}\right]_{\mathrm{EL,Coul}} = K_{\mathrm{Coul}}\,\frac{Z_a^2\,Z_A^2}{\varepsilon_i^2}\mathcal{P}(E,0,w), \tag{4.24}$$

where $\mathcal{P}$ is the same line shape function (typically a Gaussian) used in the collective excitation model and with the same width parameter as for the nuclear elastic contribution. The empirical normalization constants, K_{Coul}, have the approximate values given in Table 4.1. The two contributions are added incoherently,

Table 4.1: *Normalization parameters for the elastic scattering cross sections.*

projectile	K_{Coul}	$1 + Z_a/A_a^2$
n		1.0
p	400	2.0
d	1000	1.25
t	1000	1.111
^{3}He	1400	1.222
α	600	1.125

neglecting any interference effects so that

$$\left[\frac{d\sigma_{a,a}(\varepsilon_i,\varepsilon_f)}{d\varepsilon_f}\right]_{\mathrm{EL}} = \left[\frac{d\sigma_{a,a}(\varepsilon_i,\varepsilon_f)}{d\varepsilon_f}\right]_{\mathrm{EL,nucl}} + \left[\frac{d\sigma_{a,a}(\varepsilon_i,\varepsilon_f)}{d\varepsilon_f}\right]_{\mathrm{EL,Coul}}. \tag{4.25}$$

The collective model elastic cross section is the only one occurring for incident neutrons and it seems to dominate for incident protons at 30 to 60 MeV (the only energies studied). For complex projectiles, the Coulomb scattering generally dominates at most of the incident energies studied (15 to 22 MeV for deuterons, 20 MeV for tritons, 21 MeV for ^{3}He, and 25 to 40 MeV for α-particles). Additional

deuteron data at 80 MeV at forward angles have significant contributions from both mechanisms and are less well reproduced, particularly for the very light targets. The angular distributions are quite important for elastic scattering, and their smooth trends are described in Chapter 5.

Since most of the elastic cross section is not included in the total reaction cross sections used in PRECO, it is the only direct cross section which is not subtracted from the entrance channel total reaction cross section in determining how much is available for the exciton model calculations. Instead the elastic cross section is stored separately and simply added in when the emission energy spectra are printed.

4.1.6. Quasi-free scattering

[Not yet included in PRECO.]

The process of quasi-free scattering is defined here as a reaction in which an incident nucleon scatters off of a single nucleon in the target essentially as if the rest of the nucleus were not there. Its experimental signature is a peak in the double-differential cross section that closely follows the kinematics of free nucleon-nucleon scattering. It was studied phenomenologically for proton induced reactions at 100 to 1000 MeV [KA90], but the simple model developed has not yet been included in PRECO since the benchmarking and use of the code has, to date, mainly involved lower projectile energies. The parameterization arrived at is summarized here for the convenience of anyone wishing or needing to add it to the code. It should be emphasized, however, that the parameterization for neutron induced reactions has not been studied and may be somewhat different from the proton results. In addition, the parameterization for proton induced reactions may well change with the availability of newer and better data. The user is referred to the original paper for further details.

The position of the quasi-free scattering peak is given in terms of the relativistic relationship for free scattering

$$E_{\mathrm{f}}(E_{\mathrm{inc}}, \theta_{\mathrm{lab}}) = \frac{E_{\mathrm{inc}} \cos^2 \theta_{\mathrm{lab}}}{1 + (E_{\mathrm{inc}}/2M) \sin^2 \theta_{\mathrm{lab}}} \tag{4.26}$$

where M is the rest mass of a nucleon or 939 MeV, E_{inc} is the laboratory energy of the projectile, and θ_{lab} is the laboratory scattering angle. The peak position is likewise given in the laboratory system. The results for quasi-free scattering are

then given by

$$E_{\rm qfs}^{(p,p')}(E_{\rm inc},\theta_{\rm lab}) = E_{\rm f}(E_{\rm inc},\theta_{\rm lab}) - 43 + \frac{44}{1+\exp\left[(200-E_{\rm inc})/70\right]} \tag{4.27}$$

$$E_{\rm qfs}^{(p,n)}(E_{\rm inc},\theta_{\rm lab}) = E_{\rm f}(E_{\rm inc},\theta_{\rm lab}) - 1 - \frac{44}{1+\exp\left[(200-E_{\rm inc})/70\right]} \tag{4.28}$$

where it is assumed that all of the energies are given in MeV. Thus at low incident energies the (p,p') peak is shifted down in energy but approaches the free scattering energy above 300 MeV, while the situation is reversed for (p,n) quasi-free scattering.

The peak shapes are described as the sum of two half-Gaussians with width parameters (half-widths at 1/e of peak intensity) of w_1 and w_2 for the low and high energy sides, respectively. These width parameters are conveniently given in terms of the cosine of the emission angle in the N-N center of mass, where this angle is calculated relativistically. The equations for determining $\theta_{\rm c}$ are

$$\cot\theta_{\rm c} = \gamma\cot\theta_{\rm lab} - \left[\frac{D_{a,\rm lab}\,R}{D_{b,\rm lab}}\right]^{1/2}\gamma\gamma_{b,\rm lab}\csc\theta_{\rm lab} \tag{4.29}$$

$$D_{a,\rm lab} = (\gamma_{a,\rm lab}+1)E_{\rm inc} \tag{4.30}$$

$$\gamma_{a,\rm lab} = 1 + E_{\rm inc}/M \tag{4.31}$$

$$D_{b,\rm lab} = (\gamma_{b,\rm lab}+1)E_{\rm qfs}(\theta_{\rm lab}) \tag{4.32}$$

$$\gamma_{b,\rm lab} = 1 + E_{\rm qfs}(\theta_{\rm lab})/M \tag{4.33}$$

$$\gamma = \left[\frac{E_{\rm inc}+2M}{2M}\right]^{1/2} \tag{4.34}$$

$$R = (\gamma_{a,\rm lab}+1)^{-2} \tag{4.35}$$

and the width parameters are given by

$$w_{1a} = \frac{E_{\rm inc}}{4.7}\sin\theta_{\rm c} - \frac{E_{\rm inc}-540}{2.8}\sin^2\theta_{\rm c}\,\Theta(E_{\rm inc}-540) \tag{4.36}$$

$$w_1 = \max(w_{1a}, 1.2E_{\rm inc}^{1/2}) \tag{4.37}$$

$$w_{2a} = \frac{E_{\rm inc}}{5.6}\sin\theta_{\rm c} - \frac{E_{\rm inc}-540}{3.9}\sin^2\theta_{\rm c}\,\Theta(E_{\rm inc}-540) \tag{4.38}$$

$$w_{2m} = \max(w_{2a}, 0.8E_{\rm inc}^{1/2}) \tag{4.39}$$

$$w_{2b} = \frac{2}{3}\left[E_{\rm inc} - E_{\rm qfs}(\theta_{\rm lab})\right] \tag{4.40}$$

$$w_2 = \min(w_{2m}, w_{2b}). \tag{4.41}$$

Here Θ is the Heaviside function which is zero for a negative argument and unity for a positive one. The extra condition of w_{2b} is imposed on the high-energy width to keep significant amounts of calculated QFS strength from falling above the physical end point of the spectrum, while the conditions that are proportional to $E_{\rm inc}^{1/2}$ are designed to keep the widths from going to zero at extremely forward angles.

The total quasi-free scattering cross section integrated over emission angle is

$$\sigma_{\rm qfs}(E_{\rm inc}, A, Z) = C_{\rm qfs}\, 2\pi\lambda^2\, r_0\, A^{1/3}\, \frac{\rho_0}{2}\left(1 - \frac{r_a}{1.26 r_0}\right)\left\langle \sigma_{NN}^{(a,b)}\right\rangle \tag{4.42}$$

where $C_{\rm qfs}$ is an empirical normalization constant which is $C_{\rm qfs} = 19 \pm 4$. Here r_0 is the nuclear radius parameter of 1.07 fm, λ is the de Broglie wavelength of the incoming particle given in fermis, ρ_0 is the central nuclear density of 0.17 fm^{-3}, and r_a is the effective radius of the projectile given by

$$r_a = \left[(0.76\,{\rm fm})^2 + (\lambda/2)^2\right]^{1/2}. \tag{4.43}$$

The last factor in Eq. (4.42) gives the average effective nucleon-nucleon cross section appropriate for the interacting particle types and is evaluated as

$$\left\langle \sigma_{NN}^{(p,p')}(E_{\rm inc}, A, Z)\right\rangle = \frac{(1 + f_{\rm qfs}) Z\, \sigma_{pp}(E_{\rm inc}) + N\, \sigma_{pn}(E_{\rm inc})}{A} \tag{4.44}$$

for (p,p') reactions and

$$\left\langle \sigma_{NN}^{(p,n)}(E_{\rm inc}, A, Z)\right\rangle = \frac{f_{\rm qfs} N\, \sigma_{pn}(E_{\rm inc})}{A} \tag{4.45}$$

for (p,n) reactions. The quantity $f_{\rm qfs}$ is the probability for the struck target nucleon to be emitted relative to the probability for the projectile to be reemitted. It adjusts the relative intensities in the (p,p') and (p,n) QFS peaks and has the empirical value of $f_{\rm qfs} = 0.64 \pm 0.03$. The free nucleon-nucleon cross sections are parameterized by the relations

$$\sigma_{pp}(E) = -\frac{1.69\times 10^6}{E^3} + \frac{1.49\times 10^5}{E^2} - \frac{692}{E} + 22.4 + \frac{E}{400} - \frac{E^2}{5\times 10^5} \tag{4.46}$$

and

$$\sigma_{pn}(E) = \frac{2.39 \times 10^5}{E^2} + \frac{1800}{E} + 27.2 - \frac{E-300}{50}\Theta(E-300) + \frac{(E-500)^2}{1.1 \times 10^5}\Theta(E-500) \tag{4.47}$$

where again all of the energies are assumed to be in MeV.

The angular distributions of the QFS peaks in the N-N center of mass are given as an exponential in $\cos\theta_c$ using the relation

$$\frac{d\sigma_{\rm qfs}(\theta_{\rm c})}{d\Omega_{\rm c}} = \frac{a_{\rm qfs}}{2\pi}\,\sigma_{\rm qfs}(E_{\rm inc}, A, Z)\,\frac{\exp(a_{\rm qfs}\cos\theta_c)}{e^{a_{\rm qfs}} - e^{-a_{\rm qfs}}} \tag{4.48}$$

This is the mathematical dependence of the multi-step direct part of the main calculations and seems adequate here. The slope parameter $a_{\rm qfs}$ is a function of the incident energy here too and has the empirical form

$$a_{\rm qfs}(E_{\rm inc}) = 0.086\ (E_{\rm inc} - 360)\ \Theta(E_{\rm inc} - 360). \tag{4.49}$$

Thus below 360 MeV, the slope parameter is zero and the angular distribution is isotropic in the N-N center of mass. Converting this result into the laboratory system using the relativisitic relationships produces the angle differential cross section

$$\frac{d\sigma_{\rm qfs}(\theta_{\rm lab})}{d\Omega_{\rm lab}} = \frac{d\sigma_{\rm qfs}(\theta_{\rm c})}{d\Omega_{\rm c}}\left[\frac{2D_{b,\rm lab}}{E_{\rm inc}}\right]^{1/2}\frac{1}{\gamma}\left\{1 - \left[\frac{D_{a,\rm lab}\,R}{D_{b,\rm lab}}\right]^{1/2}\gamma_{b,\rm lab}\cos\theta_{\rm lab}\right\}^{-1}. \tag{4.50}$$

This in turn can be combined with the previously described line shape to yield the double differential cross sections

$$\frac{d^2\sigma_{\rm qfs}(E_{\rm lab},\theta_{\rm lab})}{dE_{\rm lab}d\Omega_{\rm lab}} = \frac{d\sigma_{\rm qfs}(\theta_{\rm lab})}{d\Omega_{\rm lab}}\,\frac{2}{(w_1+w_2)\pi^{1/2}}\,\exp\left[-\left(\frac{E_{\rm qfs}-E_{\rm lab}}{w_i}\right)^2\right] \tag{4.51}$$

where either w_1 or w_2 is substituted for w_i depending on whether $E_{\rm lab}$ is below or above $E_{\rm qfs}$.

4.1.7. Projectile breakup

[Not yet included in PRECO.]

A study [KA88] of the systematics of continuum angular distributions for reactions induced by complex particles at energies of 36 to 720 MeV (but mainly

up to 172 MeV) revealed that the energy spectra for emission of particles lighter than the projectile contain extra cross section at forward angles that has a spectral shape centered close to the projectile velocity. This cross section is more forward peaked than either the other direct reactions or the preequilibrium cross section or the equilibrium cross section. It is also clearly visible [KA05] in angle-integrated energy specta and corresponds to break-up of the projectile in the vicinity of the target nucleus. A preliminary study of the energy spectrum for deuteron breakup has been made, but this work has not yet been extended to other complex projectiles, or to the angular distribution systematics.

A preliminary model for estimating this process was developed based on measured breakup peaks reported in the literature for (d,p) reactions at incident energies of 15 to 80 MeV. The subscripts below refer to the participants in the reaction A(a,b)B. All energies are assumed to be given in MeV and all cross sections in mb. Energy differential cross sections are thus in mb/MeV. The centroid energy of the breakup peak is given by

$$\varepsilon_0 = \frac{A_b}{A_a}\left(\varepsilon_a - B_{a,b} - \frac{Z_a Z_A}{9.5}\right) + \frac{Z_b Z_B}{9.5}. \tag{4.52}$$

where ε represents the channel energy (the energy of both the emitted particle and the recoiling nucleus in the center of mass), and $B_{a,b}$ is the binding energy in the projectile for the indicated breakup channel. The terms with the Z factors account for the slowing down of the projectile and the speeding up of an emitted charged particle due to Coulomb forces. The peak is assumed to be described by a Gaussian line shape with a width parameter of

$$\Gamma = 1.15 + 0.12E_a - \frac{A_A}{140}, \tag{4.53}$$

where E_a is the laboratory energy of the incident deuteron, and the width parameter is again given in MeV. Finally the breakup cross section is assumed to be

$$\sigma_{\mathrm{BU(d,b)}} = K_{\mathrm{d,b}} \frac{\left(A_A^{1/3} + 0.8\right)^2}{1 + \exp\left(\frac{13 - E_a}{6}\right)}. \tag{4.54}$$

The numerator indicates that the cross section is proportional to the square of the nuclear radius, while the denominator describes the onset of the cross section at lower incident energies.

The normalization factor for inclusive (d,p) breakup is

$$K_{\mathrm{d,p-tot}} = 21. \tag{4.55}$$

Of this cross section, some 80 to 85% appears to involve having the breakup neutron interact with the target nucleus. This is sometimes referred to as inelastic breakup. The assumed normalization constant for this is

$$K_{\mathrm{d,p-inel}} = 18. \tag{4.56}$$

The absorbed neutron would then initiate an equilibration process. The equilibrating nucleus would be the same as that formed by primary exciton-model proton emission and by (d,p) direct nucleon transfer, so that the equilibration processes and secondary preequilibrium emission for the three processes would all be calculated together. What about (d,n) breakup? This is handled in the same way but is assumed to have a somewhat smaller cross section due to the likely orientation of the deuteron in the Coulomb field of the nucleus. A factor of 0.8 to 0.85 is again used, so that

$$K_{\mathrm{d,n-tot}} = 18, \tag{4.57}$$

$$K_{\mathrm{d,n-inel}} = 15. \tag{4.58}$$

Clearly, there is greater uncertainty with regard to the last three normalization constants than with regard to the first.

4.1.8. Secondary emission following direct reactions

Only the residual nuclei formed by nucleon emission in direct stripping reactions such as (d,p) or (α,n) are allowed to undergo secondary preequilibrium emission. Other direct stripping reactions involve complex particle emission and are not allowed to undergo secondary emission for reasons similar to those that apply in the exciton model. Pickup reactions and nucleon exchange with complex projectiles also involve complex particle emission and, again, no secondary emission is calculated. For residual nuclei with cluster degrees of freedom or collective excitations, it is often unclear how to parameterize the particle-hole nature of their states, so secondary preequilibrium emission in the exciton model is not considered. In addition, the average emission energies in direct reactions tend to be high, which reduces secondary preequilibrium emission. All direct reaction residual nuclei formed by nucleon emission are, however, allowed to undergo secondary equilibrium emission of nucleons, as is done when the primary emission is calculated in the exciton model.

4.2. Particle Emission at Equilibrium

In principle, the exciton model can be extended to the equilibrated composite nucleus if master equations are used in place of the approximate closed form equations employed here to describe the energy redistribution in the composite nucleus. The master equations are solved numerically beginning with the initial target-projectile interaction and extending the numerical integration until all of the cross section has been exhausted. However, most of the preequilibrium particle emission happens in the first few interactions, where the closed form expressions are a good approximation, and so this involves needless work. Even worse, the assumption that the passive particles and holes remain passive is probably reasonable early in the reaction but would not be expected to be valid at equilibrium and can alter the relative yields calculated for ejectiles of different masses.

When the closed form approach to the preequilibrium calculations is adopted, as in PRECO-2006, the formalism cannot be extended to the equilibrium limit, but it is still possible to use the particle-hole states with their emission rates at equilibrium by assuming that all states of the system are equally likely to be populated. The difficulty of the passive particles and holes is avoided by assuming that $p_\pi = h_\pi$ and $p_\nu = h_\nu$ at equilibrium, but this approach still involves unnecessary effort since it has previously been demonstrated that the sum over the equi-spacing model particle-hole state densities has the same energy dependence as the normal Fermi-gas model state densities, which are much simpler to use. Thus the particle-hole formalism is abandoned at the equilibrium limit in favor of a more traditional evaporation calculation.

4.2.1. Primary evaporation rates

The equilibrium calculations are performed using a simple Weisskopf-Ewing evaporation formula. In this model, the isospin mixed particle emission rates are given by

$$W_b(E,\varepsilon) = \frac{2s_b+1}{\pi^2\hbar^3}\,\mu_b\,\varepsilon\,\sigma_b(\varepsilon)\,\frac{\omega(U)}{\omega(E)}. \tag{4.59}$$

This has much the same form as the preequilibrium emission rates given in Eq. (3.7) on page 39, and the variables have the same meaning, but here the state densities are characterized only by the excitation energy of the nucleus. The state density in the numerator is evaluated in the residual nucleus formed by emission of a particle of type b, while the state density in the denominator is evaluated for the emitting nucleus.

The basic equilibrium state densities are given by the two-Fermi-gas formula. For nuclei away from shell closures this state density has the form

$$\omega_{\rm FG}(E) \propto a_0^{-1/4}\, E_{\rm eff}^{-5/4}\, \exp\left(2\sqrt{a_0\, E_{\rm eff}}\right) \tag{4.60}$$

where the effective excitation energy $E_{\rm eff}$ is given by

$$E_{\rm eff} = E - C_{\pi 0}(Z) - C_{\nu 0}(N). \tag{4.61}$$

The pairing condensation energies are typically the same as those used in the preequilibrium calculations but different values can also be used. The quantity a_0 is the level density parameter which is related to the single particle state density through the relation

$$a_0 = \pi^2\, g_0/6 = \pi^2(g_{\pi 0} + g_{\nu 0})/6. \tag{4.62}$$

The difficulty with Eq. (4.60) is that it does not extend down to the physical ground state, and, in fact, becomes unphysically large as $E_{\rm eff}$ approaches zero. This can cause problems both at low residual excitation energies and when secondary equilibrium emission is calculated [KA98]. To correct this, the usual transition to a constant temperature state density formula is made at low excitation energies. The equation for this state density is

$$\omega_{\rm T}(E) \propto t^{-1} \exp(E/t) \tag{4.63}$$

where t is the constant nuclear temperature. The constant temperature form is matched for both slope and value to the Fermi-gas form at the point [GI65]

$$E_{\rm eff,m} = (2.5 + 150/A)\ \ {\rm MeV}. \tag{4.64}$$

The slope matching condition leads to a value of the nuclear temperature of

$$t = \left(\sqrt{a_0/E_{\rm eff,m}} - 1.25/E_{\rm eff,m}\right)^{-1}. \tag{4.65}$$

4.2.2. Shell corrections

When the emitting and residual nuclei are near a shell closure, then shell effects are also included in the equilibrium state densities. The effective excitation energies contain a shell correction so that

$$E_{\rm eff} = E - C_{\pi 0}(Z) - C_{\nu 0}(N) - S_\pi(Z) - S_\nu(N). \tag{4.66}$$

Since shell effects are assumed to have washed out at equilibrium, the S's for a nucleus with a closed-shell configuration represent the amount by which the ground state of the nucleus in question is lowered by the presence of the shell gap in the shell-shifted equi-spacing model (S^2-ESM) relative to its position in the ESM. Using the notation of Sect. 2.5 the proton equilibrium shell correction in PRECO-2006 is given by

$$S_{\pi,\mathrm{cl}}(Z_{\mathrm{mag}}) = \frac{D_\pi}{2} M_\pi - \frac{d_\pi}{2} M_\pi^2, \tag{4.67}$$

with an analogous expression for $S_{\nu,\mathrm{cl}}(N_{\mathrm{mag}})$. For nuclei that are near but not at a shell closures, the shell shift is evaluated according to Eq. (4.67) but using the single particle spacing, d_π, of the near-shell nucleus. Then the shell-washout factors of Eq. (2.35) on page 26 are applied giving

$$S_\pi(Z) = F_{\pi,\mathrm{shell}}(Z, Z_{\mathrm{mag}})\, S_{\pi,\mathrm{cl}}(Z) \tag{4.68}$$

and similarly for $S_\nu(N)$. Thus $S_\pi(Z_{\mathrm{mag}}) = S_{\pi,\mathrm{cl}}(Z_{\mathrm{mag}})$. If either shell gap is zero (signifying that the nucleus is not near a shell closure for that type of nucleon), then the corresponding S is also set equal to zero.

The level density parameter also contains a shell correction that was added in [KA99]. First the level density parameter is divided into a neutron and proton part so that $a_0 = a_{\pi 0} + a_{\nu 0}$ where $a_{\pi 0} = \pi^2\, g_{\pi 0}/6$ and is typically proportional to Z (and similarly for $a_{\nu 0}$ and N). For a closed-shell configuration, the single particle state density for the appropriate type of nucleon, $a_{\pi,\mathrm{cl}}$ or $a_{\nu,\mathrm{cl}}$, is obtained by averaging over the S^2-ESM single particle states using a staircase weighting function centered in the middle of the shell gap. The width of the averaging function was determined empirically for the lead region, where the shell effects are largest, and it was assumed to scale with the temperature, t of the constant temperature state density, evaluated in the absence of shell effects. The result is that the averaging interval is assumed to extend for an energy of $k_{\mathrm{shell}} t$ in either direction from the center of the shell gap, and the optimum value of the scaling constant seems to be about $k_{\mathrm{shell}} = 2.3$. This is the default value, but others can be read in. For nuclei with a near-shell configuration, the shell correction to the level density parameter is assumed to wash out in the same way and over the same mass range as the shell corrections to the effective excitation energy so that

$$a_\pi(Z) = F_{\pi,\mathrm{shell}}(Z, Z_{\mathrm{mag}})\, a_{\pi,\mathrm{cl}}(Z) + [1 - F_{\pi,\mathrm{shell}}(Z, Z_{\mathrm{mag}})]\, a_{\pi 0}(Z). \tag{4.69}$$

Finally, a_0 in the equilibrium state densities is replaced by

$$a(N,Z) = a_\pi(Z) + a_\nu(N). \tag{4.70}$$

To calculate the state densities at low excitation energies, a new nuclear temperature, $t_{\rm shell}$, is evaluated using Eq. (4.65) but with the level density parameter of Eq. (4.70) in place of a_0. Thus shell effects in a only affect the constant temperature state densities through the matching conditions. As shown in Ref. [KA98], the level density parameter of Eq. (4.70) shows the same general pattern as a function of target mass as is found in several empirical parameter sets derived from studying compound nucleus reactions. The current formulation, however, has the advantage of being derived from the set of single particle states used in the preequilibrium part of the calculations.

4.2.3. Isospin conservation

If isospin is assumed to be conserved during the preequilibrium phase of the reaction, then the fraction of isospin conservation at equilibrium is given by the parameter $F_{\rm Teq}$, which can be supplied as input. If default isospin parameters are used, isospin is assumed to be conserved during the preequilibrium phase when $E/E_{\rm sym} < 4$. In this case the quantity $F_{\rm Teq}$ defaults to [KA05a]

$$F_{\rm Teq} = \frac{0.4}{1+\exp\left[6(E/E_{\rm sym}-3.5)\right]} \qquad \text{for } E/E_{\rm sym} < 4, \tag{4.71}$$

which has a value close to 0.4 for most systems. For partial conservation of isospin at equilibrium, evaporation rates are calculated separately for the isospin mixed and isospin conserved parts of the strength and a weighted sum is taken. The particle emission rates at equilibrium for the isospin conserved part of the calculations become

$$W_b(E,\varepsilon,T) = \frac{2s_b+1}{\pi^2\hbar^3}\,\mu_b\,\varepsilon\,\sigma_b(\varepsilon)\sum_{T_B}\left[C_b(T,T_B)\right]^2\frac{\omega(U,T_B)}{\omega(E,T)} \tag{4.72}$$

where C_b is again the exit channel isospin coupling Clebsch-Gordan coefficient.

The main isospin-dependent state densites are still given by Eq. (4.60) but with the appropriate symmetry energy subtracted in the calculation of the effective excitation energy. Thus the state density is

$$\omega_{\rm FG}(E,T) \propto a_0^{-1/4}E_{\rm eff}^{-5/4}\exp\left(2\sqrt{a_0\,E_{\rm eff}}\right) \tag{4.73}$$

with

$$E_{\text{eff}} = E - E_{\text{sym}}(T, T_z) - C_{\pi 0}(Z) - C_{\nu 0}(N) - S_\pi(Z) - S_\nu(N). \tag{4.74}$$

At lower excitation energies, the constant temperature state density formula is still used, but the matching point will shift with E_{eff}, and the state density goes to zero at $E - E_{\text{sym}}(T, T_z)$, the ground state energy for this isospin value.

4.2.4. Secondary evaporation rates

Secondary evaporation is handled using the same emission rate and state density formulae as primary evaporation. As in the case of secondary preequilibrium emission, only nucleons are considered and then only after primary nucleon emission. The reasons are again the generally weak emission rates for deuterons, tritons and ^{3}He due to their binding energies coupled with the high Coulomb barrier for ^{3}He and α-particles which further reduce evaporation. On the other hand, for the higher incident energies, secondary evaporation of complex particles, particularly α-particles should be included.

At present, a separate calculation is done for each nucleon type (neutron or proton) and each energy of primary particle. Strength going into secondary evaporation comes from direct reactions, from primary preequilibrium emission when no secondary preequilibrium emission occurs, and from primary evaporation. The flow of the direct nucleon transfer, exciton model and primary evaporation strength (but not the other direct reaction strength) is shown in Fig. 3.1 on page 45. As in the secondary preequilibrium calculations, the correct binding energies, pairing condensation energies and shell corrections for the new emitting and residual nuclei are used, and the total reaction cross sections occuring in the emission rates are also recalculated.

A new piece of physics must, however, be considered with secondary equilibrium emission: possibile competition from γ-ray emission. In general, particle emission occurs on a much faster time scale than γ emission and so γ-rays need only be considered in the final de-excitation of residual nuclei with energies below the particle emission threshold. This is typically done in a Hauser-Feshbach model calculation and is not considered in PRECO. On the other hand, a primary residual nucleus at low excitation energy might have the neutron channel closed because of binding energy considerations while the proton channel is technically open but severely hindered by the Coulomb barrier. Under these circumstances the competition from γ-ray emission must be considered or else the secondary proton emission will be dramatically over-estimated.

In PRECO, this is handled by introducing a new criterion for the calculation of secondary evaporation [KA99]. The standard criterion would be that at least one of the nucleon exit channels be open so that $U \geq \varepsilon_{\min} + \min(B_n, B_p)$, where $\varepsilon_{\min}$ is the lowest emission energy considered in the calculations. This is now modified to the requirement that

$$U \geq \min(\varepsilon_{\min} + B_n, \varepsilon_{\mathrm{p,\,min}} + B_p) \tag{4.75}$$

where $\varepsilon_{\mathrm{p,\,min}}$ is the lowest emission energy in the grid of considered energies that fulfills the condition

$$\sigma_{\mathrm{p,rxn}}(\varepsilon)/\sigma_{\mathrm{n,rxn}}(\varepsilon) \geq R_\gamma = 0.005. \tag{4.76}$$

The indicated value of R_γ is the default and was determined empirically, but other values can be read in. This method is clearly approximate in that it assumes a sharp rather than a gradual cutoff in proton emission as the energy of the primary residual nucleus decreases. In addition, the results are not a smooth function of R_γ as it is varied because of the discrete set of emission energies considered. However the chosen value of R_γ seems to work reasonably well for most reactions and represents a vast improvement over the original criterion for secondary evaporation calculations.

4.2.5. Fission Rates

A very simple treatment of nuclear fission is included as a competing mechanism for equilibrium particle emission (both primary and secondary). In the isospin mixed case the fission rate is given by

$$W_{\mathrm{fiss}}(E) = \frac{1}{2\pi\hbar}\int_0^{E-B_f} \frac{\omega(E - B_f - \varepsilon)}{\omega(E)} d\varepsilon \tag{4.77}$$

where the state densities are evaluated as in the equilibrium particle emission rates except that both state densities are evaluated in the composite nucleus and no shell corrections are made at the top of the fission barrier (*i.e.* in the numerator). When isospin is conserved as a quantum number, then Eq. (4.77) is modified by including the isospin of the composite nucleus as a label on the state densities. The fission barriers in the composite and primary residual nuclei are provided as input when fission competition is to be considered. This feature of the code has never been tested or benchmarked against data.

A weakness of this approach, aside from the approximate nature of the model, is that when fission makes a significant contribution to the reaction cross section it will typically also produce two or three prompt neutrons which will appear in the measured inclusive neutron spectra but which are not currently calculated in PRECO. It is hoped to add this in the future.

5. Angular Distributions

The exciton model from its beginnings was designed to describe the energy spectra of the emitted particles. The description of angular distributions was not included, partly because angular momentum is ignored in the calculations. In addition, many theoretical attempts to describe preequilibrium angular distributions have proven to be of limited usefulness. In PRECO, a phenomenological approach is adopted. The systematics described here apply to particles emitted during direct nucleon transfer reactions, during inelastic scattering and knockout reactions involving cluster degrees of freedom, during preequilibrium emission (both primary and secondary) as described by the exciton model, and during equilibrium particle evaporation (both primary and secondary). The systematics were developed in a series of papers [KA81, KA88, KA93a], and the results are summarized here. The angular distributions for quasi-free scattering and the breakup of complex projectiles do not follow these systematics. The QFS component has already been discussed in Sect. 4.1.6 on page 57, while the breakup component of the angular distributions is still awaiting study. Finally, collective excitations and elastic scattering follow systematics that are different from but related to the main angular distribution systematics. They are described later in this chapter.

5.1. Main Systematics

The original angular distribution formalism divides the cross section into two components, multi-step direct and multi-step compound, following the suggestion of [FE80]. The multi-step direct (or MSD) part is defined as always having at least one unbound particle degree of freedom at each stage of the reaction, while in the multi-step compound (or MSC) part the system passes through at least one configuration where all of the particles are bound so that information about the original projectile direction is largely lost. The MSD cross section is thus assumed to exhibit forward-peaked angular distributions, while the MSC cross section has angular distributions which are symmetric about 90° in the center of mass. In

the two-component exciton model, the MSD and MSC cross sections are not specifically calculated, so that beginning in PRECO-E the MSD/MSC distinction was abandoned in favor of a preequilibrium/equilibrium division which yields very similar (though occasionally slightly more forward peaked) results [KA86].

The basic formula for the double differential cross section for the included mechanisms in the reaction A(a,b)B can be written in the three equivalent forms

$$\begin{aligned}\frac{d^2\sigma}{d\Omega d\varepsilon_b} &= \frac{1}{4\pi}\frac{a_{\rm ex}}{e^{a_{\rm ex}}-e^{-a_{\rm ex}}}\left(\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm msd} 2e^{a_{\rm ex}\cos\theta} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm msc}\left[e^{a_{\rm ex}\cos\theta}+e^{-a_{\rm ex}\cos\theta}\right]\right)\\ &= \frac{1}{4\pi}\frac{d\sigma}{d\varepsilon_b}\frac{a_{\rm ex}}{e^{a_{\rm ex}}-e^{-a_{\rm ex}}}\left[(1+f_{\rm msd})\,e^{a_{\rm ex}\cos\theta}+(1-f_{\rm msd})\,e^{-a_{\rm ex}\cos\theta}\right]\\ &= \frac{1}{4\pi}\frac{d\sigma}{d\varepsilon_b}\frac{a_{\rm ex}}{\sinh(a_{\rm ex})}\left[\cosh(a_{\rm ex}\cos\theta)+f_{\rm msd}\sinh(a_{\rm ex}\cos\theta)\right], \qquad (5.1)\end{aligned}$$

where $a_{\rm ex}$ is the slope parameter associated with the exciton model and its related components. The quantity $f_{\rm msd}(\varepsilon_b)$ is the fraction of the cross section at the specified emission energy which is multi-step direct and is here replaced with the fraction that is preequilibrium. The angle θ is measured in the center-of-mass system. Physically this relationship means that the MSD or preequilibrium or forward-peaked component of the cross section has an angular distribution that is given by an exponential in $\cos\theta$, while the MSC or equilibrium or symmetric component is the sum of exponentials in $\pm\cos\theta$. The remaining physics is hidden in the slope parameter.

5.1.1. Slope parameter

To first order, the slope parameter is a function of the emission energy at lower incident energies (below about 100 MeV for nucleons); is a function of the ratio between the emission and incident energies at higher incident energies (in excess of about 170 MeV for nucleons); and shows a transitional behavior in between these two limits. The transition region is characterized by the transition energy parameter E_{t1}. In addition there are second order dependences which vary with the specific nature of the incoming and outgoing particles and which frequently show a similar transition in their energy dependence, but at a much lower transition energy given by E_{t3}. The general form for the slope parameter is

$$a_{\rm ex}(e_a,e_b) = 5.2(X_1) + 4.0(X_1)^3 + 1.9M_aM_b(X_3)^4 \qquad (5.2)$$

$$X_1 = \frac{e_b\, E_1(e_a)}{130 \text{ MeV } e_a} \tag{5.3}$$

$$X_3 = \frac{e_b\, E_3(e_a)}{35 \text{ MeV } e_a} \tag{5.4}$$

where e_a and e_b are given by the channel energies of the incoming and outgoing particles, ε_a and ε_b, plus the corresponding liquid drop model separation (or binding) energies. Thus

$$e_i = \varepsilon_i + B_{i,\text{ld}} \tag{5.5}$$

where the separation energies are obtained from the liquid drop model mass formula of Myers and Swiatecki [MY66]. For the separation of a composite nucleus C into a particle b and a nucleus B they are given by

$$\begin{aligned} B_{b,\text{ld}} = {} & 15.68\,[A_C - A_B] - 28.07 \left[\frac{(N_C - Z_C)^2}{A_C} - \frac{(N_B - Z_B)^2}{A_B}\right] \\ & - 18.56 \left[A_C^{2/3} - A_B^{2/3}\right] + 33.22 \left[\frac{(N_C - Z_C)^2}{A_C^{4/3}} - \frac{(N_B - Z_B)^2}{A_B^{4/3}}\right] \\ & - 0.717 \left[\frac{Z_C^2}{A_C^{1/3}} - \frac{Z_B^2}{A_B^{1/3}}\right] + 1.211 \left[\frac{Z_C^2}{A_C} - \frac{Z_B^2}{A_B}\right] - I_b \end{aligned} \tag{5.6}$$

where I_b is the internal binding energy of the particle b (if it is complex).

The parameters E_1 and E_3 in Eqs. (5.3) and (5.4) accomplish the change in the important physical parameters for the main and secondary dependences. The pertinent equation for both of them is

$$E_i(e_a) = e_a \left[1 + \exp\left(\frac{e_a - E_{ti}}{\Delta_i}\right)\right]^{-1} + E_{ti} \left[1 + \exp\left(\frac{E_{ti} + 0.5\Delta_i - e_a}{\Delta_i}\right)\right]^{-1} \tag{5.7}$$

$$\Delta_i = 0.092 E_{ti} \tag{5.8}$$

where Δ_i is the energy range over which the transition takes place. The values adopted for the transition energies are

$$E_{t1} = \begin{cases} 130 \text{ MeV} & \text{for incident } n,\, p,\, d,\, t,\, {}^3\text{He} \\ 260 \text{ MeV} & \text{for incident } \alpha \end{cases} \tag{5.9}$$

$$E_{t3} = 35 \text{ MeV} \qquad \text{for incident } n,\, p,\, d,\, t,\, {}^3\text{He}. \tag{5.10}$$

where only the incident nucleon value of E_{t1} has been determined, and the value for incident α-particles is indicated to be above 140 MeV. Similarly, E_{t3} has been determined for incident nucleons and deuterons, and it is not needed for incident α-particles. Other values are only assumptions at this point. The behavior of $E_1(e_a)$ for incident nucleons is shown in Fig. 5.1 along with the extrapolation of the low energy and high energy limiting dependences. With this dependence of

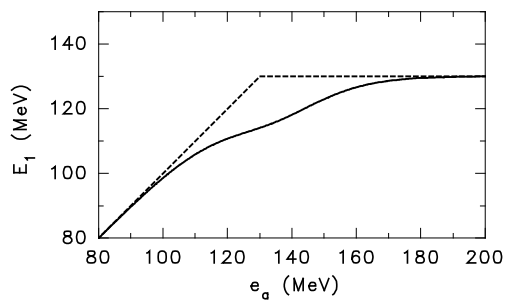

Figure 5.1: *Values of the parameter E_1 as a function of the incident energy parameter e_a in the transition region. The quantity E_1 determines the functional dependence of the angular distribution slope parameter. The dashed lines show the extrapolations of the limiting behavior of E_1. Note the supressed zero on the e_a axis.*

E_1, the parameter X_1 goes from a values of $e_b/(130\text{ MeV})$ at low bombarding energies to a value of e_b/e_a at high bombarding energies. The quantities M_a and M_b in Eq. (5.2) are multipliers that depend on the nature of the incident and emitted particles, respectively. The currently known values are

$$M_a = \begin{cases} 2 & \text{for n} \\ 1 & \text{for p, d} \\ 0 & \text{for } \alpha \\ ? & \text{for t, } ^3\text{He} \end{cases} \tag{5.11}$$

$$M_b = \begin{cases} 0.5 & \text{for n} \\ 1 & \text{for p, d, t, } ^3\text{He} \\ 2 & \text{for } \alpha \end{cases} . \tag{5.12}$$

The value of M_a for incident neutrons was 1 in previous versions of the code and has been provisionally revised based on new data for neutron induced charged particle emission at energies up to 63 MeV. Previous data extended mainly up to

25 MeV and were much less sensitive to M_a.. The value of $M_a = 0$ for incident α-particles means that E_{t3} is not needed.

Obviously there are still some open questions. One is the value M_a for mass 3 projectiles. PRECO currently assumes a value of 1, but the systematics of M_a suggest that it might vary with the projectile charge, making 0 a more appropriate choice for incident ^{3}He. Other open questions are the transition energies for complex projectiles. All that is known is that E_{t1} for incident α-particles must be greater than 165 MeV and that E_{t3} is not needed for them.

5.1.2. Fraction that is 'MSD'

The division of the cross section into the preequilibrium and equilibrium parts in order to generate $f_{\rm msd}$ is quite straightforward, though there is a separate value for each exit channel and emission energy. The 'MSD' or preequilibrium or forward-peaked component includes the exciton model preequilibrium components (both primary and secondary) as well as the cross sections from nucleon transfer, knockout and inelastic scattering involving cluster degrees of freedom. Collective excitations and elastic scattering are treated separately. Thus for inelastic scattering

$$\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm msd} = \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm pre,1} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm pre,2} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm NT} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm IN}. \tag{5.13}$$

For other reaction channels it is

$$\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm msd} = \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm pre,1} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm pre,2} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm NT} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm KO}, \tag{5.14}$$

where the knockout contribution occurs only for (N,α), (C,N) and (C,α) reactions, where N is a nucleon and C is a complex particle (d, t, ^{3}He or α-particle). The corresponding equilibrium or symmetric component contains only the primary and secondary evaporation cross sections and is given by

$$\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm msc} = \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm eq,1} + \left[\frac{d\sigma}{d\varepsilon_b}\right]_{\rm eq,2}. \tag{5.15}$$

These are then combined to yield the fraction of the cross section which is forward peaked:

$$f_{\rm msd}(\varepsilon_b) = \frac{[d\sigma/d\varepsilon_b]_{\rm msd}}{[d\sigma/d\varepsilon_b]_{\rm msd} + [d\sigma/d\varepsilon_b]_{\rm msc}}. \tag{5.16}$$

5.2. Collective Excitations and Elastic Scattering

The angular distributions for collective excitations and elastic scattering often show diffraction maxima and minima. These are not reproduced in these calculations. Instead, an attempt is made to describe the general smoothed trend of the data. For both spectroscopic and giant resonance collective excitations, this trend can again be described by an exponential in $\cos\theta$, as was the case for MSD cross section in the main systematics. The slope parameter, $a_{\rm col}$, is a simple multiple of the main slope parameter, $a_{\rm ex}$. For elastic scattering, two exponentials are needed, one which follows the collective state systematics and another which is more forward peaked. The slope parameters for the collective states are given by

$$a_{\rm col}(e_a, e_b) = K_{\rm col}\, a_{\rm ex}(e_a, e_b) \tag{5.17}$$

where the multipliers are projectile dependent and have the empirical values given in Table 5.1. Here the α-particle multiplier seems to be out of line with the others,

Table 5.1: *Parameters for collective state and elastic scattering angular distributions.*

projectile	$K_{\rm col}$	$F_{\rm EL,Coul}$
n	1.0	
p	1.0	0.020
d	1.5	$0.004 + (N-Z)/9A$
t	1.9	$0.040 - (N-Z)/6A$
^{3}He	1.5	$0.006 + (N-Z)/7A$
α	4.3	0.032

but this is due to the fact that the third term in the main slope parameter is not used for incident α-particles. If it were used and had the same transition energy (35 MeV) as the other light projectiles, then the α-particle value of $K_{\rm col}$ would be about 1.9. The slope parameters for the more forward-peaked elastic scattering components are given approximately by

$$a_{\rm el}(e_a, e_b) = a_{\rm col}(e_a, e_b) + 18. \tag{5.18}$$

For the collective excitations, all the necessary information is in hand, and the

double differential cross section is given by

$$\left[\frac{d^2\sigma_{a,a'}}{d\Omega d\varepsilon_b}\right]_{\mathrm{COL}} = \frac{1}{4\pi}\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\mathrm{COL}} \frac{2a_{\mathrm{col}}}{e^{a_{\mathrm{col}}} - e^{-a_{\mathrm{col}}}} e^{a_{\mathrm{col}}\cos\theta}. \tag{5.19}$$

For elastic scattering, the double differential cross section is given by

$$\left[\frac{d^2\sigma_{a,a'}}{d\Omega d\varepsilon_b}\right]_{\mathrm{EL}} = \frac{1}{4\pi}\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\mathrm{EL}} \left[F_{\mathrm{EL}} \frac{2a_{\mathrm{col}}}{e^{a_{\mathrm{col}}} - e^{-a_{\mathrm{col}}}} e^{a_{\mathrm{col}}\cos\theta} + (1 - F_{\mathrm{EL}}) \frac{2a_{\mathrm{el}}}{e^{a_{\mathrm{el}}} - e^{-a_{\mathrm{el}}}} e^{a_{\mathrm{el}}\cos\theta}\right]. \tag{5.20}$$

and it is still necessary to specify the fraction, F_{EL}, which follows the collective state systematics. This fraction is different for the nuclear and Coulomb parts of the elastic scattering. For the nuclear part, calculated using the collective excitation model, the fraction is given by

$$F_{\mathrm{EL,nucl}} = \frac{E_{2+} + E_{3-}}{2\,A_a\,\varepsilon_i} \tag{5.21}$$

where E_{2+} and E_{3-} are the excitation energies of the strong 2+ and 3− collective strength. Their average represents a measure of the stiffness of the nucleus. The values of F_{EL} for the Coulomb part of the elastic cross section are given in Table 5.1. All of the results represent empirical trends. The final value for F_{EL} is a weighted average of the values for the two separate mechanisms so that

$$F_{\mathrm{EL}} = \left\{F_{\mathrm{EL,nucl}}\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\mathrm{EL,nucl}} + F_{\mathrm{EL,Coul}}\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\mathrm{EL,Coul}}\right\}\left[\frac{d\sigma}{d\varepsilon_b}\right]_{\mathrm{EL}}^{-1}. \tag{5.22}$$

6. Recommended Global Input Set

Much of the work on the exciton model and the code PRECO in recent years has involved careful comparisons of their results with experiment and, where necessary, a reworking of the physics and parameters which they contain. In the process a set of recommended global input has been developed and verified against a large number of energy spectra from the literature. The results are described in this chapter. It must be emphasized that the exciton model parameters and default non-elastic cross sections really do form an input *set* and should be used with caution if individual parameter values are changed.

6.1. Exciton Model Input Parameters

In general, the recommended global input set for the exciton model has been included as the default values in PRECO. They have typically been mentioned in the discussion of the physics underlying the code but are summarized here. The input can generally be divided into two categories: parameters unique to the exciton model, for which little or no guidance is available from other sources, and parameters for which at least approximate values can be obtained independent of the exciton model.

6.1.1. Unique parameters

The single parameter group that is most unique to the exciton model is the effective mean-square matrix elements for the residual two-body interactions responsible for energy equilibration in the composite nucleus. These have been determined phenomenologically, though they have been confirmed to be significantly smaller than the full two-body matrix elements, and some theoretical guidance has been used for extending them to incident (or excitation) energies outside the range investigated. The mathematical form for these mean square matrix elements, given

by Eq. (3.2), is

$$|M_{ij}|^2 = K_{ij}\, A_a\, g_0^{-3} \left(\frac{E}{3A_a} + 20.9 \right)^{-3}, \tag{6.1}$$

while the normalization parameters have the recommended values

$$K_{\pi\pi} = 2200 \text{ MeV}^2 \tag{6.2a}$$

$$K_{\pi\nu} = K_{\nu\pi} \;=\; K_{\nu\nu} \;=\; 900 \text{ MeV}^2. \tag{6.2b}$$

Reverting to an earlier choice of having the mean square matrix elements depend on E/n rather than $E/3$ produces larger matrix elements and thus less preequilibrium emission at later stages of the reaction and is not indicated by the data. Similarly, the inclusion of a dependence on the projectile mass number, A_a, is found to give improved agreement with complex particle induced reactions.

Approximate values for the ESM single particle state densities can be estimated from the level density parameters obtained from studying evaporation spectra, but 15-20% uncertainties remain. As part of the benchmarking process for PRECO-2000, the values for the single particle state densities obtained were

$$g_{\pi 0}(Z) = \frac{Z}{K_{\rm g}} \;=\; \frac{Z}{15 \text{ MeV}} \tag{6.3}$$

$$g_{\nu 0}(N) = \frac{N}{K_{\rm g}} \;=\; \frac{N}{15 \text{ MeV}}. \tag{6.4}$$

With the mean square matrix elements given in terms of g_0 rather than A, the values for the K_{ij} are now not as strongly coupled to the choice for the ESM single particle state densities for protons and neutrons as was the case in PRECO-2000. (In [KA95a] it was shown that changing $K_{{\rm g}\pi} = K_{{\rm g}\nu}$ from 15 MeV to 13 MeV required lowering the K_{ij} by about a factor of two in order to obtain the same cross section for direct preequilibrium emission. It also produced a slight lowering of preequilibrium emission from the more complex states.) The reason for the old strong coupling between the $K_{\rm g}$ and K_{ij} can be inferred from Eqs. (3.3) and (3.7) which show that previously the ratio of the nucleon emission rates to the particle-hole pair creation rates was proportional to $K_{\rm g}^4/K_{ij}$, but with the new formula for M^2 it is now only proportional to $K_{\rm g}/K_{ij}$. This ratio of rates is closely related to the preequilibrium emission cross sections, which are the main experimental observables.

Finally, it is necessary to specify the initial particle-hole configuration for the equilibration calculations. This is programmed into PRECO. The calculations are

started with only the projectile nucleons as degrees of freedom, $(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a, 0, N_a, 0)$, in order to insure that proton and neutron particle-hole pairs will be excited in the correct relative proportions based on the pair creation rates. However, particle emission is only allowed after the creation of the first particle-hole pair to form states with $(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a + 1, 1, N_a, 0)$ and $(Z_a, 0, N_a + 1, 1)$. For nucleon induced reactions, this is the only reasonable choice because after particle emission there must be at least one degree of freedom to carry the residual nucleus' excitation energy. For light complex projectiles (those with $A = 2$ to 4), particle emission from the states with $(p_\pi, h_\pi, p_\nu, h_\nu) = (Z_a, 0, N_a, 0)$ is possible but currently yields too much preequilibrium emission. Once projectile breakup is included in the calculations and is allowed to deplete the reaction strength available to the exciton model equilibration process, the issue of the initial configuration for particle emission from complex particle induced reactions will be reconsidered.

6.1.2. Shell structure parameters

The only new parameters that are essential for including shell structure effects in the calculations are the Z and N of the closed-shell configurations and an estimate of the size of the corresponding shell gaps in the single particle states for protons and neutrons. The widths of the shell gaps, D_π and D_ν, were estimated in a model-independent way [KA95] using a table of nuclear masses. They represent the gap occuring at a closed-shell configuration minus any pairing contributions. The results are given in Table 6.1 and are compared with typical single particle spacings from Eqs. (6.3) and (6.4). The gaps for magic numbers 8 and 20 have been adjusted slightly from the originally published values to reflect changes in the default single particle spacings. The uncertainties quoted in the shell gaps are probably overestimates since the quoted values represent averages and much of the deviations come from correlated even-odd differences. These shell gaps are available as a default option in the code input, and, if requested, the code will decide whether the particular values of Z and N involved in a reaction require the inclusion of shell effects.

Another set of parameters that can be read in are the degeneracies of the single particle levels above and below the shell gaps in the shell-shifted equi-spacing model. By default these are calculated from the shell gaps and single

Table 6.1: *Widths of the shell gaps estimated from nuclear mass tables.*

Magic number	D_π (MeV)	D_ν (MeV)	d_π or d_ν (MeV)
8	2.5±1.2	3.1±1.1	1.88
20	1.6±0.8	2.4±0.6	0.75
28	1.5±0.6	1.3±0.6	0.54
50	2.0±0.3	2.3±0.5	0.30
82	1.4±0.5	1.9±0.4	0.18
126		1.6±0.4	0.12

particle spacings according to Eq. (2.23) which is repeated here:

$$M_\pi = \text{integer}\left(\frac{D_\pi + d_\pi}{2d_\pi}\right). \tag{6.5}$$

This is the recommended value, but other choices (such as the degeneracies of the shell model orbitals) can be read in so that different degeneracies are used for the levels above and below each shell gap. Studies in [KA95] indicate that, at least in the vicinity of the $N = 50$ shell closure, the default degeneracies are the more appropriate values to use.

6.1.3. Pairing condensation energies

There are a number of schemes that have been proposed for pairing energies in nuclear state densities, but it is often difficult to disentangle the pairing and shell components to an energy shift. The recommended global input set for PRECO uses a smoothed fit to the Gilbert and Cameron pairing condensation energies [GI65] for nuclei away from shell closures. The mathematical form was taken from the work of Nemirovsky and Adamchuk [NE62], but their results were normalized by a factor of 0.85 to follow the trends of the Gilbert and Cameron values. The recommended pairing energies are thus

$$C_{\pi 0}(Z) = 9.69 Z^{-0.567} \tag{6.6a}$$

$$C_{\nu 0}(N) = 9.83 N^{-0.552} \tag{6.6b}$$

which are also the default values in the code.

There are two pairing options available in the preequilibrium part of the calculations, a simple constant pairing shift and a collective pairing correction that

varies with the configuration. The differences between the two in the calculated energy spectra have so far been found to be quite small and restricted to the highest emission energies where the spectrum is least amenable to description by statistical models. Thus there is no strong recommendation on which option to use.

6.1.4. Isospin parameters

The first parameter needed with regard to isospin is the extent to which it is conserved in a given reaction. In the preequilibrium phase of the reaction, only the extreme options of full conservation or full mixing are considered, and many reactions are insensitive to the choice between them. Information from the preequilibrium part of the spectrum can, however, be supplemented from the equilibrium part. If the equilibrium part of the spectrum indicates at least partial isospin conservation, then isospin must have been largely conserved during the preceding equilibration process. A study [KA05a] including many reactions with complex particles in either the entrance or exit channel, has yielded the results summarized in Fig. 6.1. A number of mathematical criteria for isospin conservation are consistent with these results, but the one that has been adopted here is the assumption that isospin is conserved in the preequilibrium phase of the reaction when $E_{\rm inc} < 4\,E_{\rm sym}$, where $E_{\rm sym}$ is the symmetry energy in the composite nucleus. This is the default in PRECO-2006. Previously a choice for each reaction had to be supplied as input.

When isospin is conserved in the preequilibrium part of the reaction, it is necessary to specify the extent to which it is conserved at equilibrium. The results from [KA05a] are shown in Fig. 6.2. The current recommendation and default is given by Eq. (4.71) which is reproduced here

$$F_{\rm Teq} = \frac{0.4}{1 + \exp\left[6(E/E_{\rm sym} - 3.5)\right]} \qquad \text{for } E/E_{\rm sym} < 4. \tag{6.7}$$

For most reactions in which isospin is conserved during equilibration, this means that roughly 40% of the equilibrium cross section involves emission while isospin is still conserved. As discussed in [KA05a], however, these equilibrium fractions are particularly model dependent.

The other isospin-related parameters needed are the isospin symmetry energies. In the recommended global input set, these are obtained from the volume and surface symmetry energy terms in the semi-empirical mass equation of Myers

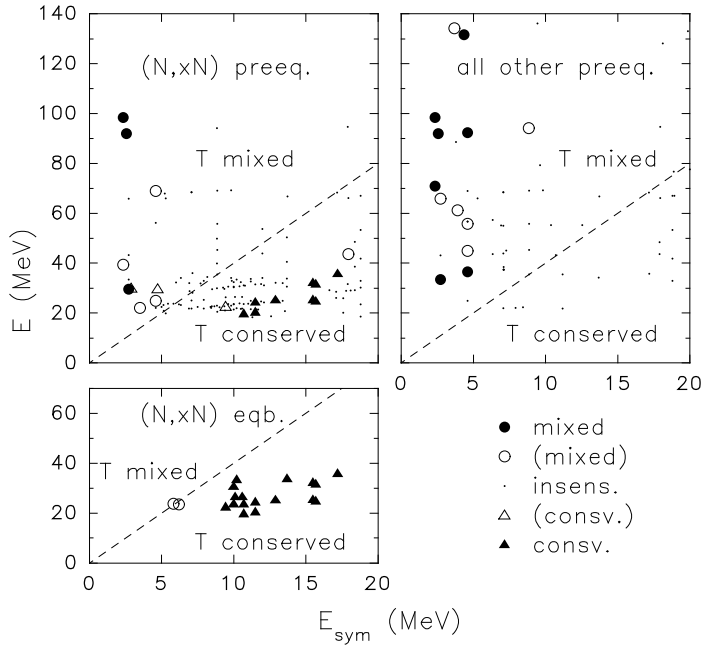

Figure 6.1: *Experimental evidence for isospin conservation during energy equilibration. The results are displayed as a function of the excitation energy E and the symmetry energy $E_{\rm sym}$. The dashed lines show the adopted criterion. The lower panel shows results inferred from the evaporation components. This figure is adapted from [KA05a].*

and Swiatecki [MY66]. The result quoted in Eq. (2.50) on page 33 is

$$E_{\rm sym}(T,T_z) = \left[\frac{112\ \text{MeV}}{A} - \frac{133\ \text{MeV}}{A^{4/3}}\right](T^2 - T_z^2) \tag{6.8}$$

and is the currently programmed option. This choice was definitely found to yield better agreement with experimental energy spectra than just using the first (volume) term in square brackets. (Implementing this latter option requires commenting out one line toward the end of subroutine SETISO. This line is marked.)

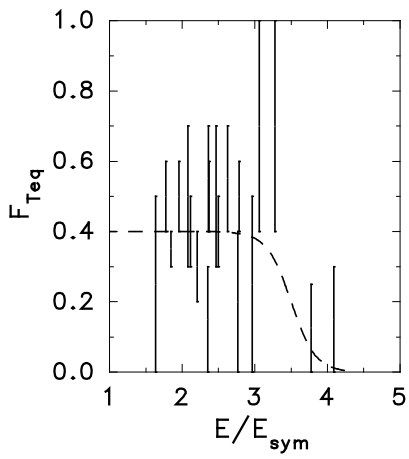

Figure 6.2: *Summary of experimental evidence on the amount on isospin conservation at equilibrium shown as a function of the ratio of the excitation energy to the symmetry energy. The vertical lines show the range of values consistent with the data, and the curve shows the adopted criterion supplied as a default in the code. This figure is taken from [KA05a].*

6.2. Default Total Reaction Cross Sections

The total reaction cross sections used in the particle emission rates in both the preequilibrium and equilibrium phases of the reaction are very important in determining the calculated energy spectra and the relative yields in the various reaction channels. Yet these cross sections are typically dependent on the optical model potentials used to generate them and differ significantly even among the commonly used potentials. At present the choice of potentials for complex particles is somewhat arbitrary and has not been benchmarked against data, while the choice for neutrons and protons and the modifications made to the resulting total reaction cross sections have been guided by comparisons with measured non-elastic cross sections.

6.2.1. Parameterization methodology

Rather than perform optical model calculations to obtain the necessary total reaction cross sections, a parameterization suggested by Chatterjee *et al* [CH81] has been adapted and extended for use here. Before summarizing the pertinent

equations, however, it should be emphasized that they are all given in terms of the *laboratory* energy of the particle considered while the equations earlier in this report which describe particle emission rates and related quantities quote the total reaction cross sections as a function of the particle's *channel* energy. In all of the remaining discussion, it is assumed that energies are always given in units of MeV, lengths in fermis, and cross sections in millibarns. The formulae are given for a particle of type b incident on a nucleus B, so that the subscripts b and B denote quantities evaluated for these entities.

The parameterization of the total reaction cross sections of [CH81] has different forms above and below the Coulomb barrier, $B_{\mathrm{coul},b}$. (For neutrons the formalism has been extended to include a centrifugal barrier, using the same sub-barrier form as for charged particles.) Each of these forms also has a limited range of validity so that additional energy domains must be defined. At very low energies, where the sub-barrier formula can go negative or pass through a minimum and then increase again, the cross sections are simply set to zero. This is done below an energy denoted $E_{b\,\mathrm{min}}$. At high energies, the above-barrier formula decreases too rapidly, and the cross sections are replaced by the geometrical cross section once this is larger than the parametric one. The comparison between these two forms is made above the energy $E_{b\mathrm{test}}$. The resulting equations for σ_b are

$$\sigma_b(\varepsilon) = \begin{cases} 0 & \text{for } E_{b\mathrm{L}} \leq E_{b\mathrm{min}} \\ p\,E_{b\mathrm{L}}^2 + \alpha\,E_{b\mathrm{L}} + \beta & \text{for } E_{b\mathrm{min}} < E_{b\mathrm{L}} < B_{\mathrm{coul},b} \\ \lambda\,E_{b\mathrm{L}} + \mu + \nu/E_{b\mathrm{L}} & \text{for } B_{\mathrm{coul},b} \leq E_{b\mathrm{L}} \leq E_{b\mathrm{test}} \\ \max\left(\lambda\,E_{b\mathrm{L}} + \mu + \nu/E_{b\mathrm{L}}\,,\ \sigma_{b,\mathrm{geom}}\right) & \text{for } E_{b\mathrm{test}} < E_{b\mathrm{L}} \end{cases} . \tag{6.9}$$

where the formulae for the parameters p, λ, μ, and ν are given in Table 6.2 along with $B_{\mathrm{coul},b}$ and $E_{b\mathrm{test}}$.

The quantities p_0, p_1, p_2, μ_0, μ_1, ν_0, ν_1, and ν_2 appearing in the table are numerical constants whose specific values depend on the optical model whose reaction cross sections are being parameterized and on any empirical adjustments that have been made. They are discussed in the following sections for the different particle types and are summarized in Table 6.3. The variables α, and β are derivative quantities given by

$$\alpha = -2p\,B_{\mathrm{coul},b} + \lambda - \nu/B_{\mathrm{coul},b}^2 \tag{6.10}$$

$$\beta = p\,B_{\mathrm{coul},b}^2 + \mu + 2\nu/B_{\mathrm{coul},b} \tag{6.11}$$

Table 6.2: *Equations for parameters describing the total reaction cross sections.*

Variable	Neutrons	Charged Particles
$B_{\mathrm{coul},b}$	0.5 MeV	$1.44\, Z_b\, Z_B / \left[1.5 A_B^{1/3} + R_b\right]$
$\mathrm{E}_{b\mathrm{test}}$	32 MeV	$\begin{cases} \sqrt{\nu/\lambda} + 7 & \text{for protons} \\ 1.2\sqrt{\nu/\lambda} & \text{for d,t,}\tau\text{,}\alpha \end{cases}$
p	p_0	$p_0 + p_1/B_{\mathrm{coul},b} + p_2/B_{\mathrm{coul},b}^2$
λ	$\lambda_0\, A_B^{-1/3} + \lambda_1$	$\lambda_0\, A_B + \lambda_1$
μ	$\mu_0\, A_B^{1/3} + \mu_1\, A_B^{2/3}$	$\mu_0\, A_B^{\mu_1}$
ν	$\nu_0\, A_B^{4/3} + \nu_1\, A_B^{2/3} + \nu_2$	$A_B^{\mu_1}\left[\nu_0 + \nu_1\, B_{\mathrm{coul},b} + \nu_2\, B_{\mathrm{coul},b}^2\right]$

while $E_{b\,\mathrm{min}}$ is given by

$$E_{b\,\mathrm{min}} = \begin{cases} \left(-\alpha + \sqrt{\alpha^2 - 4p\beta}\right)/2p & \text{for } \alpha^2 - 4p\beta > 0 \\ -\alpha/2p & \text{for } \alpha^2 - 4p\beta \leq 0 \end{cases} . \tag{6.12}$$

Finally, the geometric cross section is given by

$$\sigma_{b,\mathrm{geom}}(E_b) = \pi\, \left[R_B + r_b + \lambda\right]^2 . \tag{6.13}$$

where

$$R_B = \begin{cases} r_0\, A_B^{1/3} & \text{for } b = \text{nucleon} \\ r_0\, A_B^{1/3} + 0.9 \text{ fm} & \text{for } b = \text{complex particle} \end{cases} \tag{6.14}$$

Both r_b in Eq. (6.13) and R_b in the relationship for $B_{\mathrm{coul},b}$ in Table 6.2 represent the radius of the particle, but they make take on different values.

6.2.2. Neutron parameters

The neutron total reaction cross sections are based on the parameterization [CH81] of the reaction cross sections obtained from the optical model potential of Mani *et al* [MA63] The main change from the original formulation is that a barrier is now included. It was originally set at 2.4 MeV, but was later reduced to 0.5 MeV based on comparisons with experiment. In addition, a number of renormalization factors have been introduced to bring the calculated reaction cross sections into

Table 6.3: *Parameter values for calculating total reaction cross sections*

Parameter	n	p	d	t	^{3}He	α
R_b		0	1.2 fm	1.2 fm	1.2 fm	1.2 fm
p_0	-312	15.7	0.80	-21.4	-2.88	10.95
p_1		9.65	420.	485.	206	-85.2
p_2		-310	-1650	-1610	-1490	1150
λ_0	12.10	0.00437	0.0062	0.0186	0.0046	0.0643
λ_1	-11.27	-16.58	-7.54	-8.90	-8.93	-14.0
μ_0	234.1	244.7	583.5	686.3	611.2	781.2
μ_1	38.26	0.503	0.337	0.325	0.35	0.29
ν_0	1.55	273	422	369	474	-305
ν_1	-106	-182	-474	-522	-468	-470
ν_2	1281	-1.87	-3.59	-5.00	-2.22	-8.58
r_0	1.23 fm	1.23 fm	1.12 fm	1.12 fm	1.12 fm	1.12 fm
r_b	0	0	0.8 fm	0.8 fm	0.8 fm	1.2 fm

better agreement in magnitude with experimental values. These renormalization factors are dependent on target mass and are given by

$$f_{\mathrm{sig},n}(A) = \begin{cases} 0.7 + 0.3A/40 & \text{for } A < 40 \\ 1.0 & \text{for } 40 \leq A \leq 210 \\ 1.0 + (A - 210)/250 & \text{for } 210 < A \end{cases} . \tag{6.15}$$

None of the other optical model potentials considered by [CH81] were able to reproduce the experimental non-elastic cross sections as well as that of Mani *et al*; nor could they avoid the use of renormalization factors. The renormalization factors do not apply to the geometric cross sections which are used at the higher energies.

6.2.3. Proton parameters

The proton total reaction cross sections start from the parameterization [CH81] of the results of the Becchetti-Greenless optical model potential [BE69]. These values also needed to be renormalized in certain mass regions in order to better reproduce experimental total non-elastic cross sections. The renormalization factors are

given by

$$f_{\mathrm{sig},p}(A) = \begin{cases} 0.92 & \text{for } A \leq 60 \\ 0.8 + 0.2A/100 & \text{for } 60 < A < 100 \\ 1.0 & \text{for } 100 \leq A \end{cases} . \tag{6.16}$$

Again, as with neutrons, this potential still seemed the most suitable of those parameterized in [CH81] in spite of the need for these factors.

In addition to the renomalization factors, which apply to the parameterized but not the geometric cross sections, it was necessary to adjust the sub-barrier parameterization for protons [KA99]. This was indicated by comparisons with experimental evaporation spectra. It was found that there was often too much proton evaporation at the peak of the distribution, while the calculated emission spectrum did not extend to sufficiently low emission energies. This was corrected by adjusting the parameter p_2 from its initial value of -449 to $p_2 = -310$, the value now indicated in Table 6.3. This allows the cross section to extend to lower emission energies but increases the already too large cross section in the sub-barrier region. To correct this, a universal empirical factor is included that has the form

$$F_{\mathrm{sig},p}(E_{p\mathrm{L}}) = \left[1 + \exp\left(\frac{B_{\mathrm{coul},p} - E_{p\mathrm{L}} - C_{\mathrm{sig},p}}{w_{\mathrm{sig},p}}\right)\right]^{-1} \tag{6.17}$$

where

$$C_{\mathrm{sig},p} = \min(3.15 \text{ MeV}, B_{\mathrm{coul},p}/2) \tag{6.18}$$

and

$$w_{\mathrm{sig},p} = 0.70\, C_{\mathrm{sig},p}/3.15. \tag{6.19}$$

Thus for most nuclei $C_{\mathrm{sig},p} = 3.15$ and $w_{\mathrm{sig},p} = 0.70$, while for light nuclei $C_{\mathrm{sig},p}$ is reduced to assure that the total reaction cross section is close to zero at zero energy and $w_{\mathrm{sig},p}$ is assumed to scale with it. The general form of $F_{\mathrm{sig},p}$ is shown in Fig. 6.3 along with the empirical values that gave rise to it.

6.2.4. Parameters for complex particles

The total reaction cross sections used for complex particles are based on parameterizations of the results for the following optical model parameters:

deuteron	Perey and Perey [PE63]
triton	Hafele, Flynn and Blair [HA67]
He-3	Gibson *et al* [GI67]
alpha	Huizenga and Igo [HU62]

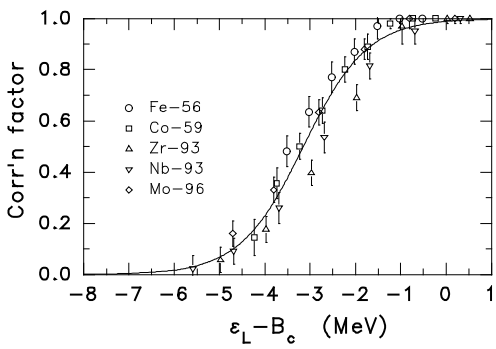

Figure 6.3: *Correction factor for the sub-barrier proton total reaction cross sections. The curve shows the adopted dependence for all but the lightest nuclei while the points show the needed empirical normalizations that gave rise to this dependence. This figure was taken from [KA99].*

These choices are somewhat arbitrary, and so far no benchmarking has been done and no A-dependent normalization factors, $f_{\mathrm{sig},i}$ have been applied. Because the need to use the sub-barrier correction function, $F_{\mathrm{sig},p}$, for protons was likely due to an inadequacy in the fundamental parameterization in this region, it should be anticipated that such a factor will be needed for other charged particles, but the values of the needed constants are currently unknown.

6.3. Collective State Parameters

6.3.1. Spectroscopic states

A set of excitation energies and deformation parameters for strong spectroscopic collective states is given in Table 6.4. The starting point was the energies and deformation parameters of the lowest states of each Jπ in even-even nuclei. The need to include the 4+ excitations and the occasional use of higher energy states of a given Jπ were determined empirically from inelastic scattering spectra. The β_4 values are generally given by $\beta_4 = 0.75\min(\beta_2, \beta_3)$. Values for odd mass targets were generally taken to be the average of the values for the neighboring even-even nuclei, except that for targets one unit of N or Z away from a closed shell, the values for the closed-shell configuration were used. The most common target nuclides are included, but not all have been verified against data.

Table 6.4: *Summary of the excitation energies and deformation parameters for the strong spectroscopic collective states in some common target nuclei. The energies are given in MeV. For* $^{2}7Al$*, both the individual 2+ states and their effective average are given.*

Target	E(2+)		E(3−)	E(4+)	β_2		β_3	β_4
^{12}C	4.44		9.64	14.08	0.82		0.40	0.40?
^{14}N	6.92		6.13	10.36	0.36		0.58	0.36?
^{16}O	6.92		6.13	10.36	0.36		0.58	0.36?
^{19}F	1.80		5.10	3.55	0.54		0.37	0.37?
^{20}Ne	1.63		5.62	4.25	0.73		0.43	0.33
^{21}Ne	1.45		5.76	3.80	0.64		0.43	0.33
^{24}Mg	1.37		7.62	4.12	0.61		0.27	0.27
	1.0				0.19			
^{27}Al	2.2	2.32	7.2	4.47	0.27	0.44	0.22	0.16
	3.0				0.29			
^{28}Si	1.78		6.88	4.62	0.41		0.28	0.21
^{40}Ca	3.90		3.74		0.12		0.34	
^{48}Ca	3.83		4.51		0.10		0.20	
^{46}Ti	0.89		3.06	2.01	0.32		0.14	0.10
^{48}Ti	0.98		3.36	2.30	0.27		0.19	0.15
^{51}V	1.49		3.90	2.52	0.20		0.16	0.12
^{50}Cr	0.78		4.05	1.88	0.29		0.15	0.11
^{52}Cr	1.43		4.56	2.77	0.22		0.15	0.11
^{53}Cr	1.43		4.56	2.77	0.22		0.15	0.11
^{55}Mn	0.84		4.32	2.3	0.24		0.18	0.18
^{54}Fe	1.41		4.78	3.83	0.20		0.114	0.11
	2.96		6.34		0.14		0.15	
^{56}Fe	0.85		4.51	3.12	0.24		0.18	0.13
^{58}Fe	0.81		3.84	3.1	0.26		0.13	0.09
^{59}Co	1.33		3.84		0.21		0.19	
^{58}Ni	1.45		4.48	2.46	0.183		0.18	0.09
				3.62				0.09
^{60}Ni	1.33		4.04	4.96	0.207		0.19	0.19
^{62}Ni	1.17		3.76	2.34	0.198		0.225	0.198
^{63}Cu	1.17		3.76	2.34	0.20		0.18	0.11
^{65}Cu	1.35		3.56	2.61	0.18		0.18	0.11
^{64}Zn	0.99		3.00	2.31	0.23		0.23	0.11

Table 6.4, cont'd

Target	E(2+)	E(3−)	E(4+)	β_2	β_3	β_4
^{70}Ge	1.04	2.56	2.15	0.224	0.24	0.11
^{72}Ge	0.83	2.51	1.73	0.242	0.223	0.11
^{89}Y	2.01	2.74	3.69	0.104	0.17	0.10
^{90}Zr	2.19	2.75	4.33	0.091	0.16	0.11
^{91}Zr	2.19	2.75	4.33	0.091	0.16	0.11
^{92}Zr	0.934	2.34	1.50	0.103	0.17	0.10
^{94}Zr	0.918	2.06	1.47	0.09	0.19	0.09
^{93}Nb	0.903	2.44	1.54	0.13	0.17	0.13
^{92}Mo	1.51	2.85		0.106	0.17	
^{94}Mo	0.871	2.53		0.161	0.163	
^{95}Mo	0.825	2.38		0.166	0.17	
^{96}Mo	0.778	2.24		0.172	0.18	
^{97}Mo	0.782	2.13		0.170	0.19	
^{98}Mo	0.787	2.02		0.168	0.198	
^{100}Mo	0.536	1.91		0.231	0.18	
^{103}Rh	0.516	2.12		0.23	0.135	
^{104}Pd	0.556	2.19		0.21	0.13	
^{105}Pd	0.534	2.14		0.22	0.15	
^{106}Pd	0.512	2.08		0.23	0.17	
^{108}Pd	0.434	2.05		0.24	0.15	
^{110}Pd	0.374	2.04		0.26	0.134	
^{107}Ag	0.573	2.14		0.20	0.19	
^{109}Ag	0.546	2.06		0.21	0.16	
^{115}In	1.29	2.27		0.112	0.18	
^{116}Sn	1.29	2.27	2.39	0.112	0.18	0.11
^{117}Sn	1.26	2.30	2.34	0.112	0.18	0.11
^{118}Sn	1.23	2.32	2.28	0.111	0.171	0.11
^{119}Sn	1.20	2.36	2.24	0.110	0.16	0.11
^{120}Sn	1.17	2.40	2.19	0.108	0.16	0.11
^{122}Sn	1.14	2.49	2.14	0.104	0.150	0.10
^{124}Sn	1.13	2.61	2.10	0.095	0.13	0.095
^{121}Sb	1.17	2.40	2.19	0.108	0.16	0.108
^{123}Sb	1.14	2.49	2.14	0.104	0.150	0.10

Table 6.4, cont'd

Target	E(2+)	E(3−)	E(4+)	β_2	β_3	β_4
^{159}Tb	0.083	1.16		0.34	0.090	
^{165}Ho	0.077	1.28		0.345	0.060	
^{169}Tm	0.112	1.41		0.32	0.057	
^{181}Ta	0.097	1.37		0.26	0.050	
^{182}W	0.100	1.37		0.249	0.050	
^{183}W	0.106	1.30		0.24	0.050	
^{184}W	0.111	1.22		0.24	0.051	
^{186}W	0.123	1.04		0.224	0.05	
^{197}Au	0.384	1.69	0.962	0.119	0.051	0.05
^{204}Pb	0.899	2.62	1.27	0.041	0.09	0.041
^{206}Pb	0.803	2.65	1.68	0.032	0.10	0.032
^{207}Pb	4.08	2.62	4.32	0.054	0.11	0.054
		5.52			0.05	
^{208}Pb	4.08	2.62	4.32	0.054	0.11	0.054
		5.52			0.05	
^{209}Bi	4.08	2.62	4.323	0.054	0.11	0.054
		5.52			0.05	
^{232}Th	0.05	0.77		0.261	0.078	
^{238}U	0.04	0.73		0.286	0.086	

In addition, if a very crude estimate of elastic scattering is desired, it should be input in the same way as the spectroscopic collective states, using $\lambda = 0$ and $E_\lambda = 0$, while β_λ can be arbitrary since it is calculated internally, as mentioned previously.

The collective state parameters are independent of the set of global exciton model input parameters and thus may be varied as necessary.

6.3.2. Giant resonance states

The parameters describing the giant resonance states are their excitation energies, their deformation parameters (determined from the amount of the energy-weighted sum rule which they exhaust), and their widths, expressed either as a full width at half maximum (FWHM) or as a Gaussian width parameter, w. The

energy-weighted sum rules are given in Eqs. (4.21) and (4.22) on page 54. The parameters for the four isoscaler resonances are given in Table 6.5 where SCS denotes contributions from spectroscopic collective states of the same spin and parity. The four resonances are the low-energy octupole resonance (or LEOR), the giant quadrupole resonance (or GQR), the giant monopole resonance (or GMR), and the high-energy octupole resonance (or HEOR). Once again, these parameters

Table 6.5: *Gerneral form for the parameters describing the isoscaler giant resonance states which might be excited in inelastic scattering. The GMR state is typically so weak that it can be ignored.*

GR state	Transition	Energy (MeV)	EWSR (MeV)	EWSR used (MeV)	FWHM (MeV)	w (MeV)
LEOR	$1\hbar\omega$ 3−	$31A^{-1/3}$	$1208A^{-5/3}$	30%−SCS	5	2.13
GQR	$2\hbar\omega$ 2+	$65A^{-1/3}$	$575A^{-5/3}$	100%−SCS	$85A^{-2/3}$	$36.2A^{-2/3}$
GMR	0+	18.7–$A/40$	$23A^{-5/3}$	100%	3	1.28
HEOR	$3\hbar\omega$ 3−	$115A^{-1/3}$	$1208A^{-5/3}$	70%	9.3–$A/40$	3.96–$A/113$

may be varied (within reasonable limits) with almost no impact on the exciton model parameters. For ease of use, the energies and β_λ values of the three important giant resonance states for common nuclei are given in Table 6.6.

There is an option to use a Lorentzian line shape in place of the Gaussian one, but this is not recommended. It is invoked by entering $-\lambda$ in place of λ for that particular resonance. In this case the width parameter, w, in the input is replaced by Γ, the FWHM, which occurs in the following normalized distribution function:

$$\mathcal{P}_{\rm Lor}(E, E_\lambda, \Gamma) = \frac{2}{\pi\Gamma}\,\frac{E^2\,\Gamma^2}{\left(E^2 - E_\lambda^2\right)^2 + E^2\,\Gamma^2}. \tag{6.20}$$

Here E is the excitation energy in the nucleus, and E_λ is the excitation energy at the peak of the distribution.

6.4. Secondary Particle Emission

When PRECO-2006 is used as a stand alone code, it is recommended that secondary particle emission always be included in the calculations. This is because it

Table 6.6: *Summary of the excitation energies, strengths and widths for the important giant resonance states in some common target nuclei. The energies and widths are given in MeV.*

Target	E_{LEOR}	β_{LEOR}	w_{LEOR}	E_{GQR}	β_{GQR}	w_{GQR}	E_{HEOR}	β_{HEOR}	w_{HEOR}
^{12}C	13.54	0.56	2.13	28.4	0.46	6.91	50.2	0.52	3.85
^{14}N	12.86	0.43	2.13	27.0	0.48	6.23	47.7	0.47	3.84
^{16}O	12.30	0.35	2.13	25.8	0.43	5.70	45.6	0.43	3.82
^{19}F	11.62	0.41	2.13	24.4	0.39	5.08	43.1	0.38	3.79
^{20}Ne	11.42	0.35	2.13	23.9	0.36	4.91	42.4	0.37	3.78
^{21}Ne	11.24	0.33	2.13	23.6	0.36	4.76	41.7	0.36	3.77
^{24}Mg	10.75	0.34	2.13	22.5	0.32	4.35	39.9	0.33	3.75
^{27}Al	10.33	0.33	2.13	21.7	0.30	4.02	38.3	0.30	3.72
^{28}Si	10.21	0.29	2.13	21.4	0.30	3.92	37.9	0.29	3.71
^{40}Ca	9.06	0.194	2.13	19.0	0.25	3.10	33.6	0.23	3.60
^{48}Ca	8.53	0.214	2.13	17.9	0.22	2.74	31.6	0.21	3.54
^{46}Ti	8.65	0.253	2.13	18.1	0.22	2.82	32.1	.021	3.55
^{48}Ti	8.53	0.229	2.13	17.9	0.216	2.74	31.6	0.21	3.54
^{51}V	8.36	0.223	2.13	17.5	0.208	2.63	31.0	0.20	3.51
^{50}Cr	8.41	0.229	2.13	17.6	0.210	2.67	31.2	0.20	3.52
^{52}Cr	8.30	0.218	2.13	17.4	0.204	2.60	30.8	0.195	3.50
^{53}Cr	8.25	0.215	2.13	17.3	0.201	2.56	30.6	0.192	3.49
^{55}Mn	8.15	0.196	2.13	17.1	0.199	2.50	30.2	0.188	3.47
^{54}Fe	8.20	0.199	2.13	17.2	.0200	2.53	30.4	0.190	3.48
^{56}Fe	8.10	0.191	2.13	17.0	.0196	2.47	30.1	0.185	3.46
^{58}Fe	8.01	0.209	2.13	16.8	0.190	2.42	29.7	0.181	3.45
^{59}Co	7.96	0.182	2.13	16.7	.0187	2.39	29.5	0.179	3.44
^{58}Ni	8.01	0.184	2.13	16.8	0.191	2.42	29.7	0.181	3.45
^{60}Ni	7.92	0.177	2.13	16.6	0.185	2.36	29.4	0.177	3.43
^{62}Ni	7.83	0.152	2.13	16.4	0.182	2.31	29.1	0.173	3.41
^{63}Cu	7.79	0.176	2.13	16.3	0.180	2.29	28.9	0.171	3.40
^{65}Cu	7.71	0.172	2.13	16.2	0.176	2.24	28.6	0.168	3.38
^{64}Zn	7.75	0.158	2.13	16.2	0.177	2.26	28.8	0.170	3.39
^{70}Ge	7.52	0.144	2.13	15.8	0.165	2.13	27.9	0.160	3.34
^{72}Ge	7.45	0.149	2.13	15.6	0.162	2.09	27.6	0.157	3.32

Table 6.6, cont'd

Target	E_{LEOR}	β_{LEOR}	w_{LEOR}	E_{GQR}	β_{LEOR}	w_{LEOR}	E_{HEOR}	β_{HEOR}	w_{HEOR}
^{89}Y	6.94	0.134	2.13	14.6	0.144	1.82	25.8	0.136	3.17
^{90}Zr	6.92	0.137	2.13	14.5	0.144	1.80	25.7	0.135	3.16
^{91}Zr	6.89	0.135	2.13	14.4	0.143	1.79	25.6	0.134	3.15
^{92}Zr	6.87	0.135	2.13	14.4	0.144	1.78	25.5	0.133	3.15
^{94}Zr	6.82	0.128	2.13	14.3	0.142	1.75	25.3	0.131	3.13
^{93}Nb	6.84	0.131	2.13	14.3	0.141	1.76	25.4	0.132	3.14
^{92}Mo	6.87	0.127	2.13	14.4	0.142	1.78	25.5	0.133	3.15
^{94}Mo	6.82	0.132	2.13	14.3	0.138	1.75	25.3	0.131	3.13
^{95}Mo	6.79	0.129	2.13	14.2	0.137	1.74	25.2	0.130	3.12
^{96}Mo	6.77	0.125	2.13	14.2	0.136	1.73	25.1	0.129	3.11
^{97}Mo	6.75	0.121	2.13	14.1	0.135	1.71	25.0	0.128	3.10
^{98}Mo	6.72	0.118	2.13	14.1	0.134	1.70	24.9	0.128	3.09
^{100}Mo	6.68	0.126	2.13	14.0	0.130	1.68	24.8	0.126	3.08
^{103}Rh	6.61	0.135	2.13	13.9	0.128	1.65	24.5	0.123	3.05
^{104}Pd	6.59	0.135	2.13	13.8	0.128	1.64	24.4	0.123	3.04
^{105}Pd	6.57	0.127	2.13	13.8	0.126	1.63	24.4	0.122	3.03
^{106}Pd	6.55	0.118	2.13	13.7	0.125	1.62	24.3	0.121	3.02
^{108}Pd	6.51	0.125	2.13	13.6	0.124	1.60	24.1	0.120	3.00
^{110}Pd	6.47	0.128	2.13	13.6	0.122	1.58	24.0	0.118	2.98
^{107}Ag	6.53	0.105	2.13	13.7	0.125	1.61	24.2	0.120	3.01
^{109}Ag	6.49	0.119	2.13	13.6	0.123	1.59	24.1	0.119	3.00
^{115}In	6.37	0.096	2.13	13.4	0.121	1.53	23.7	.0115	2.94
^{116}Sn	6.36	0.095	2.13	13.3	0.120	1.52	23.6	0.114	2.93
^{117}Sn	6.34	0.093	2.13	13.3	0.120	1.51	23.5	0.113	2.92
^{118}Sn	6.32	0.097	2.13	13.2	0.119	1.50	23.4	0.113	2.92
^{119}Sn	6.30	0.102	2.13	13.2	0.118	1.50	23.4	0.112	2.91
^{120}Sn	6.28	0.100	2.13	13.2	0.118	1.49	23.3	0.112	2.90
^{122}Sn	6.25	0.102	2.13	13.1	0.117	1.47	23.2	0.110	2.88
^{124}Sn	6.22	0.109	2.13	13.0	0.116	1.45	23.1	0.109	2.86
^{121}Sb	6.27	0.099	2.13	13.1	0.117	1.48	23.2	0.111	2.89
^{123}Sb	6.23	0.101	2.13	13.1	0.116	1.46	23.1	0.110	2.87

Table 6.6, cont'd

Target	E_{LEOR}	β_{LEOR}	w_{LEOR}	E_{GQR}	β_{GQR}	w_{GQR}	E_{HEOR}	β_{HEOR}	w_{HEOR}
^{159}Tb	5.72	0.109	2.13	12.0	0.097	1.23	21.2	0.092	2.55
^{165}Ho	5.65	0.110	2.13	11.8	0.095	1.20	21.0	0.090	2.50
^{169}Tm	5.61	0.108	2.13	11.8	0.092	1.18	20.8	0.089	2.46
^{181}Ta	5.48	0.104	2.13	11.5	0.090	1.13	20.3	0.085	2.36
^{182}W	5.47	0.104	2.13	11.5	0.090	1.13	20.3	0.084	2.35
^{183}W	5.46	0.103	2.13	11.4	0.089	1.12	20.2	0.084	2.34
^{184}W	5.45	0.103	2.13	11.4	0.089	1.12	20.2	0.084	2.33
^{186}W	5.43	0.103	2.13	11.4	0.088	1.11	20.1	0.083	2.31
^{197}Au	5.33	0.097	2.13	11.2	0.085	1.07	19.8	0.080	2.22
^{204}Pb	5.27	0.076	2.13	11.0	0.085	1.04	19.5	0.078	2.15
^{206}Pb	5.25	0.067	2.13	11.0	0.085	1.04	19.5	0.078	2.14
^{207}Pb	5.24	0.028	2.13	11.0	0.078	1.03	19.4	0.075	2.13
^{208}Pb	5.23	0.026	2.13	11.0	0.078	1.03	19.4	0.077	2.12
^{209}Bi	5.22	0.025	2.13	11.0	0.078	1.03	19.4	0.077	2.11
^{232}Th	5.04	0.085	2.13	10.6	0.077	0.96	18.7	0.072	1.91
^{238}U	5.00	0.083	2.13	10.5	0.075	0.94	18.6	0.071	1.85

can make an important contribution to the evaporation spectra even at incident energies as low as 12 to 14 MeV, when primary preequilibrum emission is just beginning to be important. On the other hand, when PRECO is used as part of a large Hauser-Feshbach code which will do the equilibrium part of the calculations, then secondary emission in the preequilibrium part is only needed at higher incident energies: roughly at or above 40 MeV for heavy targets and probably still higher for lighter targets.

7. Description of the Code

The code PRECO is written in standard FORTRAN-77 and is designed to be compatible with most computer systems. It has been developed and run on a personal computer running in DOS (command prompt) mode and compiled with a fairly old Microsoft FORTRAN compiler. The source code is supported by a significant number of comment lines as well as by this manual.

The code is modular and is currently compiled as four separate source files for manageability. These contain (i) the main program, (ii) two self-contained pieces (COMPOUND and PRODUCT) broken off of the main program, (iii) interconnected sub-programs, and (iv) fairly independent sub-programs. The general code structure is shown in Fig. 7.1, with the calculations generally proceeding down the main segmented block. The names of subprograms are given in upper case and enclosed in small boxes. The calculations performed by each subprogram are summarized in Table 7.1.

When the main calculations for a given reaction are completed, there are a number of 'recycling' options. These take care of multiple particle emission, a second isospin in the composite nucleus and accepting input for a new reaction. Each option transfers the calculations to an appropriate point in the segment of the main block designated 'Input and Preliminary Calculations,' and appropriate adjustments are made to the requisite variables. Arrays of product nuclide production cross sections or of preequilibrium cross sections for input to Hauser-Feshbach model calculations are generated only when requested. The labels TCOR/ALPHA, SINGLE/FACT and ANGEL/BIND in Fig. 7.1 signify that ALPHA, FACT and BIND are small subprograms called only by their partner subprograms.

7.1. Code Input

Input is assumed to be read from a file named `precom.dat`, and each such file would normally include the information for calculating a number of different reactions. All integer values are read in with an 'i5' format with blanks currently

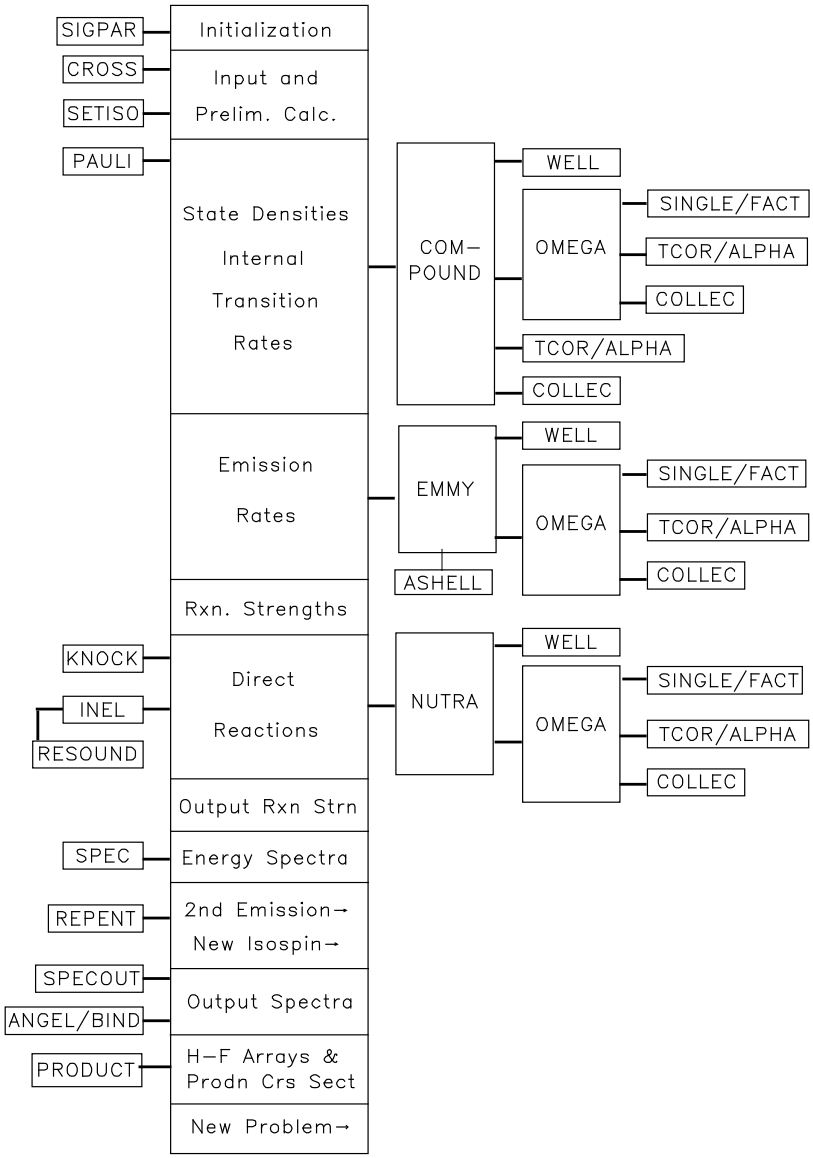

Figure 7.1: *Structure of* PRECO-2006. *The large segmented block is the main program in file* `precom.for`. *All of the blocks on the right except for* COMPOUND *are interconnected subprograms in the file* `precom2.for`, *while all those on the left except for* PRODUCT *are the more independent subprograms in file* `precom3.for`. *The routines* COMPOUND *and* PRODUCT *are in* `precom4.for`. *The right-arrows in the main block are branchs to earlier points in the code for auxilliary calculations or a new problem.*

Table 7.1: *Alphabetical list of the subprograms in* PRECO-2006 *and their function in the code calculations.*

Subprogram	Purpose
ALPHA	Simplified particle-hole state density (no shell effects or pairing)
ANGEL	Continuum angular distributions from empirical systematics
ASHELL	Shell-corrected equilibrium level density parameter
BIND	Binding energies of particles in a nucleus (from the mass equation)
COLLEC	Correction to the Pauli energy due to collective pairing
COMPOUND	Composite nucleus state densities and internal transition rates
CROSS	Total reaction cross sections (optical model and geometric)
EMMY	Preequilibrium and equilibrium particle emission rates
FACT	Factorials using a modified Sterling's approximation
INEL	Energy spectra from inelastic scattering; cluster degrees of freedom
KNOCK	Energy spectra from knockout of nucleons or α-particles
NUTRA	Energy spectra from direct nucleon transfer reactions
OMEGA	Particle-hole state densities in the shell-shifted ESM
PAULI	Pauli correction function for state densities (ESM or S^2-ESM)
PRODUCT	Finalize and print arrays of final nucleus production cross sections
REPENT	Set-up for secondary emission and recycling to points in `MAIN`
RESOUND	Inelastic energy spectra from collective excitations
SETISO	Isospin parameters T_z, $2T$, $E_{\rm sym}$, and $C_{\rm T}^2$
SIGPAR	Parameters for calculating total reaction cross sections
SINGLE	Effective single particle state densities in the shell-shifted ESM
SPEC	Angle-integrated energy spectra normalized to unit strength
SPECOUT	Normalize and print angle-integrated energy spectra
TCOR	Correction factors to particle-hole state densities for good isospin
WELL	Finite well depth correction factor for particle-hole state densities

designated as not significant so that the value can be left-adjusted in the 5 character space. All floating point numbers are read using an 'f10.2' format, though the actual location of the decimal point should override the format statement. Default values are invoked by entering values of zero, unless otherwise specified. A sample input file is shown in Appendix B.

7.1.1. Initial global parameters

The first three lines of the input file are global values that are retained for all problems included in that file. They are:

(A) $I_{\mathrm{HF}}, V_0, V_1, V_2$ [3F10.2]
"Hauser-Feshbach" control variable; the central well depth; the average well depth for the first interaction when it excites a target proton; and the average well depth for the first interaction when it excites a target neutron. A value of $I_{\mathrm{HF}} = 0$ means that the calculation of arrays of production cross sections is bypassed; $|I_{\mathrm{HF}}| = 1$ means that PRECO is being used as a preequilibrium module for a Hauser-Feshbach code so that arrays of cross section feeding from preequilibrium emission into various product nuclei at all the possible excitation energies are calculated and available for output or to be passed to the H-F equilibrium calculations; $|I_{\mathrm{HF}}| = 2$ means that PRECO is being used alone to estimate nuclide production cross sections, so that arrays of cross sections for various product nuclides resulting from both preequilibrium and equilibrium emission are calculated. If $I_{\mathrm{HF}} > 0$, the cross sections resulting from emission of two particles will be printed as full two dimensional arrays, with the rows labelled by the emission energy of the first particle and the columns by the energy of the second particle. If $I_{\mathrm{HF}} < 0$, the cross sections for each of these product nucleus will be collapsed into a column where each entry corresponds to a given value of $\varepsilon_1 + \varepsilon_2$. However, this is only done when an equally spaced energy grid is used and the minimum emission energy is equal to the energy spacing. [Default values are $I_{\mathrm{HF}} = 0$, $V_0 = 38$ MeV, and surface effects systematics for V_1 and V_2.]

(B) $K_{\pi\pi}$, $K_{\pi\nu}$, $K_{\nu\nu}$, $K_{\mathrm{g}} = Z/g_{\pi 0} = N/g_{\nu 0} = A/g_0$ [5F10.2]
Normalization factors for the mean square matrix elements for the residual two-body interactions; normalization constant for the ESM single particle state densities. [Default values are 2200, 900, 900, and 15.]

(C) $f_{\rm shell}$, $k_{\rm shell}$, R_γ [3F10.2]
Constants determining the range of mass numbers, $f_{\rm shell}D/(2d)$, over which shell effects wash out; the energy range, $k_{\rm shell}t$, over which the S^2-ESM single particle states are averaged to determine the shell-corrected equilibrium level density parameter; and the amount of γ-ray competition with secondary equilibrium emission. [Default values are $f_{\rm shell} = 2$, $k_{\rm shell} = 2.3$, and $R_\gamma = 0.005$]

7.1.2. Problem specific input

Following these three lines, the remaining lines are read in for each reaction calculation in the file. Most are required for each problem, but some are needed only when a particular option is invoked.

(1) Title [A64]
A title or descriptor with up to 64 characters identifying the problem to be calculated.

(2) E, B_a, $I_{\rm t}$, $F_{\rm Teq}$ [4F10.2]
Excitation energy in MeV of the composite nucleus; projectile binding energy in the composite nucleus in MeV; control variable or flag for isospin conservation; and (if isospin is conserved in the preequilibrium calculations) the fraction of the time it is conserved at equilibrium. A value of $I_{\rm t} = 0$ signifies isospin is mixed, $I_{\rm t} = 1$ specifies isospin conserved calculations using the default symmetry energies, while $I_{\rm t} > 1$ uses the default conditions to determine whether isospin should be conserved in the calculation or not. When isospin is conserved, the default symmetry energies are always used, and when $I_{\rm t} > 1$, the default prescription for $F_{\rm Teq}$ is also used. [Note that $I_{\rm t}$ is actually read in as a floating point number but is immediately converted to an integer.]

(3) $Z_{\rm tar}$, $N_{\rm tar}$, $Z_{\rm mag}$, $N_{\rm mag}$, D_π, D_ν [6F10.2]
Proton and neutron numbers of the target; proton and neutron numbers of the shell closures to be considered (if any); and width in MeV of the proton and neutron shell gaps. If either $Z_{\rm mag}$ or $N_{\rm mag}$ is zero, then the corresponding D is not needed and may be zero or blank, while if $Z_{\rm mag} + N_{\rm mag} = 0$, then shell structure is not considered further for this problem. If $Z_{\rm mag} < 0$, then default values for $Z_{\rm mag}$, $N_{\rm mag}$, D_π, and D_ν are generated in the code when

shell effects are needed. The shell gaps are those given in Table 6.1 on page 80.

(4) $M_{\pi\mathrm{lo}}$, $M_{\pi\mathrm{hi}}$, $M_{\nu\mathrm{lo}}$, $M_{\nu\mathrm{hi}}$ [4I5]
(This line is read in only if the input values of $Z_{\mathrm{mag}} + N_{\mathrm{mag}} > 0$. If default values are used or if no shell effects are desired, then this line is not read in.)
Degeneracies of the piled up levels below and above the shell gaps for protons and neutrons in the S^2-ESM. [Default (if values of 0 are read in or if defaults are requested for all shell parameters) is the S^2-ESM values given by Eq. (2.23) on page 19. These are the same for the levels above and below the gap. Shell model values can be read in.]

(5) Z_a, N_a, I_{multi} [2I5]
Proton and neutron number of the projectile; and flag to determine if secondary particle emission is to be calculated. A value of $I_{\mathrm{multi}} = 0$ implies no secondary emission, whereas if $I_{\mathrm{multi}} = 1$ secondary emission is calculated.

(6) B_n, B_p, B_d, B_t, $B_{^3He}$, B_α, B_f [7F10.2]
Binding energies in MeV for the six types of emitted particles considered from the composite nucleus; fission barrier for the composite nucleus, also in MeV.

(7) $B_n(Z, N\text{-}1)$, $B_p(Z, N\text{-}1)$, $B_n(Z\text{-}1, N)$, $B_p(Z\text{-}1, N)$, $B_f(Z, N\text{-}1)$, $B_f(Z\text{-}1, N)$ [4F10.2]
(Read in only if $I_{\mathrm{multi}} > 0$)
Neutron and proton binding energies in the residual nuclei following primary emission of neutrons and protons; fission barriers for neutron and proton residual nuclei. Fission competition at equilibrium is only calculated if $B_f(Z\text{-}1, N) > 0$.

(8) K_{ang}, K_n, K_p, K_d, K_t, $K_{^3He}$, K_α [7I5]
Output control variables. A value of $K_{\mathrm{ang}} = 1$ causes double differential cross sections to be printed following the energy spectra for all particle types requested. A value of $K_b = 1$ causes the energy spectra for particles of type b to be printed, while a value of zero supresses printing.

(9) λ_i, $E_{\lambda i}$, $\beta_{\lambda i}$, w_i [4F10.2]
(Up to 10 such lines are read in until a negative value of w_i is encountered)

Parameters for collective states. These are their multipolarities, excitation energies in MeV, deformation parameters, and Gaussian width parameters in MeV. Both spectroscopic and giant resonance collective states (plus the elastic peak, if it is needed) can be read in, one resonance per line. If no collective states are to be considered, then one line should be read in with $\beta_\lambda = 0$, $w_i < 0$ and a positive value of λ and/or E_λ (so that it is not interpreted as the elastic peak). If elastic scattering is to be considered it should be read in first with $\lambda = 0$, $E_\lambda = 0$, and an arbitrary value of β_λ (which is generated internally). It must be immediately followed by the main 2+ and 3− spectroscopic collective states since the energies of these states are used in calculating the elastic scattering angular distributions. If a Lorentzian line shape is desired for any of the resonances, this can be obtained by supplying $-\lambda_i$ in place of λ_i for those resonances. In this case the input width should be, Γ, the FWHM. [Default values for the widths are 1 MeV for the first resonance and the value for the previous resonance for the others.]

(10) $\sigma_{\rm CN}$ [F10.2]
Composite nucleus formation cross section in millibarns. [The default value for incident particles with A from 1 to 4 (nucleons through α-particles) is calculated using the parameterization described in Sect. 6.2. There are no default values for γ-rays or particles above mass 4.]

(11) N_ε, $\varepsilon_{\rm min}$, $\Delta\varepsilon$ [1I5, 2F10.2]
Number of emission energies to be considered; lowest emission energy in MeV; and emission energy increment. If $\varepsilon_{\rm min}$=0, then a set of emission energies and total reaction cross sections is read in at (12). Otherwise, a set of emission energies is generated using N_ε and $\Delta\varepsilon$, and the total reaction cross sections for the emitted particles are calculated using the parameterization of Sect. 6.2. [Default value of $\Delta\varepsilon$ is 1.]

(12) ε_i, $\sigma_n(\varepsilon)$, $\sigma_p(\varepsilon)$, $\sigma_d(\varepsilon)$, $\sigma_t(\varepsilon)$, $\sigma_{^3He}(\varepsilon)$, $\sigma_\alpha(\varepsilon)$ [7F10.2]
(N_ε such lines are read in only if $\varepsilon_{\rm min}$=0.)
Each line contains an emission energy in MeV and the corresponding total reaction cross sections in millibarns for the six exit channels considered. If these are read in, they are also used for secondary particle emission.

(13) $g_{\pi 0}$, $g_{\nu 0}$, $g_{\pi f}$, $g_{\nu f}$ [4F10.2]
Equi-spacing model proton and neutron single particle state densities in the

composite nucleus and at the top of the fission barrier. The latter only needs to be entered if fission is being calculated. [Default values are $g_{\pi 0} = Z/K_g$, $g_{\nu 0} = N/K_g$, $g_{\pi f} = g_{\pi 0}$, and $g_{\nu f} = g_{\nu 0}$.]

(14) $g_{\pi 0}(k)$ for $k = n, p, d, t, {}^3He, \alpha$ residual nuclei [6F10.2] and
$g_{\nu 0}(k)$ for $k = n, p, d, t, {}^3He, \alpha$ residual nuclei [6F10.2]
(These two lines are read in only if a non-zero value of $g_{\pi 0}$ was read in above.)
Single particle state densities in the residual nuclei from primary particle emission when non-default values are used in the composite nucleus. [If $g_{\pi 0}(n\text{-residual})$=0, then all of these quantities default to the corresponding composite nucleus values scaled with Z or N.] The corresponding state densities for the residual nuclei from secondary emission are generated from those for primary emission using nuclei with the same N or Z.

(15) I_{pair}, $C_{\pi 0}^{(\text{pre})}(Z)$, $C_{\nu 0}^{(\text{pre})}(N)$, $C_{\pi 0}^{(\text{pre})}(Z\text{-}2)$, $C_{\nu 0}^{(\text{pre})}(N\text{-}2)$ [1I5,4F10.2]
Flag for determining the preequilibrium pairing option; condensation energies to be used in the preequilibrium calculations. $C_{\pi 0}^{(\text{pre})}(Z)$ is used for nuclei with the Z of the composite nucleus or one unit less (though it is only applied for even Z). Similar considerations apply for $C_{\nu 0}^{(\text{pre})}(N)$. The significance of I_{pair} is

$$I_{\text{pair}} = \begin{cases} -3 & \text{simple pairing with default } C\text{'s} \\ -2 & \text{simple pairing with input } C\text{'s} \\ -1 & \text{simple pairing with equilibrium } C\text{'s} \\ 0 & \text{simple pairing with input } C\text{'s} \\ 1 & \text{collective pairing with equilibrium } C\text{'s} \\ 2 & \text{collective pairing with input } C\text{'s} \\ 3 & \text{collective pairing with default } C\text{'s} \end{cases}$$

Thus $I_{\text{pair}} \leq 0$ signifies simple pairing corrections while $I_{\text{pair}} > 0$ is for collective pairing. Similarly $|I_{\text{pair}}|$ determines the source of the condensation energies. Clearly if the default condensation energies are used for the *equilibrium* pairing corrections, then $I_{\text{pair}} = 1$ and 3 are equivalent, as are values of -1 and -3. The options with $I_{\text{pair}} = 0$ and -2 are identical, and the zero option is included so that a blank line can be entered if no pairing corrections are desired. If default or equilibrium condensation energies are to be used, then the C's should be left blank on this line. [Default condensation energies are the smooth trend of the Gilbert and Cameron values given in Eq. (6.6) on page 80.]

(16) I_{epair}, $C_{\pi 0}^{(\text{eqb})}(Z)$, $C_{\nu 0}^{(\text{eqb})}(N)$, $C_{\pi 0}^{(\text{eqb})}(Z\text{-}2)$, $C_{\nu 0}^{(\text{eqb})}(N\text{-}2)$ [1I5,4F10.2]
Flag for determining the equilibrium pairing option; condensation energies to be used in the equilibrium calculations. It is similar to the previous input item except that the significance of I_{epair} is

$$I_{\text{epair}} = \begin{cases} 0 & \text{input } C\text{'s (including zero)} \\ 1 & \text{default } C\text{'s} \end{cases}$$

Thus, once again, a blank line means that no pairing corrections are made.

(17) I_{newp} [1I5]
Control variable signaling whether input for another reaction calculation is to be read from the input file. $I_{\text{newp}} \geq 0$ causes input to return to item (1) in this list for a new reaction to be read, while $I_{\text{newp}} < 0$ terminates the calculations with the current reaction.

7.2. Calculations

The calculations are divided into a number of different parts whose inter-relationships can be visualized using Fig. 7.1 on page 97.

7.2.1. Preliminary calculations

The calculations begin with an initialization step that is common to all the problems in an input file. It uses the three lines of global input and generates starting values for a number of variables and arrays.

The reaction-specific calculations begin with the evaluation of preliminary quantities such as

- total reaction cross sections in the entrance and exit channels (when they are not read in) and the geometric cross sections needed in the collective state calculations (calculations run in CROSS);
- single particle states densities $g_{\pi 0}$ and $g_{\nu 0}$ for those nuclei for which they are not read in (including residual nuclei following secondary particle emission);
- neutron and proton pairing condensation energies for each nucleus involved in the reaction (including the residual nuclei following secondary particle emission), based on the even or odd character of the nucleus (no pairing for odd-N or odd-Z) and the default or input pairing energies;

- the isospin related quantities T_z, $2T$, the isospin coupling Clebsch-Gordan coefficients, and the symmetry energies for all the nuclei involved in calculating primary particle emission (executed only when isospin is conserved; calculations run in subroutine SETISO);

- averaged inverse reaction cross sections for all six exit channels (to be used in knockout and inelastic direct reaction calculations involving cluster degrees of freedom);

- upper limit on the number of excitons in the states considered in the preequilibrium calculations.

7.2.2. State density and rate calculations

The next sections of the code calculate some of the quantities used in evaluating the particle-hole state densities. First, the non-energy-dependent parts of the Pauli correction function, $A(p, p_\pi, E)$, are evaluated in the S^2-ESM (if shell closures are active) or the ESM. Most of this work is done in subroutine PAULI. Then preliminary calculations related to the finite well depth correction functions are generated.

The main calculations of the particle-hole state densities in the composite nucleus and of its internal transition rates (creation of particle-hole pairs and converting a proton pair to a neutron pair or *vice versa*) are done in subroutine COMPOUND. This in turn calls a number of other subprograms whose functions are as follows:

- WELL: finite well depth corrections for the particle-hole state densities and the internal transition rates (if needed)

- OMEGA: particle-hole state densities (makes calls to SINGLE, TCOR and COLLEC)

- SINGLE: neutron and proton single particle state densities corrected for shell structure effects (called only if shell closures are active)

- TCOR: correction factor to the particle-hole state densities for isospin conservation (called only when isospin conservation is active)

- COLLEC: collective pairing contribution to the Pauli correction function (when collective pairing is requested)

Both the preequilibrium and equilibrium particle emission rates for the six types of emitted particles are calculated next. This is done in subroutine EMMY which in turn has calls to WELL, ASHELL, and OMEGA. If fission competition at equilibrium is requested, the fission rates are calculated in the main program.

Finally the preequilibrium transition rates and particle emission rates are used to calculated the branching ratios for these processes for the different particle-hole configurations.

7.2.3. Reaction calculations

With the constituent ingredients in hand, the preequilibrium reaction calculations are performed. This involves evaluating the amount of strength passing through each class of particle-hole states during energy equilibration. This is followed by the calculation of the various direct reaction mechanisms considered, using the following subroutines:

- KNOCK: knockout processes involving cluster degrees of freedom
- INEL: inelastic scattering processes involving cluster degrees of freedom and those involving excitation of collective states (call to RESOUND)
- RESOUND: excitation of collective states, both spectroscopic and giant resonance, as well as elastic scattering
- NUTRA: nucleon transfer reactions (pickup, stripping and exchange)

Following these calculations, an evaluation is made of the amount of the entrance channel total reaction cross section which is depleted by the direct reactions (but not by elastic scattering) and which therefore is not available for the exciton model calculations. This conserves cross section.

At this point the amount of strength passing through the different configurations involved in the primary preequilibrium phase of the reaction is sent to the output file `precom.out`.

7.2.4. Particle energy spectra

The components of the emitted particle energy spectra which are due to exciton model preequilibrium emission and to equilibrium emission are calculated in subroutine SPEC. There they are normalized to unit strength entering the initial

particle-hole configuration. If the calculation of secondary particle emission has been requested, then the strength in each of the primary residual nucleus configurations is stored for use in those calculations. When isospin is conserved in the preequilibrium part of the calculation, then both the T-conserved and T-mixed components to the equilibrium spectra are calculated.

The final normalization of the exciton model and evaporation components to obtain energy differential cross sections is done in SPECOUT, which also generates the spectral output, when that has been requested, and directs it to the output file. However, when secondary emission has been requested, SPECOUT is not called until secondary emission has also been calculated as described in the next section.

7.2.5. Secondary emission

When the calculation of secondary particle emission has been requested, control returns to the appropriate place in the reaction specific preliminary calculations. For each primary residual nucleus and excitation energy (and isospin value, when isospin is conserved) for which secondary emission is considered, the calculations then proceed through the same sequence of steps as for primary emission, up to the calculation of the particle energy spectra. Thus the main part of the program will be used many times in a single reaction calculation. After all of the secondary emission has been calculated, the requested spectral output is written to the file `precom.out`.

7.2.6. Isospin conservation

When more than one value of the isospin is possible in the initial composite nucleus, then the above calculations are performed for the lowest value first. Following generation of the requested spectral output, the total emission spectra (*i.e.* the sum of contributions from all of the component mechanisms) are stored in memory. Then control passes again to the appropriate point in the reaction specific preliminary calculations, and the whole process is repeated for the higher isospin. Now, however, an additional column of output is provided for each type of emitted particle, showing the spectrum containing the contributions from both composite nucleus isospins.

7.2.7. Arrays for Hauser-Feshbach Codes

Since PRECO is sometimes used as a preequilibrium module in larger Hauser-Feshbach model codes, there is an option to generate arrays of cross sections populating the possible residual nuclei at the possible excitation energies formed by preequilibrium emission before any equilibrium emission is calculated. The Hauser-Feshbach code does the equilibrium calculations. This option is activated when the control variable `ihfp` is read in with an absolute value of unity.

The arrays are stored in the named common `/hauser/`, and are also printed out following all of the energy spectra. There is one set of arrays for the cross sections and another for the excitation energies of the residual nuclei. The arrays are:

No. of Emissions	Cross Section Array	Energy Array
0	csres0	eres0
1	csres1(kp,ne)	eres1(kp,ne)
2	csres2(kpp,ne1,ne2)	eres2(kpp,ne1,ne2)

Here `csres0` is given in units of millibarns and is the amount of the entrance channel cross section which has not undergone preequilibrium or direct particle emission. Initially, the arrays `csres1` and `csres2` correspond to the residual nuclei formed by emission of one particle and two particles, respectively, and are given in units of mb/MeV. The corresponding `eres` quantities are the excitation energies of the corresonding residual nuclei and are given in MeV.

For the case when the emission energies are not evenly spaced or the minimum energy is different from the energy spacing, it is important to note that `csres1` $= d\sigma(\varepsilon_1)/d\varepsilon_1$ while `csres2` $= d\sigma(\varepsilon_1, \varepsilon_2)/d\varepsilon_2$. In the latter case, the "integration" (actually a weighted sum) over ε_1 was done in obtaining the strength available for secondary emission. The indices `(kp,ne)` refer to the residual nucleus formed by emission into the `kp` channel with an emission energy specified by `ne` (where the values of `kp` and `ne` are explained in Appendix A). Similarly, the indices `kpp,ne1,ne2` refer to the residual nucleus formed by emission of two particles (`kpp`=1,2,3 for *nn*, *np* plus *pn*, and *pp* emission) with energies specified by `ne1` and `ne2`.

If an equally spaced grid of emission energies is used and the minimum energy is equal to the energy spacing (the normal case), then the `csres2` and `eres2` arrays can be collapsed into a linear form since only `ne1+ne2` is significant and all of the weighting factors for the cross section "integration" are equal to the energy spacing so that $\Delta\varepsilon_1 = \Delta\varepsilon_2$. This consolidation will be done if requested, and the

results are stored in the arrays `csres1` and `eres1` with the indices `kp=kpp+6` and `ne=ne1+ne2-2`.

7.2.8. Arrays of Nuclide Production Cross Sections

Specifying `ihf=2` generates arrays for nuclide production cross sections including both preequilibrium and equilibrium emission. Since it was not the main purpose of PRECO to calculate such production cross sections, primary emission is considered for all the light ejectiles, but secondary emission is restricted to reactions in which both emitted particles are nucleons, while tertiary emission is not considered at all, and γ-ray competition to secondary particle evaporation is treated only approximately. Still, in situations where direct and preequilibrium emission is dominant, especially for complex particle induced reactions, this output can be useful, and it is easy to estimate corrections for tertiary particle emission. These arrays are an alternative to the arrays in the previous section and are stored in the same place with the same storage indices. They are likewise printed after the emission spectra.

7.3. Code Output

The main output of the code is directed to a file called `precom.out`. In addition, status output is directed to the user's computer screen. Both types of output are described below. In addition, the main output generated from the input file of Appendix B is contained in Appendix C.

7.3.1. Status output

During the calculations, the program displays on the user's computer screen the title of the problem currently being calculated so that the program's progress through the batch input file can be monitored. In addition, when the calculation of secondary particle emission has been requested, additional screen output informs the user when calculations have been started for the primary neutron residual nuclei and then for the proton residual nuclei. This output can easily be supressed where it is inappropriate for the user's computer system.

7.3.2. Summary and reaction strength information

The first page of output for a given reaction calculation contains a summary of many of the main reaction variables and a table of the reaction strength passing through the various particle-hole configurations during the primary equilibration process.

Most of the quantities in the block of summary information are self explanatory. They include the title of the reaction problem being calculated; the identity of the target and projectile, and the N and Z of any closed-shell configurations; the excitation energy of the initial composite nucleus, the entrance channel total reaction cross section and the width of any shell gaps used; the values of $g_{\pi 0}$ and $g_{\nu 0}$, and the three matrix element normalization constants; the flag variables that determine the kinds of pairing corrections that were made; the value of the well depths V_0, V_1, and V_2; parameters related to the isospin properties of the entrance channel and composite nucleus (when isospin is conserved); the cross sections going into direct (non-exciton-model) reactions and exciton model preequilibrium processes, and the fraction of preequilibrium emission. The last quantity is the fraction of the cross section available for exciton model preequilibrium emission that actually goes into such preequilibrium emission. It is thus $1-\sum_{p_\pi} P_1(p_{\max}+1, p_\pi)$, where $p_{\max}$ is the last particle number for which emission is considered. It does *not* include the cross section from other direct reaction mechanisms.

The table of reaction strengths passing through the various particle-hole configurations is normalized to unity at the beginning of the calculations for the exciton model equilibration process. The values printed have thus *not* been corrected for the depletion due to the direct reaction calculations. The quantity printed out is $P_2(p, p_\pi)$ which includes contributions from exciton scattering transitions. There is one row to the table for each value of p, and the various columns correspond to different values of p_π. The last column gives $\sum_{p_\pi} P_2(p, p_\pi)$ which is the total amount of strength passing through states with $n = 2p - A_a$ excitons, where A_a is the mass number of the projectile. This sum is greater than the amount of strength passed on to the next hierarchy of states, which is $\sum_{p_\pi} P_1(p+1, p_\pi)$ since the former sum contains the contributions from exciton scattering which causes strength to pass through more than one configuration with p excitons (see Sect. 3.3).

7.3.3. Particle emission spectra

The energy spectra for the emitted particle types which have been requested are printed out next, with each particle type on a new page. The heading of the table gives the exit channel isospin coupling coefficients and the symmetry energies whenever isospin conservation is considered. All of the cross sections are given in millibarns/MeV. The columns in the tables of energy spectra have the following significance:

eps/cm	center-of-mass energy of the emitted particle
eps/ch	channel emission energy
direct/nutra	direct nucleon transfer cross section
direct/knock	knockout or inelastic cross section involving complex particles, plus any collective and elastic cross section
exciton/primary	primary exciton model preequilibrium cross section
exciton/secondary	secondary preequilibrium cross section (if calculated)
equilibrium/primary	primary equilibrium cross section
equilibrium/secondary	secondary equilibrium cross section (if calculated)
sum	inclusive spectrum (sum of the preceding 6 columns)
tsum	sum for both composite nucleus isospins if T is conserved and this calculation is for the higher of two allowed T values.

In general the last line of the table gives the energy integral of each column. For the inelastic channel when elastic scattering is considered, the sum beneath the direct/knock column does not include the elastic contributions. These are integrated separately and printed out on the next line. When fission is considered, the equilibrium fission yield is printed out just below the neutron particle spectrum.

When output of the double differential cross sections has been requested, they are printed just after the table of energy spectra for each particle type. These are printed in two blocks, one for the forward hemisphere and one for the backward hemisphere, and the heading for this section of output includes the value of the systematic binding energy for the particle type whose angular distribution is given. All of the cross sections are given in mb/(sr·MeV) and are printed as a function of the center-of-mass angle and the channel energy. Contributions from all of the components in the energy spectrum are combined.

7.3.4. Arrays for Hauser-Feshbach Codes

The arrays of preequilibrium production cross sections for input into Hauser-Feshbach model codes are automatically printed whenever they are generated. They follow the output of the emission spectra.

The first line after the problem title gives the amount of cross section remaining in the original composite nucleus after all direct and preequilibrium emission has occurred, as well as the excitation energy of this nucleus. There are two tables just below that. The first gives the excitation energies, U, and the preequilibrium cross sections (denoted as `cs`) for the residual nuclei resulting from primary emission of neutrons, protons and deuterons for all possible emission channel energies. The second is a similar table for the residual nuclei following primary emission of tritons, He-3, and α-particles. The production cross sections have been reduced for any secondary preequilibrium emission if the calculation of secondary emission has been requested.

There are two possible forms for the results for secondary particle emission, depending on what was requested. The full form consists of an excitation energy array and a cross section array for each of the three nuclei that can be populated by secondary emission. These correspond to nn, np plus pn, and pp emission. Here again, the left column contains the channel energy for the first particle emission, while the column labels give the channel energy of the second particle emitted. The cross sections for np and pn emission are added together since they populate the same residual nucleus. If compact output has been requested by reading in a negative value for `ihfp`, and if an equally spaced emission energy grid has been specified with the minimum energy equal to the energy spacing, then the arrays for secondary emission are replaced by a single block of output giving the residual excitation energies and the preequilibrium production cross sections. The left hand column then gives the sum of the emission energies of the two particles while the other columns are labelled in the same way as the tables for the residual nuclei from primary particle emission.

7.3.5. Nuclide Production Cross Sections

The arrays of nuclide production cross sections are also printed out automatically whenever they are generated.

There will be no cross section remaining in the initial composite nucleus, and the first line after the title gives the total production cross sections in mb for the residual nuclides formed by primary emission of each of the six light ejectiles

considered in PRECO, after any secondary emission has occurred. The next line gives the cross sections for producing the residual nuclei formed by emission of two nucleons. Then the arrays for primary and secondary emission are printed as in the case of the Hauser-Feshbach arrays, except that now both preequilibrium and equilibrium contributions are included. The main advantage of these arrays is so that approximate corrections for emission of a third particle can be made. This is accomplished by taking all the cross section to the residual nuclei from secondary emission that leaves the final nucleus with enough energy for tertiary emission (taking into account the Coulomb barriers) and assuming that such emission will occur.

8. Final Note to Users

If you decide to use PRECO, I would appreciate hearing from you. This code is being distributed through two major code distribution centers, which will also handle updates to it. However, it would help me to know who is using the code and the kind of work for which it is being used. This information is also meaningful to the U.S. Department of Energy which funded most of this research as part of the U.S. Nuclear Data Program. In addition, it will help me to gauge what additional features would be useful in the code and to notify you of any minor errors that are found but which would not warrant a special notice through the distribution centers. Your feedback is also welcome, particularly with regard to any errors you may find in the code or the manual. I can be reached via email at `cwalker@tunl.duke.edu`.

I know of no major problems in adapting PRECO for use on other computer systems. It will probably be necessary to go into the file `precom.for` to reset the input and output device numbers and to delete (or comment out) the statements which write to the console, if they are not applicable to your system. These have the form `write (*,...)`. In addition, there are two variables you might need to alter. They are `newpage`, which sets the character for a page break command and `length`, which sets the number of lines per page for determining how to format the printout of the angular distributions. Both variables are set at the beginning of the file `precom.for`. Generally, however, an effort has been made to keep the program portable. Please let me know of any difficulties that you encounter.

Finally I want to again emphasize two points about the code. First, the code has been most thoroughly studied and benchmarked for reactions with only nucleons in the entrance and exit channels and for incident energies up to around 30 MeV. It seems to work well up to 60 MeV and even 90 MeV. Almost no work has been done at incident energies above 100 MeV. Calculations for complex particles emitted in nucleon induced reactions are more reliable than calculations for complex projectiles, due to the continuing need to include projectile breakup mechanisms. Please be patient; this is coming soon.

Second, in using the code it is very important to remember that the global input set is just that; a *set* designed to produce good overall agreement to a wide range of data. Because of couplings between parameters, changing one piece of input to reproduce a small group of data may have unexpected and even unphysical consequences in other mass/energy domains or for other types of reactions. Therefore, please make such changes with care. The strongest coupling (though it is much weaker than in PRECO-2000) is still between the normalizations of the single particle state densities and the exciton-model residual two-body matrix elements. However, the single particle state densities also have an important effect on the yields for nucleon transfer reactions, and both of these parameters can be affected if the total reaction cross sections in the entrance and/or exit channels are changed significantly. I have tried to comment on such couplings in various places in the writeup.

I sincerely hope that this code will be useful to you.

Bibliography

[BE69] F. D. Becchetti, Jr., and G. W. Greenlees, *Phys. Rev. C* **182** (1969) 1190.

[BO74] R Bonetti and L. Milazzo-Colli, *Phys. Lett. B* **49** (1974) 17.

[CH81] K. H. Narasimha Murthy, A. Chatterjee, and S. K. Gupta, "Proc. Int'l Conf. on Nucl. Cross Sections for Technology," Knoxville TN, 1979, NBS Spec. Pub. 594, p 793;
A. Chatterjee, K. H. N. Murthy, and S. K. Gupta, *Pramāna* **16** (1981) 391.

[FE80] H. Feshbach, A. Kerman, and S. Koonin, *Ann. Phys. (N.Y.)* **125** (1980) 429.

[FU84] C. Y. Fu, *Nucl. Sci. Eng.* **86** (1984) 344.

[GI65] A. Gilbert and A. G. W. Cameron, *Can. J. Phys.* **43** (1965) 1446.

[GI67] E. F. Gibson, B. W. Ridley, J. J. Kraushaar, M. E. Rickey, and R. H. Bassel, *Phys. Rev.* **155** (1967) 1194.

[GR66] J. J. Griffin, *Phys. Rev. Lett.* **17** (1966) 478.

[HA67] J. C. Hafele, E. R. Flynn, and A. G. Blair, *Phys. Rev.* **155** (1967) 1238.

[HU62] J. R. Huizenga and G. Igo, *Nucl. Phys.* **29** (1962) 462.

[KA81] C. Kalbach and F. M. Mann, *Phys. Rev. C* **23** (1981) 112.

[KA85] C. Kalbach, *Phys. Rev. C* **32** (1985) 1157.

[KA85a] C. Kalbach, "PRECO-D2: Program for Calculating Preequilibrium and Direct Double Differential Cross Sections," Los Alamos Report LA-10248-MS (1985).

[KA86] C. Kalbach, *Phys. Rev. C* **33** (1986) 818.

[KA87] C. Kalbach, *Nucl. Sci. Eng.* **95** (1987) 70.

[KA88] C. Kalbach, *Phys. Rev. C* **37** (1988) 2350.

[KA89] H. Kalka, M. Torjman, and D. Seeliger, *Phys. Rev. C* **40** (1989) 1619.

[KA90] C. Kalbach, *Phys. Rev. C* **41** (1990) 1656.

[KA91] C. Kalbach, "PRECO-E: Two-Component Exciton Model Code with Direct Reactions and Angular Distributions," LA-UR-91-2300 (1991).

[KA93] C. Kalbach, *Phys. Rev. C* **47** (1993) 587.

[KA93a] C. Kalbach, *Nucl. Sci. Eng.* **115** (1993) 43.

[KA95] C. Kalbach, *J. Phys. G: Nucl. Part. Phys.* **21** (1995) 1499.

[KA95a] C. Kalbach, *J. Phys. G: Nucl. Part. Phys.* **21** (1995) 1519.

[KA95b] C. Kalbach, *Acta Phys. Slov.* **45** (1995) 685.

[KA98] C. Kalbach, *J. Phys. G: Nucl. Part. Phys.* **24** (1998) 847.

[KA99] C. Kalbach, *J. Phys. G: Nucl. Part. Phys.* **25** (1999) 75.

[KA00] C. Kalbach, *Phys. Rev. C* **62** (2000) 044608.

[KA04] C. Kalbach, *Phys. Rev. C* **69** (2004) 014605.

[KA05] C. Kalbach, *Phys. Rev. C* **71** (2005) 034606.

[KA05a] C. Kalbach, *Phys. Rev. C* **72** (2005) 024607.

[KA06] C. Kalbach, *Phys. Rev. C* **73** (2006) 024614.

[KO04] A. J. Koning and M. C. Duivestijn, *Nucl. Phys.* **A 744** (2004) 15-76.

[MA63] G. S. Mani, M. A. Melkanoff, and I. Iori, Centre d'Etudes Nucléaires de Saclay report CEA 2380 (1963).

[MI75] L. Milazzo-Colli, G. M. Braga-Marcazzan, and M. Milazzo, *Nuovo Cim.* **30A** (1975) 632.

[MI77] L. Milazzo Colli, G. M. Braga Marcazzan, R. Bonetti, M. Milazzo, and J. W. Smits, *Nuovo Cim* **39A** (1977) 171.

[MY66] W. D. Myers and W. J. Swiatecki, *Nucl. Phys.* **81** (1966) 1.

[NE62] P. E. Nemirovsky and Y. V. Adamchuk, *Nucl. Phys.* **39** (1962) 551.

[PE63] C. M. Perey and F. G. Perey, *Phys. Rev.* **132** (1963) 735.

[WI71] F. C. Williams, Jr., *Nucl. Phys.* **A166** (1971) 231.

A. List of Major Variables in PRECO-2006

The major variables in PRECO-2006 and their significance is summarized here. All energies are assumed to be in MeV and all cross sections in millibarns.

`acom(kc)`
: Mass number of primary or secondary composite nucleus as designated by `kc` (see definition of `kc`).

`act`
: Number of active exciton classes (those with at least one exciton).

`atar, aout, ares`
: Mass numbers of target, emitted particle and residual nucleus.

`asp, afish`
: Level density parameter, a, of composite nucleus in its normal state and at the top of the fission barrier.

`avail`
: Fraction of the reaction cross section surviving the direct reactions and entering the exciton model equilibration calculations.

`ben(kc,kp)`
: Binding energies of particles of type `kp` in the composite nucleus designated by `kc` (see definition of `kp`).

`betalam(i)`
: Deformation parameter of the $\mathtt{i}^{\mathrm{th}}$ collective state

`ceq(kc,kp,ia), cpre(kc,kp,ia)`
: Equilibrium and preequilibrium pairing condensation energies for the nuclei

formed by emitting particles of type `kp` from the composite nucleus designated by `kc`. Values of `ia`=1,2 are for proton and neutron pairing energies, respectively.

`clos(np1,nppi1)`
: Time integrated strength, $P_2(p, p_\pi)$, passing through the indicated configuration. The array indices in the code are are p+1 and p_π+1. (Compare with variable `p1(nppi1)` described in this appendix.)

`coll, collec`
: Collective pairing correction, $E_{\rm th}^{\rm coll}(p, p_\pi, E) - E_{\rm th}^{\rm ESM}(p, p_\pi)$. Function COLLEC generates the variable `coll`.

`coul(kp)`
: Coulomb barrier for particles of type `kp` for use in direct knockout/inelastic calculations involving cluster degrees of freedom.

`csr(kp)`
: Cross section populating the residual nucleus formed by primary emission (both preequilibrium and equilibrium) of a particle of type `kp` after secondary emission has been allowed to deplete that strength. It is given in units of millibarns.

`csres0`
: Cross section remaining in the initial composite nucleus after all preequilibrium emission has been calculated. It is given in units of millibarns.

`csres1(kp,ne)`
: Cross section remaining in the primary residual nucleus formed by emission of a particle of type `kp` (`kp=1,6`) and emission energy specified by `ne` after all secondary emission has been calculated. If `ihf=1`, only the strength feeding in and out of these nuclei due to direct and preequilibrium emission is included, since equilibrium calculations are presumed to be calculated subsequently using a Hauser-Feshbach model code. If `ihf=2`, both preequilibrium (including direct) and equilibrium contributions are included. The excitation energies of these residual nuclei are given in the array `eres1`. If secondary emission is considered and if compact output has been requested, then the production cross section arrays for nn, $np+pn$, and pp emission are stored in this array for values of `kp=kpp+6` (`kpp=1,3`) and `ne=ne1+ne2-2`. (See discussion of `csres2`, below.)

`csres2(kpp,ne1,ne2)`

Cross section in the secondary residual nucleus formed by direct+preequilibrium emission (if `ihf=1`) or by direct+preequilibrium+equilibrium emission (if `ihf=2`)of two particles of types specified by `kpp` (`kpp`=1,2,3 for nn, $np+pn$, and pp emission) and emission energies specified by `ne1` and `ne2`. The excitation energies of these residual nuclei are given in the array `eres2`.

`ct(kc,kp,it)`

Squares of the isospin coupling Clebsch-Gordan coefficents for the exit channel designated by `kp` in the emitting nucleus designated by `kc`. The index `it` specifies the isospin in the residual nucleus, with `it`=1 indicating the minimum residual isospin for the current isospin in the emitting nucleus and `it`=2 indicating the next higher residual isospin.

`db(ia)`

Shell gaps in the proton (`ia`=1) and neutron (`ia`=2) single particle states in the shell-shifted equi-spacing model.

`denu1, denu2, dpnu1, dpnu2`

Neutron pairing gaps for use in equilibrium (`denu`) and preequilibrium (`dpnu`) calculations. Gaps with the number `1` are used for nuclei with $N = N_{\rm CN}$ or $N_{\rm CN} - 1$ (whichever is even) and those with the number `2` are for nuclei with $N = N_{\rm CN} - 2$ if this number is even.

`depi1, depi2, dppi1, dppi2`

Proton pairing gaps for use in equilibrium (`depi`) and preequilibrium (`dppi`) calculations. The numbers `1` and `2` now refer to the Z of the nuclei.

`dodd(kp,ia)`

The odd single particle spacing just above and just below the shell gap in the nucleus specified by `kp`. The index `ia` is 1 for proton single particle states and 2 for neutron states. [Generated in subroutine SINGLE.]

`ds(kp,ia)`

ESM single particle spacings, with `kp` and `ia` as above.

`e`

Excitation energy of the current composite nucleus (either the original composite nucleus or a residual nucleus from primary neutron or proton emission).

`ee`

A variant of the excitation energy of the current nucleus; often the excitation energy minus the symmetry energy (if any) for the current value of the isospin of the nucleus.

`ehbar, epbar`

Average energy of the hole and particle degrees of freedom (corrected for finite well depth effects) for the main configurations being considered. These are used in COLLEC to calculate the collective pairing corrections to the particle-hole state densities.

`ehbhi, epbhi`

Average energy of the hole and particle degrees of freedom (corrected for finite well depth effects) for configurations formed in particle-hole pair creation interactions from the current configuration.

`ehole1, ehole2`

Global values for the effective well depth after the first pair creation interaction, with `ehole1` applying for proton pair excitation and `ehole2` for neutron pair excitation. If ehole1 is read in as zero, problem-specific well depths are generated based on the surface localization of the initial interaction.

`ehole(ia)`

Problem-specific values of the effective well depths after the first particle-hole pair creation interaction. The indices refer to proton pair excitation (`ia`=1) and neutron pair excitation (`ia`=2). The values of `ehole` will either be set to `ehole1` and `ehole2` or, if `ehole1` is read in as zero, to default well depths generated based on the suface localization of the initial interaction.

`elab`

Laboratory energy of the projectile.

`elam(i)`

Excitation energy of the `i`th collective state considered in the calculations.

`elast(ne)`

Cross section going into elastic scattering at the emission energy specified by `ne`. [Generated in subroutine RESOUND.]

`elastf(ne)`

The part of the elastic scattering cross section that has the more forward-peaked angular distributions. [Generated in subroutine SPECOUT.]

`elcoll(ne)`

Cross section at the specified emission energy which is due to collective state excitations (both spectrocopic and giant resonance) plus the part of the elastic scattering cross sections which follows the same angular distribution systematics as the collective cross section. [Generated in subroutine SPECOUT.]

`epauli(kp,q,ia)`

Main part of the Pauli correction function for the nucleus specified by `kp` and for the nucleon type `ia` exhibiting a total of `q` particle-hole pairs (both active and passive) so that $q = \max(p_{\rm ia}, h_{\rm ia})$. This array includes shell effects and simple pairing but not the last two terms in Eq. (2.4) or (2.53) or the collective pairing corrections, all of which depend on excitation energy. [Generated in subroutine PAULI.]

`eps(ne)`

Array of emission energies. The lowest energy for which emission is considered has an index of 2. The value of 1 is reserved for the energy to be used as the lower limit in taking energy 'integrals' of the calculated spectra.

`eres0`

Excitation energy of the original composite nucleus, stored in common block `/hauser/` as part of the information on preequilibrium residual nuclei.

`eres1(kp,ne)`

Excitation energies of the residual nuclei following emission of a particle of type `kp` (`kp=1-6`) and energy specified by `ne`. When compact output is requested for the production cross sections due to emission of two particles, the residual nucleus excitation energies from `eres2` below are stored in `eres1` for values of `kp=7-9`, where `kp=kpp+6` and `ne=ne1-ne2-2`.

`eres2(kpp,ne1,ne2)`

Excitation energies of the residual nuclei formed by emission of two particles (`kpp`=1,2,3 for nn, $np+pn$, and pp emission) with energies specified by `ne1` and `ne2`.

`esym(kc,kp,it)`

Symmetry energies for the nucleus specified by `kp` when the composite nucleus is specificed by `kc`. The index `it` determines the isospin of the residual nucleus: $T = T_{\rm min}$+`it`–1 where $T_{\rm min}$ is the minimum isospin in the `kp` nucleus for the current composite nucleus isospin.

`fac(i)`

Array of integer factorials, (`i`−1)!

`fishw, fishwt`

Fission rates for the isospin mixed and isospin conserved parts of the equilibrium calculations.

`fiss(kc)`

Equilibrium cross section going into fission in the composite nucleus specified by `kc`.

`flow, spill`

10^{-18} and 10^{+18}; used for checks to avoid underflow and overflow conditions.

`fnn, fnp, fpp`

Normalization factors $K_{\nu\nu}$, $K_{\nu\pi}$, and $K_{\pi\pi}$ for the mean square matrix elements. They default to values of 900, 900 and 2200, respectively.

`fracel`

Variable $f_{\rm EL}$ specifying the fraction of the elastic cross section which follows the collective state angular distribution systematics. [Generated in subroutine RESOUND.]

`frange`

Variable $f_{\rm shell}$ specifying the range, $f_{\rm shell}D/2d$, of N or Z over which shell structure effects wash out (see Sect. 2.5.6 on page 25). It defaults to a value of $f_{\rm shell} = 2.0$.

`fspan`

Variable $k_{\rm shell}$ specifying the energy span, $k_{\rm shell} \cdot t$ over which the single particle state density is averaged in the S^2-ESM to obtain the shell-corrected equilibrium level density parameter. It defaults to a value of $k_{\rm shell} = 2.3$.

`fwd(i,j)`

Correction factor for finite well depth and surface effects in the state densities. The index `j` is the number of prior interactions and usually `j` = h. A value of `i` = 1 gives the usual $f_{\rm fwd}(n, h, E, V)$ while `i` = 2 gives $f_{\rm fwd}(n+1, h, E, V)$ for use in evaluating `epbar` and `ehbar`. [Generated in function WELL.]

`fweis, fweist`

Factors normalizing the equilibrium emission rates in the calculation of the equilibrium energy spectra. They are the strength available for the isospin mixed (`fweis`) or isospin conserved (`fweist`) equilibrium emission divided by the corresponding total equilibrium emission rates (all particle types and energies). The entrance channel cross section and any isospin coupling coefficients are applied separately.

`fteq`

The fraction, $F_{\rm Teq}$, of isospin conservation at equilibrium.

`gamhn(np1,nppi1), gamhp(np1,nppi1)`

Internal transition rates $\lambda_{\nu+}(p, p_\pi, E)$ and $\lambda_{\pi+}(p, p_\pi, E)$ for neutron and proton pair creation interactions. The indices are p+1 and p_π+1. These variables are later converted to branching ratios.

`gamnp(np1,nppi1), gampn(np1,nppi1)`

Internal transition rates $\lambda_{\nu\pi}(p, p_\pi, E)$ and $\lambda_{\pi\nu}(p, p_\pi, E)$ for converting a neutron particle-hole pair into a proton pair and *vice versa*. The indices are p+1 and p_π+1. These variables are later converted to branching ratios.

`ghole(ia),gpart(ia)`

Effective single state densities for hole and particle degrees of freedom, respectively, for the current particle-hole configuration in the S^2-ESM. The index specifies whether they are for the proton (`ia`=1) or neutron (`ia`=2) single particle states. [Generated in subroutine SINGLE.]

`gres(kc,kp,ia)`

Equi-spacing model single particle state densities for nucleons of type `ia` in the nucleus specified by `kp` when the composite nucleus is specifed by `kc`.

`ia`

Index variable specifying the type of nucleon in the nucleus being considered. Values of `ia` $= 1, 2$ signify protons and neutrons, respectively.

`icol`

Control variable for the type of preequilibrium pairing correction to be applied (`icol` > 0 indicates collective pairing corrections).

`idif(kp,ia)`

The quantities $Z - Z_{\mathrm{mag}}$ (for `ia`=1) and $N - N_{\mathrm{mag}}$ (for `ia`=2) for the current nucleus specified by `kp`.

`iepair, ipair`

Control variables for equilibrium and preequilibrium pairing options. (See discussion of items 15 and 16 of the code input on page 103.)

`ihf,ihfp`

"Hauser-Feshbach" control variables. The variable `ihfp` is read in, and `ihf` is set to its absolute value. The quantity `ihf` determines which calculations of nuclide production cross sections are performed, while the sign of `ihfp` governs the form of the output. (See discussion of item (A) of the code input on page 99.)

`irea, iwri`

Input and output device numbers. These are initially set to values of 5 and 6, respectively.

`ishell`

Control variable for shell structure effects. A value of `ishell` > 0 means that shell corrections are to be made. Its value is set based on the values for `rzmag` and `rnmag` that are read in.

`iso`

Control variable for isospin conservation. A value of `iso`=0 means that isospin is totally mixed, and `iso`=1 signifies that isospin is conserved as a quantum number during the preequilibrium phase of the reaction. If `iso`=2 is supplied as input, default conditions are used to determine whether or not isospin should be assumed to be conserved during equilibration and, if so, the amount of isospin conservation at equilibrium.

`jin, jnin, jpin`
Values of A, N, and Z of the projectile.

`jout, jnout(kp), jpout(kp)`
Values of A, N, and Z of the emitted particle in the `kp` channel.

`jrn, jrz`
Integer form of the neutron and proton numbers, N and Z, of the target. (The floating point forms are `rnn, rzz`.)

`kang`
Control variable for printing double differential cross sections. A value of `kang` > 1 causes these to be be printed for all exit channels for which energy differential cross section printout is requested.

`kc`
Index designating the current composite nucleus. Values of 1, 2 and 3 correspond to the initial composite nucleus, and the residual nuclei produced by primary neutron and proton emission.

`kin`
The `kp` value for the entrance channel, `kin` $= A_a + Z_a$.

`kp`
Index specifying the reaction channel. In general `kp` $= A_b + Z_b$, so that values of `kp` $= 1$ to 6 correspond to the n, p, d, t, ^{3}He, and α channels. A value of `kp` $= 7$ can refer to the entrance channel or, more commonly, the composite nucleus.

`kpp`
Index specifying the residual nucleus following secondary particle emission. Values of `kpp` $= 1$ to 3 correspond to the nn, $np+pn$, and pp residual nuclei.

`kprint(kp)`
Control variable for printing the energy spectra and (if `kang`>0) the double differential cross sections in the `kp` channel. A value of `kprint(kp)`> 0 causes the spectra for that channel to be printed.

`lam(i)`
The multipolarity, λ, of the ith collective state to be considered. A negative

value is read in to signify that a Lorentzian (rather than a Gaussian) line shape is desired, but it is then converted to the corresponding positive value.

`lamax`
: The number of 'collective' states (spectroscopic, giant resonance, and elastic) considered in the current calculation.

`mlo(ia), mhi(ia)`
: Degeneracies of the piled up single particle levels below (`mlo`) and above (`mhi`) the shell gap for nucleons of type `ia`. Typically default values are used and `mlo(ia)=mhi(ia)`.

`mdfar(kp,ia), mdnear(kp,ia)`
: Degeneracies of the piled up levels on the opposite and same side of the shell gap as the Fermi level for the nucleus in the `kp` channel and for nucleons of type `ia`. Again, with default parameters for shell structure, `mdfar(kp,ia)=mdnear(kp,ia)`.

`mxdime, mxdimp, mxdim2`
: Dimensions of the energy index and the particle number indices for primary and secondary emission calculations for the code's arrays. These are currently set at 51, 13 and 9, which allows for 50 emission energies, and maximum particles numbers of $p_{\max} = 12$ for equilibration of the primary composite nucleus and $p_{\max} = 8$ for the secondary composite nuclei.

`ndwn, ndwn1`
: Lower limit on the particle number and `ndwn`+1.

`neps, neps1(kc,kp)`
: The number of emission energies considered in the calculation, and the maximum energy index for allowed emission in the `kp` channel for the composite nucleus specified by `kc`.

`np1, nppi1`
: Main indices used to specify the particle-hole configuration being considered. They have values of `np1` $= p + 1$ and `nppi1` $= p_\pi + 1$.

`nphd(kc,kp,ia)`
: Particle/hole difference $p_\pi - h_\pi$ (for `ia`=1) or $p_\nu - h_\nu$ (for `ia`=2) in the nucleus of the `kp` channel when the composite nucleus is specified by `kc`.

`nppi, nhpi, npnu, nhnu`
: The variables p_π, h_π, p_ν, and h_ν.

`nt(kc)`
: The quantity $T - T_z$ in the composite nucleus specified by `kc`.

`ntmin(k), ntmax(k)`
: Minimum and maximum values of $T - T_z$ for the residual nuclei formed by neutron (`k`=1) and proton (`k`=2) emission. These are used to set `nt(kc)` for secondary emission.

`nup, nup1, nup2`
: Maximum particle number considered in the current calculation, `nup`+1, and `nup`+2.

`omega(kc,nppi,nhpi,npnu,nhnu,ee,kp,it,in)`
: Function generating the state density for the indicated nucleus (specified by `kc` and `kp`) and configuration. A value of `in`=1 indicates that `omega` is called from NUTRA, the subroutine calculating the direct nucleon transfer reaction cross sections. In this case, the usual simple pairing correction is not made if two nucleons of the same type are being transferred, because they can be transferred in a paired state. If OMEGA is called from other subprograms, `in`=0.

`p1(nppi1)`
: The strength $P_1(p, p_\pi)$ populated directly by pair creation from simpler states. (See Sect. 3.3 on page 40. Compare with variable `clos(np1,nppi1)` described in this appendix.) This variable is stored for only one value of p at a time with an index of p_π+1.

`preeq1(kp,ne), preeq2(kp,ne)`
: Reaction strength going into primary (`preeq1`) or secondary (`preeq2`) preequilibrium emission of particles of type `kp` and channel energy `eps(ne)`.

`ptot`
: Fraction of the available strength left, $\sum_{p_\pi} P_1(p, p_\pi)$, at the end of the closed form preequilibrium calculations.

`range(ia)`
: Range of Z (`ia`=1) or N (`ia`=2) over which shell effects wash out in moving away from a closed-shell configuration.

`rho(np1,nppi1)`

Array of particle-hole state densities for the active composite nucleus. The indices are p+1 and p_π+1.

`rgamma`

Parameter R_γ used to approximate the competition of γ-ray emission with secondary evaporation. Secondary evaporation is only considered if the neutron channel is open and/or if the proton channel is open for emission energies with $\sigma_{\mathrm{p,rxn}}(\varepsilon)/\sigma_{\mathrm{n,rxn}}(\varepsilon) > R_\gamma$. The parameter defaults to $R_\gamma = 0.005$.

`rncn(kc), rzcn(kc)`

Neutron and proton numbers, N and Z, of the composite nucleus specified by `kc`.

`rn, rz`

The ratios N/A and Z/A for the target nucleus.

`rnn, rzz`

Floating point form for the neutron and proton numbers, N and Z, of the target nucleus. (The integer forms are `jrn, jrz`.)

`rnmag, rzmag`

The neutron and proton numbers, N_{mag} and Z_{mag}, for the closed-shell configurations to be considered.

`rose(kp)`

Equilibrium energy-shift shell correction in the nucleus specified by `kp`. [Generated in subroutine PAULI.]

`scoll(ne)`

Cross section for the excitation of collective states (both spectroscopic and giant resonance) at the emission energy specified by `ne`. [Generated for the inelastic channel in subroutine RESOUND.]

`seq(kp,ne), seq2(kp,ne)`

Isospin-mixed strength going into primary (`seq`) or secondary (`seq2`) equilibrium emission into the `kp` channel with a channel energy of `eps(ne)`. It is generated in SPEC and converted into evaporation cross sections in SPECOUT. (See also `steq`.)

`sigcni`
: Entrance channel total reaction cross section.

`siggeom(ne)`
: Geometric cross sections for emission of particles of energy `eps(ne)` into the inelastic channel.

`sigin(kp,ne)`
: Total reaction cross sections in the `kp` channel for emission of particles of energy `eps(ne)`.

`snock(kp,ne)`
: Reaction cross section going into direct inelastic scattering and knockout processes involving cluster degrees of freedom. Prior to output, the cross section for collective state excitation and elastic scattering is included for the inelastic channel. The index `kp` specifies the reaction channel, and the emission energy is `eps(ne)`.

`snutra(kp,ne)`
: Reaction cross section going into direct nucleon transfer in the `kp` channel with emission energy `eps(ne)`.

`spre(kp,ne)`
: Strength from primary emission of particles of type `kp` and channel energy `eps(ne)` which populates states with p-values greater than the maximum dimensioned for secondary preequilibrium emission. This strength is reserved and made available for secondary evaporation. When isospin in conserved and more than one isospin value is allowed in the residual nucleus from primary emission, `spre` is generated in subroutine SPEC for states with the lower T and reset for the higher T in subroutine REPENT.

`steq(kp,ne), steq2(kp,ne)`
: Isospin-conserved strength going into primary (`steq`) or secondary (`steq2`) equilibrium emission into the `kp` channel with a channel energy of `eps(ne)`. It is generated in SPEC and converted into evaporation cross sections in SPECOUT. (See also `seq`.)

`strong(np1,nppi1,ne)`
: Strength populating states of the specified configuration in the residual nucleus by primary emission in the energy bin centered at `eps(ne)`. The indices

are p+1 and p_π+1 for primary neutron emission while dummy indices (as described in the listing) are used for proton emission to save storage memory. When isospin is conserved, the array is set first in subroutine SPEC for the lowest allowed isospin in the residual nucleus from primary emission and then is reset in REPENT if a higher value is also allowed. This strength feeds into the equilibration calculations leading to secondary preequilibrium particle emission.

`tau(np1,nppi1)`
: Lifetimes $\tau(p, p_\pi)$ for the different particle-hole configurations. Contributing processes are pair creation and exciton scattering interactions as well as particle emission. (See Sect. 3.3 on page 40.) The indices are p+1 and p_π+1.

`tau2(nppi1)`
: Lifetimes $\tau'(p, p_\pi)$ for the different particle-hole configurations including only pair creation and particle emission. Only the index p_π+1 is specified since values for only one value of p at a time are stored.

`tomsc(ne), tomsd(ne)`
: Cross sections with channel energy `eps(ne)` going into all equilibrium emission (`tomsc`) and all direct+preequilibrium emission except collective excitations and elastic scattering (`tomsd`) into the current channel. These are used in calculating double differential cross sections, when requested.

`twot(kp)`
: Two times the lowest allowed isospin value in the residual nucleus of the `kp` channel for the current composite nucleus isospin being considered. (A value of `kp` = 7 is for the composite nucleus.)

`tz(kp), tze(kp)`
: Real and effective values to T_z in the nucleus in the `kp` channel. The value of `tze` is typically $|T_{z,\mathrm{tar}}|$, the absolute value of T_z for the target nucleus. [Generated in subroutine SETISO.]

`tzeff`
: Value of $|T_{z,\mathrm{tar}}|$, the absolute value of T_z for the target nucleus.

`used`
: Energy integrated direct reaction cross section summed over all exit chan-

nels. This is the amount of the total reaction cross section which is not available for the exciton model preequilibrium calculations.

`vfull`
: Central depth of the nuclear potential measured relative to the Fermi level. It defaults to 38 MeV.

`w(kp,np1,nppi1,ne)`
: Particle emission rates for the exit channel `kp`, channel energy `eps(ne)`, and the configuration specified by `np1` $= p+1$, and `nppi1` $= p_\pi+1$. As explained in the program listing, dummy indices are used for `kp` > 3 to reduce memory requirements in this very large array, since `nppi1`$\leq$`np1`.

`wcol(i)`
: Gaussian width parameter of the `i`th collective state (or the FWHM, if a Lorentzian lineshape has been requested).

`weiss(kp,ne), weist(kp,ne)`
: Equilibrium particle emission rates in the Weisskopf-Ewing model calculated for the isospin mixed strength (`weiss`) and the isospin conserved strength (`weisst`) in the `kp` exit channel. The channel emission energy is `eps(ne)`.

`xin, xnin, xpin`
: Floating point form of A, N and Z of the projectile. (The integer forms are `jin`, `jnin` and `jpin`.)

`xiso(np1,nppi1,ne)`
: Fraction of the primary preequilibrium nucleon emission going to the lowest allowed isospin value in the residual nucleus and later reset for the amount going to a higher isospin, if one is allowed. The indices have the same significance as in `w(kp,np1,nppi1,ne)`. Normal indices are used for neutron emission and dummy indices (as explained in the program listing) are used for proton emission to reduce memory requirements. This array is used in calculating secondary particle emission when isospin is conserved in the calculations.

`xisoeq(kp,ne)`
: Fraction of the primary isospin-conserved nucleon emission at equilibrium that goes to the lowest allowed isospin in the residual nucleus of the `kp`

channel when the emission energy is `eps(ne)`. It is used in calculating secondary evaporation.

`xncrit(kp,ia)`
: Values of $n_{\pi c}$ (for `ia`=1) or $n_{\nu c}$ (for `ia`=2) in the nucleus of the `kp` channel. It is used in the calculation of collective pairing energy corrections in the particle-hole state densities.

`xnout, xpout`
: Floating point form for N and Z of the current emitted particle type. (The integer forms are `jnout(kp)` and `jpout(kp)`.)

`xs(kp)`
: Mass excess (in MeV) of the emitted particle in the `kp` channel.

B. Sample Input

The sample input file uses most of the options available in PRECO-2006 and includes five reaction calculations. The individual lines of input are labeled according to the input items described in Sect. 7.1 on page 96. Those labels are *not* part of the input file. The first three lines contain global parameters that are used for all reaction calculations and show the default values for most of the parameters. Identical results are achieved by entering a value of 0 on all three lines.

The first problem (protons incident on a relatively light target) makes maximal use of default input parameters, while the second problem is the same reaction with everything read in. The output differs slightly because not all input is exactly equivalent. The third problem is for a heavier target, where isospin is conserved. The last two problems are for incident neutrons and α-particles, respectively.

```
    column number:
    1         11        21        31        41        51        61
    |---------|---------|---------|---------|---------|---------|---------|
A)  0    38.       0.        0.
B)  2200.     900.      900.      15.
C)  2.0       2.3       0.005
 1) 54Fe+p at 28.8 MeV -- default parameters
 2) 33.5      5.05      2.        0.
 3) 26.       28.       -1.
 5) 1    0    1
 6) 14.08     5.05      16.21     20.63     18.24     8.2
 7) 13.       4.35      13.38     8.85
 8) 0    1    1    1    1    1    1
 9) 2    1.41      0.195     2.
    3    6.34      0.15      2.
    2    17.20     0.201     2.53
    3    8.20      0.200     2.13
    4    3.83      0.11      -2.
```

```
10) 0.
11) 27   1.        1.
13) 0.
15) 1
16) 1
17) 1
 1) 54Fe+p at 28.8 MeV -- default options, but input explicitly
 2) 33.5      5.05      0.        0.
 3) 26.       28.       28.       28.       1.5       1.3
 4) 1    1    1    1
 5) 1    0    1
 6) 14.08     5.05      16.21     20.63     18.24     8.2
 7) 13.       4.35      13.38     8.85
 8) 0    1    1    1    1    1    1
 9) 2    1.41      0.195     2.
    3    6.34      0.15      2.
    2    17.20     0.201     2.53
    3    8.20      0.200     2.13
    4    3.83      0.11      -2.
10) 999.3
11) 27
12) 1.00      1503.     0.52      0.        0.        0.        0.
    2.00      1455.     7.67      0.        0.        0.        0.
    3.00      1433.     48.4      50.8      44.8      0.        0.
    4.00      1418.     157.      258.      320.      0.        0.
    5.00      1406.     300.      514.      625.      0.        0.
    6.00      1395.     447.      780.      915.      0.        32.9
    7.00      1385.     595.      972.      1123.     87.1      105.8
    8.00      1375.     701.      1115.     1277.     237.      209.
    9.00      1366.     780.      1224.     1394.     395.      343.
    10.00     1357.     840.      1310.     1487.     560.      506.
    11.00     1348.     887.      1378.     1561.     713.      660.
    12.00     1339.     923.      1435.     1621.     839.      787.
    13.00     1331.     952.      1481.     1671.     944.      892.
    14.00     1322.     974.      1520.     1713.     1033.     981.
    15.00     1313.     991.      1552.     1748.     1109.     1056.
    16.00     1305.     1004.     1580.     1777.     1174.     1120.
```

```
    17.00     1296.     1014.     1603.     1802.     1231.     1176.
    18.00     1288.     1020.     1623.     1823.     1280.     1224.
    19.00     1279.     1025.     1640.     1841.     1323.     1266.
    20.00     1271.     1028.     1655.     1857.     1360.     1302.
    21.00     1262.     1029.     1667.     1870.     1394.     1334.
    22.00     1254.     1028.     1678.     1881.     1423.     1362.
    23.00     1246.     1026.     1687.     1891.     1449.     1386.
    24.00     1237.     1023.     1695.     1899.     1472.     1408.
    25.00     1229.     1019.     1701.     1906.     1493.     1427.
    26.00     1221.     1014.     1706.     1911.     1511.     1443.
    27.00     1212.     1009.     1711.     1916.     1528.     1457.
13) 1.800     1.867
14) 1.800     1.733     1.733     1.733     1.667     1.667
    1.800     1.867     1.800     1.733     1.800     1.733
15) 1
16) 0    1.528     1.562     1.599     1.627
17) 1
 1) 120Sn+p at 45 MeV -- with angular distributions
 2) 50.40     5.78      2.        0.
 3) 50.       70.       -1.
 5) 1    0    1
 6) 9.25      5.78      12.66     12.89     17.07     3.09
 7) 7.00      5.64      9.10      10.67
 8) 1    1    1
 9) 0    0.        0.        2.0
    2    1.171     0.108     2.0
    3    2.401     0.156     2.0
    2    13.18     0.118     1.49
    3    6.28      0.102     2.13
    4    2.194     0.108     -2.0
10) 0.
11) 27   2.        2.
13) 0.
15) 1
16) 1
17) 1
 1) 238U+n at 14.1 MeV -- no secondary emission; fission
```

```
 2) 18.84     4.80      2.        0.
 3) 92.       146.      -1.
 5) 0    1    0
 6) 4.80      7.98      10.24     9.91      10.5      -4.0      6.2
 8) 0    1    1    0    0    0    1
 9) 0    0.        0.        0.50
    2    0.04      0.286     0.50
    3    0.73      0.086     0.50
    3    5.00      0.0878    5.00
    2    10.49     0.0754    -2.21
10) 0.
11) 44   0.5       0.5
13) 0.
15) -1
16) 1
17) 1
 1) 54Fe+alpha  at 59 MeV
 2) 61.15     6.41      2.        0.
 3) 26.       28.       -1.
 5) 2    2    1
 6) 12.20     8.18      17.33     21.17     17.69     6.41
 7) 10.27     7.35      11.38     6.03
 8) 0    0    1    1    1    0    1
 9) 2    1.41      0.195     1.5
    3    6.34      0.15      1.5
    4    3.83      0.11      1.5
    2    17.19     0.201     2.53
    3    8.2       0.200     2.13
    3    30.42     0.19      -3.47
10) 0.
11) 34   2.        2.
13) 0.
15) -1
16) 1
17) -1
```

C. Sample Output File

The sample output given below was generated from the input file given in Appendix B. Where page breaks have been omitted to save pages, their location is indicated by a horizontal dashed line. Font sizes have been adjusted to allow the full output to fit across the page. The output for each calculation is shown as a separate section of this appendix, though the output for a given input file forms a single output file. Sections C.1 through C.5 correspond to the five reactions in the sample input file. Sections C.6 through C.9 contain the additional output obtained for the reaction in Sect. C.1 when $I_{\mathrm{HF}} = 1$,-1, 2, and -2, respectively.

C.1. Problem 1

```
54Fe+p at 28.8 MeV -- default parameters
Reaction Strength Passing Thru Configurations
Target  Z= 26  N= 28     Projectile  z= 1  n= 0   Shells  Z= 28  N= 28
Excit Energy=  33.50     Rxn Cross Sect.= 999.3   Shell gaps=  1.50  1.30
gpi= 1.800  gnu= 1.867   Kpp=2200.  Knn= 900.     Knp= 900.
ipair= 1                 iepair= 1
V(central)= 38.00        Veff(1)= 17.00           Veff(2)= 17.00
Direct sigma=  79.58     Preeq sigma= 469.03      Frac Preeq=  .510

 p,ppi= 1        2        3        4        5        6        7      sum

 1  1.00000   .00000   .00000   .00000   .00000   .00000   .00000  1.00000
 2   .47811   .55301   .00000   .00000   .00000   .00000   .00000  1.03112
 3   .16306   .40401   .24287   .00000   .00000   .00000   .00000   .80994
 4   .06467   .27067   .30909   .10905   .00000   .00000   .00000   .75349
 5   .02695   .18105   .34526   .20153   .04193   .00000   .00000   .79672
 6   .01166   .12148   .37232   .34448   .09762   .01115   .00000   .95871
```

54Fe+p at 28.8 MeV -- default parameters
Particle Spectra (mb/MeV) z= 0 n= 1

eps cm	eps-- chan--	direct nutra	knock	-- exciton --primary	second	--equilibrium --primary	second	-- sum
.98	1.0	2.58E-2	0.00E+0	4.83E+0	3.48E-1	1.92E+1	6.04E+1	8.48E+1
1.96	2.0	4.76E-2	0.00E+0	6.95E+0	4.29E-1	2.25E+1	4.91E+1	7.90E+1
2.95	3.0	6.64E-2	0.00E+0	7.74E+0	4.06E-1	1.99E+1	3.05E+1	5.86E+1
3.93	4.0	8.23E-2	0.00E+0	7.84E+0	3.40E-1	1.55E+1	1.68E+1	4.05E+1
4.91	5.0	9.56E-2	0.00E+0	7.59E+0	2.61E-1	1.11E+1	8.50E+0	2.76E+1
5.89	6.0	1.07E-1	0.00E+0	7.19E+0	1.85E-1	7.57E+0	4.05E+0	1.91E+1
6.87	7.0	1.16E-1	0.00E+0	6.75E+0	1.19E-1	4.92E+0	1.81E+0	1.37E+1
7.85	8.0	1.21E-1	0.00E+0	6.26E+0	6.63E-2	3.07E+0	7.48E-1	1.03E+1
8.84	9.0	1.24E-1	0.00E+0	5.77E+0	3.14E-2	1.85E+0	2.77E-1	8.04E+0
9.82	10.0	1.24E-1	0.00E+0	5.29E+0	1.11E-2	1.07E+0	8.87E-2	6.58E+0
10.80	11.0	1.23E-1	0.00E+0	4.83E+0	2.31E-3	5.95E-1	2.20E-2	5.58E+0
11.78	12.0	1.20E-1	0.00E+0	4.38E+0	2.30E-4	3.18E-1	3.41E-3	4.82E+0
12.76	13.0	1.13E-1	0.00E+0	3.88E+0	7.52E-6	1.62E-1	2.69E-4	4.15E+0
13.75	14.0	1.04E-1	0.00E+0	3.40E+0	0.00E+0	7.85E-2	7.27E-6	3.58E+0
14.73	15.0	9.28E-2	0.00E+0	2.89E+0	0.00E+0	3.72E-2	0.00E+0	3.02E+0
15.71	16.0	7.88E-2	0.00E+0	2.31E+0	0.00E+0	1.76E-2	0.00E+0	2.41E+0
16.69	17.0	6.72E-2	0.00E+0	1.87E+0	0.00E+0	8.25E-3	0.00E+0	1.94E+0
17.67	18.0	3.08E-2	0.00E+0	6.47E-1	0.00E+0	3.87E-3	0.00E+0	6.81E-1
18.65	19.0	2.33E-2	0.00E+0	3.82E-1	0.00E+0	1.81E-3	0.00E+0	4.07E-1
sums		1.66E+0	0.00E+0	9.08E+1	2.20E+0	1.08E+2	1.72E+2	3.75E+2

54Fe+p at 28.8 MeV -- default parameters
Particle Spectra (mb/MeV) z= 1 n= 0

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second	sum --
.98	1.0	2.22E-5	6.46E-7	1.86E-2	2.11E-3	8.56E-2	2.52E+0	2.62E+0
1.96	2.0	6.25E-4	2.16E-5	4.05E-1	3.86E-2	1.64E+0	4.03E+1	4.24E+1
2.95	3.0	5.59E-3	3.01E-4	2.81E+0	2.11E-1	9.90E+0	8.62E+1	9.91E+1
3.93	4.0	2.28E-2	2.62E-3	8.95E+0	5.31E-1	2.71E+1	1.28E+2	1.64E+2
4.91	5.0	5.15E-2	1.44E-2	1.59E+1	7.72E-1	4.06E+1	1.20E+2	1.77E+2
5.89	6.0	8.67E-2	5.70E-2	2.13E+1	8.63E-1	4.49E+1	8.94E+1	1.57E+2
6.87	7.0	1.27E-1	1.75E-1	2.52E+1	9.73E-1	4.28E+1	5.80E+1	1.27E+2
7.85	8.0	1.61E-1	4.07E-1	2.63E+1	8.46E-1	3.49E+1	3.25E+1	9.51E+1
8.84	9.0	1.88E-1	7.57E-1	2.59E+1	6.76E-1	2.62E+1	1.67E+1	7.04E+1
9.82	10.0	2.11E-1	1.16E+0	2.48E+1	5.01E-1	1.85E+1	7.99E+0	5.32E+1
10.80	11.0	2.30E-1	1.47E+0	2.36E+1	3.41E-1	1.25E+1	3.57E+0	4.17E+1
11.78	12.0	2.43E-1	1.57E+0	2.22E+1	2.08E-1	8.11E+0	1.46E+0	3.38E+1
12.76	13.0	2.50E-1	1.41E+0	2.07E+1	1.06E-1	5.08E+0	5.24E-1	2.81E+1
13.75	14.0	2.54E-1	1.09E+0	1.93E+1	4.12E-2	3.08E+0	1.52E-1	2.40E+1
14.73	15.0	2.54E-1	7.77E-1	1.80E+1	1.45E-2	1.81E+0	2.80E-2	2.09E+1
15.71	16.0	2.51E-1	6.42E-1	1.68E+1	3.00E-3	1.02E+0	4.34E-3	1.87E+1
16.69	17.0	2.42E-1	8.26E-1	1.55E+1	2.98E-4	5.59E-1	3.41E-4	1.71E+1
17.67	18.0	2.29E-1	1.38E+0	1.41E+1	9.73E-6	2.93E-1	9.18E-6	1.60E+1
18.65	19.0	2.13E-1	2.19E+0	1.27E+1	0.00E+0	1.47E-1	0.00E+0	1.53E+1
19.64	20.0	1.95E-1	2.97E+0	1.14E+1	0.00E+0	7.02E-2	0.00E+0	1.46E+1
20.62	21.0	1.74E-1	3.43E+0	9.98E+0	0.00E+0	3.31E-2	0.00E+0	1.36E+1
21.60	22.0	1.48E-1	3.44E+0	8.40E+0	0.00E+0	1.55E-2	0.00E+0	1.20E+1
22.58	23.0	1.18E-1	3.22E+0	6.76E+0	0.00E+0	7.26E-3	0.00E+0	1.01E+1
23.56	24.0	8.54E-2	3.15E+0	4.96E+0	0.00E+0	3.38E-3	0.00E+0	8.20E+0
24.55	25.0	4.29E-2	3.47E+0	2.57E+0	0.00E+0	1.57E-3	0.00E+0	6.09E+0
25.53	26.0	1.59E-2	3.98E+0	1.22E+0	0.00E+0	7.30E-4	0.00E+0	5.22E+0
26.51	27.0	0.00E+0	4.13E+0	0.00E+0	0.00E+0	3.38E-4	0.00E+0	4.13E+0
sums		3.80E+0	4.17E+1	3.60E+2	6.13E+0	2.79E+2	5.87E+2	1.28E+3

```
54Fe+p at 28.8 MeV -- default parameters
 Particle Spectra (mb/MeV)  z= 1  n= 1

  eps   eps--     direct     --exciton-- equil --  sum
   cm  chan-- nutra    knock --       --       --

  2.89  3.0  1.31E-2  0.00E+0  1.18E-1  2.74E-1  4.04E-1
  3.85  4.0  9.01E-2  0.00E+0  5.53E-1  1.03E+0  1.68E+0
  4.82  5.0  2.28E-1  0.00E+0  9.71E-1  1.40E+0  2.60E+0
  5.78  6.0  4.19E-1  0.00E+0  1.27E+0  1.36E+0  3.05E+0
  6.75  7.0  6.16E-1  0.00E+0  1.36E+0  1.03E+0  3.00E+0
  7.71  8.0  8.13E-1  0.00E+0  1.35E+0  6.76E-1  2.84E+0
  8.67  9.0  1.01E+0  0.00E+0  1.29E+0  4.05E-1  2.70E+0
  9.64 10.0  1.21E+0  0.00E+0  1.22E+0  2.24E-1  2.65E+0
 10.60 11.0  1.40E+0  0.00E+0  1.16E+0  1.17E-1  2.68E+0
 11.56 12.0  1.60E+0  0.00E+0  1.11E+0  5.95E-2  2.76E+0
 12.53 13.0  1.80E+0  0.00E+0  1.09E+0  2.99E-2  2.92E+0
 13.49 14.0  2.00E+0  0.00E+0  1.06E+0  1.48E-2  3.08E+0
 14.45 15.0  2.20E+0  0.00E+0  1.09E+0  7.28E-3  3.29E+0
 15.42 16.0  2.40E+0  0.00E+0  1.14E+0  3.55E-3  3.55E+0
 16.38 17.0  0.00E+0  0.00E+0  0.00E+0  1.72E-3  1.72E-3

 sums        1.58E+1  0.00E+0  1.48E+1  6.64E+0  3.72E+1

-------------------------------------------------------------------------------

54Fe+p at 28.8 MeV -- default parameters
 Particle Spectra (mb/MeV)  z= 1  n= 2

  eps   eps--     direct     --exciton-- equil --  sum
   cm  chan-- nutra    knock --       --       --

  2.84  3.0  4.33E-3  0.00E+0  1.53E-3  4.75E-3  1.06E-2
  3.78  4.0  3.69E-2  0.00E+0  8.93E-3  2.12E-2  6.70E-2
  4.73  5.0  8.02E-2  0.00E+0  1.35E-2  2.34E-2  1.17E-1
  5.67  6.0  1.24E-1  0.00E+0  1.48E-2  1.87E-2  1.57E-1
  6.62  7.0  1.50E-1  0.00E+0  1.34E-2  1.21E-2  1.75E-1
  7.56  8.0  1.59E-1  0.00E+0  1.11E-2  7.11E-3  1.78E-1
  8.51  9.0  1.54E-1  0.00E+0  5.90E-3  3.95E-3  1.64E-1
  9.45 10.0  1.34E-1  0.00E+0  5.79E-3  2.12E-3  1.41E-1
 10.40 11.0  0.00E+0  0.00E+0  0.00E+0  1.11E-3  1.11E-3
 11.35 12.0  0.00E+0  0.00E+0  0.00E+0  5.68E-4  5.68E-4

 sums        8.43E-1  0.00E+0  7.50E-2  9.49E-2  1.01E+0
```

54Fe+p at 28.8 MeV -- default parameters
Particle Spectra (mb/MeV) z= 2 n= 1

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	--	equil --	--	sum
6.62	7.0	2.96E-2	0.00E+0	2.57E-2	6.16E-2	1.17E-1
7.56	8.0	8.23E-2	0.00E+0	4.97E-2	9.57E-2	2.28E-1
8.51	9.0	1.33E-1	0.00E+0	5.80E-2	8.60E-2	2.77E-1
9.45	10.0	1.78E-1	0.00E+0	5.78E-2	6.22E-2	2.98E-1
10.40	11.0	2.07E-1	0.00E+0	5.19E-2	3.95E-2	2.98E-1
11.35	12.0	2.11E-1	0.00E+0	4.15E-2	2.30E-2	2.75E-1
12.29	13.0	2.08E-1	0.00E+0	3.32E-2	1.27E-2	2.54E-1
13.24	14.0	1.62E-1	0.00E+0	2.27E-2	6.79E-3	1.91E-1
14.18	15.0	0.00E+0	0.00E+0	0.00E+0	3.54E-3	3.54E-3
sums		1.21E+0	0.00E+0	3.40E-1	3.91E-1	1.94E+0

54Fe+p at 28.8 MeV -- default parameters
Particle Spectra (mb/MeV) z= 2 n= 2

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	--	equil --	--	sum
5.56	6.0	5.33E-2	2.04E-3	7.23E-2	2.70E+0	2.82E+0
6.49	7.0	1.82E-1	7.21E-3	1.96E-1	6.16E+0	6.54E+0
7.42	8.0	3.72E-1	1.53E-2	3.16E-1	8.35E+0	9.05E+0
8.35	9.0	6.13E-1	2.63E-2	4.09E-1	9.11E+0	1.02E+1
9.27	10.0	8.94E-1	4.00E-2	4.61E-1	8.72E+0	1.01E+1
10.20	11.0	1.13E+0	5.30E-2	4.46E-1	7.17E+0	8.80E+0
11.13	12.0	1.29E+0	6.32E-2	3.82E-1	5.24E+0	6.98E+0
12.05	13.0	1.37E+0	7.06E-2	3.02E-1	3.55E+0	5.29E+0
12.98	14.0	1.37E+0	7.52E-2	2.23E-1	2.27E+0	3.93E+0
13.91	15.0	1.31E+0	7.71E-2	1.56E-1	1.37E+0	2.92E+0
14.84	16.0	1.22E+0	7.64E-2	1.04E-1	7.91E-1	2.19E+0
15.76	17.0	1.08E+0	7.30E-2	6.52E-2	4.34E-1	1.65E+0
16.69	18.0	9.16E-1	6.70E-2	3.95E-2	2.26E-1	1.25E+0
17.62	19.0	7.33E-1	5.85E-2	2.27E-2	1.13E-1	9.27E-1
18.55	20.0	5.50E-1	4.75E-2	1.18E-2	5.59E-2	6.66E-1
19.47	21.0	3.93E-1	0.00E+0	5.84E-3	2.75E-2	4.27E-1
20.40	22.0	2.28E-1	0.00E+0	2.69E-3	1.34E-2	2.44E-1
21.33	23.0	6.30E-2	0.00E+0	7.92E-4	6.54E-3	7.03E-2
22.25	24.0	3.72E-2	0.00E+0	5.86E-4	3.17E-3	4.09E-2
23.18	25.0	0.00E+0	0.00E+0	0.00E+0	1.53E-3	1.53E-3
sums		1.38E+1	7.52E-1	3.22E+0	5.63E+1	7.41E+1

C.2. Problem 2

```
 54Fe+p at 28.8 MeV -- default options, but input explicitly
 Reaction Strength Passing Thru Configurations
 Target  Z= 26  N= 28     Projectile  z= 1  n= 0   Shells  Z= 28  N= 28
 Excit Energy=  33.50     Rxn Cross Sect.= 999.3   Shell gaps=  1.50  1.30
 gpi= 1.800  gnu= 1.867   Kpp=2200.  Knn= 900.     Knp= 900.
 ipair= 1                 iepair= 0
 V(central)= 38.00        Veff(1)= 17.00           Veff(2)= 17.00
 Direct sigma=  79.59     Preeq sigma= 468.79      Frac Preeq=  .510

  p,ppi= 1        2        3        4        5        6        7      sum

  1  1.00000   .00000   .00000   .00000   .00000   .00000   .00000  1.00000
  2   .47821   .55291   .00000   .00000   .00000   .00000   .00000  1.03112
  3   .16315   .40408   .24282   .00000   .00000   .00000   .00000   .81004
  4   .06473   .27079   .30913   .10903   .00000   .00000   .00000   .75367
  5   .02698   .18118   .34538   .20154   .04192   .00000   .00000   .79701
  6   .01167   .12160   .37253   .34456   .09761   .01114   .00000   .95911

-------------------------------------------------------------------------------

54Fe+p at 28.8 MeV -- default options, but input explicitly
 Particle Spectra (mb/MeV)  z= 0  n= 1

  eps   eps--     direct     --    exciton     --  equilibrium   --  sum
   cm  chan-- nutra    knock --primary  second --primary  second --

   .98  1.0  2.58E-2  0.00E+0  4.82E+0  3.48E-1  1.92E+1  6.61E+1  9.05E+1
  1.96  2.0  4.76E-2  0.00E+0  6.95E+0  4.31E-1  2.25E+1  5.36E+1  8.35E+1
  2.95  3.0  6.64E-2  0.00E+0  7.74E+0  4.08E-1  1.99E+1  3.33E+1  6.14E+1
  3.93  4.0  8.22E-2  0.00E+0  7.83E+0  3.42E-1  1.55E+1  1.83E+1  4.20E+1
  4.91  5.0  9.56E-2  0.00E+0  7.58E+0  2.63E-1  1.11E+1  9.26E+0  2.83E+1
  5.89  6.0  1.07E-1  0.00E+0  7.19E+0  1.86E-1  7.57E+0  4.41E+0  1.95E+1
  6.87  7.0  1.16E-1  0.00E+0  6.74E+0  1.19E-1  4.92E+0  1.97E+0  1.39E+1
  7.85  8.0  1.21E-1  0.00E+0  6.25E+0  6.68E-2  3.07E+0  8.13E-1  1.03E+1
  8.84  9.0  1.24E-1  0.00E+0  5.76E+0  3.16E-2  1.85E+0  3.01E-1  8.06E+0
  9.82 10.0  1.24E-1  0.00E+0  5.29E+0  1.12E-2  1.07E+0  9.59E-2  6.59E+0
 10.80 11.0  1.23E-1  0.00E+0  4.83E+0  2.32E-3  5.95E-1  2.37E-2  5.58E+0
 11.78 12.0  1.20E-1  0.00E+0  4.38E+0  2.31E-4  3.18E-1  3.67E-3  4.82E+0
 12.76 13.0  1.13E-1  0.00E+0  3.88E+0  7.63E-6  1.62E-1  2.89E-4  4.15E+0
 13.75 14.0  1.04E-1  0.00E+0  3.40E+0  0.00E+0  7.86E-2  7.84E-6  3.58E+0
 14.73 15.0  9.28E-2  0.00E+0  2.89E+0  0.00E+0  3.72E-2  0.00E+0  3.02E+0
 15.71 16.0  7.89E-2  0.00E+0  2.31E+0  0.00E+0  1.76E-2  0.00E+0  2.41E+0
 16.69 17.0  6.72E-2  0.00E+0  1.87E+0  0.00E+0  8.26E-3  0.00E+0  1.94E+0
 17.67 18.0  3.08E-2  0.00E+0  6.47E-1  0.00E+0  3.87E-3  0.00E+0  6.81E-1
 18.65 19.0  2.33E-2  0.00E+0  3.82E-1  0.00E+0  1.81E-3  0.00E+0  4.07E-1

 sums        1.66E+0  0.00E+0  9.07E+1  2.21E+0  1.08E+2  1.88E+2  3.91E+2
```

54Fe+p at 28.8 MeV -- default options, but input explicitly
Particle Spectra (mb/MeV) z= 1 n= 0

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second	sum --
.98	1.0	2.23E-5	7.06E-7	1.87E-2	1.89E-3	8.63E-2	2.74E+0	2.85E+0
1.96	2.0	6.24E-4	2.16E-5	4.04E-1	3.40E-2	1.64E+0	3.74E+1	3.95E+1
2.95	3.0	5.59E-3	3.01E-4	2.81E+0	1.96E-1	9.90E+0	7.87E+1	9.16E+1
3.93	4.0	2.28E-2	2.62E-3	8.94E+0	5.29E-1	2.71E+1	1.22E+2	1.59E+2
4.91	5.0	5.14E-2	1.44E-2	1.59E+1	8.07E-1	4.06E+1	1.18E+2	1.75E+2
5.89	6.0	8.68E-2	5.70E-2	2.13E+1	9.36E-1	4.50E+1	8.93E+1	1.57E+2
6.87	7.0	1.27E-1	1.75E-1	2.52E+1	9.49E-1	4.29E+1	5.87E+1	1.28E+2
7.85	8.0	1.61E-1	4.07E-1	2.62E+1	8.32E-1	3.50E+1	3.32E+1	9.58E+1
8.84	9.0	1.88E-1	7.57E-1	2.59E+1	6.67E-1	2.62E+1	1.71E+1	7.08E+1
9.82	10.0	2.11E-1	1.16E+0	2.48E+1	4.97E-1	1.85E+1	8.23E+0	5.34E+1
10.80	11.0	2.30E-1	1.47E+0	2.36E+1	3.39E-1	1.25E+1	3.69E+0	4.18E+1
11.78	12.0	2.43E-1	1.57E+0	2.22E+1	2.07E-1	8.11E+0	1.51E+0	3.38E+1
12.76	13.0	2.51E-1	1.41E+0	2.07E+1	1.05E-1	5.09E+0	5.43E-1	2.81E+1
13.75	14.0	2.54E-1	1.09E+0	1.93E+1	4.08E-2	3.08E+0	1.58E-1	2.40E+1
14.73	15.0	2.54E-1	7.77E-1	1.80E+1	1.44E-2	1.81E+0	2.98E-2	2.09E+1
15.71	16.0	2.51E-1	6.42E-1	1.68E+1	2.99E-3	1.02E+0	4.61E-3	1.87E+1
16.69	17.0	2.43E-1	8.27E-1	1.55E+1	2.98E-4	5.59E-1	3.61E-4	1.71E+1
17.67	18.0	2.29E-1	1.38E+0	1.41E+1	9.78E-6	2.93E-1	9.78E-6	1.60E+1
18.65	19.0	2.13E-1	2.19E+0	1.27E+1	0.00E+0	1.47E-1	0.00E+0	1.53E+1
19.64	20.0	1.95E-1	2.97E+0	1.14E+1	0.00E+0	7.03E-2	0.00E+0	1.46E+1
20.62	21.0	1.74E-1	3.43E+0	9.98E+0	0.00E+0	3.31E-2	0.00E+0	1.36E+1
21.60	22.0	1.48E-1	3.44E+0	8.40E+0	0.00E+0	1.55E-2	0.00E+0	1.20E+1
22.58	23.0	1.18E-1	3.22E+0	6.75E+0	0.00E+0	7.26E-3	0.00E+0	1.01E+1
23.56	24.0	8.54E-2	3.15E+0	4.96E+0	0.00E+0	3.39E-3	0.00E+0	8.20E+0
24.55	25.0	4.29E-2	3.47E+0	2.57E+0	0.00E+0	1.57E-3	0.00E+0	6.09E+0
25.53	26.0	1.59E-2	3.98E+0	1.22E+0	0.00E+0	7.30E-4	0.00E+0	5.22E+0
26.51	27.0	0.00E+0	4.13E+0	0.00E+0	0.00E+0	3.38E-4	0.00E+0	4.13E+0
sums		3.80E+0	4.17E+1	3.60E+2	6.16E+0	2.80E+2	5.71E+2	1.26E+3

```
54Fe+p at 28.8 MeV -- default options, but input explicitly
 Particle Spectra (mb/MeV)  z= 1  n= 1

  eps   eps--     direct     --exciton-- equil --  sum
   cm  chan-- nutra    knock --       --       --

  2.89  3.0  1.31E-2  0.00E+0  1.17E-1  2.73E-1  4.04E-1
  3.85  4.0  9.01E-2  0.00E+0  5.52E-1  1.03E+0  1.67E+0
  4.82  5.0  2.27E-1  0.00E+0  9.69E-1  1.40E+0  2.60E+0
  5.78  6.0  4.19E-1  0.00E+0  1.27E+0  1.36E+0  3.05E+0
  6.75  7.0  6.15E-1  0.00E+0  1.36E+0  1.03E+0  3.00E+0
  7.71  8.0  8.13E-1  0.00E+0  1.35E+0  6.76E-1  2.83E+0
  8.67  9.0  1.01E+0  0.00E+0  1.29E+0  4.05E-1  2.70E+0
  9.64 10.0  1.21E+0  0.00E+0  1.22E+0  2.24E-1  2.65E+0
 10.60 11.0  1.40E+0  0.00E+0  1.16E+0  1.17E-1  2.68E+0
 11.56 12.0  1.60E+0  0.00E+0  1.11E+0  5.95E-2  2.77E+0
 12.53 13.0  1.80E+0  0.00E+0  1.09E+0  2.99E-2  2.92E+0
 13.49 14.0  2.00E+0  0.00E+0  1.06E+0  1.48E-2  3.08E+0
 14.45 15.0  2.20E+0  0.00E+0  1.09E+0  7.28E-3  3.29E+0
 15.42 16.0  2.41E+0  0.00E+0  1.14E+0  3.55E-3  3.55E+0
 16.38 17.0  0.00E+0  0.00E+0  0.00E+0  1.72E-3  1.72E-3

 sums        1.58E+1  0.00E+0  1.48E+1  6.63E+0  3.72E+1

-------------------------------------------------------------------------------

54Fe+p at 28.8 MeV -- default options, but input explicitly
 Particle Spectra (mb/MeV)  z= 1  n= 2

  eps   eps--     direct     --exciton-- equil --  sum
   cm  chan-- nutra    knock --       --       --

  2.84  3.0  4.32E-3  0.00E+0  1.53E-3  4.75E-3  1.06E-2
  3.78  4.0  3.69E-2  0.00E+0  8.93E-3  2.12E-2  6.70E-2
  4.73  5.0  8.03E-2  0.00E+0  1.35E-2  2.34E-2  1.17E-1
  5.67  6.0  1.24E-1  0.00E+0  1.48E-2  1.86E-2  1.57E-1
  6.62  7.0  1.50E-1  0.00E+0  1.34E-2  1.21E-2  1.75E-1
  7.56  8.0  1.59E-1  0.00E+0  1.11E-2  7.11E-3  1.78E-1
  8.51  9.0  1.54E-1  0.00E+0  5.89E-3  3.95E-3  1.64E-1
  9.45 10.0  1.33E-1  0.00E+0  5.79E-3  2.12E-3  1.41E-1
 10.40 11.0  0.00E+0  0.00E+0  0.00E+0  1.11E-3  1.11E-3
 11.35 12.0  0.00E+0  0.00E+0  0.00E+0  5.68E-4  5.68E-4

 sums        8.42E-1  0.00E+0  7.49E-2  9.50E-2  1.01E+0
```

54Fe+p at 28.8 MeV -- default options, but input explicitly
Particle Spectra (mb/MeV) z= 2 n= 1

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	equil --	sum
6.62	7.0	2.96E-2	0.00E+0	2.57E-2	6.17E-2	1.17E-1
7.56	8.0	8.21E-2	0.00E+0	4.96E-2	9.56E-2	2.27E-1
8.51	9.0	1.33E-1	0.00E+0	5.80E-2	8.61E-2	2.77E-1
9.45	10.0	1.78E-1	0.00E+0	5.78E-2	6.23E-2	2.98E-1
10.40	11.0	2.07E-1	0.00E+0	5.18E-2	3.96E-2	2.98E-1
11.35	12.0	2.11E-1	0.00E+0	4.15E-2	2.30E-2	2.75E-1
12.29	13.0	2.08E-1	0.00E+0	3.31E-2	1.27E-2	2.54E-1
13.24	14.0	1.62E-1	0.00E+0	2.27E-2	6.80E-3	1.91E-1
14.18	15.0	0.00E+0	0.00E+0	0.00E+0	3.54E-3	3.54E-3
sums		1.21E+0	0.00E+0	3.40E-1	3.91E-1	1.94E+0

54Fe+p at 28.8 MeV -- default options, but input explicitly
Particle Spectra (mb/MeV) z= 2 n= 2

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	equil --	sum
5.56	6.0	5.33E-2	2.04E-3	7.23E-2	2.70E+0	2.83E+0
6.49	7.0	1.82E-1	7.21E-3	1.96E-1	6.16E+0	6.55E+0
7.42	8.0	3.72E-1	1.53E-2	3.16E-1	8.35E+0	9.05E+0
8.35	9.0	6.14E-1	2.63E-2	4.09E-1	9.12E+0	1.02E+1
9.27	10.0	8.93E-1	4.00E-2	4.61E-1	8.72E+0	1.01E+1
10.20	11.0	1.13E+0	5.30E-2	4.46E-1	7.17E+0	8.80E+0
11.13	12.0	1.29E+0	6.32E-2	3.82E-1	5.25E+0	6.98E+0
12.05	13.0	1.37E+0	7.06E-2	3.02E-1	3.55E+0	5.29E+0
12.98	14.0	1.37E+0	7.52E-2	2.23E-1	2.27E+0	3.94E+0
13.91	15.0	1.31E+0	7.71E-2	1.56E-1	1.37E+0	2.92E+0
14.84	16.0	1.21E+0	7.63E-2	1.04E-1	7.92E-1	2.19E+0
15.76	17.0	1.08E+0	7.30E-2	6.52E-2	4.35E-1	1.65E+0
16.69	18.0	9.16E-1	6.70E-2	3.95E-2	2.26E-1	1.25E+0
17.62	19.0	7.33E-1	5.86E-2	2.27E-2	1.13E-1	9.27E-1
18.55	20.0	5.50E-1	4.75E-2	1.18E-2	5.60E-2	6.66E-1
19.47	21.0	3.93E-1	0.00E+0	5.84E-3	2.75E-2	4.27E-1
20.40	22.0	2.28E-1	0.00E+0	2.69E-3	1.35E-2	2.44E-1

C.3. Problem 3

```
120Sn+p at 45 MeV -- with angular distributions
Reaction Strength Passing Thru Configurations
Target  Z= 50  N= 70     Projectile  z= 1  n= 0   Shells  Z= 50  N=  0
Excit Energy=  50.40     Rxn Cross Sect.=1582.1   Shell gaps=  2.00   .00
gpi= 3.400  gnu= 4.667   Kpp=2200.  Knn= 900.     Knp= 900.
ipair= 1                 iepair= 1
V(central)= 38.00        Veff(1)= 17.00           Veff(2)= 17.00
T=Tz+0 fteq= .15         Esym(cn)=  .00           Ct2= .952
Direct sigma= 123.94     Preeq sigma=1020.15      Frac Preeq=  .738
```

p,ppi=	1	2	3	4	5	6	7	sum
1	1.00000	.00000	.00000	.00000	.00000	.00000	.00000	1.00000
2	.62309	.38463	.00000	.00000	.00000	.00000	.00000	1.00772
3	.24140	.36674	.10498	.00000	.00000	.00000	.00000	.71311
4	.10422	.26267	.17819	.03215	.00000	.00000	.00000	.57722
5	.04640	.16889	.19139	.07726	.01022	.00000	.00000	.49416
6	.02104	.10399	.17272	.11274	.03183	.00295	.00000	.44527
7	.00951	.06229	.14313	.13404	.05942	.01109	.00071	.42021
8	.00422	.03599	.11178	.14415	.08951	.02521	.00307	.41406
9	.00178	.02008	.08231	.14296	.12070	.04709	.00823	.42379
10	.00071	.01081	.05804	.13287	.14894	.07910	.01889	.45137
11	.00027	.00595	.03956	.11792	.17181	.12099	.03952	.50179

120Sn+p at 45 MeV -- with angular distributions
Particle Spectra (mb/MeV) z= 0 n= 1
T(cn)=Tz+0 Esym(b)= .000 13.147 Ct2(b)=1.000 .048

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second	sum --
1.98	2.0	4.07E-2	0.00E+0	3.12E+1	7.86E+0	7.39E+1	3.71E+2	4.84E+2
3.97	4.0	7.72E-2	0.00E+0	3.49E+1	7.45E+0	5.32E+1	1.48E+2	2.44E+2
5.95	6.0	1.06E-1	0.00E+0	3.03E+1	5.50E+0	2.70E+1	4.93E+1	1.12E+2
7.93	8.0	1.28E-1	0.00E+0	2.49E+1	3.80E+0	1.17E+1	1.48E+1	5.54E+1
9.92	10.0	1.45E-1	0.00E+0	2.04E+1	2.57E+0	4.62E+0	4.04E+0	3.18E+1
11.90	12.0	1.56E-1	0.00E+0	1.68E+1	1.72E+0	1.68E+0	1.01E+0	2.14E+1
13.88	14.0	1.64E-1	0.00E+0	1.41E+1	1.15E+0	5.68E-1	2.31E-1	1.62E+1
15.87	16.0	1.67E-1	0.00E+0	1.20E+1	7.52E-1	1.81E-1	4.77E-2	1.32E+1
17.85	18.0	1.67E-1	0.00E+0	1.04E+1	4.79E-1	5.37E-2	8.75E-3	1.11E+1
19.83	20.0	1.65E-1	0.00E+0	9.18E+0	2.89E-1	1.49E-2	1.40E-3	9.65E+0
21.82	22.0	1.60E-1	0.00E+0	8.15E+0	1.58E-1	3.84E-3	1.88E-4	8.47E+0
23.80	24.0	1.54E-1	0.00E+0	7.33E+0	7.16E-2	9.11E-4	2.02E-5	7.56E+0
25.79	26.0	1.44E-1	0.00E+0	6.53E+0	2.19E-2	1.97E-4	1.61E-6	6.70E+0
27.77	28.0	1.33E-1	0.00E+0	5.82E+0	2.61E-3	3.80E-5	9.79E-8	5.96E+0
29.75	30.0	1.19E-1	0.00E+0	5.09E+0	8.28E-5	6.40E-6	5.77E-9	5.21E+0
31.74	32.0	1.03E-1	0.00E+0	4.33E+0	1.02E-6	9.10E-7	0.00E+0	4.44E+0
33.72	34.0	8.64E-2	0.00E+0	3.57E+0	0.00E+0	1.03E-7	0.00E+0	3.66E+0
35.70	36.0	6.68E-2	0.00E+0	2.71E+0	0.00E+0	8.35E-9	0.00E+0	2.78E+0
37.69	38.0	4.58E-2	0.00E+0	1.80E+0	0.00E+0	0.00E+0	0.00E+0	1.85E+0
39.67	40.0	2.16E-2	0.00E+0	7.67E-1	0.00E+0	0.00E+0	0.00E+0	7.89E-1
sums		4.70E+0	0.00E+0	5.01E+2	6.36E+1	3.46E+2	1.18E+3	2.09E+3

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 0 n= 1
sys. excit. en.= 52.37; sys. bind. en.= 7.90

eps:deg	0	10	20	30	40	50	60	70	80	90
2.00	4.18E+1	4.17E+1	4.13E+1	4.08E+1	4.02E+1	3.95E+1	3.89E+1	3.83E+1	3.78E+1	3.75E+1
4.00	2.25E+1	2.24E+1	2.21E+1	2.17E+1	2.12E+1	2.06E+1	2.00E+1	1.95E+1	1.90E+1	1.87E+1
6.00	1.15E+1	1.14E+1	1.12E+1	1.09E+1	1.05E+1	1.00E+1	9.59E+0	9.16E+0	8.78E+0	8.47E+0
8.00	6.51E+0	6.46E+0	6.30E+0	6.06E+0	5.75E+0	5.40E+0	5.04E+0	4.70E+0	4.38E+0	4.11E+0
10.00	4.33E+0	4.29E+0	4.16E+0	3.95E+0	3.70E+0	3.41E+0	3.11E+0	2.82E+0	2.55E+0	2.31E+0
12.00	3.31E+0	3.27E+0	3.16E+0	2.98E+0	2.75E+0	2.49E+0	2.22E+0	1.97E+0	1.73E+0	1.52E+0
14.00	2.78E+0	2.74E+0	2.63E+0	2.46E+0	2.24E+0	2.00E+0	1.76E+0	1.53E+0	1.31E+0	1.13E+0
16.00	2.45E+0	2.41E+0	2.30E+0	2.13E+0	1.93E+0	1.70E+0	1.47E+0	1.25E+0	1.06E+0	8.87E-1
18.00	2.22E+0	2.19E+0	2.08E+0	1.91E+0	1.71E+0	1.49E+0	1.27E+0	1.06E+0	8.79E-1	7.24E-1
20.00	2.07E+0	2.03E+0	1.92E+0	1.75E+0	1.55E+0	1.33E+0	1.12E+0	9.20E-1	7.47E-1	6.04E-1
22.00	1.94E+0	1.91E+0	1.79E+0	1.62E+0	1.42E+0	1.20E+0	9.93E-1	8.03E-1	6.40E-1	5.07E-1
24.00	1.86E+0	1.82E+0	1.71E+0	1.53E+0	1.32E+0	1.10E+0	8.95E-1	7.10E-1	5.55E-1	4.30E-1
26.00	1.77E+0	1.73E+0	1.61E+0	1.43E+0	1.22E+0	1.00E+0	7.99E-1	6.21E-1	4.75E-1	3.60E-1
28.00	1.69E+0	1.65E+0	1.53E+0	1.34E+0	1.13E+0	9.13E-1	7.13E-1	5.43E-1	4.06E-1	3.00E-1
30.00	1.59E+0	1.55E+0	1.42E+0	1.24E+0	1.03E+0	8.16E-1	6.24E-1	4.64E-1	3.38E-1	2.44E-1
32.00	1.46E+0	1.42E+0	1.29E+0	1.11E+0	9.08E-1	7.07E-1	5.29E-1	3.84E-1	2.72E-1	1.91E-1
34.00	1.30E+0	1.25E+0	1.13E+0	9.65E-1	7.74E-1	5.91E-1	4.31E-1	3.05E-1	2.10E-1	1.44E-1
36.00	1.06E+0	1.02E+0	9.19E-1	7.71E-1	6.08E-1	4.53E-1	3.23E-1	2.22E-1	1.48E-1	9.82E-2
38.00	7.61E-1	7.31E-1	6.51E-1	5.39E-1	4.17E-1	3.03E-1	2.10E-1	1.40E-1	9.08E-2	5.81E-2
40.00	3.51E-1	3.36E-1	2.96E-1	2.41E-1	1.83E-1	1.30E-1	8.73E-2	5.62E-2	3.52E-2	2.17E-2

eps:deg	100	110	120	130	140	150	160	170	180	total
2.00	3.74E+1	3.74E+1	3.77E+1	3.80E+1	3.83E+1	3.87E+1	3.90E+1	3.92E+1	3.93E+1	4.84E+2
4.00	1.85E+1	1.84E+1	1.84E+1	1.86E+1	1.87E+1	1.89E+1	1.91E+1	1.92E+1	1.93E+1	2.44E+2
6.00	8.25E+0	8.11E+0	8.04E+0	8.03E+0	8.07E+0	8.13E+0	8.19E+0	8.23E+0	8.25E+0	1.12E+2
8.00	3.89E+0	3.73E+0	3.62E+0	3.55E+0	3.52E+0	3.51E+0	3.51E+0	3.52E+0	3.52E+0	5.54E+1
10.00	2.11E+0	1.96E+0	1.84E+0	1.75E+0	1.69E+0	1.65E+0	1.63E+0	1.62E+0	1.61E+0	3.18E+1
12.00	1.35E+0	1.20E+0	1.09E+0	1.00E+0	9.36E-1	8.92E-1	8.63E-1	8.47E-1	8.42E-1	2.14E+1
14.00	9.67E-1	8.38E-1	7.35E-1	6.56E-1	5.97E-1	5.55E-1	5.26E-1	5.10E-1	5.05E-1	1.62E+1
16.00	7.45E-1	6.31E-1	5.40E-1	4.71E-1	4.19E-1	3.81E-1	3.57E-1	3.42E-1	3.38E-1	1.32E+1
18.00	5.97E-1	4.95E-1	4.15E-1	3.55E-1	3.10E-1	2.78E-1	2.57E-1	2.45E-1	2.41E-1	1.11E+1
20.00	4.88E-1	3.97E-1	3.27E-1	2.74E-1	2.36E-1	2.09E-1	1.91E-1	1.81E-1	1.78E-1	9.65E+0
22.00	4.01E-1	3.20E-1	2.59E-1	2.14E-1	1.81E-1	1.58E-1	1.43E-1	1.35E-1	1.32E-1	8.47E+0
24.00	3.34E-1	2.61E-1	2.07E-1	1.68E-1	1.40E-1	1.21E-1	1.09E-1	1.02E-1	9.94E-2	7.56E+0
26.00	2.73E-1	2.09E-1	1.62E-1	1.29E-1	1.06E-1	9.06E-2	8.05E-2	7.50E-2	7.32E-2	6.70E+0
28.00	2.22E-1	1.66E-1	1.27E-1	9.88E-2	7.98E-2	6.72E-2	5.91E-2	5.47E-2	5.33E-2	5.96E+0
30.00	1.76E-1	1.29E-1	9.56E-2	7.32E-2	5.81E-2	4.81E-2	4.19E-2	3.85E-2	3.74E-2	5.21E+0
32.00	1.35E-1	9.56E-2	6.93E-2	5.19E-2	4.04E-2	3.30E-2	2.84E-2	2.59E-2	2.51E-2	4.44E+0
34.00	9.81E-2	6.77E-2	4.78E-2	3.50E-2	2.67E-2	2.14E-2	1.82E-2	1.65E-2	1.59E-2	3.66E+0
36.00	6.50E-2	4.35E-2	2.99E-2	2.13E-2	1.59E-2	1.25E-2	1.05E-2	9.43E-3	9.10E-3	2.78E+0
38.00	3.72E-2	2.41E-2	1.60E-2	1.11E-2	8.09E-3	6.26E-3	5.18E-3	4.61E-3	4.43E-3	1.85E+0
40.00	1.34E-2	8.39E-3	5.41E-3	3.64E-3	2.58E-3	1.95E-3	1.59E-3	1.40E-3	1.35E-3	7.89E-1

120Sn+p at 45 MeV -- with angular distributions
Particle Spectra (mb/MeV) z= 1 n= 0
T(cn)=Tz+0 Esym(b)= .000 14.530 Ct2(b)= .952 .000

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second	sum --
1.98	2.0	2.10E-6	4.59E-8	2.53E-3	7.41E-4	9.91E-4	1.15E-2	1.58E-2
3.97	4.0	6.48E-5	1.48E-6	4.72E-2	1.22E-2	1.22E-2	7.72E-2	1.49E-1
5.95	6.0	3.32E-3	7.94E-5	1.58E+0	3.39E-1	2.45E-1	8.65E-1	3.04E+0
7.93	8.0	2.64E-2	6.60E-4	8.89E+0	1.54E+0	7.44E-1	1.56E+0	1.28E+1
9.92	10.0	6.18E-2	1.62E-3	1.57E+1	2.24E+0	6.47E-1	8.77E-1	1.95E+1
11.90	12.0	9.30E-2	2.55E-3	1.89E+1	2.20E+0	3.51E-1	3.13E-1	2.18E+1
13.88	14.0	1.16E-1	3.32E-3	1.97E+1	1.85E+0	1.52E-1	8.97E-2	2.19E+1
15.87	16.0	1.33E-1	3.95E-3	1.95E+1	1.44E+0	5.83E-2	2.22E-2	2.12E+1
17.85	18.0	1.43E-1	4.44E-3	1.90E+1	1.08E+0	2.02E-2	4.83E-3	2.02E+1
19.83	20.0	1.49E-1	4.79E-3	1.83E+1	7.65E-1	6.44E-3	9.13E-4	1.92E+1
21.82	22.0	1.52E-1	5.01E-3	1.76E+1	5.19E-1	1.89E-3	1.47E-4	1.82E+1
23.80	24.0	1.50E-1	5.12E-3	1.68E+1	3.35E-1	5.09E-4	1.92E-5	1.73E+1
25.79	26.0	1.47E-1	8.35E-3	1.60E+1	2.08E-1	1.25E-4	1.93E-6	1.63E+1
27.77	28.0	1.39E-1	1.94E-1	1.51E+1	1.23E-1	2.78E-5	1.44E-7	1.56E+1
29.75	30.0	1.31E-1	1.80E+0	1.40E+1	6.11E-2	5.44E-6	9.82E-9	1.60E+1
31.74	32.0	1.18E-1	2.80E+0	1.27E+1	2.02E-2	9.20E-7	0.00E+0	1.56E+1
33.72	34.0	1.03E-1	8.59E-1	1.10E+1	0.00E+0	1.28E-7	0.00E+0	1.20E+1
35.70	36.0	8.62E-2	7.59E-1	9.12E+0	0.00E+0	1.36E-8	0.00E+0	9.97E+0
37.69	38.0	6.65E-2	3.50E+0	6.97E+0	0.00E+0	1.01E-9	0.00E+0	1.05E+1
39.67	40.0	4.46E-2	3.41E+1	4.46E+0	0.00E+0	0.00E+0	0.00E+0	3.86E+1
41.65	42.0	1.74E-2	1.95E+2	1.09E+0	0.00E+0	0.00E+0	0.00E+0	1.96E+2
43.64	44.0	0.00E+0	4.37E+2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.37E+2
45.62	46.0	0.00E+0	3.64E+2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.64E+2
47.60	48.0	0.00E+0	1.12E+2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.12E+2
49.59	50.0	0.00E+0	1.26E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.26E+1
51.57	52.0	0.00E+0	5.24E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.24E-1
sums		3.76E+0	5.11E+1	4.93E+2	2.55E+1	4.48E+0	7.65E+0	5.85E+2
elastic			2.28E+3					

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 1 n= 0
sys. excit. en.= 52.37; sys. bind. en.= 7.75

eps:deg	0	10	20	30	40	50	60	70	80	90
2.00	1.42E-3	1.42E-3	1.40E-3	1.38E-3	1.36E-3	1.33E-3	1.30E-3	1.27E-3	1.24E-3	1.22E-3
4.00	1.50E-2	1.49E-2	1.47E-2	1.43E-2	1.39E-2	1.34E-2	1.28E-2	1.23E-2	1.18E-2	1.14E-2
6.00	3.53E-1	3.50E-1	3.43E-1	3.31E-1	3.16E-1	2.98E-1	2.80E-1	2.62E-1	2.45E-1	2.29E-1
8.00	1.70E+0	1.68E+0	1.64E+0	1.56E+0	1.47E+0	1.37E+0	1.26E+0	1.15E+0	1.04E+0	9.47E-1
10.00	2.90E+0	2.87E+0	2.78E+0	2.63E+0	2.45E+0	2.24E+0	2.02E+0	1.80E+0	1.60E+0	1.42E+0
12.00	3.55E+0	3.50E+0	3.37E+0	3.17E+0	2.92E+0	2.63E+0	2.34E+0	2.05E+0	1.78E+0	1.55E+0
14.00	3.86E+0	3.81E+0	3.65E+0	3.40E+0	3.10E+0	2.76E+0	2.41E+0	2.08E+0	1.77E+0	1.51E+0
16.00	4.04E+0	3.98E+0	3.79E+0	3.51E+0	3.16E+0	2.77E+0	2.39E+0	2.02E+0	1.69E+0	1.41E+0
18.00	4.17E+0	4.10E+0	3.89E+0	3.57E+0	3.17E+0	2.75E+0	2.32E+0	1.93E+0	1.58E+0	1.29E+0
20.00	4.28E+0	4.20E+0	3.96E+0	3.60E+0	3.16E+0	2.69E+0	2.24E+0	1.82E+0	1.47E+0	1.17E+0
22.00	4.42E+0	4.32E+0	4.05E+0	3.64E+0	3.16E+0	2.65E+0	2.16E+0	1.72E+0	1.35E+0	1.05E+0
24.00	4.55E+0	4.44E+0	4.14E+0	3.68E+0	3.14E+0	2.58E+0	2.06E+0	1.60E+0	1.23E+0	9.33E-1
26.00	4.69E+0	4.57E+0	4.22E+0	3.71E+0	3.11E+0	2.51E+0	1.96E+0	1.48E+0	1.11E+0	8.17E-1
28.00	4.89E+0	4.75E+0	4.35E+0	3.78E+0	3.11E+0	2.46E+0	1.87E+0	1.38E+0	9.95E-1	7.13E-1
30.00	5.47E+0	5.29E+0	4.81E+0	4.11E+0	3.33E+0	2.56E+0	1.89E+0	1.35E+0	9.48E-1	6.56E-1
32.00	5.86E+0	5.66E+0	5.09E+0	4.29E+0	3.40E+0	2.55E+0	1.82E+0	1.26E+0	8.52E-1	5.68E-1
34.00	4.92E+0	4.73E+0	4.21E+0	3.49E+0	2.70E+0	1.97E+0	1.36E+0	9.07E-1	5.89E-1	3.77E-1
36.00	4.61E+0	4.39E+0	3.82E+0	3.08E+0	2.32E+0	1.63E+0	1.09E+0	6.98E-1	4.34E-1	2.65E-1
38.00	1.02E+1	8.38E+0	5.25E+0	3.22E+0	2.15E+0	1.44E+0	9.22E-1	5.64E-1	3.34E-1	1.95E-1
40.00	1.05E+2	7.69E+1	3.16E+1	8.87E+0	2.94E+0	1.54E+0	9.17E-1	5.33E-1	3.00E-1	1.65E-1
42.00	6.40E+2	4.61E+2	1.77E+2	3.94E+1	7.42E+0	2.49E+0	1.31E+0	7.18E-1	3.81E-1	1.98E-1
44.00	1.48E+3	1.06E+3	3.96E+2	8.34E+1	1.35E+1	3.66E+0	1.75E+0	9.00E-1	4.48E-1	2.19E-1
46.00	1.26E+3	8.99E+2	3.30E+2	6.69E+1	1.01E+1	2.51E+0	1.12E+0	5.39E-1	2.51E-1	1.14E-1
48.00	3.96E+2	2.80E+2	1.01E+2	1.98E+1	2.86E+0	6.74E-1	2.82E-1	1.27E-1	5.47E-2	2.30E-2
50.00	4.58E+1	3.21E+1	1.13E+1	2.15E+0	3.00E-1	6.77E-2	2.66E-2	1.11E-2	4.41E-3	1.70E-3
52.00	1.95E+0	1.36E+0	4.66E-1	8.56E-2	1.15E-2	2.50E-3	9.18E-4	3.51E-4	1.28E-4	4.52E-5

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 1 n= 0

eps:deg	100	110	120	130	140	150	160	170	180	total
2.00	1.21E-3	1.20E-3	1.20E-3	1.20E-3	1.20E-3	1.21E-3	1.21E-3	1.22E-3	1.22E-3	1.58E-2
4.00	1.11E-2	1.08E-2	1.06E-2	1.05E-2	1.05E-2	1.05E-2	1.05E-2	1.05E-2	1.05E-2	1.49E-1
6.00	2.16E-1	2.05E-1	1.97E-1	1.91E-1	1.86E-1	1.83E-1	1.82E-1	1.81E-1	1.80E-1	3.04E+0
8.00	8.65E-1	7.96E-1	7.40E-1	6.96E-1	6.64E-1	6.40E-1	6.24E-1	6.16E-1	6.13E-1	1.28E+1
10.00	1.26E+0	1.13E+0	1.02E+0	9.35E-1	8.69E-1	8.21E-1	7.89E-1	7.71E-1	7.65E-1	1.95E+1
12.00	1.34E+0	1.17E+0	1.04E+0	9.27E-1	8.44E-1	7.83E-1	7.42E-1	7.18E-1	7.11E-1	2.18E+1
14.00	1.28E+0	1.10E+0	9.49E-1	8.32E-1	7.44E-1	6.81E-1	6.37E-1	6.13E-1	6.04E-1	2.19E+1
16.00	1.18E+0	9.85E-1	8.35E-1	7.20E-1	6.33E-1	5.71E-1	5.30E-1	5.06E-1	4.98E-1	2.12E+1
18.00	1.06E+0	8.67E-1	7.21E-1	6.10E-1	5.29E-1	4.71E-1	4.32E-1	4.10E-1	4.03E-1	2.02E+1
20.00	9.34E-1	7.50E-1	6.11E-1	5.08E-1	4.33E-1	3.80E-1	3.46E-1	3.26E-1	3.20E-1	1.92E+1
22.00	8.19E-1	6.44E-1	5.13E-1	4.18E-1	3.50E-1	3.03E-1	2.73E-1	2.56E-1	2.50E-1	1.82E+1
24.00	7.09E-1	5.43E-1	4.23E-1	3.37E-1	2.77E-1	2.37E-1	2.11E-1	1.96E-1	1.91E-1	1.73E+1
26.00	6.03E-1	4.49E-1	3.41E-1	2.66E-1	2.14E-1	1.80E-1	1.58E-1	1.46E-1	1.42E-1	1.63E+1
28.00	5.10E-1	3.69E-1	2.72E-1	2.07E-1	1.63E-1	1.34E-1	1.17E-1	1.07E-1	1.04E-1	1.56E+1
30.00	4.54E-1	3.18E-1	2.27E-1	1.68E-1	1.29E-1	1.04E-1	8.94E-2	8.12E-2	7.86E-2	1.60E+1
32.00	3.79E-1	2.56E-1	1.77E-1	1.27E-1	9.50E-2	7.52E-2	6.33E-2	5.70E-2	5.50E-2	1.56E+1
34.00	2.41E-1	1.56E-1	1.04E-1	7.22E-2	5.26E-2	4.07E-2	3.37E-2	3.00E-2	2.88E-2	1.20E+1
36.00	1.62E-1	1.01E-1	6.45E-2	4.31E-2	3.04E-2	2.29E-2	1.86E-2	1.64E-2	1.57E-2	9.97E+0
38.00	1.13E-1	6.72E-2	4.11E-2	2.64E-2	1.80E-2	1.32E-2	1.05E-2	9.10E-3	8.67E-3	1.05E+1
40.00	9.13E-2	5.13E-2	2.99E-2	1.83E-2	1.20E-2	8.54E-3	6.64E-3	5.69E-3	5.40E-3	3.86E+1
42.00	1.03E-1	5.48E-2	3.02E-2	1.77E-2	1.11E-2	7.63E-3	5.78E-3	4.88E-3	4.61E-3	1.96E+2
44.00	1.07E-1	5.32E-2	2.77E-2	1.53E-2	9.22E-3	6.10E-3	4.50E-3	3.73E-3	3.50E-3	4.37E+2
46.00	5.18E-2	2.41E-2	1.18E-2	6.15E-3	3.51E-3	2.23E-3	1.60E-3	1.30E-3	1.21E-3	3.64E+2
48.00	9.68E-3	4.18E-3	1.90E-3	9.34E-4	5.05E-4	3.07E-4	2.12E-4	1.70E-4	1.57E-4	1.12E+2
50.00	6.59E-4	2.63E-4	1.11E-4	5.07E-5	2.58E-5	1.49E-5	9.98E-6	7.80E-6	7.17E-6	1.26E+1
52.00	1.59E-5	5.81E-6	2.25E-6	9.56E-7	4.56E-7	2.51E-7	1.61E-7	1.23E-7	1.12E-7	5.24E-1

```
120Sn+p at 45 MeV -- with angular distributions
Reaction Strength Passing Thru Configurations
Target  Z= 50  N= 70     Projectile  z= 1  n= 0   Shells  Z= 50  N=  0
Excit Energy=  50.40     Rxn Cross Sect.=1582.1   Shell gaps=  2.00   .00
gpi= 3.400  gnu= 4.667   Kpp=2200.  Knn= 900.     Knp= 900.
ipair= 1                 iepair= 1
V(central)= 38.00        Veff(1)= 17.00           Veff(2)= 17.00
T=Tz+1 fteq= .15         Esym(cn)=14.07           Ct2= .048
Direct sigma=   3.55     Preeq sigma=  58.82      Frac Preeq=  .819
```

p,ppi= 1	2	3	4	5	6	7	sum
1 1.00000	.00000	.00000	.00000	.00000	.00000	.00000	1.00000
2 .62031	.39195	.00000	.00000	.00000	.00000	.00000	1.01226
3 .24597	.38369	.11633	.00000	.00000	.00000	.00000	.74598
4 .10794	.27802	.19698	.03776	.00000	.00000	.00000	.62071
5 .04870	.18059	.21088	.08727	.01234	.00000	.00000	.53977
6 .02188	.11078	.18921	.12328	.03525	.00348	.00000	.48388
7 .00942	.06427	.15358	.14263	.06183	.01140	.00080	.44392
8 .00382	.03477	.11188	.14450	.08922	.02378	.00279	.41090
9 .00137	.01707	.07402	.12957	.10931	.04185	.00674	.38043

```
120Sn+p at 45 MeV -- with angular distributions
Particle Spectra (mb/MeV)  z= 0  n= 1
T(cn)=Tz+1   Esym(b)=13.147  27.677   Ct2(b)= .952   .087
```

eps cm	eps-- chan	direct -- nutra	direct -- knock	exciton -- primary	exciton -- second	equilibrium -- primary	equilibrium -- second	sum	tsum
1.98	2.0	1.14E-3	0.00E+0	1.95E+0	2.48E-1	2.45E+0	1.37E+1	1.83E+1	5.02E+2
3.97	4.0	2.13E-3	0.00E+0	2.06E+0	1.93E-1	1.73E+0	6.58E+0	1.06E+1	2.54E+2
5.95	6.0	2.89E-3	0.00E+0	1.72E+0	1.16E-1	8.66E-1	2.33E+0	5.03E+0	1.17E+2
7.93	8.0	3.41E-3	0.00E+0	1.37E+0	6.42E-2	3.71E-1	7.06E-1	2.52E+0	5.79E+1
9.92	10.0	3.76E-3	0.00E+0	1.10E+0	3.45E-2	1.44E-1	1.91E-1	1.48E+0	3.32E+1
11.90	12.0	3.93E-3	0.00E+0	8.95E-1	1.85E-2	5.19E-2	4.67E-2	1.02E+0	2.24E+1
13.88	14.0	3.91E-3	0.00E+0	7.35E-1	1.00E-2	1.75E-2	1.03E-2	7.76E-1	1.70E+1
15.87	16.0	3.81E-3	0.00E+0	6.13E-1	5.64E-3	5.52E-3	2.05E-3	6.30E-1	1.38E+1
17.85	18.0	3.52E-3	0.00E+0	5.04E-1	3.30E-3	1.64E-3	3.61E-4	5.13E-1	1.17E+1
19.83	20.0	3.14E-3	0.00E+0	4.12E-1	1.92E-3	4.53E-4	5.54E-5	4.18E-1	1.01E+1
21.82	22.0	2.62E-3	0.00E+0	3.21E-1	1.02E-3	1.17E-4	7.20E-6	3.25E-1	8.79E+0
23.80	24.0	1.97E-3	0.00E+0	2.30E-1	4.56E-4	2.76E-5	7.57E-7	2.32E-1	7.79E+0
25.79	26.0	1.18E-3	0.00E+0	1.28E-1	1.36E-4	5.97E-6	5.97E-8	1.30E-1	6.83E+0
27.77	28.0	0.00E+0	0.00E+0	0.00E+0	1.41E-5	1.15E-6	3.59E-9	1.52E-5	5.96E+0
29.75	30.0	0.00E+0	0.00E+0	0.00E+0	2.52E-7	1.94E-7	0.00E+0	4.47E-7	5.21E+0
31.74	32.0	0.00E+0	0.00E+0	0.00E+0	7.25E-9	2.76E-8	0.00E+0	3.49E-8	4.44E+0
33.72	34.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.12E-9	0.00E+0	3.12E-9	3.66E+0
35.70	36.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.78E+0
37.69	38.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.85E+0
39.67	40.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.89E-1
sums		7.48E-2	0.00E+0	2.41E+1	1.39E+0	1.13E+1	4.71E+1	8.39E+1	

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 0 n= 1
sys. excit. en.= 52.37; sys. bind. en.= 7.90

eps:deg	0	10	20	30	40	50	60	70	80	90
2.00	1.60E+0	1.60E+0	1.59E+0	1.57E+0	1.54E+0	1.51E+0	1.48E+0	1.46E+0	1.44E+0	1.42E+0
4.00	9.92E-1	9.87E-1	9.75E-1	9.55E-1	9.31E-1	9.03E-1	8.75E-1	8.49E-1	8.27E-1	8.10E-1
6.00	5.25E-1	5.22E-1	5.12E-1	4.97E-1	4.78E-1	4.57E-1	4.35E-1	4.14E-1	3.95E-1	3.80E-1
8.00	3.03E-1	3.00E-1	2.93E-1	2.81E-1	2.66E-1	2.50E-1	2.32E-1	2.16E-1	2.00E-1	1.87E-1
10.00	2.05E-1	2.03E-1	1.97E-1	1.87E-1	1.75E-1	1.61E-1	1.46E-1	1.32E-1	1.19E-1	1.07E-1
12.00	1.59E-1	1.57E-1	1.52E-1	1.43E-1	1.32E-1	1.19E-1	1.06E-1	9.40E-2	8.25E-2	7.23E-2
14.00	1.33E-1	1.32E-1	1.26E-1	1.18E-1	1.08E-1	9.62E-2	8.45E-2	7.32E-2	6.28E-2	5.38E-2
16.00	1.17E-1	1.15E-1	1.10E-1	1.02E-1	9.22E-2	8.13E-2	7.03E-2	5.99E-2	5.05E-2	4.24E-2
18.00	1.03E-1	1.01E-1	9.58E-2	8.82E-2	7.88E-2	6.86E-2	5.85E-2	4.90E-2	4.05E-2	3.34E-2
20.00	8.95E-2	8.79E-2	8.31E-2	7.59E-2	6.71E-2	5.77E-2	4.84E-2	3.98E-2	3.24E-2	2.61E-2
22.00	7.47E-2	7.32E-2	6.89E-2	6.24E-2	5.45E-2	4.62E-2	3.81E-2	3.08E-2	2.46E-2	1.95E-2
24.00	5.72E-2	5.59E-2	5.24E-2	4.70E-2	4.06E-2	3.39E-2	2.75E-2	2.18E-2	1.70E-2	1.32E-2
26.00	3.43E-2	3.35E-2	3.12E-2	2.77E-2	2.36E-2	1.94E-2	1.55E-2	1.20E-2	9.19E-3	6.97E-3
28.00	4.17E-6	4.06E-6	3.76E-6	3.31E-6	2.78E-6	2.25E-6	1.76E-6	1.35E-6	1.02E-6	7.67E-7
30.00	1.08E-7	1.05E-7	9.62E-8	8.40E-8	7.00E-8	5.60E-8	4.36E-8	3.35E-8	2.60E-8	2.09E-8
32.00	7.01E-9	6.80E-9	6.22E-9	5.38E-9	4.44E-9	3.52E-9	2.73E-9	2.12E-9	1.71E-9	1.50E-9
34.00	**********	**********	**********	**********	**********	**********	**********	**********	**********	**********

eps:deg	100	110	120	130	140	150	160	170	180	total
2.00	1.41E+0	1.41E+0	1.41E+0	1.42E+0	1.43E+0	1.45E+0	1.46E+0	1.46E+0	1.46E+0	1.83E+1
4.00	7.98E-1	7.92E-1	7.91E-1	7.94E-1	8.00E-1	8.07E-1	8.13E-1	8.17E-1	8.19E-1	1.06E+1
6.00	3.68E-1	3.60E-1	3.55E-1	3.54E-1	3.54E-1	3.56E-1	3.58E-1	3.59E-1	3.60E-1	5.03E+0
8.00	1.76E-1	1.68E-1	1.61E-1	1.57E-1	1.55E-1	1.54E-1	1.53E-1	1.53E-1	1.53E-1	2.52E+0
10.00	9.75E-2	8.96E-2	8.34E-2	7.88E-2	7.55E-2	7.33E-2	7.19E-2	7.12E-2	7.10E-2	1.48E+0
12.00	6.36E-2	5.64E-2	5.07E-2	4.63E-2	4.30E-2	4.07E-2	3.92E-2	3.83E-2	3.80E-2	1.02E+0
14.00	4.61E-2	3.98E-2	3.48E-2	3.09E-2	2.80E-2	2.59E-2	2.45E-2	2.37E-2	2.34E-2	7.76E-1
16.00	3.56E-2	3.00E-2	2.57E-2	2.23E-2	1.98E-2	1.80E-2	1.68E-2	1.61E-2	1.59E-2	6.30E-1
18.00	2.75E-2	2.28E-2	1.91E-2	1.63E-2	1.42E-2	1.27E-2	1.18E-2	1.12E-2	1.10E-2	5.13E-1
20.00	2.11E-2	1.72E-2	1.41E-2	1.19E-2	1.02E-2	9.03E-3	8.26E-3	7.82E-3	7.67E-3	4.18E-1
22.00	1.54E-2	1.23E-2	9.93E-3	8.20E-3	6.95E-3	6.08E-3	5.51E-3	5.18E-3	5.08E-3	3.25E-1
24.00	1.02E-2	8.00E-3	6.35E-3	5.15E-3	4.30E-3	3.71E-3	3.33E-3	3.12E-3	3.05E-3	2.32E-1
26.00	5.29E-3	4.04E-3	3.14E-3	2.50E-3	2.06E-3	1.75E-3	1.56E-3	1.45E-3	1.42E-3	1.30E-1
28.00	5.86E-7	4.61E-7	3.80E-7	3.31E-7	3.06E-7	2.95E-7	2.93E-7	2.94E-7	2.95E-7	1.52E-5
30.00	1.81E-8	1.73E-8	1.80E-8	2.01E-8	2.30E-8	2.63E-8	2.93E-8	3.15E-8	3.22E-8	4.47E-7
32.00	1.49E-9	1.65E-9	1.97E-9	2.45E-9	3.02E-9	3.62E-9	4.16E-9	4.53E-9	4.66E-9	3.49E-8
34.00	**********	**********	**********	**********	**********	**********	**********	**********	**********	3.12E-9

120Sn+p at 45 MeV -- with angular distributions
Particle Spectra (mb/MeV) z= 1 n= 0
T(cn)=Tz+1 Esym(b)= .000 14.530 Ct2(b)= .048 .913

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second --	sum	tsum
1.98	2.0	5.31E-8	2.29E-9	1.21E-3	1.00E-3	2.92E-4	6.90E-3	9.40E-3	2.52E-2
3.97	4.0	1.61E-6	7.40E-8	1.92E-2	1.15E-2	3.60E-3	3.96E-2	7.39E-2	2.23E-1
5.95	6.0	8.11E-5	3.97E-6	5.09E-1	2.12E-1	7.21E-2	4.19E-1	1.21E+0	4.25E+0
7.93	8.0	6.34E-4	3.30E-5	2.13E+0	6.11E-1	2.18E-1	7.65E-1	3.73E+0	1.65E+1
9.92	10.0	1.46E-3	8.09E-5	2.76E+0	5.03E-1	1.90E-1	4.23E-1	3.87E+0	2.34E+1
11.90	12.0	2.16E-3	1.27E-4	2.47E+0	3.01E-1	1.03E-1	1.49E-1	3.02E+0	2.48E+1
13.88	14.0	2.62E-3	1.66E-4	2.02E+0	1.68E-1	4.46E-2	4.20E-2	2.28E+0	2.42E+1
15.87	16.0	2.89E-3	1.97E-4	1.66E+0	9.18E-2	1.71E-2	1.02E-2	1.78E+0	2.30E+1
17.85	18.0	2.94E-3	2.22E-4	1.39E+0	4.95E-2	5.92E-3	2.18E-3	1.46E+0	2.17E+1
19.83	20.0	2.84E-3	2.40E-4	1.16E+0	2.64E-2	1.89E-3	4.03E-4	1.20E+0	2.04E+1
21.82	22.0	2.55E-3	2.51E-4	9.58E-1	1.50E-2	5.53E-4	6.34E-5	9.76E-1	1.92E+1
23.80	24.0	2.11E-3	2.56E-4	7.40E-1	8.43E-3	1.49E-4	8.16E-6	7.51E-1	1.80E+1
25.79	26.0	1.51E-3	4.18E-4	4.96E-1	4.62E-3	3.67E-5	8.09E-7	5.03E-1	1.68E+1
27.77	28.0	7.14E-4	9.71E-3	2.11E-1	2.40E-3	8.12E-6	5.99E-8	2.24E-1	1.58E+1
29.75	30.0	3.27E-4	8.99E-2	1.22E-1	1.08E-3	1.59E-6	4.06E-9	2.14E-1	1.62E+1
31.74	32.0	2.95E-4	1.40E-1	1.03E-1	3.31E-4	2.69E-7	0.00E+0	2.44E-1	1.59E+1
33.72	34.0	2.58E-4	4.30E-2	8.49E-2	0.00E+0	3.75E-8	0.00E+0	1.28E-1	1.21E+1
35.70	36.0	2.16E-4	4.69E-2	6.78E-2	0.00E+0	3.99E-9	0.00E+0	1.15E-1	1.01E+1
37.69	38.0	1.66E-4	5.79E-1	5.06E-2	0.00E+0	0.00E+0	0.00E+0	6.30E-1	1.12E+1
39.67	40.0	1.11E-4	8.42E+0	3.20E-2	0.00E+0	0.00E+0	0.00E+0	8.45E+0	4.70E+1
41.65	42.0	4.35E-5	5.08E+1	7.76E-3	0.00E+0	0.00E+0	0.00E+0	5.08E+1	2.47E+2
43.64	44.0	0.00E+0	1.14E+2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.14E+2	5.51E+2
45.62	46.0	0.00E+0	9.45E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.45E+1	4.58E+2
47.60	48.0	0.00E+0	2.88E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.88E+1	1.40E+2
49.59	50.0	0.00E+0	3.23E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.23E+0	1.58E+1
51.57	52.0	0.00E+0	1.33E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.33E-1	6.57E-1
sums		4.79E-2	2.55E+0	3.40E+1	4.01E+0	1.31E+0	3.71E+0	4.57E+1	
elastic			5.99E+2						

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 1 n= 0
sys. excit. en.= 52.37; sys. bind. en.= 7.75

eps:deg	0	10	20	30	40	50	60	70	80	90
2.00	8.56E-4	8.53E-4	8.45E-4	8.32E-4	8.15E-4	7.96E-4	7.77E-4	7.59E-4	7.43E-4	7.29E-4
4.00	7.49E-3	7.45E-3	7.34E-3	7.16E-3	6.93E-3	6.67E-3	6.40E-3	6.13E-3	5.88E-3	5.66E-3
6.00	1.39E-1	1.38E-1	1.35E-1	1.30E-1	1.24E-1	1.18E-1	1.11E-1	1.04E-1	9.73E-2	9.15E-2
8.00	4.80E-1	4.76E-1	4.63E-1	4.43E-1	4.18E-1	3.89E-1	3.59E-1	3.29E-1	3.02E-1	2.77E-1
10.00	5.57E-1	5.51E-1	5.33E-1	5.06E-1	4.71E-1	4.32E-1	3.92E-1	3.52E-1	3.15E-1	2.81E-1
12.00	4.81E-1	4.75E-1	4.58E-1	4.31E-1	3.96E-1	3.58E-1	3.19E-1	2.81E-1	2.46E-1	2.14E-1
14.00	3.98E-1	3.92E-1	3.76E-1	3.51E-1	3.19E-1	2.85E-1	2.49E-1	2.15E-1	1.84E-1	1.57E-1
16.00	3.38E-1	3.33E-1	3.18E-1	2.94E-1	2.65E-1	2.32E-1	2.00E-1	1.70E-1	1.42E-1	1.19E-1
18.00	3.00E-1	2.94E-1	2.79E-1	2.56E-1	2.28E-1	1.97E-1	1.67E-1	1.39E-1	1.14E-1	9.30E-2
20.00	2.67E-1	2.61E-1	2.47E-1	2.24E-1	1.97E-1	1.68E-1	1.39E-1	1.14E-1	9.13E-2	7.29E-2
22.00	2.36E-1	2.31E-1	2.17E-1	1.95E-1	1.69E-1	1.42E-1	1.15E-1	9.19E-2	7.22E-2	5.63E-2
24.00	1.98E-1	1.93E-1	1.80E-1	1.60E-1	1.36E-1	1.12E-1	8.95E-2	6.97E-2	5.34E-2	4.05E-2
26.00	1.44E-1	1.40E-1	1.30E-1	1.14E-1	9.58E-2	7.72E-2	6.02E-2	4.57E-2	3.40E-2	2.51E-2
28.00	7.01E-2	6.81E-2	6.24E-2	5.41E-2	4.47E-2	3.52E-2	2.68E-2	1.97E-2	1.43E-2	1.02E-2
30.00	7.32E-2	7.08E-2	6.44E-2	5.51E-2	4.45E-2	3.43E-2	2.53E-2	1.81E-2	1.27E-2	8.78E-3
32.00	9.15E-2	8.83E-2	7.95E-2	6.69E-2	5.30E-2	3.97E-2	2.85E-2	1.97E-2	1.33E-2	8.86E-3
34.00	5.27E-2	5.07E-2	4.52E-2	3.74E-2	2.89E-2	2.11E-2	1.46E-2	9.72E-3	6.31E-3	4.04E-3
36.00	8.24E-2	7.08E-2	4.98E-2	3.44E-2	2.46E-2	1.72E-2	1.15E-2	7.33E-3	4.55E-3	2.79E-3
38.00	1.69E+0	1.25E+0	5.15E-1	1.44E-1	4.69E-2	2.49E-2	1.55E-2	9.44E-3	5.59E-3	3.26E-3
40.00	2.77E+1	2.00E+1	7.72E+0	1.70E+0	2.82E-1	7.82E-2	4.06E-2	2.33E-2	1.31E-2	7.23E-3
42.00	1.72E+2	1.24E+2	4.67E+1	9.80E+0	1.42E+0	3.04E-1	1.39E-1	7.51E-2	3.98E-2	2.07E-2
44.00	3.94E+2	2.82E+2	1.05E+2	2.13E+1	2.93E+0	5.78E-1	2.46E-1	1.25E-1	6.23E-2	3.04E-2
46.00	3.32E+2	2.36E+2	8.62E+1	1.70E+1	2.26E+0	4.28E-1	1.73E-1	8.26E-2	3.84E-2	1.74E-2
48.00	1.03E+2	7.30E+1	2.61E+1	5.01E+0	6.42E-1	1.18E-1	4.53E-2	2.02E-2	8.70E-3	3.66E-3
50.00	1.18E+1	8.31E+0	2.91E+0	5.39E-1	6.68E-2	1.19E-2	4.33E-3	1.79E-3	7.11E-4	2.75E-4
52.00	5.00E-1	3.48E-1	1.19E-1	2.13E-2	2.53E-3	4.39E-4	1.50E-4	5.69E-5	2.07E-5	7.30E-6

120Sn+p at 45 MeV -- with angular distributions
angular distributions (mb/MeV) z= 1 n= 0

eps:deg	100	110	120	130	140	150	160	170	180	total
2.00	7.19E-4	7.13E-4	7.09E-4	7.09E-4	7.10E-4	7.12E-4	7.15E-4	7.16E-4	7.17E-4	9.40E-3
4.00	5.49E-3	5.35E-3	5.26E-3	5.20E-3	5.17E-3	5.15E-3	5.15E-3	5.15E-3	5.15E-3	7.39E-2
6.00	8.66E-2	8.27E-2	7.96E-2	7.74E-2	7.59E-2	7.50E-2	7.44E-2	7.42E-2	7.41E-2	1.21E+0
8.00	2.55E-1	2.38E-1	2.24E-1	2.13E-1	2.06E-1	2.01E-1	1.97E-1	1.96E-1	1.95E-1	3.73E+0
10.00	2.53E-1	2.30E-1	2.11E-1	1.96E-1	1.86E-1	1.78E-1	1.74E-1	1.71E-1	1.70E-1	3.87E+0
12.00	1.88E-1	1.66E-1	1.48E-1	1.35E-1	1.25E-1	1.18E-1	1.13E-1	1.10E-1	1.09E-1	3.02E+0
14.00	1.34E-1	1.16E-1	1.01E-1	8.95E-2	8.09E-2	7.48E-2	7.07E-2	6.83E-2	6.76E-2	2.28E+0
16.00	9.92E-2	8.34E-2	7.10E-2	6.16E-2	5.45E-2	4.95E-2	4.62E-2	4.42E-2	4.36E-2	1.78E+0
18.00	7.60E-2	6.25E-2	5.21E-2	4.42E-2	3.84E-2	3.43E-2	3.16E-2	3.01E-2	2.96E-2	1.46E+0
20.00	5.82E-2	4.68E-2	3.82E-2	3.18E-2	2.71E-2	2.39E-2	2.17E-2	2.05E-2	2.01E-2	1.20E+0
22.00	4.39E-2	3.45E-2	2.75E-2	2.24E-2	1.88E-2	1.63E-2	1.47E-2	1.38E-2	1.35E-2	9.76E-1
24.00	3.08E-2	2.36E-2	1.84E-2	1.47E-2	1.21E-2	1.03E-2	9.16E-3	8.53E-3	8.33E-3	7.51E-1
26.00	1.85E-2	1.38E-2	1.05E-2	8.17E-3	6.59E-3	5.53E-3	4.87E-3	4.50E-3	4.38E-3	5.03E-1
28.00	7.31E-3	5.29E-3	3.90E-3	2.96E-3	2.34E-3	1.93E-3	1.67E-3	1.53E-3	1.49E-3	2.24E-1
30.00	6.07E-3	4.25E-3	3.04E-3	2.25E-3	1.73E-3	1.40E-3	1.20E-3	1.09E-3	1.05E-3	2.14E-1
32.00	5.91E-3	3.99E-3	2.76E-3	1.98E-3	1.48E-3	1.17E-3	9.88E-4	8.89E-4	8.58E-4	2.44E-1
34.00	2.58E-3	1.68E-3	1.12E-3	7.74E-4	5.64E-4	4.36E-4	3.61E-4	3.21E-4	3.09E-4	1.28E-1
36.00	1.71E-3	1.06E-3	6.78E-4	4.53E-4	3.19E-4	2.41E-4	1.95E-4	1.72E-4	1.65E-4	1.15E-1
38.00	1.90E-3	1.12E-3	6.88E-4	4.41E-4	3.01E-4	2.20E-4	1.75E-4	1.52E-4	1.45E-4	6.30E-1
40.00	3.99E-3	2.24E-3	1.31E-3	8.02E-4	5.26E-4	3.74E-4	2.90E-4	2.49E-4	2.36E-4	8.45E+0
42.00	1.08E-2	5.72E-3	3.16E-3	1.85E-3	1.16E-3	7.97E-4	6.04E-4	5.10E-4	4.81E-4	5.08E+1
44.00	1.48E-2	7.40E-3	3.85E-3	2.13E-3	1.28E-3	8.48E-4	6.25E-4	5.19E-4	4.87E-4	1.14E+2
46.00	7.93E-3	3.69E-3	1.80E-3	9.42E-4	5.38E-4	3.42E-4	2.45E-4	1.99E-4	1.86E-4	9.45E+1
48.00	1.54E-3	6.66E-4	3.03E-4	1.49E-4	8.04E-5	4.88E-5	3.38E-5	2.70E-5	2.50E-5	2.88E+1
50.00	1.06E-4	4.23E-5	1.78E-5	8.17E-6	4.16E-6	2.41E-6	1.61E-6	1.26E-6	1.16E-6	3.23E+0
52.00	2.58E-6	9.39E-7	3.64E-7	1.55E-7	7.38E-8	4.05E-8	2.60E-8	1.99E-8	1.81E-8	1.33E-1

C.4. Problem 4

```
238U+n at 14.1 MeV -- no secondary emission; fission
Reaction Strength Passing Thru Configurations
Target  Z= 92  N=146     Projectile  z= 0  n= 1   Shells  Z= 82  N=  0
Excit Energy=  18.84     Rxn Cross Sect.=3060.2   Shell gaps=  1.40   .00
gpi= 6.133  gnu= 9.800   Kpp=2200.  Knn= 900.     Knp= 900.
ipair=-1                 iepair= 1
V(central)= 38.00        Veff(1)= 10.74           Veff(2)=  7.00
T=Tz+0 fteq= .40         Esym(cn)=  .00           Ct2=1.000
Direct sigma= 946.90     Preeq sigma= 578.45      Frac Preeq=  .274
```

p,ppi= 0	1	2	3	4	5	6	sum
1	1.00000	.00000	.00000	.00000	.00000	.00000	.00000	1.00000
2	.52278	.49099	.00000	.00000	.00000	.00000	.00000	1.01376
3	.26078	.47931	.16538	.00000	.00000	.00000	.00000	.90547
4	.14010	.38212	.29583	.05344	.00000	.00000	.00000	.87148
5	.07588	.27725	.35726	.14588	.01562	.00000	.00000	.87188
6	.04010	.18834	.36160	.24848	.05980	.00389	.00000	.90220
7	.01984	.11947	.32722	.33978	.13745	.02002	.00077	.96454
8	.00874	.06948	.26998	.40563	.24818	.06078	.00522	1.06813
9	.00323	.03602	.20392	.43750	.38671	.14386	.02077	1.23299
10	.00096	.01612	.14144	.43526	.54238	.29301	.06442	1.49864

238U+n at 14.1 MeV -- no secondary emission; fission
Particle Spectra (mb/MeV) z= 0 n= 1
T(cn)=Tz+0 Esym(b)= .000 20.460 Ct2(b)=1.000 .018

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	equil --	sum
.50	.5	1.83E-1	2.91E-1	3.71E+1	5.78E+2	6.16E+2
1.00	1.0	4.49E-1	8.79E-1	6.59E+1	7.34E+2	8.01E+2
1.49	1.5	6.99E-1	1.63E+0	7.67E+1	5.83E+2	6.62E+2
1.99	2.0	9.32E-1	2.50E+0	7.88E+1	3.92E+2	4.74E+2
2.49	2.5	1.15E+0	3.43E+0	7.70E+1	2.40E+2	3.21E+2
2.99	3.0	1.34E+0	4.34E+0	7.35E+1	1.38E+2	2.17E+2
3.49	3.5	1.51E+0	5.13E+0	6.94E+1	7.51E+1	1.51E+2
3.98	4.0	1.67E+0	5.70E+0	6.52E+1	3.93E+1	1.12E+2
4.48	4.5	1.80E+0	6.03E+0	6.11E+1	1.98E+1	8.88E+1
4.98	5.0	1.92E+0	6.09E+0	5.73E+1	9.64E+0	7.49E+1
5.48	5.5	2.02E+0	5.94E+0	5.37E+1	4.52E+0	6.62E+1
5.97	6.0	2.09E+0	5.64E+0	5.05E+1	2.05E+0	6.03E+1
6.47	6.5	2.13E+0	5.26E+0	4.76E+1	8.92E-1	5.59E+1
6.97	7.0	2.14E+0	4.89E+0	4.50E+1	3.73E-1	5.24E+1
7.47	7.5	2.13E+0	4.56E+0	4.20E+1	1.50E-1	4.88E+1
7.97	8.0	2.10E+0	4.31E+0	3.91E+1	5.73E-2	4.55E+1
8.46	8.5	2.05E+0	4.14E+0	3.62E+1	2.08E-2	4.25E+1
8.96	9.0	1.98E+0	4.03E+0	3.35E+1	7.10E-3	3.95E+1
9.46	9.5	1.86E+0	3.96E+0	3.07E+1	2.26E-3	3.66E+1
9.96	10.0	1.71E+0	3.91E+0	2.79E+1	6.84E-4	3.35E+1
10.46	10.5	1.54E+0	3.85E+0	2.45E+1	2.07E-4	2.99E+1
10.95	11.0	1.34E+0	3.78E+0	2.10E+1	6.24E-5	2.61E+1
11.45	11.5	1.12E+0	3.73E+0	1.72E+1	1.88E-5	2.20E+1
11.95	12.0	8.72E-1	5.49E+0	1.31E+1	5.64E-6	1.95E+1
12.45	12.5	5.85E-1	3.97E+1	8.80E+0	1.69E-6	4.91E+1
12.95	13.0	2.63E-1	3.78E+2	3.92E+0	5.06E-7	3.82E+2
13.44	13.5	0.00E+0	1.70E+3	0.00E+0	1.51E-7	1.70E+3
13.94	14.0	0.00E+0	3.00E+3	0.00E+0	4.52E-8	3.00E+3
14.44	14.5	0.00E+0	1.97E+3	0.00E+0	0.00E+0	1.97E+3
14.94	15.0	0.00E+0	4.80E+2	0.00E+0	0.00E+0	4.80E+2
15.44	15.5	0.00E+0	4.47E+1	0.00E+0	0.00E+0	4.47E+1
15.93	16.0	0.00E+0	3.21E+0	0.00E+0	0.00E+0	3.21E+0
sums		1.88E+1	9.28E+2	5.78E+2	1.41E+3	2.93E+3
elastic			2.93E+3			
fission					1.26E+2	

```
238U+n at 14.1 MeV -- no secondary emission; fission
Particle Spectra (mb/MeV)  z= 1  n= 0
T(cn)=Tz+0   Esym(b)=  .000  21.204   Ct2(b)= .982   .000

 eps   eps--     direct     --exciton-- equil --  sum
  cm  chan-- nutra    knock --       --       --

 5.97  6.0  3.40E-6  0.00E+0  1.78E-4  7.83E-7  1.82E-4
 6.47  6.5  3.80E-6  0.00E+0  1.86E-4  3.38E-7  1.91E-4
 6.97  7.0  3.91E-6  0.00E+0  1.81E-4  1.28E-7  1.85E-4
 7.47  7.5  5.13E-6  0.00E+0  2.26E-4  5.91E-8  2.32E-4
 7.97  8.0  1.35E-5  0.00E+0  5.72E-4  5.25E-8  5.86E-4
 8.46  8.5  4.61E-5  0.00E+0  1.88E-3  6.21E-8  1.93E-3
 8.96  9.0  1.39E-4  0.00E+0  5.49E-3  6.78E-8  5.63E-3
 9.46  9.5  3.44E-4  0.00E+0  1.31E-2  6.45E-8  1.34E-2
 9.96 10.0  6.53E-4  0.00E+0  2.37E-2  5.34E-8  2.43E-2
10.46 10.5  7.82E-4  0.00E+0  2.50E-2  3.80E-8  2.57E-2

sums        9.97E-4  0.00E+0  3.52E-2  8.24E-7  3.62E-2
```

```
238U+n at 14.1 MeV -- no secondary emission; fission
Particle Spectra (mb/MeV)  z= 2  n= 2
T(cn)=Tz+0   Esym(b)=  .000  21.076   Ct2(b)=1.000   .000

 eps   eps--     direct     --exciton-- equil --  sum
  cm  chan-- nutra    knock --       --       --

19.67 20.0  2.76E-2  4.56E-2  1.06E-5  3.99E-6  7.32E-2
20.16 20.5  4.52E-2  8.88E-2  1.32E-5  2.88E-6  1.34E-1
20.65 21.0  4.58E-2  1.12E-1  1.02E-5  1.44E-6  1.57E-1
21.14 21.5  3.23E-2  1.05E-1  5.34E-6  6.28E-7  1.38E-1
21.63 22.0  1.00E-2  0.00E+0  1.81E-6  2.54E-7  1.00E-2

sums        8.05E-2  1.76E-1  2.06E-5  4.60E-6  2.56E-1
```

C.5. Problem 5

```
54Fe+alpha  at 59 MeV
Reaction Strength Passing Thru Configurations
Target  Z= 26  N= 28     Projectile  z= 2  n= 2   Shells  Z= 28  N= 28
Excit Energy=  61.15     Rxn Cross Sect.=1518.7   Shell gaps=  1.50  1.30
gpi= 1.867  gnu= 2.000   Kpp=2200.  Knn= 900.     Knp= 900.
ipair=-1                 iepair= 1
V(central)= 38.00        Veff(1)= 25.00           Veff(2)= 25.00
Direct sigma= 548.07     Preeq sigma= 306.48      Frac Preeq=  .316
```

p,ppi= 2	3	4	5	6	7	8	sum
4 1.00000	.00000	.00000	.00000	.00000	.00000	.00000	1.00000
5 .46122	.58343	.00000	.00000	.00000	.00000	.00000	1.04465
6 .19288	.55519	.29914	.00000	.00000	.00000	.00000	1.04721
7 .07871	.39626	.47671	.14006	.00000	.00000	.00000	1.09174
8 .03126	.25257	.51829	.33512	.05671	.00000	.00000	1.19396
9 .01193	.15337	.48246	.52276	.19489	.01825	.00000	1.38366

54Fe+alpha at 59 MeV
Particle Spectra (mb/MeV) z= 1 n= 0

eps cm	eps-- chan--	direct nutra	knock	exciton --primary	second	equilibrium --primary	second	sum --
1.97	2.0	1.01E-2	5.87E-5	1.04E-1	5.35E-2	6.37E-1	3.70E+0	4.51E+0
3.93	4.0	4.26E-1	2.69E-3	3.04E+0	1.12E+0	1.57E+1	4.94E+1	6.97E+1
5.90	6.0	1.72E+0	1.18E-2	8.50E+0	2.36E+0	3.67E+1	8.20E+1	1.31E+2
7.86	8.0	3.26E+0	2.43E-2	1.11E+1	2.44E+0	3.96E+1	6.79E+1	1.24E+2
9.83	10.0	4.34E+0	3.52E-2	1.03E+1	1.85E+0	2.97E+1	4.02E+1	8.64E+1
11.79	12.0	5.02E+0	4.44E-2	8.40E+0	1.28E+0	1.92E+1	2.06E+1	5.46E+1
13.76	14.0	5.39E+0	5.20E-2	6.45E+0	8.70E-1	1.14E+1	9.66E+0	3.38E+1
15.72	16.0	5.51E+0	5.81E-2	4.80E+0	5.89E-1	6.31E+0	4.22E+0	2.15E+1
17.69	18.0	5.45E+0	6.27E-2	3.52E+0	3.99E-1	3.33E+0	1.73E+0	1.45E+1
19.66	20.0	5.24E+0	6.61E-2	2.55E+0	2.69E-1	1.68E+0	6.67E-1	1.05E+1
21.62	22.0	4.92E+0	6.81E-2	1.82E+0	1.80E-1	8.18E-1	2.42E-1	8.05E+0
23.59	24.0	4.53E+0	6.89E-2	1.29E+0	1.18E-1	3.82E-1	8.17E-2	6.48E+0
25.55	26.0	4.10E+0	6.86E-2	9.00E-1	7.50E-2	1.72E-1	2.56E-2	5.34E+0
27.52	28.0	3.64E+0	6.73E-2	6.13E-1	4.56E-2	7.41E-2	7.37E-3	4.45E+0
29.48	30.0	3.18E+0	6.49E-2	4.05E-1	2.60E-2	3.06E-2	1.92E-3	3.71E+0
31.45	32.0	2.72E+0	6.17E-2	2.57E-1	1.34E-2	1.21E-2	4.43E-4	3.07E+0
33.41	34.0	2.29E+0	5.76E-2	1.55E-1	5.93E-3	4.53E-3	9.02E-5	2.51E+0
35.38	36.0	1.87E+0	5.27E-2	8.77E-2	1.94E-3	1.60E-3	1.64E-5	2.02E+0
37.34	38.0	1.49E+0	4.72E-2	4.51E-2	3.01E-4	5.30E-4	2.48E-6	1.58E+0
39.31	40.0	1.15E+0	4.13E-2	2.04E-2	1.28E-6	1.63E-4	1.79E-7	1.22E+0
41.28	42.0	8.61E-1	3.52E-2	7.54E-3	0.00E+0	4.61E-5	1.80E-8	9.04E-1
43.24	44.0	6.03E-1	2.84E-2	1.99E-3	0.00E+0	1.15E-5	0.00E+0	6.34E-1
45.21	46.0	3.84E-1	2.10E-2	2.40E-4	0.00E+0	2.45E-6	0.00E+0	4.05E-1
47.17	48.0	2.01E-1	1.29E-2	0.00E+0	0.00E+0	4.64E-7	0.00E+0	2.14E-1
49.14	50.0	5.75E-2	0.00E+0	0.00E+0	0.00E+0	8.77E-8	0.00E+0	5.75E-2
51.10	52.0	2.78E-3	0.00E+0	0.00E+0	0.00E+0	1.65E-8	0.00E+0	2.78E-3
sums		1.37E+2	2.11E+0	1.29E+2	2.34E+1	3.31E+2	5.61E+2	1.18E+3

54Fe+alpha at 59 MeV
Particle Spectra (mb/MeV) z= 1 n= 1

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	--	equil --	--	sum
3.86	4.0	1.45E-1	0.00E+0	1.54E+0	3.44E+0	5.12E+0
5.79	6.0	6.45E-1	0.00E+0	4.36E+0	8.09E+0	1.31E+1
7.72	8.0	1.16E+0	0.00E+0	4.95E+0	7.54E+0	1.37E+1
9.66	10.0	1.56E+0	0.00E+0	4.27E+0	5.22E+0	1.11E+1
11.59	12.0	1.88E+0	0.00E+0	3.31E+0	3.16E+0	8.34E+0
13.52	14.0	2.11E+0	0.00E+0	2.44E+0	1.75E+0	6.30E+0
15.45	16.0	2.27E+0	0.00E+0	1.76E+0	9.09E-1	4.94E+0
17.38	18.0	2.37E+0	0.00E+0	1.26E+0	4.47E-1	4.07E+0
19.31	20.0	2.41E+0	0.00E+0	9.02E-1	2.09E-1	3.52E+0
21.24	22.0	2.40E+0	0.00E+0	6.43E-1	9.27E-2	3.13E+0
23.17	24.0	2.35E+0	0.00E+0	4.53E-1	3.92E-2	2.84E+0
25.10	26.0	2.26E+0	0.00E+0	3.14E-1	1.57E-2	2.59E+0
27.03	28.0	2.14E+0	0.00E+0	2.11E-1	5.92E-3	2.36E+0
28.97	30.0	1.99E+0	0.00E+0	1.36E-1	2.09E-3	2.13E+0
30.90	32.0	1.81E+0	0.00E+0	8.19E-2	6.82E-4	1.90E+0
32.83	34.0	1.61E+0	0.00E+0	4.49E-2	2.03E-4	1.65E+0
34.76	36.0	1.38E+0	0.00E+0	2.10E-2	5.36E-5	1.40E+0
36.69	38.0	1.12E+0	0.00E+0	7.30E-3	1.21E-5	1.13E+0
38.62	40.0	8.38E-1	0.00E+0	1.48E-3	2.41E-6	8.39E-1
40.55	42.0	5.66E-1	0.00E+0	0.00E+0	4.76E-7	5.66E-1
sums		6.60E+1	0.00E+0	5.34E+1	6.18E+1	1.81E+2

54Fe+alpha at 59 MeV
Particle Spectra (mb/MeV) z= 1 n= 2

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	equil --	sum
3.79	4.0	3.40E-2	0.00E+0	2.24E-1	2.99E-1	5.57E-1
5.69	6.0	1.49E-1	0.00E+0	5.75E-1	6.45E-1	1.37E+0
7.59	8.0	2.70E-1	0.00E+0	6.00E-1	5.62E-1	1.43E+0
9.48	10.0	3.76E-1	0.00E+0	4.79E-1	3.68E-1	1.22E+0
11.38	12.0	4.67E-1	0.00E+0	3.42E-1	2.10E-1	1.02E+0
13.28	14.0	5.47E-1	0.00E+0	2.33E-1	1.10E-1	8.89E-1
15.17	16.0	6.15E-1	0.00E+0	1.56E-1	5.33E-2	8.24E-1
17.07	18.0	6.74E-1	0.00E+0	1.05E-1	2.43E-2	8.03E-1
18.97	20.0	7.24E-1	0.00E+0	7.13E-2	1.04E-2	8.06E-1
20.86	22.0	7.69E-1	0.00E+0	4.92E-2	4.18E-3	8.22E-1
22.76	24.0	8.08E-1	0.00E+0	3.41E-2	1.57E-3	8.44E-1
24.66	26.0	8.45E-1	0.00E+0	2.34E-2	5.44E-4	8.69E-1
26.55	28.0	8.81E-1	0.00E+0	1.56E-2	1.73E-4	8.97E-1
28.45	30.0	9.17E-1	0.00E+0	9.86E-3	4.89E-5	9.27E-1
30.34	32.0	9.55E-1	0.00E+0	5.64E-3	1.20E-5	9.60E-1
32.24	34.0	9.95E-1	0.00E+0	2.57E-3	2.55E-6	9.98E-1
34.14	36.0	1.04E+0	0.00E+0	6.38E-4	5.34E-7	1.04E+0
36.03	38.0	1.80E+0	0.00E+0	0.00E+0	1.11E-7	1.80E+0
sums		2.57E+1	0.00E+0	5.85E+0	4.58E+0	3.62E+1

54Fe+alpha at 59 MeV
Particle Spectra (mb/MeV) z= 2 n= 2

eps cm	eps-- chan--	direct nutra	knock --	--exciton--	--	equil --	--	sum
5.59	6.0	1.13E-2	1.81E-2	1.49E-1		9.65E-1		1.14E+0
7.45	8.0	1.25E-1	2.06E-1	1.16E+0		5.92E+0		7.41E+0
9.31	10.0	3.68E-1	6.25E-1	2.38E+0		9.53E+0		1.29E+1
11.17	12.0	6.72E-1	1.17E+0	2.96E+0		9.37E+0		1.42E+1
13.03	14.0	9.25E-1	1.66E+0	2.71E+0		6.85E+0		1.21E+1
14.90	16.0	1.13E+0	2.08E+0	2.16E+0		4.37E+0		9.75E+0
16.76	18.0	1.30E+0	2.45E+0	1.58E+0		2.57E+0		7.90E+0
18.62	20.0	1.43E+0	2.79E+0	1.07E+0		1.42E+0		6.71E+0
20.48	22.0	1.53E+0	3.08E+0	6.92E-1		7.47E-1		6.05E+0
22.34	24.0	1.60E+0	3.30E+0	4.24E-1		3.75E-1		5.69E+0
24.21	26.0	1.64E+0	3.42E+0	2.49E-1		1.81E-1		5.49E+0
26.07	28.0	1.65E+0	3.45E+0	1.41E-1		8.34E-2		5.32E+0
27.93	30.0	1.64E+0	3.43E+0	7.76E-2		3.68E-2		5.18E+0
29.79	32.0	1.60E+0	3.40E+0	4.22E-2		1.55E-2		5.05E+0
31.66	34.0	1.53E+0	3.43E+0	2.31E-2		6.23E-3		4.99E+0
33.52	36.0	1.44E+0	3.49E+0	1.30E-2		2.36E-3		4.95E+0
35.38	38.0	1.32E+0	3.40E+0	7.63E-3		8.40E-4		4.74E+0
37.24	40.0	1.19E+0	3.05E+0	4.68E-3		2.77E-4		4.24E+0
39.10	42.0	1.04E+0	2.65E+0	3.00E-3		8.31E-5		3.69E+0
40.97	44.0	8.82E-1	2.43E+0	1.97E-3		2.22E-5		3.31E+0
42.83	46.0	7.04E-1	2.36E+0	1.31E-3		5.08E-6		3.06E+0
44.69	48.0	5.13E-1	2.17E+0	8.50E-4		1.06E-6		2.68E+0
46.55	50.0	3.04E-1	1.58E+0	4.79E-4		2.21E-7		1.89E+0
48.41	52.0	5.32E-2	1.33E+0	1.03E-4		4.59E-8		1.38E+0
50.28	54.0	0.00E+0	9.30E-1	0.00E+0		9.51E-9		9.30E-1
52.14	56.0	0.00E+0	1.69E-1	0.00E+0		0.00E+0		1.69E-1
54.00	58.0	0.00E+0	6.52E-3	0.00E+0		0.00E+0		6.52E-3
55.86	60.0	0.00E+0	4.27E-5	0.00E+0		0.00E+0		4.27E-5
sums		4.92E+1	1.16E+2	3.17E+1		8.49E+1		2.82E+2

C.6. Extra output from Problem 1 when ihfp=1

```
54Fe+p at 28.8 MeV -- default parameters

Cross Sect in C.N. =  450.7 mb;   Energy =  33.5 MeV

Primary residual cross section after preeq emission
```

	Neutron-Residual		Proton-Residual		Deuteron-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.84E+1	4.65E+0	2.75E+1	1.81E-2	1.63E+1	0.00E+0
2.0	1.74E+1	6.69E+0	2.65E+1	3.95E-1	1.53E+1	0.00E+0
3.0	1.64E+1	7.46E+0	2.55E+1	2.74E+0	1.43E+1	1.31E-1
4.0	1.54E+1	7.58E+0	2.45E+1	8.71E+0	1.33E+1	6.43E-1
5.0	1.44E+1	7.37E+0	2.35E+1	1.55E+1	1.23E+1	1.20E+0
6.0	1.34E+1	7.03E+0	2.25E+1	2.08E+1	1.13E+1	1.69E+0
7.0	1.24E+1	6.66E+0	2.15E+1	2.47E+1	1.03E+1	1.97E+0
8.0	1.14E+1	6.24E+0	2.05E+1	2.60E+1	9.29E+0	2.16E+0
9.0	1.04E+1	5.81E+0	1.95E+1	2.60E+1	8.29E+0	2.30E+0
10.0	9.42E+0	5.38E+0	1.85E+1	2.55E+1	7.29E+0	2.43E+0
11.0	8.42E+0	4.95E+0	1.75E+1	2.47E+1	6.29E+0	2.56E+0
12.0	7.42E+0	4.50E+0	1.65E+1	2.35E+1	5.29E+0	2.71E+0
13.0	6.42E+0	3.99E+0	1.54E+1	2.22E+1	4.29E+0	2.89E+0
14.0	5.42E+0	3.50E+0	1.44E+1	2.06E+1	3.29E+0	3.06E+0
15.0	4.42E+0	2.98E+0	1.34E+1	1.91E+1	2.29E+0	3.28E+0
16.0	3.42E+0	2.39E+0	1.24E+1	1.77E+1	1.29E+0	3.54E+0
17.0	2.42E+0	1.93E+0	1.14E+1	1.65E+1	2.90E-1	0.00E+0
18.0	1.42E+0	6.78E-1	1.04E+1	1.57E+1	0.00E+0	0.00E+0
19.0	4.20E-1	4.05E-1	9.45E+0	1.51E+1	0.00E+0	0.00E+0
20.0	0.00E+0	0.00E+0	8.45E+0	1.46E+1	0.00E+0	0.00E+0
21.0	0.00E+0	0.00E+0	7.45E+0	1.36E+1	0.00E+0	0.00E+0
22.0	0.00E+0	0.00E+0	6.45E+0	1.20E+1	0.00E+0	0.00E+0
23.0	0.00E+0	0.00E+0	5.45E+0	1.01E+1	0.00E+0	0.00E+0
24.0	0.00E+0	0.00E+0	4.45E+0	8.20E+0	0.00E+0	0.00E+0
25.0	0.00E+0	0.00E+0	3.45E+0	6.09E+0	0.00E+0	0.00E+0
26.0	0.00E+0	0.00E+0	2.45E+0	5.22E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	1.45E+0	4.13E+0	0.00E+0	0.00E+0

	Triton-Residual		3He-Residual		Alpha-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.19E+1	0.00E+0	1.43E+1	0.00E+0	2.43E+1	0.00E+0
2.0	1.09E+1	0.00E+0	1.33E+1	0.00E+0	2.33E+1	0.00E+0
3.0	9.87E+0	5.86E-3	1.23E+1	0.00E+0	2.23E+1	0.00E+0
4.0	8.87E+0	4.58E-2	1.13E+1	0.00E+0	2.13E+1	0.00E+0
5.0	7.87E+0	9.37E-2	1.03E+1	0.00E+0	2.03E+1	0.00E+0
6.0	6.87E+0	1.39E-1	9.26E+0	0.00E+0	1.93E+1	1.28E-1
7.0	5.87E+0	1.63E-1	8.26E+0	5.53E-2	1.83E+1	3.86E-1
8.0	4.87E+0	1.71E-1	7.26E+0	1.32E-1	1.73E+1	7.03E-1
9.0	3.87E+0	1.60E-1	6.26E+0	1.91E-1	1.63E+1	1.05E+0
10.0	2.87E+0	1.39E-1	5.26E+0	2.36E-1	1.53E+1	1.40E+0
11.0	1.87E+0	0.00E+0	4.26E+0	2.59E-1	1.43E+1	1.63E+0
12.0	8.70E-1	0.00E+0	3.26E+0	2.52E-1	1.33E+1	1.73E+0
13.0	0.00E+0	0.00E+0	2.26E+0	2.41E-1	1.23E+1	1.74E+0
14.0	0.00E+0	0.00E+0	1.26E+0	1.85E-1	1.13E+1	1.67E+0
15.0	0.00E+0	0.00E+0	2.60E-1	0.00E+0	1.03E+1	1.55E+0
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.30E+0	1.40E+0
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.30E+0	1.22E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.30E+0	1.02E+0
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.30E+0	8.14E-1
20.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.30E+0	6.10E-1
21.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.30E+0	3.99E-1
22.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.30E+0	2.31E-1
23.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.30E+0	6.37E-2
24.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.30E+0	3.77E-2
25.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.00E-1	0.00E+0
26.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Secondary residuals; kpp=1,2,3 for nn,np,pp

Final excitation energy (MeV), kpp=1

e1\e2=	1.0	2.0	3.0	4.0	5.0
1.0	4.42E+0	3.42E+0	2.42E+0	1.42E+0	4.20E-1
2.0	3.42E+0	2.42E+0	1.42E+0	4.20E-1	0.00E+0
3.0	2.42E+0	1.42E+0	4.20E-1	0.00E+0	0.00E+0
4.0	1.42E+0	4.20E-1	0.00E+0	0.00E+0	0.00E+0
5.0	4.20E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=1

e1\e2=	1.0	2.0	3.0	4.0	5.0
1.0	7.47E-5	0.00E+0	0.00E+0	0.00E+0	0.00E+0
2.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
3.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
4.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
5.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=2

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	1.31E+1	1.21E+1	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0
2.0	1.21E+1	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0
3.0	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0
4.0	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0
5.0	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0
6.0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0
7.0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2
8.0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0
9.0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0
10.0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0
11.0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
12.0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
13.0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
14.0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=2

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	8.88E-5	9.84E-4	5.46E-3	1.46E-2	2.15E-2	2.43E-2	2.49E-2	2.28E-2
2.0	6.33E-4	2.10E-3	8.75E-3	2.18E-2	3.21E-2	3.68E-2	3.82E-2	3.57E-2
3.0	3.75E-3	6.14E-3	1.34E-2	2.77E-2	3.94E-2	4.50E-2	4.71E-2	4.83E-2
4.0	1.17E-2	1.60E-2	2.32E-2	3.71E-2	4.85E-2	5.40E-2	6.09E-2	6.09E-2
5.0	2.07E-2	2.78E-2	3.51E-2	4.78E-2	5.83E-2	6.88E-2	7.44E-2	7.99E-2
6.0	2.83E-2	3.79E-2	4.53E-2	5.72E-2	7.26E-2	8.16E-2	9.38E-2	1.21E-1
7.0	3.45E-2	4.64E-2	5.43E-2	7.08E-2	8.46E-2	1.00E-1	1.39E-1	0.00E+0
8.0	3.69E-2	5.02E-2	6.31E-2	7.84E-2	9.89E-2	1.42E-1	0.00E+0	0.00E+0
9.0	3.72E-2	5.55E-2	6.79E-2	8.88E-2	1.37E-1	0.00E+0	0.00E+0	0.00E+0
10.0	3.94E-2	5.76E-2	7.53E-2	1.20E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
11.0	3.95E-2	6.24E-2	1.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
12.0	4.16E-2	8.21E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
13.0	5.44E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
14.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=2

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0
1.0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2
2.0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0
3.0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0
4.0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0
5.0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
6.0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=2

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0
1.0	2.02E-2	1.89E-2	1.73E-2	1.69E-2	1.90E-2	0.00E+0
2.0	3.46E-2	3.22E-2	3.18E-2	3.64E-2	0.00E+0	0.00E+0
3.0	4.61E-2	4.65E-2	5.43E-2	0.00E+0	0.00E+0	0.00E+0
4.0	6.29E-2	7.52E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
5.0	9.85E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
6.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	1.76E+1	1.66E+1	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1
2.0	1.66E+1	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0
3.0	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0
4.0	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0
5.0	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0
6.0	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0
7.0	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0
8.0	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0
9.0	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0
10.0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0
11.0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1
12.0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0
13.0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0
14.0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0
15.0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
16.0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
17.0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
18.0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=3

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	6.88E-8	1.64E-6	8.85E-6	2.10E-5	2.92E-5	3.21E-5	3.15E-5	2.79E-5
2.0	1.48E-6	3.50E-5	1.88E-4	4.47E-4	6.27E-4	6.99E-4	7.01E-4	6.26E-4
3.0	1.02E-5	2.39E-4	1.29E-3	3.07E-3	4.36E-3	4.96E-3	5.01E-3	4.55E-3
4.0	3.23E-5	7.53E-4	4.06E-3	9.81E-3	1.42E-2	1.63E-2	1.67E-2	1.56E-2
5.0	5.68E-5	1.32E-3	7.19E-3	1.77E-2	2.58E-2	3.00E-2	3.17E-2	2.98E-2
6.0	7.51E-5	1.76E-3	9.74E-3	2.41E-2	3.56E-2	4.27E-2	4.52E-2	4.35E-2
7.0	8.32E-5	2.06E-3	1.16E-2	2.91E-2	4.42E-2	5.30E-2	5.75E-2	5.83E-2
8.0	8.84E-5	2.15E-3	1.21E-2	3.13E-2	4.75E-2	5.83E-2	6.66E-2	6.97E-2
9.0	8.65E-5	2.10E-3	1.22E-2	3.13E-2	4.86E-2	6.28E-2	7.39E-2	8.29E-2
10.0	8.14E-5	2.03E-3	1.17E-2	3.06E-2	5.00E-2	6.64E-2	8.38E-2	1.03E-1
11.0	7.66E-5	1.89E-3	1.10E-2	3.05E-2	5.11E-2	7.27E-2	1.02E-1	1.35E-1
12.0	6.95E-5	1.74E-3	1.07E-2	3.03E-2	5.44E-2	8.63E-2	1.31E-1	0.00E+0
13.0	6.33E-5	1.66E-3	1.05E-2	3.19E-2	6.43E-2	0.00E+0	0.00E+0	0.00E+0
14.0	5.87E-5	1.58E-3	1.06E-2	3.64E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
15.0	5.49E-5	1.55E-3	1.19E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
16.0	5.23E-5	1.71E-3	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
17.0	5.64E-5	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
1.0	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0
2.0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0
3.0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1
4.0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0
5.0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0
6.0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0
7.0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
8.0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
9.0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
10.0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=3

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
1.0	2.35E-5	1.95E-5	1.62E-5	1.35E-5	1.14E-5	1.00E-5	9.13E-6	8.81E-6
2.0	5.37E-4	4.58E-4	3.85E-4	3.28E-4	2.92E-4	2.67E-4	2.59E-4	2.68E-4
3.0	4.02E-3	3.45E-3	2.98E-3	2.68E-3	2.47E-3	2.41E-3	2.51E-3	2.73E-3
4.0	1.38E-2	1.22E-2	1.11E-2	1.04E-2	1.02E-2	1.07E-2	1.17E-2	0.00E+0
5.0	2.71E-2	2.52E-2	2.38E-2	2.36E-2	2.51E-2	2.78E-2	0.00E+0	0.00E+0
6.0	4.18E-2	4.02E-2	4.05E-2	4.35E-2	4.88E-2	0.00E+0	0.00E+0	0.00E+0
7.0	5.78E-2	5.95E-2	6.51E-2	7.41E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
8.0	7.40E-2	8.30E-2	9.66E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
9.0	9.64E-2	1.15E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
10.0	1.29E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	17.0	18.0
1.0	1.60E+0	6.00E-1
2.0	6.00E-1	0.00E+0

Cross section (mb), kpp=3

e1\e2=	17.0	18.0
1.0	9.07E-6	9.73E-6
2.0	2.89E-4	0.00E+0

C.7. Extra output from Problem 1 when ihfp=-1

```
54Fe+p at 28.8 MeV -- default parameters

Cross Sect in C.N. =  450.7 mb;   Energy =  33.5 MeV

Primary residual cross section after preeq emission
```

	Neutron-Residual		Proton-Residual		Deuteron-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.84E+1	4.65E+0	2.75E+1	1.81E-2	1.63E+1	0.00E+0
2.0	1.74E+1	6.69E+0	2.65E+1	3.95E-1	1.53E+1	0.00E+0
3.0	1.64E+1	7.46E+0	2.55E+1	2.74E+0	1.43E+1	1.31E-1
4.0	1.54E+1	7.58E+0	2.45E+1	8.71E+0	1.33E+1	6.43E-1
5.0	1.44E+1	7.37E+0	2.35E+1	1.55E+1	1.23E+1	1.20E+0
6.0	1.34E+1	7.03E+0	2.25E+1	2.08E+1	1.13E+1	1.69E+0
7.0	1.24E+1	6.66E+0	2.15E+1	2.47E+1	1.03E+1	1.97E+0
8.0	1.14E+1	6.24E+0	2.05E+1	2.60E+1	9.29E+0	2.16E+0
9.0	1.04E+1	5.81E+0	1.95E+1	2.60E+1	8.29E+0	2.30E+0
10.0	9.42E+0	5.38E+0	1.85E+1	2.55E+1	7.29E+0	2.43E+0
11.0	8.42E+0	4.95E+0	1.75E+1	2.47E+1	6.29E+0	2.56E+0
12.0	7.42E+0	4.50E+0	1.65E+1	2.35E+1	5.29E+0	2.71E+0
13.0	6.42E+0	3.99E+0	1.54E+1	2.22E+1	4.29E+0	2.89E+0
14.0	5.42E+0	3.50E+0	1.44E+1	2.06E+1	3.29E+0	3.06E+0
15.0	4.42E+0	2.98E+0	1.34E+1	1.91E+1	2.29E+0	3.28E+0
16.0	3.42E+0	2.39E+0	1.24E+1	1.77E+1	1.29E+0	3.54E+0
17.0	2.42E+0	1.93E+0	1.14E+1	1.65E+1	2.90E-1	0.00E+0
18.0	1.42E+0	6.78E-1	1.04E+1	1.57E+1	0.00E+0	0.00E+0
19.0	4.20E-1	4.05E-1	9.45E+0	1.51E+1	0.00E+0	0.00E+0
20.0	0.00E+0	0.00E+0	8.45E+0	1.46E+1	0.00E+0	0.00E+0
21.0	0.00E+0	0.00E+0	7.45E+0	1.36E+1	0.00E+0	0.00E+0
22.0	0.00E+0	0.00E+0	6.45E+0	1.20E+1	0.00E+0	0.00E+0
23.0	0.00E+0	0.00E+0	5.45E+0	1.01E+1	0.00E+0	0.00E+0
24.0	0.00E+0	0.00E+0	4.45E+0	8.20E+0	0.00E+0	0.00E+0
25.0	0.00E+0	0.00E+0	3.45E+0	6.09E+0	0.00E+0	0.00E+0
26.0	0.00E+0	0.00E+0	2.45E+0	5.22E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	1.45E+0	4.13E+0	0.00E+0	0.00E+0

	Triton-Residual		3He-Residual		Alpha-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.19E+1	0.00E+0	1.43E+1	0.00E+0	2.43E+1	0.00E+0
2.0	1.09E+1	0.00E+0	1.33E+1	0.00E+0	2.33E+1	0.00E+0
3.0	9.87E+0	5.86E-3	1.23E+1	0.00E+0	2.23E+1	0.00E+0
4.0	8.87E+0	4.58E-2	1.13E+1	0.00E+0	2.13E+1	0.00E+0
5.0	7.87E+0	9.37E-2	1.03E+1	0.00E+0	2.03E+1	0.00E+0
6.0	6.87E+0	1.39E-1	9.26E+0	0.00E+0	1.93E+1	1.28E-1
7.0	5.87E+0	1.63E-1	8.26E+0	5.53E-2	1.83E+1	3.86E-1
8.0	4.87E+0	1.71E-1	7.26E+0	1.32E-1	1.73E+1	7.03E-1
9.0	3.87E+0	1.60E-1	6.26E+0	1.91E-1	1.63E+1	1.05E+0
10.0	2.87E+0	1.39E-1	5.26E+0	2.36E-1	1.53E+1	1.40E+0
11.0	1.87E+0	0.00E+0	4.26E+0	2.59E-1	1.43E+1	1.63E+0
12.0	8.70E-1	0.00E+0	3.26E+0	2.52E-1	1.33E+1	1.73E+0
13.0	0.00E+0	0.00E+0	2.26E+0	2.41E-1	1.23E+1	1.74E+0
14.0	0.00E+0	0.00E+0	1.26E+0	1.85E-1	1.13E+1	1.67E+0
15.0	0.00E+0	0.00E+0	2.60E-1	0.00E+0	1.03E+1	1.55E+0
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.30E+0	1.40E+0
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.30E+0	1.22E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.30E+0	1.02E+0
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.30E+0	8.14E-1
20.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.30E+0	6.10E-1
21.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.30E+0	3.99E-1
22.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.30E+0	2.31E-1
23.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.30E+0	6.37E-2
24.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.30E+0	3.77E-2
25.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.00E-1	0.00E+0
26.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Secondary residuals; kpp=1,2,3 for nn,np,pp

	nn-Residual		np-Residual		pp-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
2.0	4.42E+0	7.47E-5	1.31E+1	8.88E-5	1.76E+1	6.88E-8
3.0	3.42E+0	0.00E+0	1.21E+1	1.62E-3	1.66E+1	3.12E-6
4.0	2.42E+0	0.00E+0	1.11E+1	1.13E-2	1.56E+1	5.41E-5
5.0	1.42E+0	0.00E+0	1.01E+1	4.12E-2	1.46E+1	4.81E-4
6.0	4.20E-1	0.00E+0	9.07E+0	9.34E-2	1.36E+1	2.57E-3
7.0	0.00E+0	0.00E+0	8.07E+0	1.63E-1	1.26E+1	9.19E-3
8.0	0.00E+0	0.00E+0	7.07E+0	2.46E-1	1.16E+1	2.39E-2
9.0	0.00E+0	0.00E+0	6.07E+0	3.31E-1	1.06E+1	4.95E-2
10.0	0.00E+0	0.00E+0	5.07E+0	4.14E-1	9.60E+0	8.56E-2
11.0	0.00E+0	0.00E+0	4.07E+0	5.33E-1	8.60E+0	1.31E-1
12.0	0.00E+0	0.00E+0	3.07E+0	6.40E-1	7.60E+0	1.84E-1
13.0	0.00E+0	0.00E+0	2.07E+0	7.99E-1	6.60E+0	2.38E-1
14.0	0.00E+0	0.00E+0	1.07E+0	1.18E+0	5.60E+0	2.94E-1
15.0	0.00E+0	0.00E+0	7.00E-2	0.00E+0	4.60E+0	3.62E-1
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.60E+0	4.39E-1
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.60E+0	5.48E-1
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.60E+0	7.32E-1
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.00E-1	7.73E-1

C.8. Extra output from Problem 1 when ihfp=2

```
54Fe+p at 28.8 MeV -- default parameters

Production cross sections (mb) in the channels:
n,p,d,t,h,a: 1.204E+01 1.053E+02 3.720E+01 1.012E+00 1.943E+00 7.407E+01
nn,np,pp:    1.435E+00 3.598E+02 4.065E+02

Primary residual cross section after all emission
```

	Neutron-Residual		Proton-Residual		Deuteron-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.84E+1	0.00E+0	2.75E+1	0.00E+0	1.63E+1	0.00E+0
2.0	1.74E+1	0.00E+0	2.65E+1	0.00E+0	1.53E+1	0.00E+0
3.0	1.64E+1	0.00E+0	2.55E+1	0.00E+0	1.43E+1	4.04E-1
4.0	1.54E+1	0.00E+0	2.45E+1	0.00E+0	1.33E+1	1.68E+0
5.0	1.44E+1	0.00E+0	2.35E+1	0.00E+0	1.23E+1	2.60E+0
6.0	1.34E+1	0.00E+0	2.25E+1	0.00E+0	1.13E+1	3.05E+0
7.0	1.24E+1	0.00E+0	2.15E+1	0.00E+0	1.03E+1	3.00E+0
8.0	1.14E+1	0.00E+0	2.05E+1	0.00E+0	9.29E+0	2.84E+0
9.0	1.04E+1	0.00E+0	1.95E+1	0.00E+0	8.29E+0	2.70E+0
10.0	9.42E+0	0.00E+0	1.85E+1	0.00E+0	7.29E+0	2.65E+0
11.0	8.42E+0	0.00E+0	1.75E+1	0.00E+0	6.29E+0	2.68E+0
12.0	7.42E+0	0.00E+0	1.65E+1	0.00E+0	5.29E+0	2.76E+0
13.0	6.42E+0	0.00E+0	1.54E+1	0.00E+0	4.29E+0	2.92E+0
14.0	5.42E+0	3.58E+0	1.44E+1	0.00E+0	3.29E+0	3.08E+0
15.0	4.42E+0	3.02E+0	1.34E+1	0.00E+0	2.29E+0	3.29E+0
16.0	3.42E+0	2.41E+0	1.24E+1	0.00E+0	1.29E+0	3.55E+0
17.0	2.42E+0	1.94E+0	1.14E+1	0.00E+0	2.90E-1	1.72E-3
18.0	1.42E+0	6.81E-1	1.04E+1	1.60E+1	0.00E+0	0.00E+0
19.0	4.20E-1	4.07E-1	9.45E+0	1.53E+1	0.00E+0	0.00E+0
20.0	0.00E+0	0.00E+0	8.45E+0	1.46E+1	0.00E+0	0.00E+0
21.0	0.00E+0	0.00E+0	7.45E+0	1.36E+1	0.00E+0	0.00E+0
22.0	0.00E+0	0.00E+0	6.45E+0	1.20E+1	0.00E+0	0.00E+0
23.0	0.00E+0	0.00E+0	5.45E+0	1.01E+1	0.00E+0	0.00E+0
24.0	0.00E+0	0.00E+0	4.45E+0	8.20E+0	0.00E+0	0.00E+0
25.0	0.00E+0	0.00E+0	3.45E+0	6.09E+0	0.00E+0	0.00E+0
26.0	0.00E+0	0.00E+0	2.45E+0	5.22E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	1.45E+0	4.13E+0	0.00E+0	0.00E+0

	Triton-Residual		3He-Residual		Alpha-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.19E+1	0.00E+0	1.43E+1	0.00E+0	2.43E+1	0.00E+0
2.0	1.09E+1	0.00E+0	1.33E+1	0.00E+0	2.33E+1	0.00E+0
3.0	9.87E+0	1.06E-2	1.23E+1	0.00E+0	2.23E+1	0.00E+0
4.0	8.87E+0	6.70E-2	1.13E+1	0.00E+0	2.13E+1	0.00E+0
5.0	7.87E+0	1.17E-1	1.03E+1	0.00E+0	2.03E+1	0.00E+0
6.0	6.87E+0	1.57E-1	9.26E+0	0.00E+0	1.93E+1	2.82E+0
7.0	5.87E+0	1.75E-1	8.26E+0	1.17E-1	1.83E+1	6.54E+0
8.0	4.87E+0	1.78E-1	7.26E+0	2.28E-1	1.73E+1	9.05E+0
9.0	3.87E+0	1.64E-1	6.26E+0	2.77E-1	1.63E+1	1.02E+1
10.0	2.87E+0	1.41E-1	5.26E+0	2.98E-1	1.53E+1	1.01E+1
11.0	1.87E+0	1.11E-3	4.26E+0	2.98E-1	1.43E+1	8.80E+0
12.0	8.70E-1	5.68E-4	3.26E+0	2.75E-1	1.33E+1	6.98E+0
13.0	0.00E+0	0.00E+0	2.26E+0	2.54E-1	1.23E+1	5.29E+0
14.0	0.00E+0	0.00E+0	1.26E+0	1.91E-1	1.13E+1	3.93E+0
15.0	0.00E+0	0.00E+0	2.60E-1	3.54E-3	1.03E+1	2.92E+0
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.30E+0	2.19E+0
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.30E+0	1.65E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.30E+0	1.25E+0
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.30E+0	9.27E-1
20.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.30E+0	6.66E-1
21.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.30E+0	4.27E-1
22.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.30E+0	2.44E-1
23.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.30E+0	7.03E-2
24.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.30E+0	4.09E-2
25.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.00E-1	1.53E-3
26.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Secondary residuals; kpp=1,2,3 for nn,np,pp

Final excitation energy (MeV), kpp=1

e1\e2=	1.0	2.0	3.0	4.0	5.0
1.0	4.42E+0	3.42E+0	2.42E+0	1.42E+0	4.20E-1
2.0	3.42E+0	2.42E+0	1.42E+0	4.20E-1	0.00E+0
3.0	2.42E+0	1.42E+0	4.20E-1	0.00E+0	0.00E+0
4.0	1.42E+0	4.20E-1	0.00E+0	0.00E+0	0.00E+0
5.0	4.20E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=1

e1\e2=	1.0	2.0	3.0	4.0	5.0
1.0	1.29E-1	1.11E-1	7.37E-2	4.36E-2	2.42E-2
2.0	1.50E-1	1.29E-1	8.57E-2	5.07E-2	0.00E+0
3.0	1.36E-1	1.18E-1	7.81E-2	0.00E+0	0.00E+0
4.0	1.14E-1	9.89E-2	0.00E+0	0.00E+0	0.00E+0
5.0	9.28E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=2

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	1.31E+1	1.21E+1	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0
2.0	1.21E+1	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0
3.0	1.11E+1	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0
4.0	1.01E+1	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0
5.0	9.07E+0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0
6.0	8.07E+0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0
7.0	7.07E+0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2
8.0	6.07E+0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0
9.0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0
10.0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0
11.0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
12.0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
13.0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
14.0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=2

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	3.86E-2	3.91E-1	1.89E+0	4.27E+0	5.16E+0	4.45E+0	3.21E+0	1.96E+0
2.0	2.41E-1	7.28E-1	2.67E+0	5.62E+0	6.49E+0	5.35E+0	3.76E+0	2.29E+0
3.0	1.33E+0	1.83E+0	3.50E+0	6.00E+0	6.37E+0	5.05E+0	3.52E+0	2.15E+0
4.0	3.81E+0	4.14E+0	4.87E+0	6.21E+0	5.93E+0	4.56E+0	3.13E+0	1.90E+0
5.0	6.08E+0	6.06E+0	5.74E+0	6.05E+0	5.39E+0	4.02E+0	2.72E+0	1.65E+0
6.0	7.22E+0	6.76E+0	5.80E+0	5.59E+0	4.77E+0	3.49E+0	2.35E+0	1.45E+0
7.0	7.37E+0	6.68E+0	5.53E+0	5.08E+0	4.21E+0	3.05E+0	2.07E+0	1.13E+0
8.0	6.57E+0	5.95E+0	4.92E+0	4.50E+0	3.73E+0	2.73E+0	1.70E+0	0.00E+0
9.0	5.65E+0	5.16E+0	4.35E+0	4.11E+0	3.50E+0	2.42E+0	0.00E+0	0.00E+0
10.0	4.87E+0	4.50E+0	4.03E+0	4.12E+0	3.48E+0	0.00E+0	0.00E+0	0.00E+0
11.0	4.32E+0	4.14E+0	4.25E+0	4.82E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
12.0	4.07E+0	4.41E+0	6.08E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
13.0	4.45E+0	7.31E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
14.0	4.93E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=2

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0
1.0	5.07E+0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2
2.0	4.07E+0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0
3.0	3.07E+0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0
4.0	2.07E+0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0
5.0	1.07E+0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0
6.0	7.00E-2	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=2

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0
1.0	1.11E+0	6.05E-1	3.23E-1	1.73E-1	9.71E-2	3.87E-2
2.0	1.31E+0	7.16E-1	3.88E-1	2.18E-1	9.11E-2	0.00E+0
3.0	1.23E+0	6.80E-1	3.84E-1	1.68E-1	0.00E+0	0.00E+0
4.0	1.09E+0	6.27E-1	2.87E-1	0.00E+0	0.00E+0	0.00E+0
5.0	9.74E-1	4.67E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
6.0	7.37E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	1.76E+1	1.66E+1	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1
2.0	1.66E+1	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0
3.0	1.56E+1	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0
4.0	1.46E+1	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0
5.0	1.36E+1	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0
6.0	1.26E+1	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0
7.0	1.16E+1	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0
8.0	1.06E+1	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0
9.0	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0
10.0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0
11.0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1
12.0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0
13.0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0
14.0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0
15.0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
16.0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
17.0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
18.0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=3

e1\e2=	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
1.0	3.63E-5	8.38E-4	4.32E-3	9.54E-3	1.20E-2	1.14E-2	9.25E-3	6.41E-3
2.0	7.99E-4	1.82E-2	9.21E-2	2.00E-1	2.45E-1	2.28E-1	1.81E-1	1.22E-1
3.0	5.63E-3	1.26E-1	6.26E-1	1.33E+0	1.60E+0	1.45E+0	1.11E+0	7.23E-1
4.0	1.82E-2	4.00E-1	1.95E+0	4.05E+0	4.73E+0	4.17E+0	3.09E+0	1.93E+0
5.0	3.29E-2	7.08E-1	3.37E+0	6.81E+0	7.73E+0	6.58E+0	4.69E+0	2.82E+0
6.0	4.46E-2	9.38E-1	4.35E+0	8.54E+0	9.36E+0	7.65E+0	5.26E+0	3.16E+0
7.0	5.31E-2	1.09E+0	4.90E+0	9.29E+0	9.78E+0	7.71E+0	5.29E+0	3.19E+0
8.0	5.52E-2	1.10E+0	4.77E+0	8.69E+0	8.81E+0	6.93E+0	4.76E+0	2.88E+0
9.0	5.36E-2	1.03E+0	4.30E+0	7.54E+0	7.64E+0	6.01E+0	4.14E+0	2.52E+0
10.0	5.03E-2	9.27E-1	3.73E+0	6.53E+0	6.62E+0	5.22E+0	3.60E+0	2.21E+0
11.0	4.65E-2	8.27E-1	3.32E+0	5.81E+0	5.89E+0	4.65E+0	3.23E+0	2.01E+0
12.0	4.37E-2	7.75E-1	3.11E+0	5.45E+0	5.53E+0	4.38E+0	3.06E+0	0.00E+0
13.0	4.52E-2	8.02E-1	3.22E+0	5.64E+0	5.73E+0	4.44E+0	0.00E+0	0.00E+0
14.0	5.55E-2	9.83E-1	3.94E+0	6.91E+0	6.95E+0	0.00E+0	0.00E+0	0.00E+0
15.0	9.77E-2	1.73E+0	6.94E+0	1.21E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
16.0	2.09E-1	3.70E+0	1.48E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
17.0	9.14E-1	1.62E+1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
1.0	9.60E+0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0
2.0	8.60E+0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0
3.0	7.60E+0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1
4.0	6.60E+0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0
5.0	5.60E+0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0
6.0	4.60E+0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0
7.0	3.60E+0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
8.0	2.60E+0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
9.0	1.60E+0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
10.0	6.00E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Cross section (mb), kpp=3

e1\e2=	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0
1.0	4.04E-3	2.36E-3	1.29E-3	6.67E-4	3.40E-4	1.74E-4	8.97E-5	4.81E-5
2.0	7.40E-2	4.16E-2	2.19E-2	1.14E-2	5.85E-3	3.03E-3	1.62E-3	9.32E-4
3.0	4.23E-1	2.29E-1	1.21E-1	6.31E-2	3.29E-2	1.76E-2	9.97E-3	6.37E-3
4.0	1.09E+0	5.92E-1	3.14E-1	1.65E-1	8.83E-2	4.95E-2	3.08E-2	0.00E+0
5.0	1.59E+0	8.68E-1	4.64E-1	2.49E-1	1.39E-1	8.42E-2	0.00E+0	0.00E+0
6.0	1.79E+0	9.81E-1	5.32E-1	2.95E-1	1.76E-1	0.00E+0	0.00E+0	0.00E+0
7.0	1.81E+0	1.00E+0	5.59E-1	3.27E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0
8.0	1.65E+0	9.31E-1	5.40E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
9.0	1.46E+0	8.50E-1	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
10.0	1.31E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Final excitation energy (MeV), kpp=3

e1\e2=	17.0	18.0
1.0	1.60E+0	6.00E-1
2.0	6.00E-1	0.00E+0

Cross section (mb), kpp=3

e1\e2=	17.0	18.0
1.0	2.81E-5	1.89E-5
2.0	6.11E-4	0.00E+0

C.9. Extra output from Problem 1 when ihfp=-2

```
54Fe+p at 28.8 MeV -- default parameters

Production cross sections (mb) in the channels:
n,p,d,t,h,a: 1.204E+01 1.053E+02 3.720E+01 1.012E+00 1.943E+00 7.407E+01
nn,np,pp:    1.435E+00 3.598E+02 4.065E+02

Primary residual cross section after all emission

      Neutron-Residual   Proton-Residual  Deuteron-Residual
 eps  U (MeV)  cs (mb)  U (MeV)  cs (mb)  U (MeV)cs (mb)
 1.0  1.84E+1  0.00E+0  2.75E+1  0.00E+0  1.63E+1  0.00E+0
 2.0  1.74E+1  0.00E+0  2.65E+1  0.00E+0  1.53E+1  0.00E+0
 3.0  1.64E+1  0.00E+0  2.55E+1  0.00E+0  1.43E+1  4.04E-1
 4.0  1.54E+1  0.00E+0  2.45E+1  0.00E+0  1.33E+1  1.68E+0
 5.0  1.44E+1  0.00E+0  2.35E+1  0.00E+0  1.23E+1  2.60E+0
 6.0  1.34E+1  0.00E+0  2.25E+1  0.00E+0  1.13E+1  3.05E+0
 7.0  1.24E+1  0.00E+0  2.15E+1  0.00E+0  1.03E+1  3.00E+0
 8.0  1.14E+1  0.00E+0  2.05E+1  0.00E+0  9.29E+0  2.84E+0
 9.0  1.04E+1  0.00E+0  1.95E+1  0.00E+0  8.29E+0  2.70E+0
10.0  9.42E+0  0.00E+0  1.85E+1  0.00E+0  7.29E+0  2.65E+0
11.0  8.42E+0  0.00E+0  1.75E+1  0.00E+0  6.29E+0  2.68E+0
12.0  7.42E+0  0.00E+0  1.65E+1  0.00E+0  5.29E+0  2.76E+0
13.0  6.42E+0  0.00E+0  1.54E+1  0.00E+0  4.29E+0  2.92E+0
14.0  5.42E+0  3.58E+0  1.44E+1  0.00E+0  3.29E+0  3.08E+0
15.0  4.42E+0  3.02E+0  1.34E+1  0.00E+0  2.29E+0  3.29E+0
16.0  3.42E+0  2.41E+0  1.24E+1  0.00E+0  1.29E+0  3.55E+0
17.0  2.42E+0  1.94E+0  1.14E+1  0.00E+0  2.90E-1  1.72E-3
18.0  1.42E+0  6.81E-1  1.04E+1  1.60E+1  0.00E+0  0.00E+0
19.0  4.20E-1  4.07E-1  9.45E+0  1.53E+1  0.00E+0  0.00E+0
20.0  0.00E+0  0.00E+0  8.45E+0  1.46E+1  0.00E+0  0.00E+0
21.0  0.00E+0  0.00E+0  7.45E+0  1.36E+1  0.00E+0  0.00E+0
22.0  0.00E+0  0.00E+0  6.45E+0  1.20E+1  0.00E+0  0.00E+0
23.0  0.00E+0  0.00E+0  5.45E+0  1.01E+1  0.00E+0  0.00E+0
24.0  0.00E+0  0.00E+0  4.45E+0  8.20E+0  0.00E+0  0.00E+0
25.0  0.00E+0  0.00E+0  3.45E+0  6.09E+0  0.00E+0  0.00E+0
26.0  0.00E+0  0.00E+0  2.45E+0  5.22E+0  0.00E+0  0.00E+0
27.0  0.00E+0  0.00E+0  1.45E+0  4.13E+0  0.00E+0  0.00E+0
```

	Triton-Residual		3He-Residual		Alpha-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
1.0	1.19E+1	0.00E+0	1.43E+1	0.00E+0	2.43E+1	0.00E+0
2.0	1.09E+1	0.00E+0	1.33E+1	0.00E+0	2.33E+1	0.00E+0
3.0	9.87E+0	1.06E-2	1.23E+1	0.00E+0	2.23E+1	0.00E+0
4.0	8.87E+0	6.70E-2	1.13E+1	0.00E+0	2.13E+1	0.00E+0
5.0	7.87E+0	1.17E-1	1.03E+1	0.00E+0	2.03E+1	0.00E+0
6.0	6.87E+0	1.57E-1	9.26E+0	0.00E+0	1.93E+1	2.82E+0
7.0	5.87E+0	1.75E-1	8.26E+0	1.17E-1	1.83E+1	6.54E+0
8.0	4.87E+0	1.78E-1	7.26E+0	2.28E-1	1.73E+1	9.05E+0
9.0	3.87E+0	1.64E-1	6.26E+0	2.77E-1	1.63E+1	1.02E+1
10.0	2.87E+0	1.41E-1	5.26E+0	2.98E-1	1.53E+1	1.01E+1
11.0	1.87E+0	1.11E-3	4.26E+0	2.98E-1	1.43E+1	8.80E+0
12.0	8.70E-1	5.68E-4	3.26E+0	2.75E-1	1.33E+1	6.98E+0
13.0	0.00E+0	0.00E+0	2.26E+0	2.54E-1	1.23E+1	5.29E+0
14.0	0.00E+0	0.00E+0	1.26E+0	1.91E-1	1.13E+1	3.93E+0
15.0	0.00E+0	0.00E+0	2.60E-1	3.54E-3	1.03E+1	2.92E+0
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	9.30E+0	2.19E+0
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.30E+0	1.65E+0
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	7.30E+0	1.25E+0
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.30E+0	9.27E-1
20.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	5.30E+0	6.66E-1
21.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	4.30E+0	4.27E-1
22.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.30E+0	2.44E-1
23.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.30E+0	7.03E-2
24.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.30E+0	4.09E-2
25.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.00E-1	1.53E-3
26.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
27.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0

Secondary residuals; kpp=1,2,3 for nn,np,pp

	nn-Residual		np-Residual		pp-Residual	
eps	U (MeV)	cs (mb)	U (MeV)	cs (mb)	U (MeV)	cs (mb)
2.0	4.42E+0	1.29E-1	1.31E+1	3.86E-2	1.76E+1	3.63E-5
3.0	3.42E+0	2.61E-1	1.21E+1	6.32E-1	1.66E+1	1.64E-3
4.0	2.42E+0	3.39E-1	1.11E+1	3.95E+0	1.56E+1	2.81E-2
5.0	1.42E+0	3.62E-1	1.01E+1	1.26E+1	1.46E+1	2.46E-1
6.0	4.20E-1	3.45E-1	9.07E+0	2.45E+1	1.36E+1	1.27E+0
7.0	0.00E+0	0.00E+0	8.07E+0	3.51E+1	1.26E+1	4.29E+0
8.0	0.00E+0	0.00E+0	7.07E+0	4.10E+1	1.16E+1	1.02E+1
9.0	0.00E+0	0.00E+0	6.07E+0	4.18E+1	1.06E+1	1.87E+1
10.0	0.00E+0	0.00E+0	5.07E+0	3.96E+1	9.60E+0	2.77E+1
11.0	0.00E+0	0.00E+0	4.07E+0	3.60E+1	8.60E+0	3.50E+1
12.0	0.00E+0	0.00E+0	3.07E+0	3.23E+1	7.60E+0	3.85E+1
13.0	0.00E+0	0.00E+0	2.07E+0	2.95E+1	6.60E+0	3.81E+1
14.0	0.00E+0	0.00E+0	1.07E+0	2.93E+1	5.60E+0	3.60E+1
15.0	0.00E+0	0.00E+0	7.00E-2	3.37E+1	4.60E+0	3.34E+1
16.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.60E+0	3.13E+1
17.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.60E+0	3.14E+1
18.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.60E+0	3.75E+1
19.0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	6.00E-1	6.29E+1