Lawrence Berkeley National Laboratory
Nuclear Sceince Division

Tungsten capture γ-ray analysis

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roving the neutron-capture γ-ray spectrum

oal

Improve and build upon spectrum of known W γ rays in neutron data libraries

Improvements to the **Evaluated Gamma-ray Activation File** (EGAF) and **Evaluated uclear Structure Data File** (ENSDF) databases: clarification of nuclear structural roblems

Changes to the ENSDF file will also be reflected in other databases: **Reference Input arameter Library** (RIPL)

ethod

Use the statistical-decay code DICEBOX to model thermal-capture γ cascade and tune put parameters to experimental data from the Evaluated Gamma-ray Activation File EGAF)

Ensure DICEBOX input files are consistent the latest developments in the Evaluated uclear Structure Data File (ENSDF) – and beyond?

eliverables

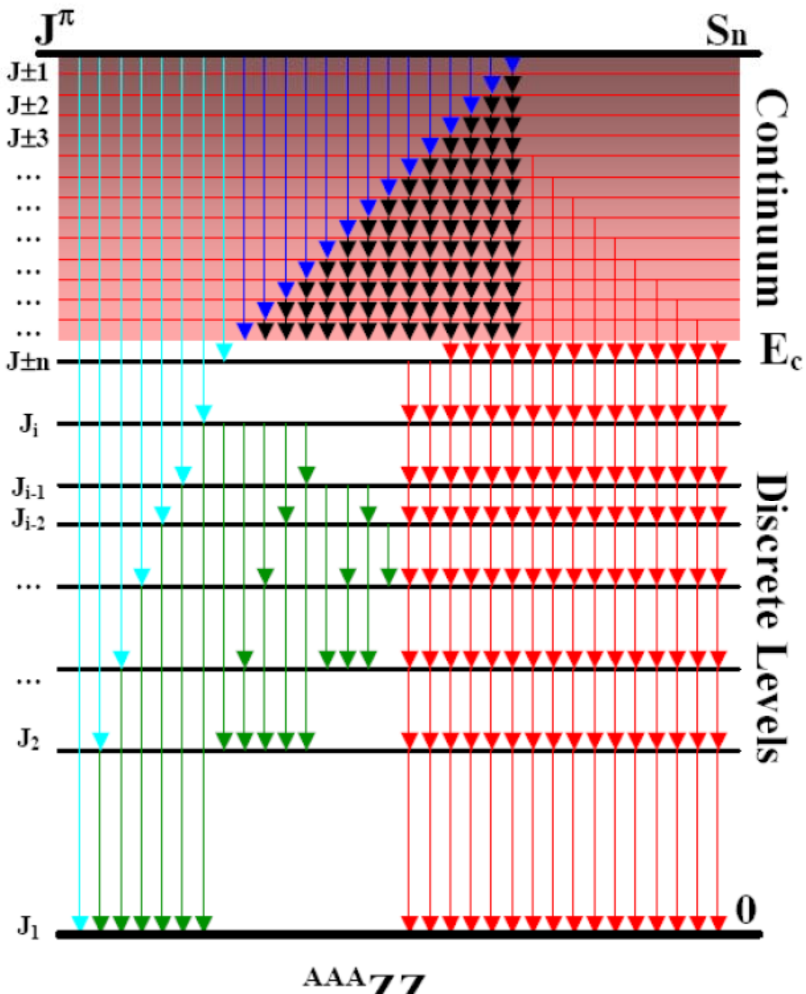
Improved γ-ray spectra and level schemes: new γ rays; new levels; clarification of nuclear ructure issues

Improved EGAF, ENSDF, RIPL (and ENDF) evaluations with primary γ rays

Total radiative thermal neutron-capture cross sections

nulations of γ-ray cascades following the rmal neutron-capture process

DICEBOX Monte Carlo Code



DICEBOX generates (n,γ) level scheme simulations (nuclear realizations) based on statistical model level densities $\rho(E_i,J^\pi_i)$ and γ-ray transition probabilities Γ_{if} where

a) All levels and γ-rays below E_{crit} are taken from experiment.

b) All levels and γ-rays above E_{crit} are generated randomly from level density and PSF models

c) Primary γ-ray cross sections are taken from experiment when known.

Typically 30,000 capture state γ-ray decay cascades are randomly generated for each nuclear realization.

50 separate realizations are usually averaged to get the statistical variation in the simulated level feedings.

tical energy / cut-off energy

eaction-model calculations (DICEBOX): complete discrete level schemes @ excitation energy; specify all possible outgoing reaction channels and test el-density models (which replace discrete levels in the quasicontinuum higher-excitation energy)

ompleteness: specified energy and spin window within which all levels are aracterized by unique energy, spin and parity values, and all γ- and particle- cay branches are known

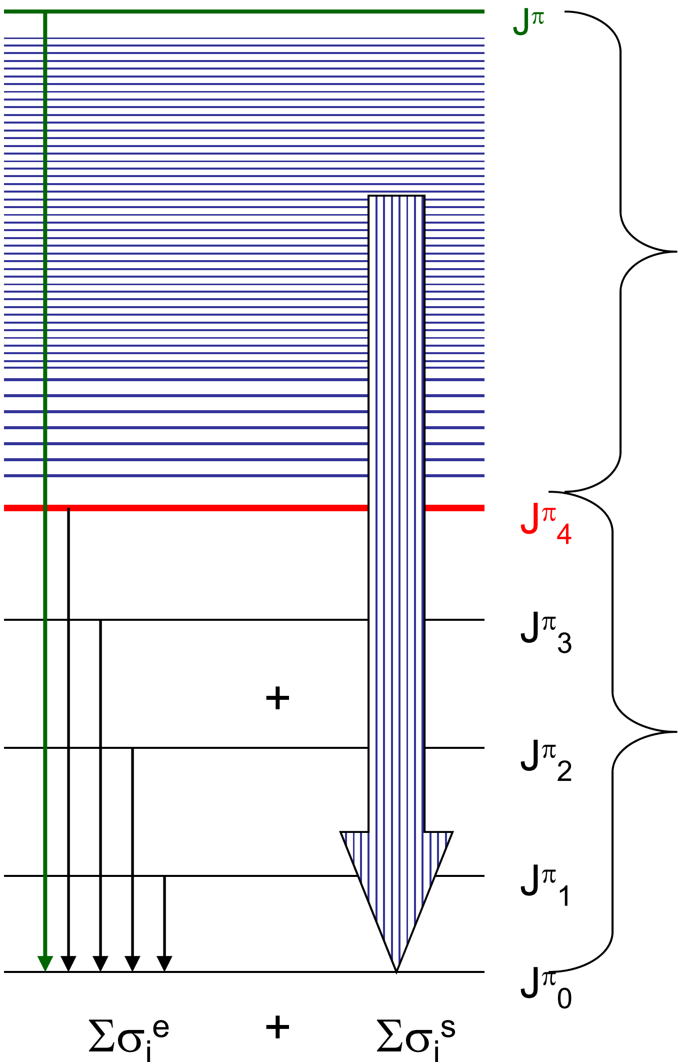
esults for W evaluations presented according to a defined upper-energy limit : (i) the ***critical energy*** E_{crit}; (ii) the ***cut-off energy*** E_c

$_{crit}$: upper-energy limit of levels characterized by ***unique*** spin and parity where γ-ray branching is known

$_c$: an empirically-determined maximum cut-off energy below which all level heme information is either ***complete*** or has only a ***very weak influence*** on the culation

egree of completeness varies largely over nuclear landscape: E_{crit} and E_c must defined separately on an individual isotope basis

al capture cross section



- New thermal neutron capture cross sections, σ_0
- Sum of
  - Measured experimental gamma cross sections which feed the ground state (primary+feeding below E_{crit}) ($\Sigma\sigma_i^e$)
  - Modeled population feeding from continuum to ground state ($\Sigma\sigma_j^s$)
- $\sigma_0 = \Sigma\sigma_i^e + \Sigma\sigma_j^s$

luation of the W isotopes

ble tungsten occurs naturally in 5 isotopic forms:

- ^{180}W (0.12%) very little (n,γ) information, not considered in evaluation
- ^{182}W (26.50%)
- ^{183}W (14.31%)
- ^{184}W (30.64%)
- ^{186}W (28.43%)

Stable $^{182-186}W$ all have large natural abundances, therefore, evaluation is needed for all isotopes

r all W data evaluations:

consider compound system i.e. $^{A}W(n,\gamma)^{A+1}W$
^{A+1}W is the compound system

calculations assuming 10 nuclear realizations, with 100,000 capture-state γ-ray decay cascades generated per realization

EBOX: simulation cf. experiment

CEBOX calculates theoretical level feedings to all excited states in the input file

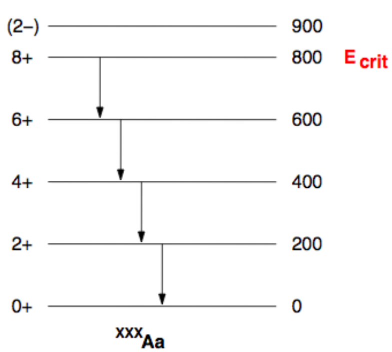
mulated populations (P_S) can then be compared to measured experimental depopulations

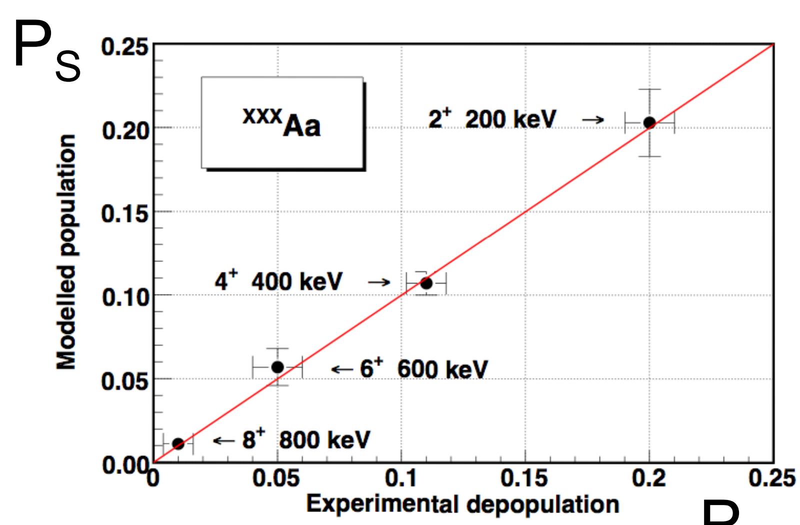
$_E$=$P_S \Rightarrow$ statistical model accurately describes nuclear properties

nsider hypothetical nucleus ^{XXX}Aa: 4 excited states in rotational sequence; E_{crit}=800 keV

tical energy (Ecrit): highest level where all structure information (γ branching, J^{π}) is known

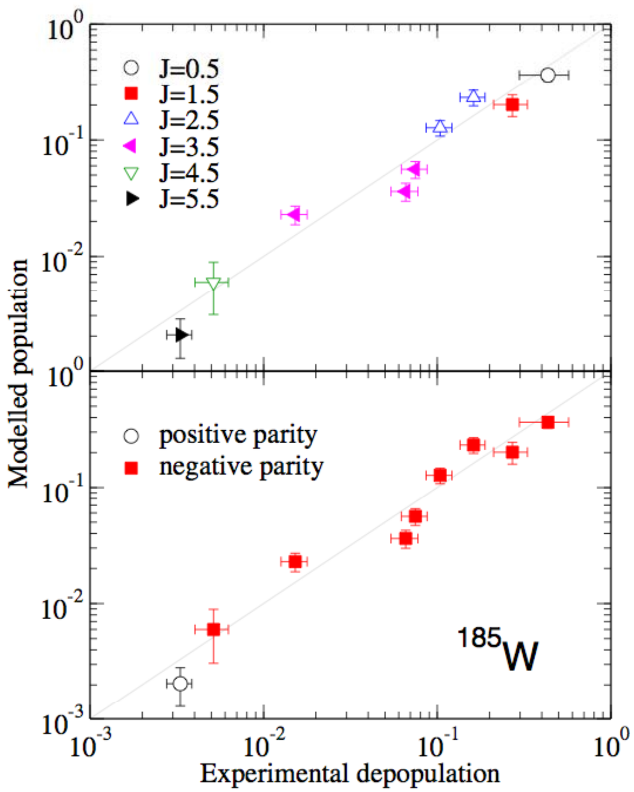
reasing transition probability upon descending band as consequence of decay process i.e. rger γ-decay branch is observed from states with decreasing excitation energy





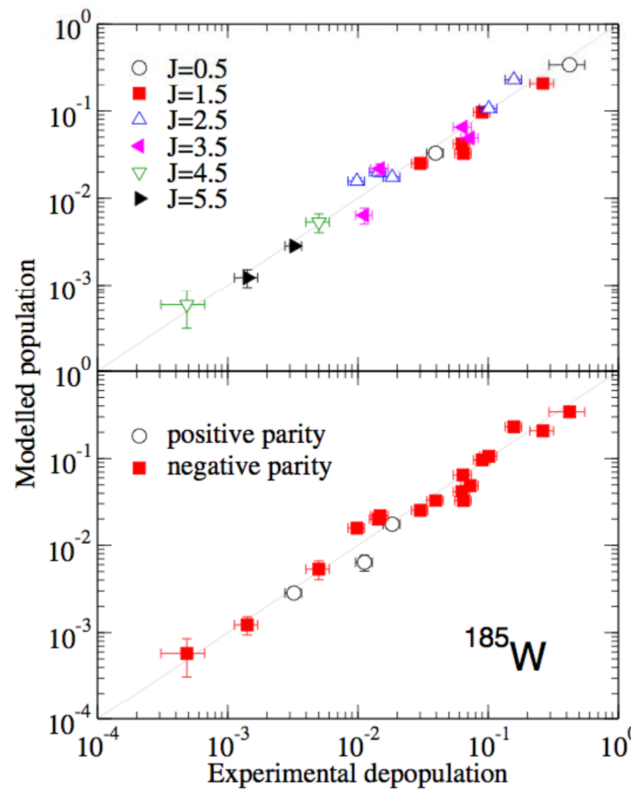
W capture-γ analysis: E_{crit} Vs E_c

E_{crit} = 332.1 keV; N = 10



- E_{crit}: 243 keV (RIPL) → 332 keV (EGAF)
- 9 new γ rays placed in level scheme
- ($13/2^+$) isomer @ 384 keV prevents rasing E_{crit}

E_c = 827.1 keV; N = 28



- E_c: 332 keV → 827 keV
- 36 new γ rays placed in level scheme
- 3 new levels placed in level scheme

V results: improving the RIPL file

firmation/determination of
ive J^{π} assignments

/ with E_c @ 827 keV:
v-lying levels; 14 with (J^{π})

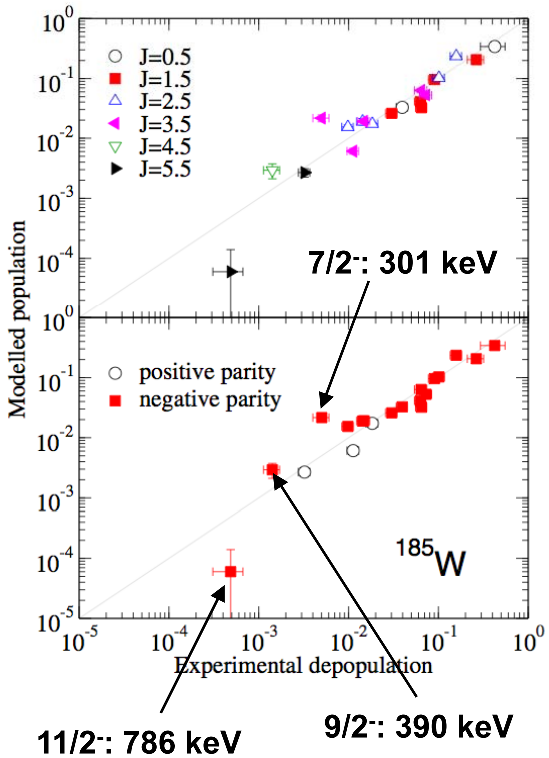
L:

keV: J^{π} = (9/2$^-$)
keV: J^{π} = (9/2$^-$)
keV: J^{π} = (9/2$^-$)

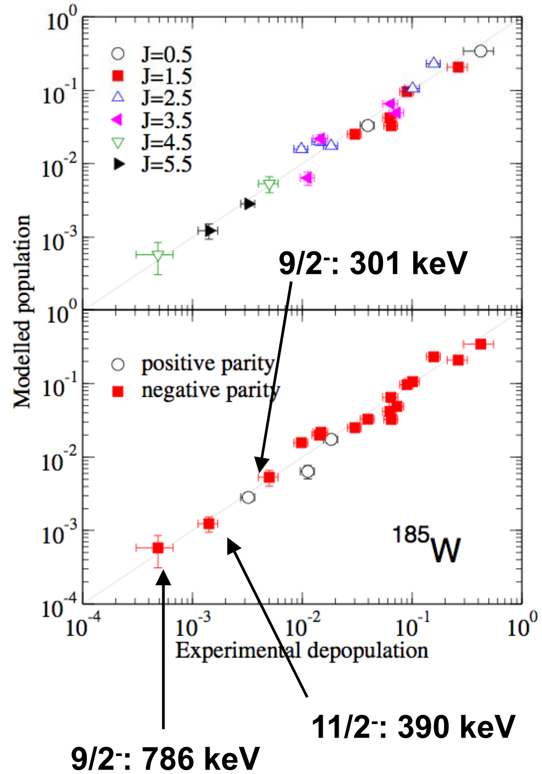
EBOX:

keV: J^{π} = 9/2$^-$
keV: J^{π} = 11/2$^-$
keV: J^{π} = 9/2$^-$

Trial



Final



Changes/improvements need to be made to the RIPL file based on DICEBOX analysis for ^{185}W

: determining the capture-state composition

E_c = 1431 keV; N=20

/(n,γ)^{184}W

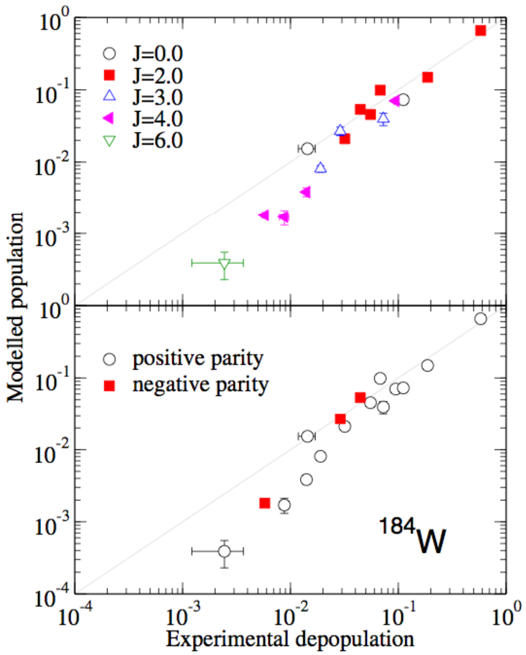
pture on odd-A ^{183}W target
round-state spin J_{gs}^{π} = ½$^-$

ure state will have spin of
osition J = J_{gs}^{π} ± ½

ure-state composition:
$^-$ or 1$^-$ in ^{184}W compound

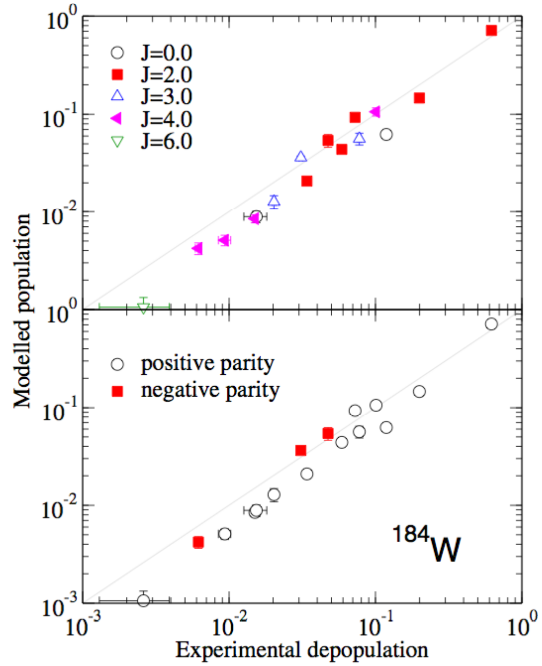
ority 1$^-$ neutron resonances

EGLO / BSFG



CS: 0$^-$(80%) 1$^-$(20%)

EGLO / BSFG



CS: 0$^-$(0%) 1$^-$(100%)

Higher-spin capture state (1$^-$) favors population of high-spin states in ^{184}W

al radiative capture cross sections for W isotopes

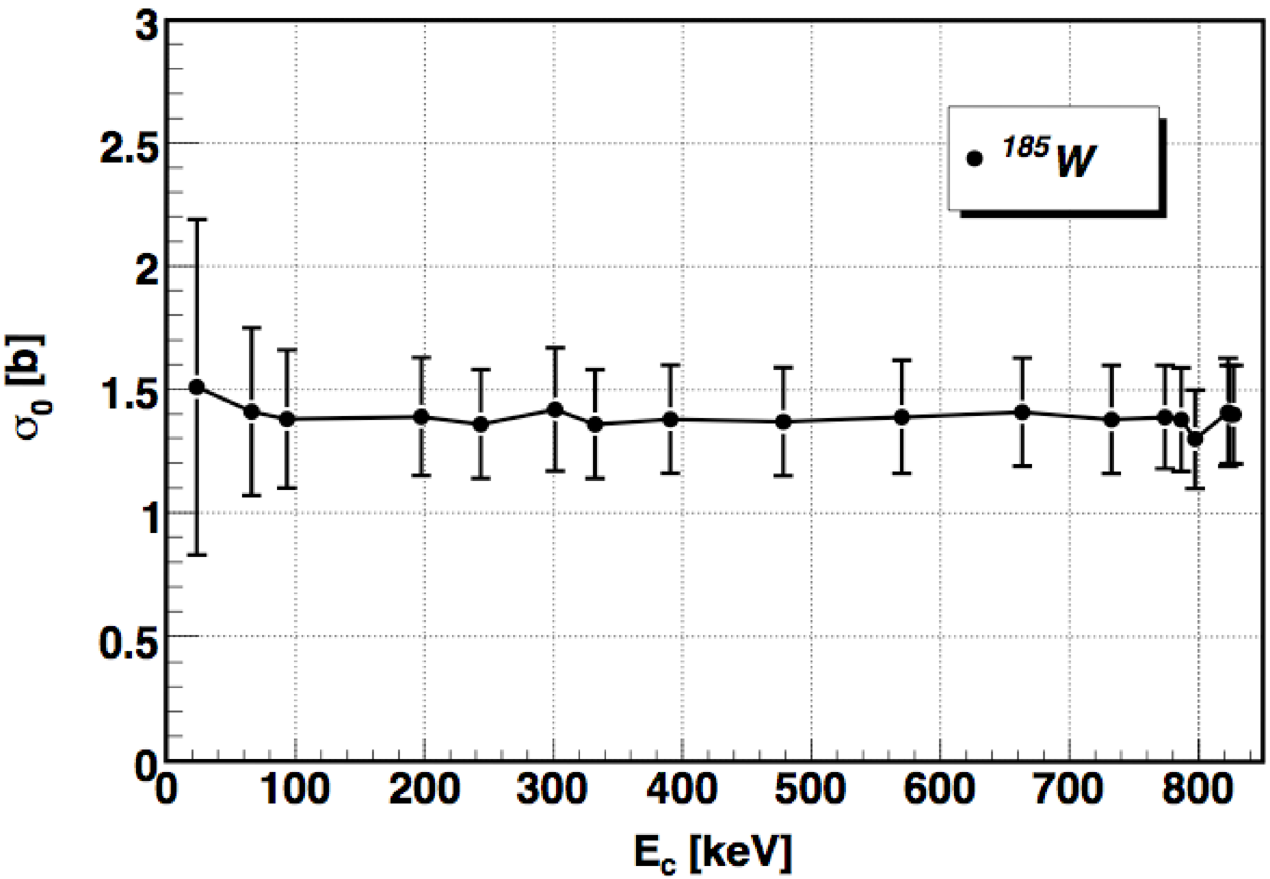
$$\sigma_0 = \sum \sigma_\gamma^{\exp}(\mathrm{GS}) + \sum \sigma_\gamma^{\mathrm{sim}}(\mathrm{GS})$$

Isotope (compound)	σ_0 [b] adopted	σ_0 [b] E_{crit}	σ_0 [b] E_c
^{183}W: ^{182}W(n,γ)	20(2)	18.0(7)	18.4(8)
^{184}W: ^{183}W(n,γ)	10.3(2)*	7.9(3)	8.0(2)
^{185}W: ^{184}W(n,γ)	1.8(2)	1.4(2)	1.4(2)
^{187}W: ^{186}W(n,γ)	34.9(2)	33.6(21)	34.1(5)

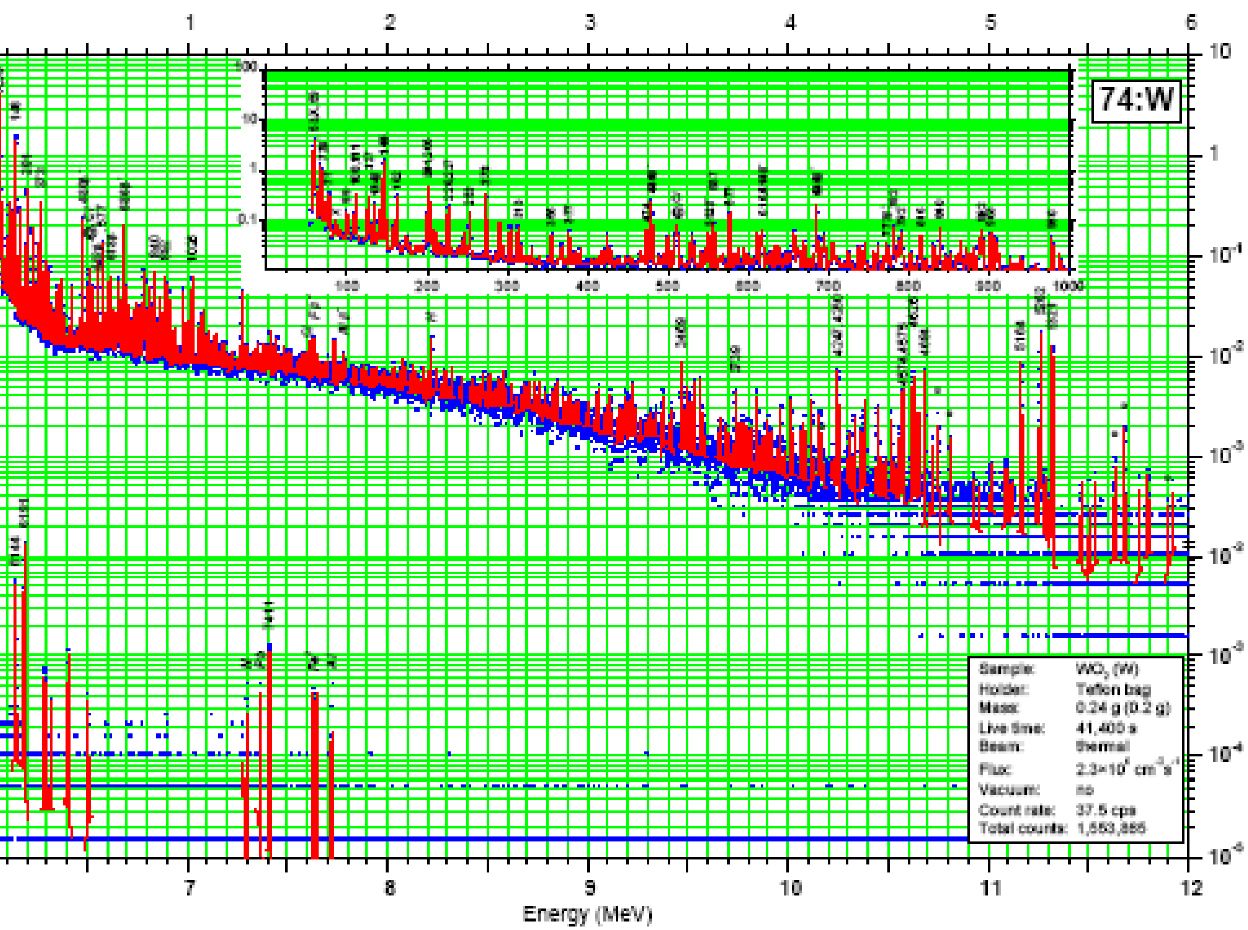
EGAF: σ_0 = 7.78(14) b

PRELIMINARY !!!

as a function of E_c



nental $_{74}W$ capture-γ spectrum



- Na_2WO_6 (s) sodium tungstate calibration
- WO_2 (s) tungsten oxide target

- $^{180}W(n,\gamma)^{181}W$ [0.12 %]
- $^{182}W(n,\gamma)^{183}W$ [26.50 %]
- $^{183}W(n,\gamma)^{184}W$ [14.31 %]
- $^{184}W(n,\gamma)^{185}W$ [30.64 %]
- $^{186}W(n,\gamma)^{187}W$ [28.43 %]

ENSDF ⇒ γ lines in individual W compound systems

Separated-W targets: definitive assignments; weaker signatures

ummary and future work

- CEBOX: useful tool for simulating γ-ray emission following thermal neutron capture he W isotopes
- aluation work on the W isotopes assuming an upper-energy limit defined by $\mathbf{E_{crit}}$ lished in the following works:
  - *Gamma spectrum from neutron capture on tungsten isotopes"* , published as proceedings to ND2010 by A.M. Hurst *et al*. in J. Kor. Nucl. Soc. (2010)
  - *Data evaluation methods and improvements to the neutron-capture γ-ray spectrum"*, published as proceedings to UBC2010 by A. M. Hurst *et al.*
- everal improvements to the EGAF and ENSDF (RIPL) file: ^{185}W and ^{187}W yields new y information and confirmation/proposal of firm J^{π} assignments
- ture: extensive EGAF measurements on all stable isotopically-enriched W targets uding ^{180}W!) at the Budapest Reactor (mid-November 2010)
- pplemental W(d,p) measurements at 88" Cyclotron @ LBNL using RS/LIBERACE to unravel structural problems in the W isotopes that otherwise vent raising of E_{crit} $\Rightarrow$ improvements to the RIPL file
- rthcoming publication in Physical Review C discussing the W evaluation with

ollaborators

BNL – A. M. Hurst, R. B. Firestone, S. Basunia

udapest Reactor – Zs. Revay, T. Belgya, L. Szentmiklósi

LNL – B. W. Sleaford, N. C. Summers, J. E. Escher

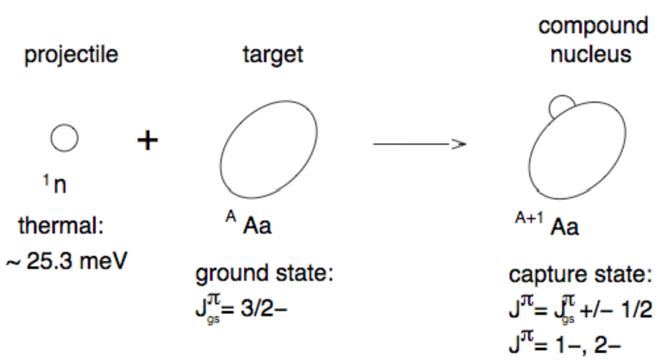
harles University (Prague) – M. Krticka

eoul National University – H. Choi

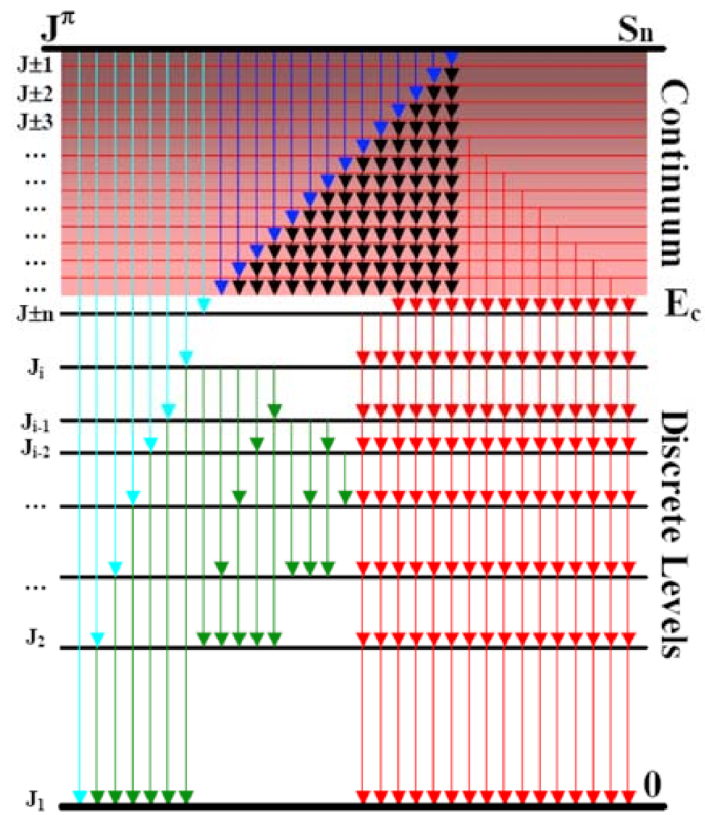
orth Carolina State University – D. Dashdorj

AEA – R. Capote, A. Nichols

ermal neutron capture



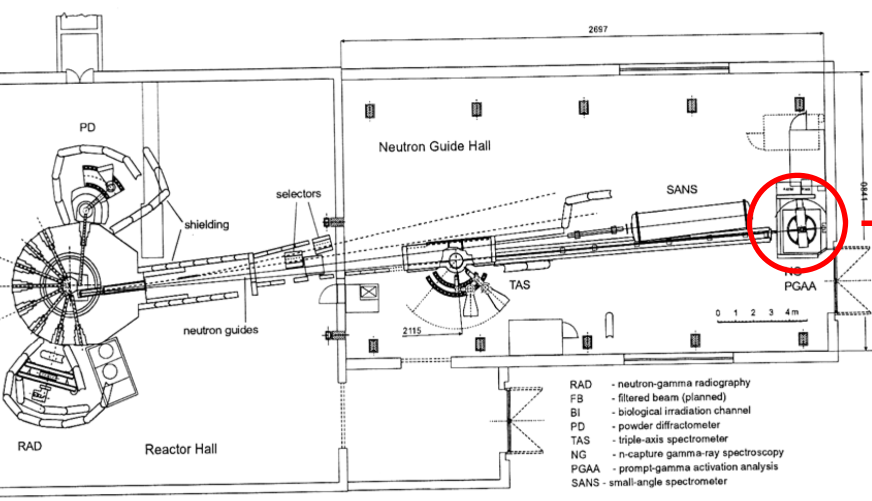
neutron separation energy



$^{A+1}$Aa

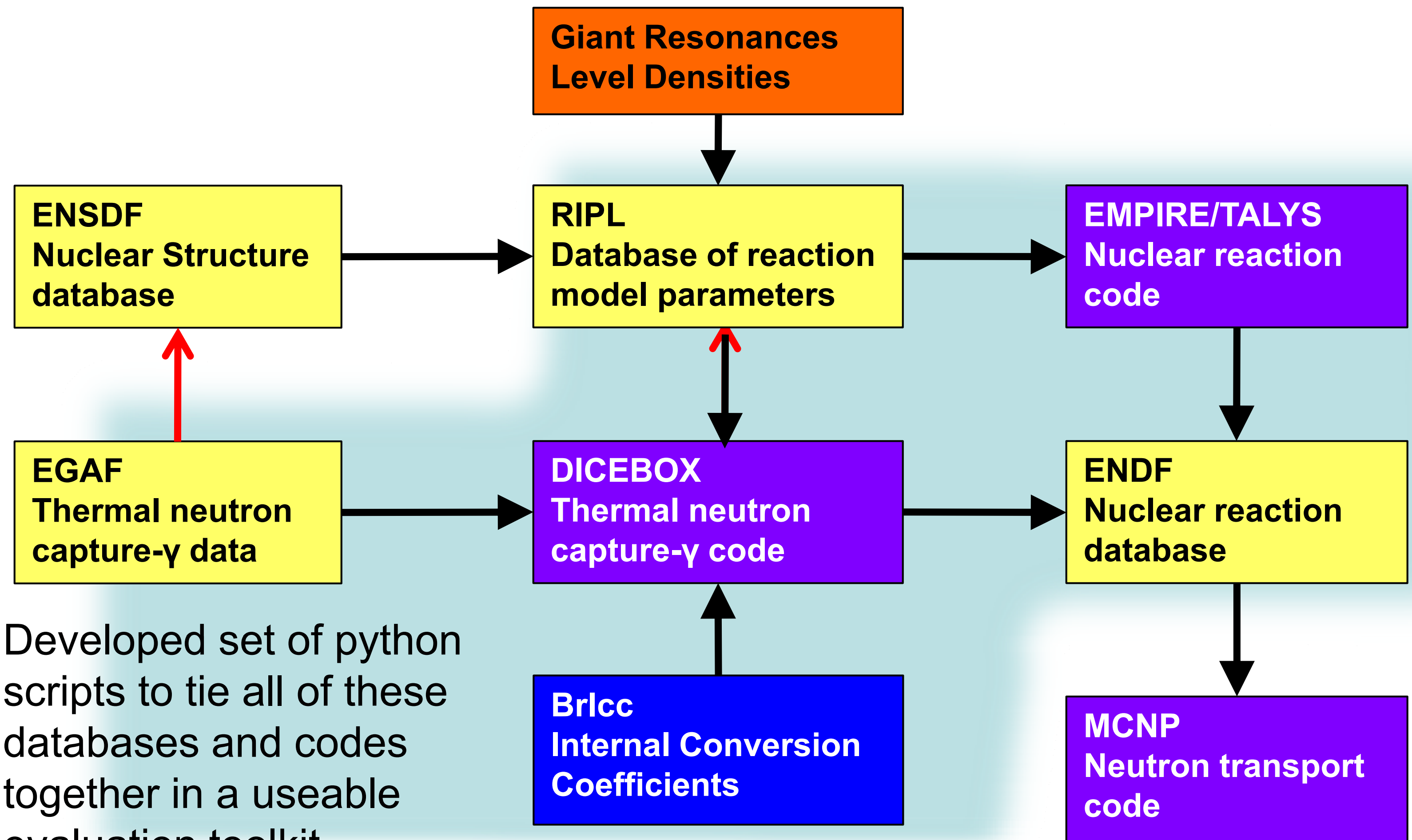
- Compound system formed at high energy
- Neutron separation energy
- Beneath threshold for particle evaporation
- Compound system deexcites through γ-ray emission
- Simulate this process using the Monte Carlo code DICEBOX

AF Project: Budapest Reactor



- 10 MW Budapest reactor
- Guided-thermal neutron beam:
  thermal flux ~ 10^6 $cm^{-2}s^{-1}$
  cold flux ~ 10^8 $cm^{-2}s^{-1}$
- PGAA (Prompt Gamma Activation Analysis) experimental station is located ~ 30 m from reactor wall
- Primary and secondary capture γ rays measured in low-background
- Compton-suppressed HPGe detector (closed-end coaxial) located 23.5 cm from target

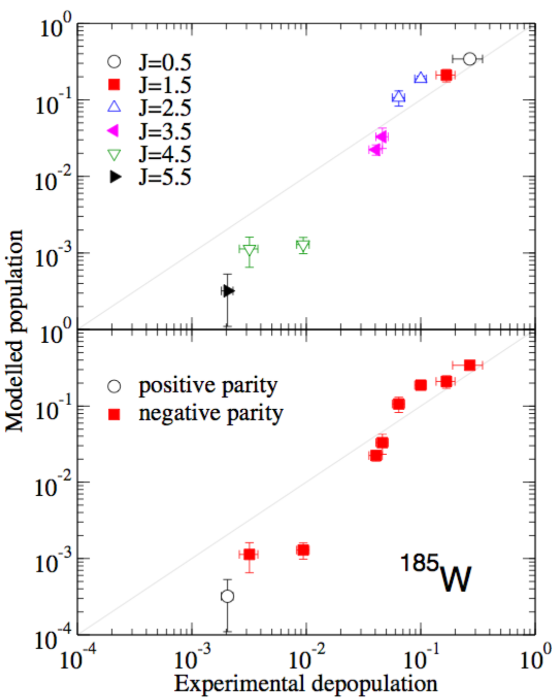
abases and codes used in evaluation
cess



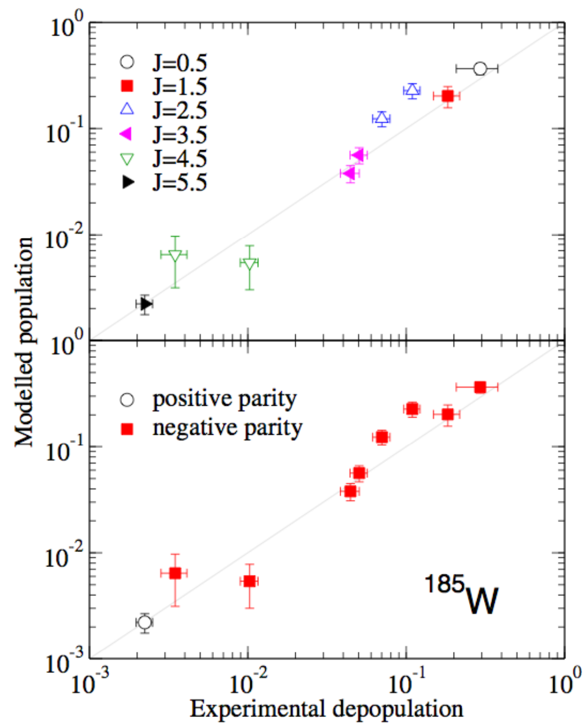
Developed set of python scripts to tie all of these databases and codes together in a useable evaluation toolkit

W results: obtaining best fit

BA / CTF

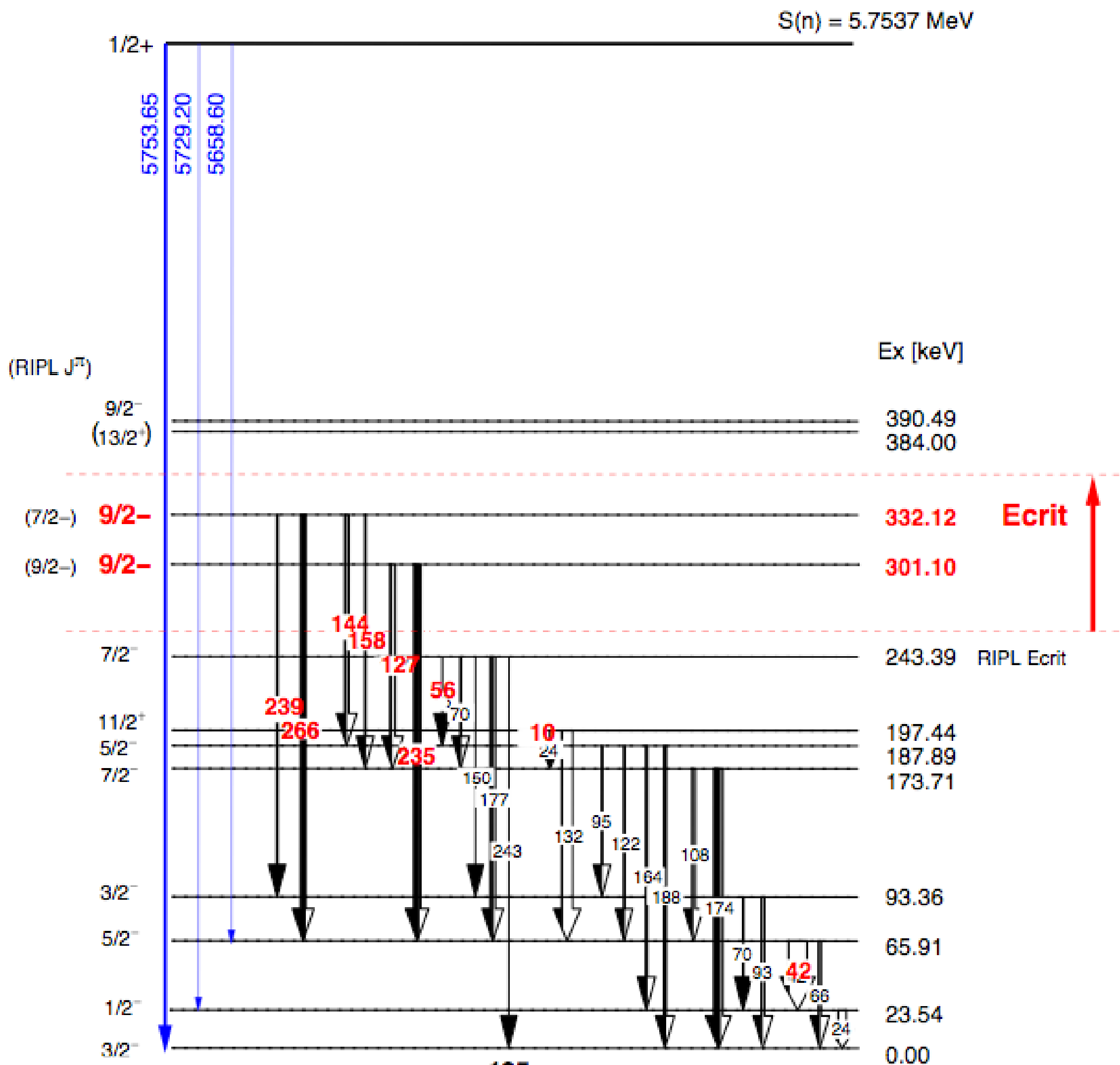


EGLO / BSFG



Best fit using EGLO PSF and BSFG level density

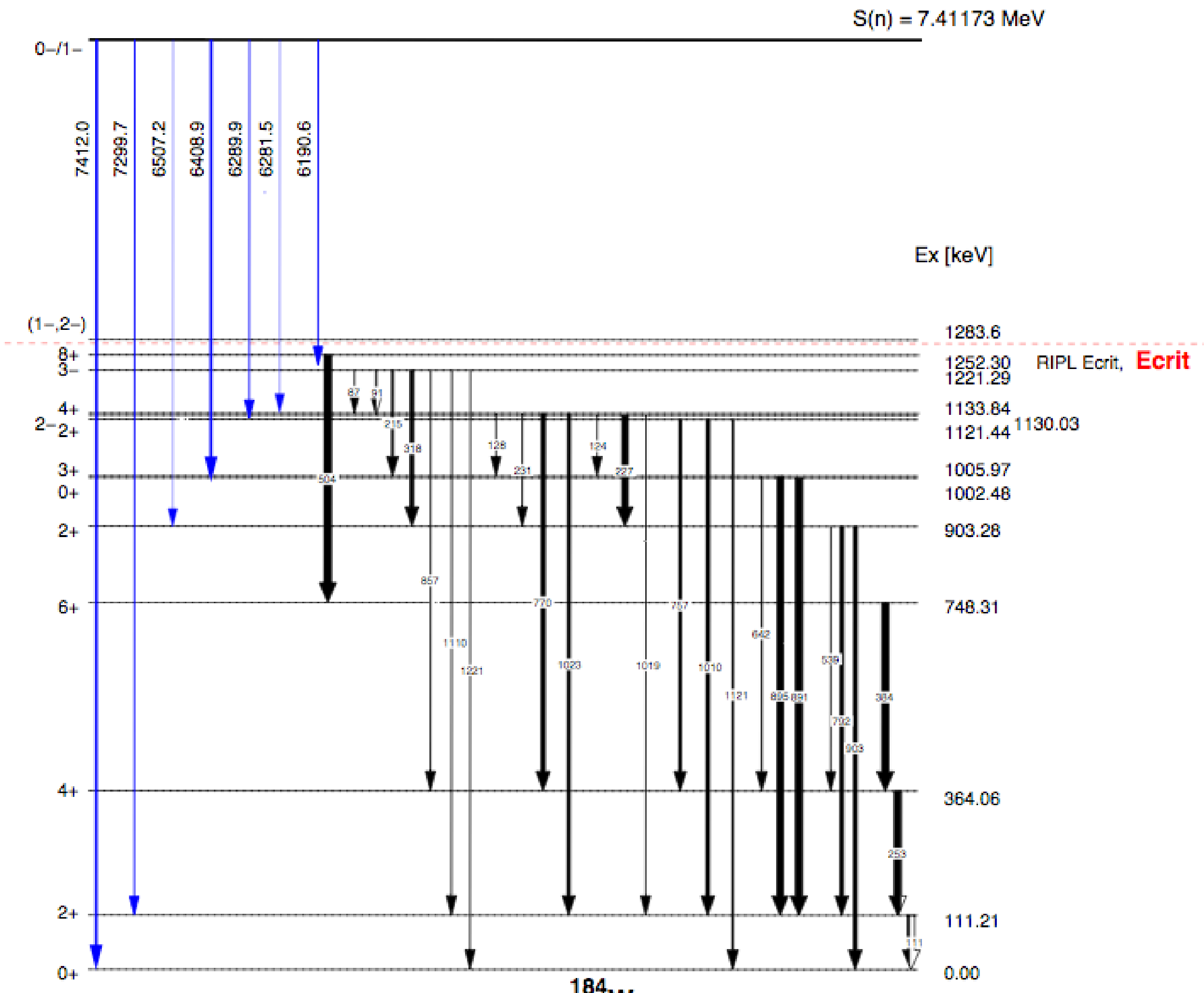
V summary: new level scheme



RIPL improvements:

- 2 new J^{π} firmly established
- E_{crit} raised by ~90 keV with 2 new levels
- 9 new γ rays added to the decay scheme

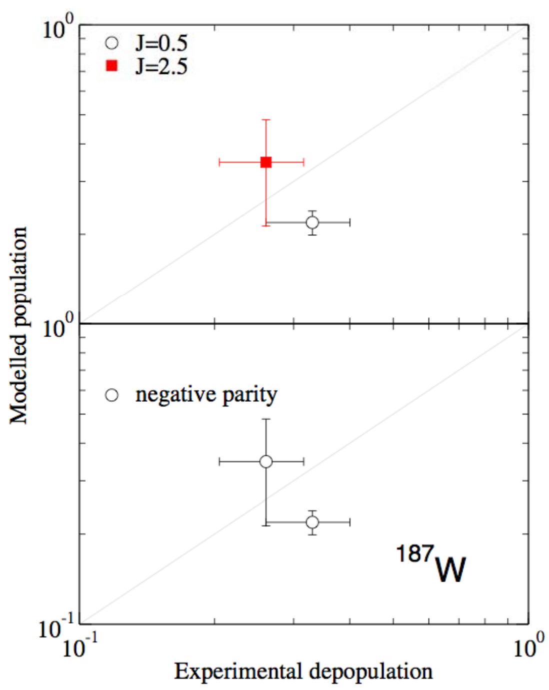
V decay scheme



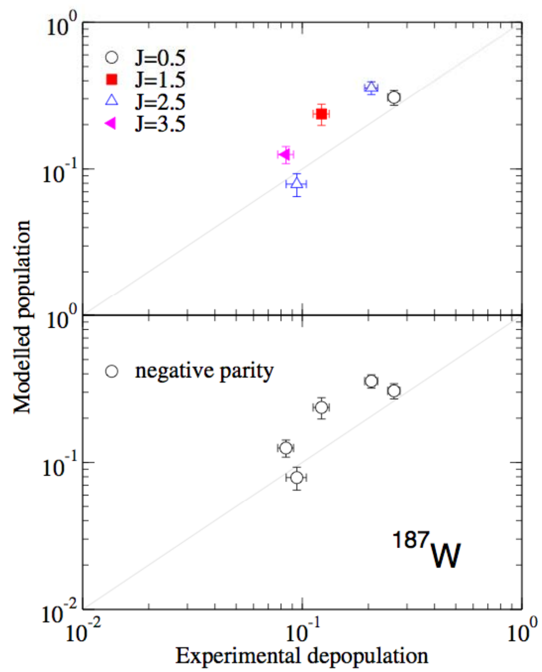
W results: improving the RIPL file

- $(n,\gamma)^{187}W$
- ious Ecrit in RIPL: 145.7 keV
- RIPL: $(7/2^-)$ @ 201.4 keV
- fit: $7/2^-$ @ 201.4 keV
- e E_{crit} to 303.2 keV

EGLO / BSFG

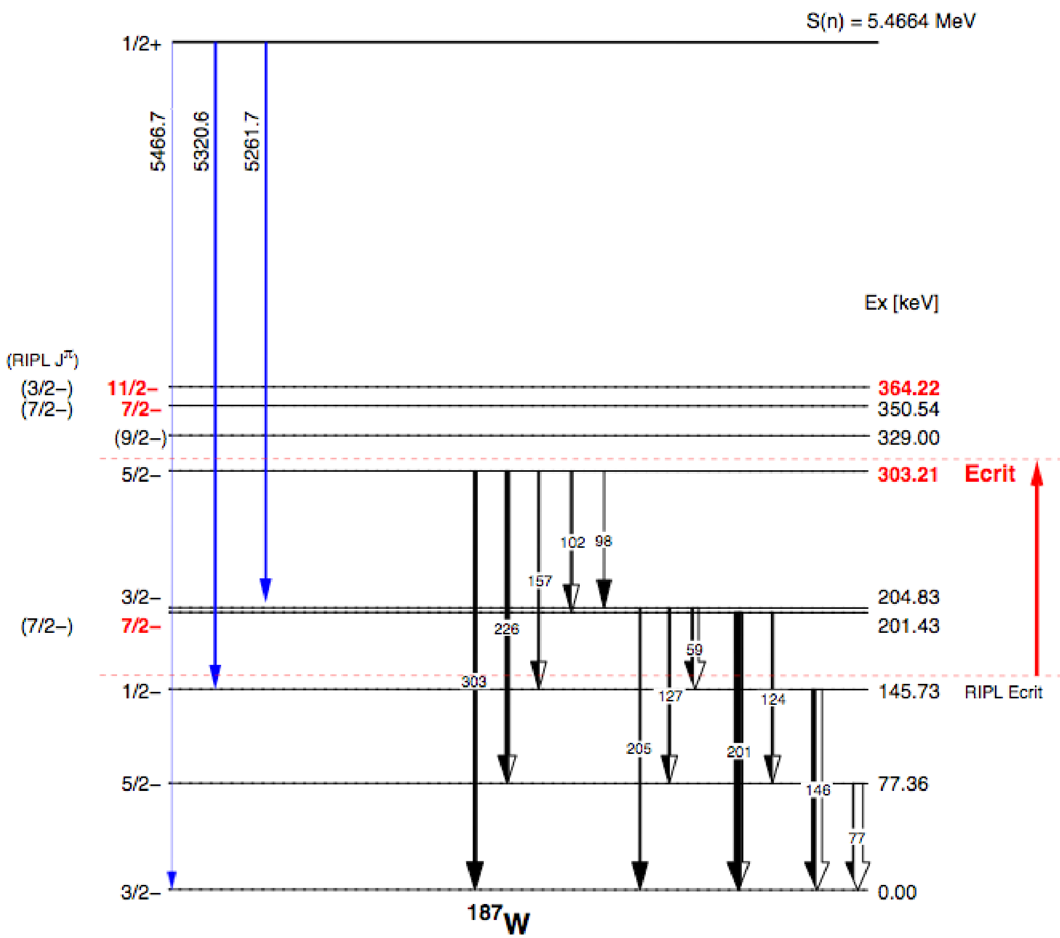


EGLO / BSFG



Changes/improvements need to be made to the RIPL file based on DICEBOX analysis for ^{187}W

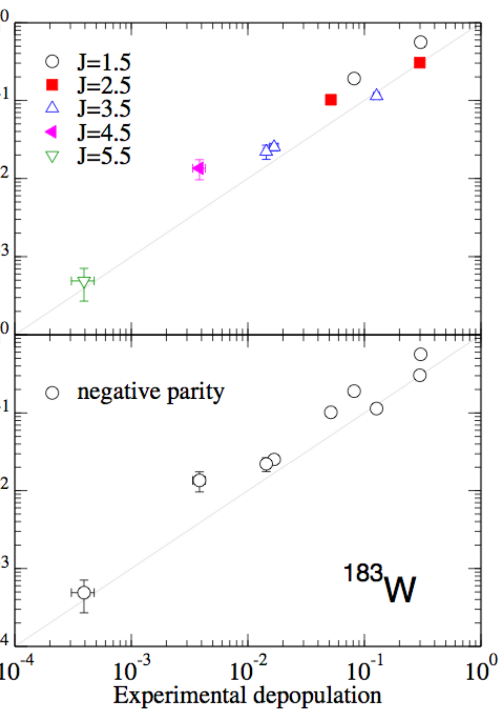
V summary: new decay scheme

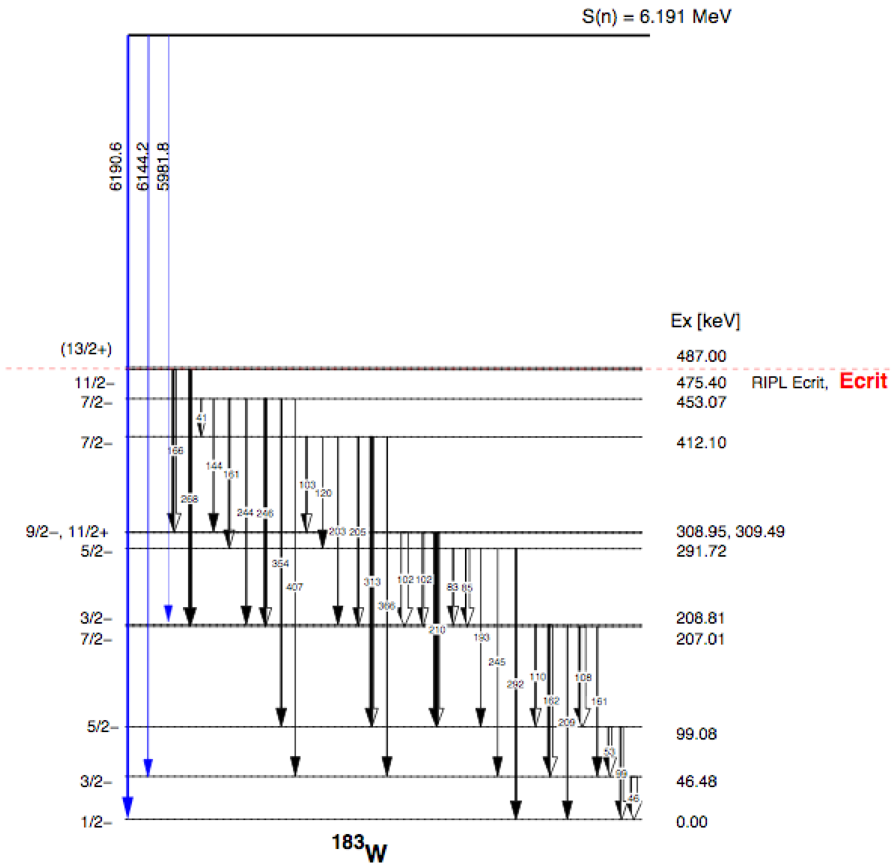


RIPL improvements:

- J$^\pi$ firmly established as 7/2- @ 201.4 keV
- E_{crit} raised by ~160 keV with 3 new levels

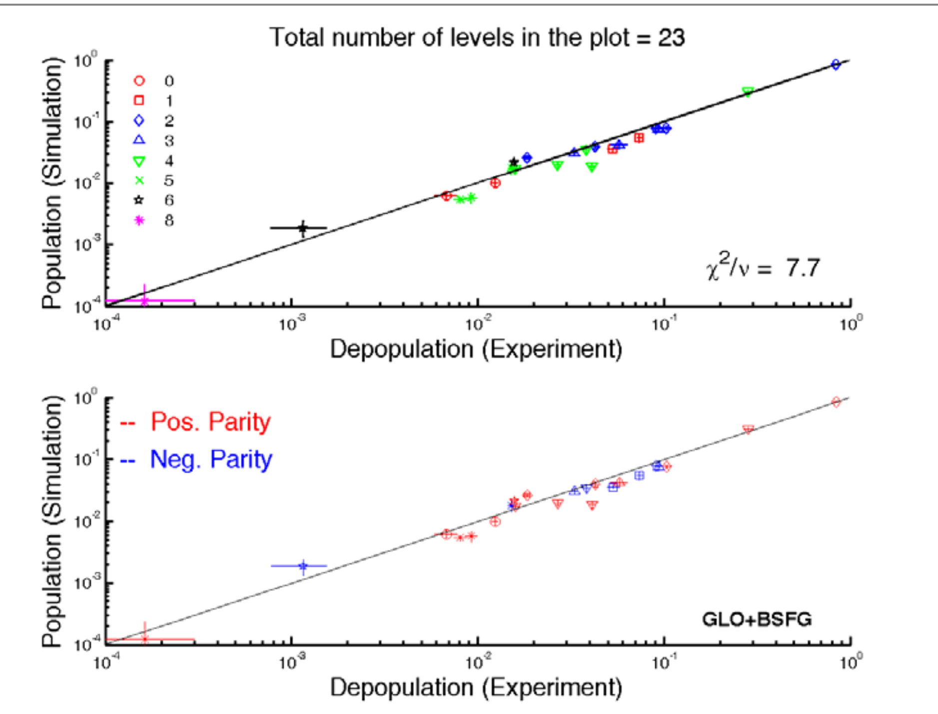
V results





- No new γ information from tentative ($13/2^+$) isomer
- E_{crit} remains unchanged at 475.4 keV i.e. old RIPL value

^{3}Gd results



- ^{158}Gd : ^{157}Gd(n,γ)

Quality of fit similar to the case of ^{156}Gd
Cap. Cross section :
216,000(5,000) b

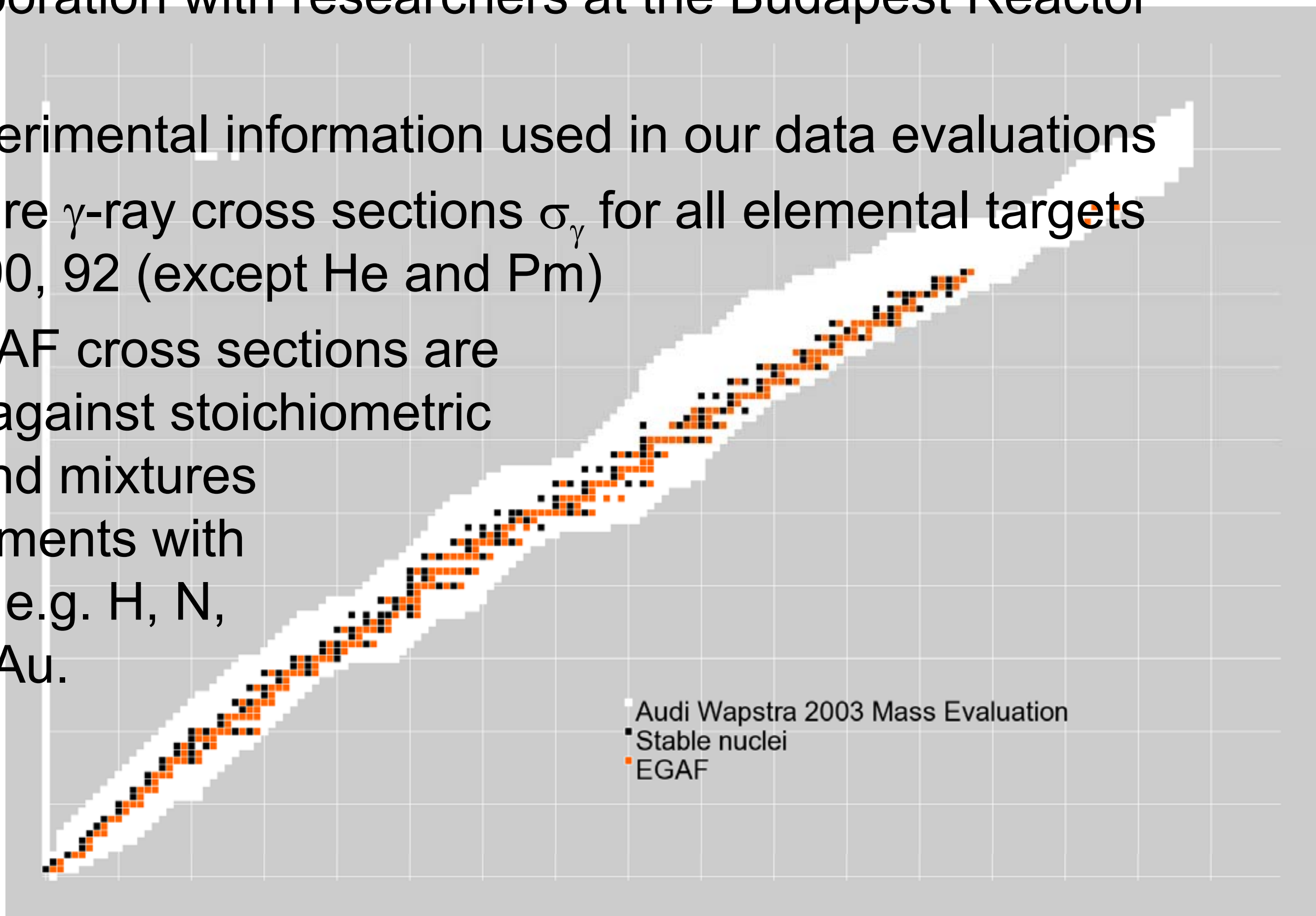
neutron radiative capture cross section of ^{157}Gd.

	ertainty) [b]	Comments
		$\sigma_0(^{157}Gd)/\sigma_0(^{155}Gd)$
	(4,500)	Transmission
	(2,000)	Pile oscillator, σ(B) = 767(4) b
Groshev (12V26, 1119) 1962Gr33	240,000 (12,000)	
Sun (JRNC256, 541, 2003)	232,000 (14,000)	Prompt k_0 method
Firestone (EGAF)	209,900 (5,000)	
Firestone (EGAF adopted)	232,000 (13,000)	Unweighted average of all values
Mughabghab (Atlas) 2006MuZx	254,000 (815)	Evaluation
Leinweber (NSE261,154,2006)	226,000	Resonance parameters and NJOY
This work	216,000 (5,000)	Combine EGAF and calculation

dong Choi

at is EGAF ?

- **EGAF** - **E**valuated **G**amma-ray **A**ctivation **F**ile developed at LBNL in collaboration with researchers at the Budapest Reactor and the IAEA.
- Source of experimental information used in our data evaluations
- Neutron-capture γ-ray cross sections σ_γ for all elemental targets with Z=1-83, 90, 92 (except He and Pm)
- Measured EGAF cross sections are standardized against stoichiometric compounds and mixtures containing elements with well-known σ_γ e.g. H, N, Cl, S, Na, Ti, Au.



EA/LBNL EGAF σ_γ Database

A Coordinated Research Project was started in 2000 to evaluate σ_γ data

luated Gamma-ray Activation File (EGAF) - 13,000 γ-rays, 79 elements

abase of Prompt Gamma Rays from Slow Neutron Capture for Elemental lysis, R.B. Firestone, et al, IAEA STI/PUB/1263, 251 pp (2007); online at: //www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubId=7030

dbook of Prompt Gamma Activation Analysis with Neutron Beams, edited G.L. Molnar (Kluwer Publishers, 2004).

A Prompt Gamma-ray Activation Analysis Viewer:
http://www-nds.iaea.org/pgaa/pgaa7/index.html

IL Capture Gamma-ray Data: http://ie.lbl.gov/ng.html

F and ENSDF

m spectroscopic EGAF properties can be established by comparison with
uated nuclear data

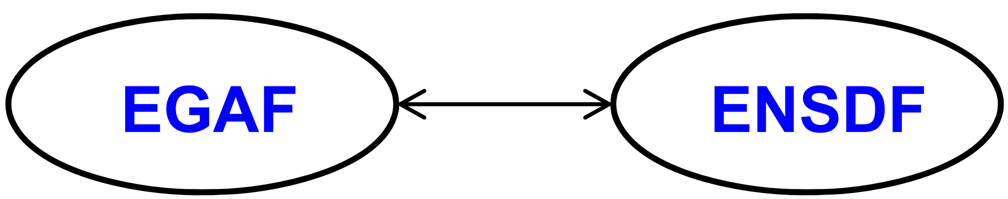
clear structure information derived from independent experimental
stigations

perimental results are reviewed from literature in the public domain

sion-evaporation, few-nucleon transfer, Coulomb excitation, beta decay, etc.

und measurements/results are used to collate an experimental database of
ear data

SDF – **E**valuated **N**uclear **S**tructure **D**ata **F**ile



Spectroscopic information pertaining to individual isotopes in the ENSDF repository can be used to identify individual isotopic features in the elemental EGAF capture-γ spectrum

lication of ENSDF: generation of RIPL

project and ENSDF comprise data complimentary to each repository

tep: information in ENSDF used to create a nuclear reaction database called

RIPL:- **R**eference **I**nput **P**arameter **L**ibrary

database also pulls in information from other sources e.g. parameterization of experimentally ed giant multipole resonances and level density parameterizations.

ical-model calculations in this work are being used to improve knowledge of the decay determine radiative capture cross sections

ical-model calculations call information directly from the RIPL databases

erimental energy-level information (e.g. energy, $J\pi$) and γ-ray information (e.g. branching nixing ratios) is taken from the **RIPL-3** database

ctric multipole parameterization sets are taken from the **RIPL-2** database, level density terization is taken from Von Egidy [PRC **72**, 044311 (2005)]

ION: RIPL is derived from ENSDF, inaccurate or out-of-date information may carry through

ION: decisions are made in RIPL on ambiguous spins (e.g. "($1/2^-$,$3/2^-$)"); often random!

ION: 10+ years may have passed since the most recent ENSDF evaluation for a certain

DF and RIPL databases

ENSDF

Evaluated Nuclear Structure Data File, an electronic database of evaluated experimental nuclear structure data maintained by the National Nuclear Data Center, Brookhaven National Laboratory; online at: http://www.nndc.bnl.gov/

RIPL

R. Capote *et al.*, *RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations,* Nuclear Data Sheets 110 (2009) 3107.

T. Belgya *et al.*, *Handbook for calculations of nuclear reaction data, RIPL-2,* IAEA-TECDOC-1506 (IAEA, Vienna, 2006); online at: http://www-nds.iaea.org/ripl2/

w important points:

provements to the RIPL file (and ENSDF database) are ongoing

atistical-model calculations can provide clarity on energy-level information e.g. ative Jπ assignments

atistical-model calculations can also test the validity of “firm assignments”

ell established experimental data can also be used test the statistical model

nning DICEBOX

ut file contains structure information extracted from RIPL databases

ut file contains internal conversion coefficient data from BrIcc

oice of level density model:
- CTF (constant temperature formula)
- BSFG (back-shifted Fermi gas)

meterization from Von Egidy

oice of models of photon strength functions for E1, M1 and E2 transitions e.g.
- SP (single particle) [E1, M1, E2]
- BA (Brink-Axel) [E1]
- KMF (Kademenski, Markushev, Furman) [E1]
- GLO (generalized Lorentzian) [E1]
- SSF (scissors + spin-flip) [M1]
- IsIv (isoscalar + isovector) [E2]

r of importance: E1>>M1>>E2. Parameterization from RIPL where available (E1) or literature (M1, E2)

Python scripts developed by Neil Summers can now automate generation of DICEBOX input files

dopted models

ack-shifted Fermi gas (level density) with Von Egidy parameterization

$$\rho(E,J) = f(J)\frac{\exp(2\sqrt{a(E-E_1)})}{12\sqrt{2}\sigma_c a^{1/4}(E-E_1)^{5/4}}$$

[Till von Egidy and Dorel Bucurescu, Phys. Rev. C 72, 044311 (2005)]

eneralized Lorentzian E1 PSF with RIPL parameterization (experimental data)

$$f_{GLO}^{E1}(E_\gamma,\Theta) = \frac{1}{3(\frac{hc}{2})^2}\left[\frac{E_\gamma \Gamma_G(E_\gamma,\Theta)}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2\Gamma_G^2(E_\gamma,\Theta)} + F_K\frac{4\pi^2\Theta^2\Gamma_G}{E_\gamma^5}\right]\sigma_G\Gamma_G$$

Resonance-shape parameters:
E_G (energy centriod), Γ_G (resonance width), σ_G (resonance cross section)

cissors + spin-flip M1 PSF with parameterization from Yb isotopes
. Agvaanluvsan et al., Phys. Rev. C 70, 054611 (2004)]

oscalar + Isovector E2 PSF or single particle