Neutron Cross Section Measurements at LBNL

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Collaborators

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Measurements

At the Budapest Reactor we have measured thermal neutron γ-ray cross sections for all elements with Z=1-83, 92 except He and Pm.

- Pure thermal guided neutron beam
- Internal standard calibrations
- Precision of <3% for strong transitions
- IAEA sponsored evaluation of σ_γ

Budapest Prompt Gamma-ray Facility

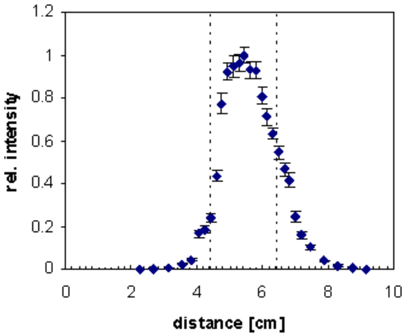
N-type coaxial HPGE detector
(25%,1.8 keV@1332)

BGO Compton shield

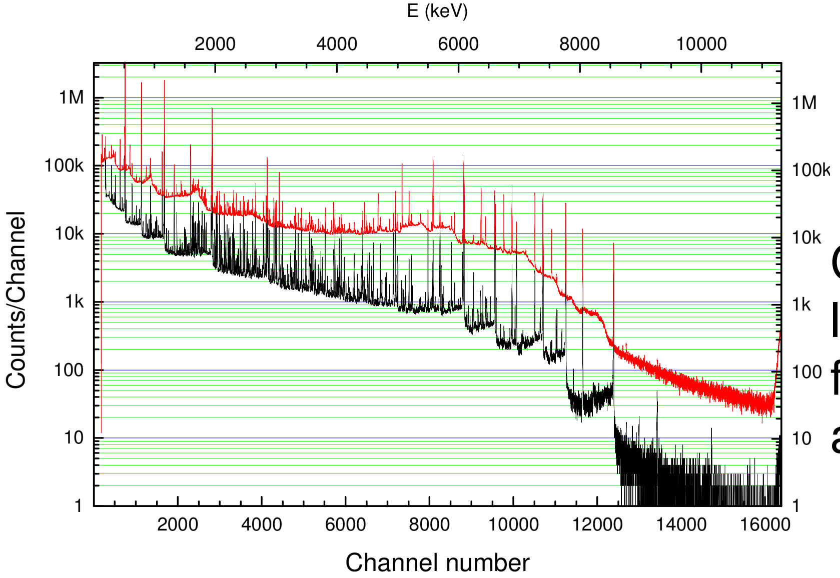
Thermal beam – 2×10^{6} n·s^{-1}cm^{-2}

Cold beam – 5×10^{7} n·s^{-1}cm^{-2}

Neutron beam



Beam profile at the target position



Compton suppression lowered background by a factor of ~5@1332 to ~40 at 7 MeV.

Internal Cross Section Calibration

Calibration Methods

- Stoichiometric compounds of well-known compostion containing elements with well-known cross sections

  e.g. H,N,Cl,S,Na,Ti,Au, → $KCl, (CH_2)_n, Pb(NO_3)_2, Tl_2SO_4$

- Homogenous mixtures
  - Aqueous solutions (H_2O) or acid solutions (20% HCl)
  - Mixed powders (TiO_2)

- Activation product cross section e.g. ^{28}Al, ^{100}Tc, ^{235}U

IAEA/EGAF σ_γ Database

The Evaluated Gamma-ray Activation File (EGAF) is the result of an IAEA CRP established in 1999 to evaluate k_0/σ_γ measurements at the Budapest Reactor and compare them with literature data. EGAF contains over 13,000 γ-rays from 81 elements. These results are published in

Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis, R.B. Firestone, H.D. Choi, R.M. Lindstrom, G.L. Molnar, S.F. Mughabghab, R. Paviotti-Corcuera, Zs. Revay, V. Zerkin, and C.M. Zhou, IAEA STI/PUB/1263, 251 pp (2007); on-line at http://www-pub.iaea.org/MTCD/publications/PubDetails.asp?pubId=7030.

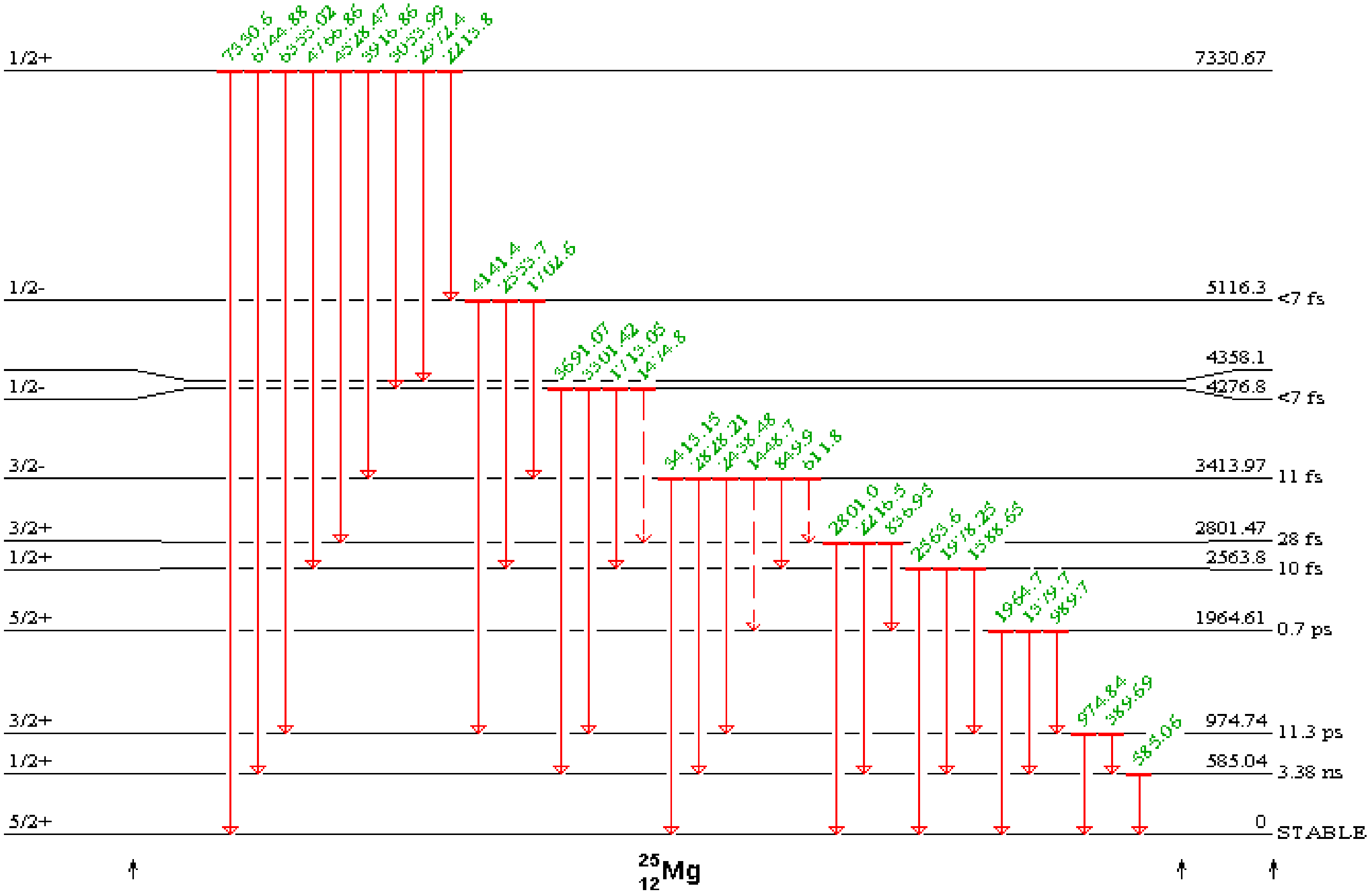
Handbook of Prompt Gamma Activation Analysis with Neutron Beams, Zs. Revay, T. Belgya, R.M. Lindstrom, Ch. Yonezawa, D.L. Anderson, Zs. Kasztovsky, and R.B. Firestone, edited by G.L. Molnar (Kluwer Publishers, 2004).

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

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

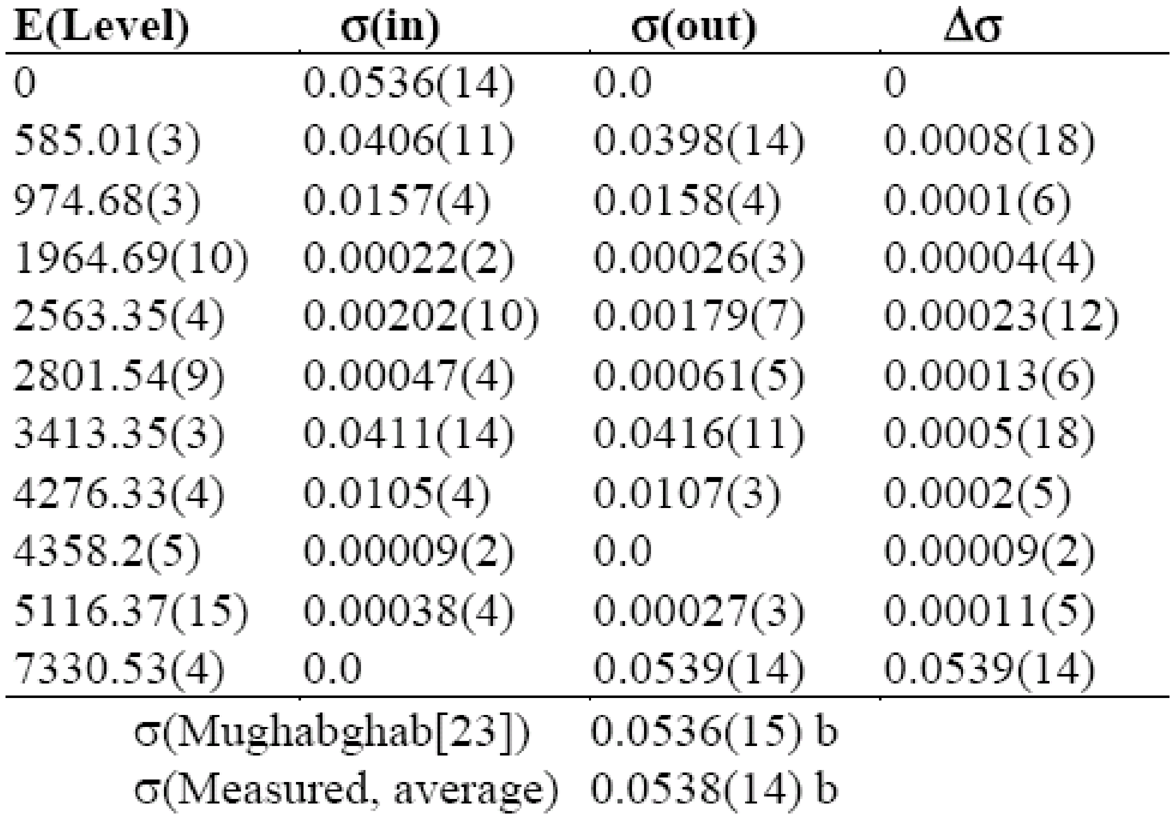
Total Thermal Neutron Radiative Cross Sections σ_0 – Low Z

For *complete decay schemes* the total thermal radiative neutron cross section $\sigma_0=\Sigma\sigma_{\gamma+e}(GS)=\Sigma\sigma_{\gamma+e}(CS)$



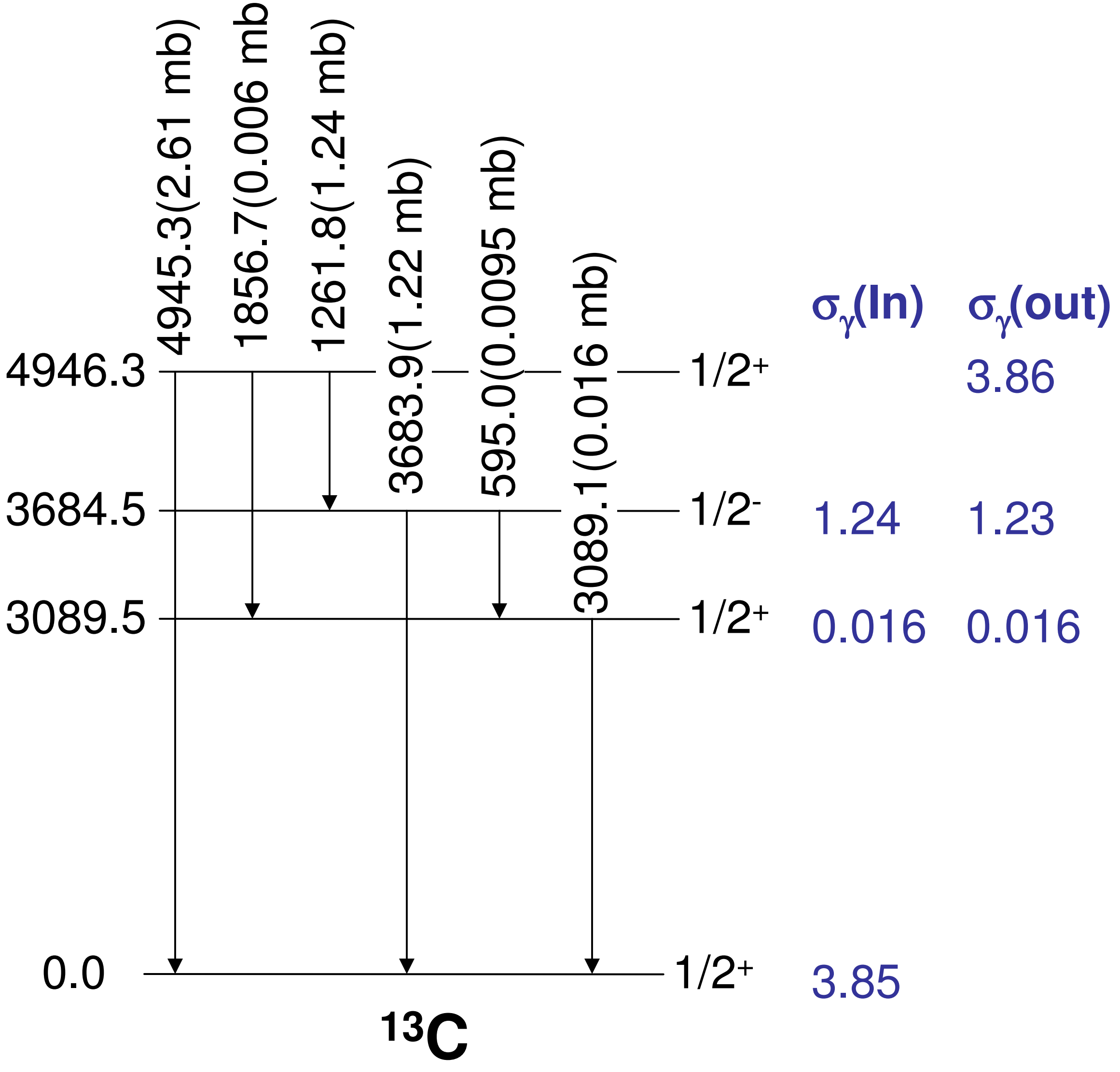
Example – ^{24}Mg(n,γ)^{25}Mg

Cross section balance for the ^{25}Mg neutron capture decay scheme



E(Level)	σ(in)	σ(out)	Δσ
0	0.0536(14)	0.0	0
585.01(3)	0.0406(11)	0.0398(14)	0.0008(18)
974.68(3)	0.0157(4)	0.0158(4)	0.0001(6)
1964.69(10)	0.00022(2)	0.00026(3)	0.00004(4)
2563.35(4)	0.00202(10)	0.00179(7)	0.00023(12)
2801.54(9)	0.00047(4)	0.00061(5)	0.00013(6)
3413.35(3)	0.0411(14)	0.0416(11)	0.0005(18)
4276.33(4)	0.0105(4)	0.0107(3)	0.0002(5)
4358.2(5)	0.00009(2)	0.0	0.00009(2)
5116.37(15)	0.00038(4)	0.00027(3)	0.00011(5)
7330.53(4)	0.0	0.0539(14)	0.0539(14)
σ(Mughabghab[23])		0.0536(15) b	
σ(Measured, average)		0.0538(14) b	

$^{12}C(n,\gamma)^{13}C$ Discrepancy



$^{12}C(n,\gamma)$ σ_0 Measurements

Reference	**σ_0(mb)**
Prestwich(1981)	3.50(16)
Jurney(1963)	3.53(7)
Nichols (1960)	3.57(3)
Mughabghab(2006)	3.53(7) mb
Sagot (1963)	3.72(15)
Starr (1962)	3.83(6)
Koechlin (1957)	3.85(15)
Yonezawa (2003)	4.01(15)
This work*	3.86(6) mb

* Average of measurements with various stoichiometric carbon compounds.

$(^{15}NH_2)_2{}^{13}CO$(Urea) Analysis

- Urea sample enriched to >99% in ^{13}C, ^{15}N
- Hydrogen internal standard (σ_0=0.3326(7) b)

	Total radiative cross section σ_0	
Isotope	**Mughabgab (2006)**	**This work**
^{13}C	1.37±0.04 mb	1.50±0.03 mb
^{15}N	24±8 μb	39±3 μb

Summary of σ_0 results for low-Z isotopes

Isotope	σ(Atlas)*	σ(EGAF)
^{1}H	332.6(7) mb	≡332.6(7) mb
^{2}H	0.508(15) mb	0.492(25) mb
^{6}Li	38.5(30) mb	52.6(22) mb
^{7}Li	45.4(27) mb	45.7(9) mb
^{9}Be	8.49(34) mb	8.8(6) mb
^{10}B	305(16) mb	384 mb 8
^{10}B(n,α)	3837(9) b	3820(135) b
^{11}B	5.5(33) mb	11.4(10) mb
^{12}C	3.53(7) mb	3.89(6) mb
^{13}C	1.37(4) mb	1.50(3) mb
^{14}N	80.1(6) mb	79.0(9) mb
^{15}N	24 μb 8	39 μb 3
^{16}O	0.190(19) mb	0.189(8) mb
^{19}F	9.51(9) mb	9.50(11) mb
^{23}Na	517(4) mb	527(7) mb
^{23}Na^{m}(472)	400(30) mb	478(4) mb

Isotope	σ(Atlas)*	σ(EGAF)
^{24}Mg	53.8(13) mb	53.7(14) mb
^{25}Mg	199(3) mb	197(5) mb
^{26}Mg	38.4(6) mb	37.7(13) mb
^{27}Al	231(3) mb	232(3) mb
^{28}Si	177(4) mb	186(3) mb
^{29}Si	119(3) mb	118(3) mb
^{30}Si	107(2) mb	116(3) mb
^{31}P	165(3) mb	167(5) mb
^{32}S	518(14) mb	536(8) mb
^{33}S	454(25) mb	461(15) mb
^{34}S	256(9) mb	277(8) mb
^{35}Cl	43.6(4) b	43.84(17) b
^{37}Cl	433(6) mb	553(23) mb
^{39}K	2.1(2) b	2.19(3) b
^{40}K	30(8) b	92(8) b
^{41}K	1.46(3) b	1.73(2) b

*S.F. Mughabghab, Atlas of Neutron Resonances, Elsevier (2006).

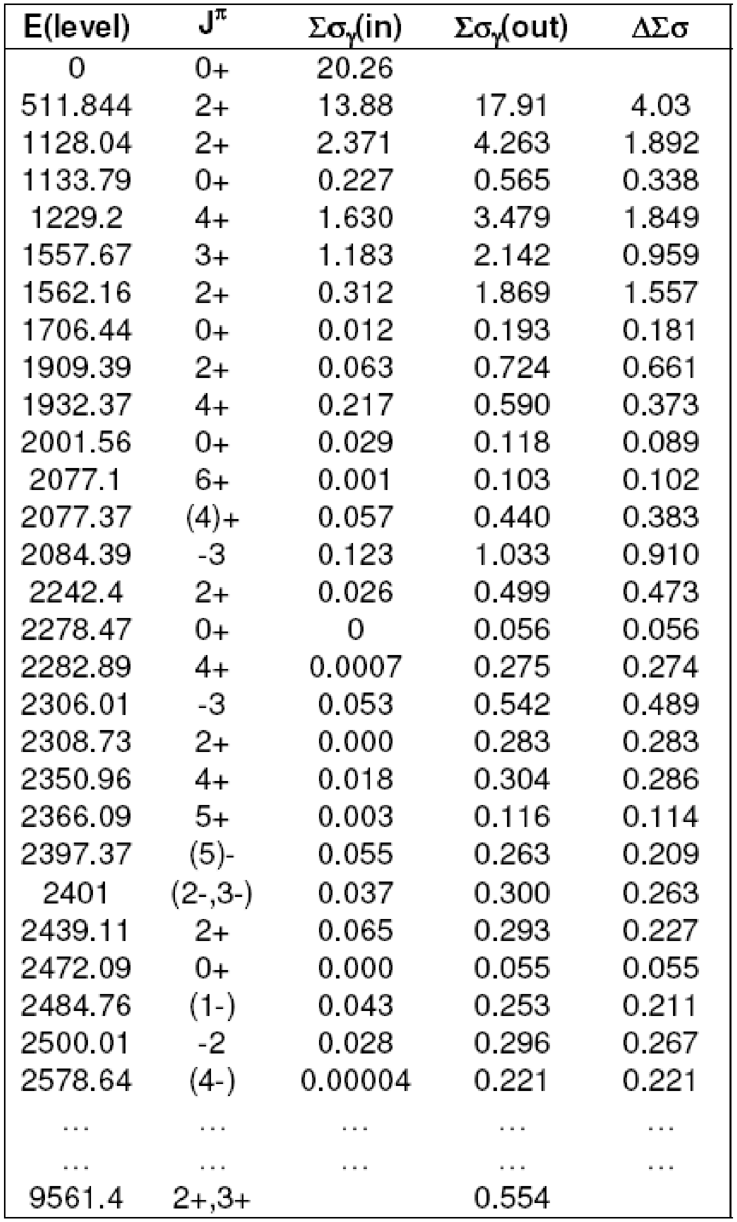
Analysis of σ_0 for heavier isotopes

For most isotopes with $Z \geq 20$ the neutron capture decay schemes are incomplete

- **High level density below the capture state**
- **Numerous unresolved continuum gamma rays**

What to do?

^{105}Pd(n,γ)^{106}Pd



E(level)	J^{π}	$\Sigma\sigma_{\gamma}$(in)	$\Sigma\sigma_{\gamma}$(out)	$\Delta\Sigma\sigma$
0	0+	20.26		
511.844	2+	13.88	17.91	4.03
1128.04	2+	2.371	4.263	1.892
1133.79	0+	0.227	0.565	0.338
1229.2	4+	1.630	3.479	1.849
1557.67	3+	1.183	2.142	0.959
1562.16	2+	0.312	1.869	1.557
1706.44	0+	0.012	0.193	0.181
1909.39	2+	0.063	0.724	0.661
1932.37	4+	0.217	0.590	0.373
2001.56	0+	0.029	0.118	0.089
2077.1	6+	0.001	0.103	0.102
2077.37	(4)+	0.057	0.440	0.383
2084.39	-3	0.123	1.033	0.910
2242.4	2+	0.026	0.499	0.473
2278.47	0+	0	0.056	0.056
2282.89	4+	0.0007	0.275	0.274
2306.01	-3	0.053	0.542	0.489
2308.73	2+	0.000	0.283	0.283
2350.96	4+	0.018	0.304	0.286
2366.09	5+	0.003	0.116	0.114
2397.37	(5)-	0.055	0.263	0.209
2401	(2-,3-)	0.037	0.300	0.263
2439.11	2+	0.065	0.293	0.227
2472.09	0+	0.000	0.055	0.055
2484.76	(1-)	0.043	0.253	0.211
2500.01	-2	0.028	0.296	0.267
2578.64	(4-)	0.00004	0.221	0.221
…	…	…	…	…
…	…	…	…	…
9561.4	2+,3+		0.554	

The cross section deexciting low-lying states in higher-Z nuclei, $\Sigma\sigma_{\gamma}$(out), is complete.

The observed cross section populating these states $\Sigma\sigma_{\gamma}$(in) is incomplete due to unresolved continuum γ-rays.

σ_0(tot)=21.0±1.5 b

Mughabghab (2006)

Statistical Model Calculations

The continuum contribution can be calculated assuming level density and γ-ray transition probability varies statistically leading to a random distribution of partial level widths $\langle \Gamma_{if} \rangle = f^{XL}(E_\gamma, \xi) E_\gamma^3 / \rho(E_i, J^\pi_i)$ where

1. Level density $\rho(E_i, J^\pi_i)$ can be described by
   a) Constant temperature formula

   $$\rho(E,J) = \frac{f(J)}{T} \exp\left(\frac{E - E_0}{T}\right)$$

   b) Back-shifted Fermi Gas formula

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

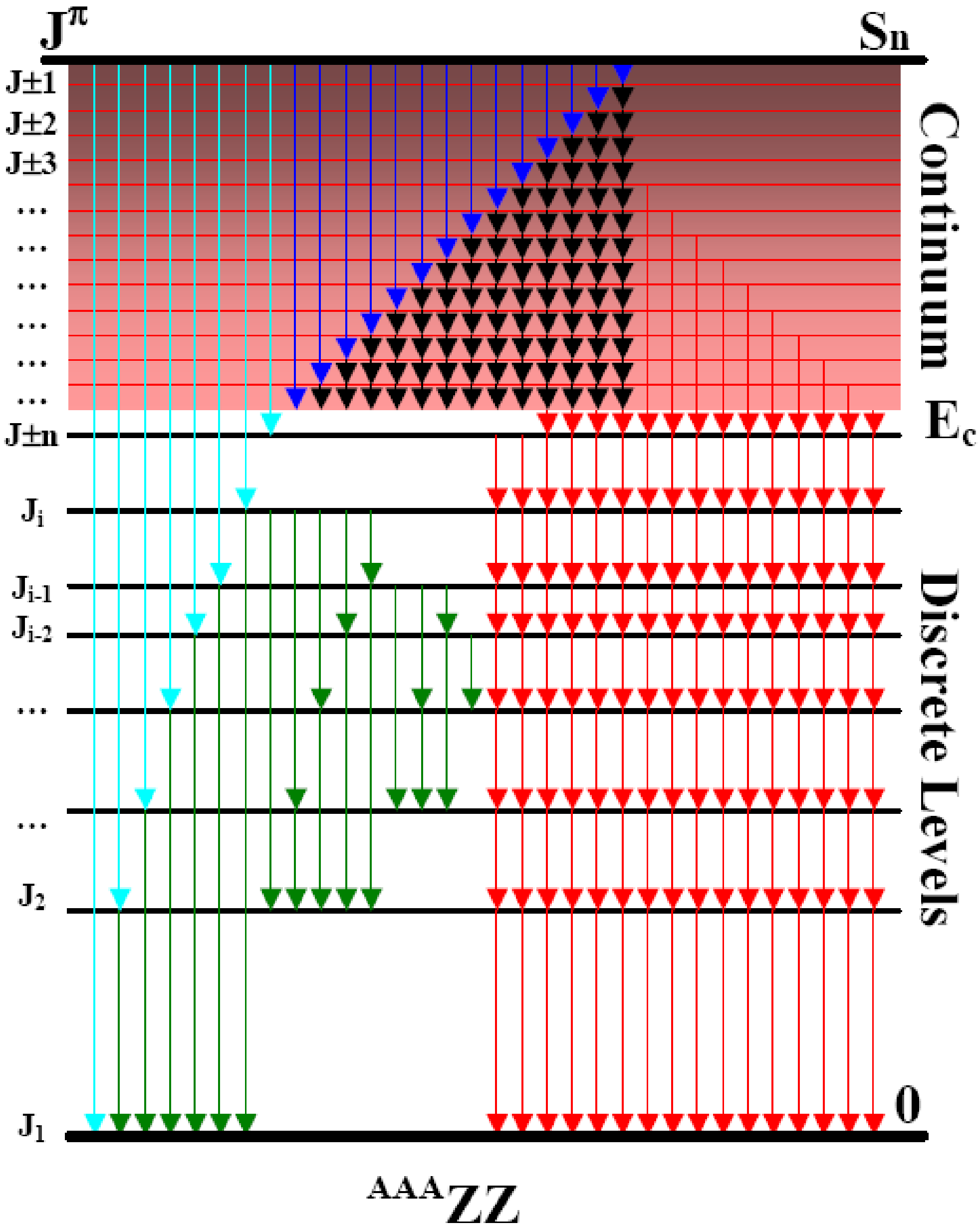
2. Photon strength $f^{XL}(E_\gamma, \xi) E_\gamma^3$ for multipolarity XL=E1, M1
   a) E1: Brink-Axel

   $$f_{\mathrm{BA}}^{(E1)}(E_\gamma) = \frac{1}{3(\pi\hbar c)^2} \frac{\sigma_G E_\gamma \Gamma_G^2}{\left(E_\gamma^2 - E_G^2\right)^2 + E_\gamma^2 \Gamma_G^2}$$

   also, Kadmenskii *et al* (KMF), Generalized Laurentzian (GLO).
   GDER parameters: Dietrich, Berman(ATNDT) or Herman (Empire)

   b) M1: Single particle, $f^{E2}(SP) = 5 \times 10^4 E_\gamma^3$, spin flip (SF), or f^{E1}/f^{M1}=5-7
   c) E2: Single particle, $f^{E2}(SP) = 1 \times 10^{-7} E_\gamma^5 / A^{4/3}$

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.

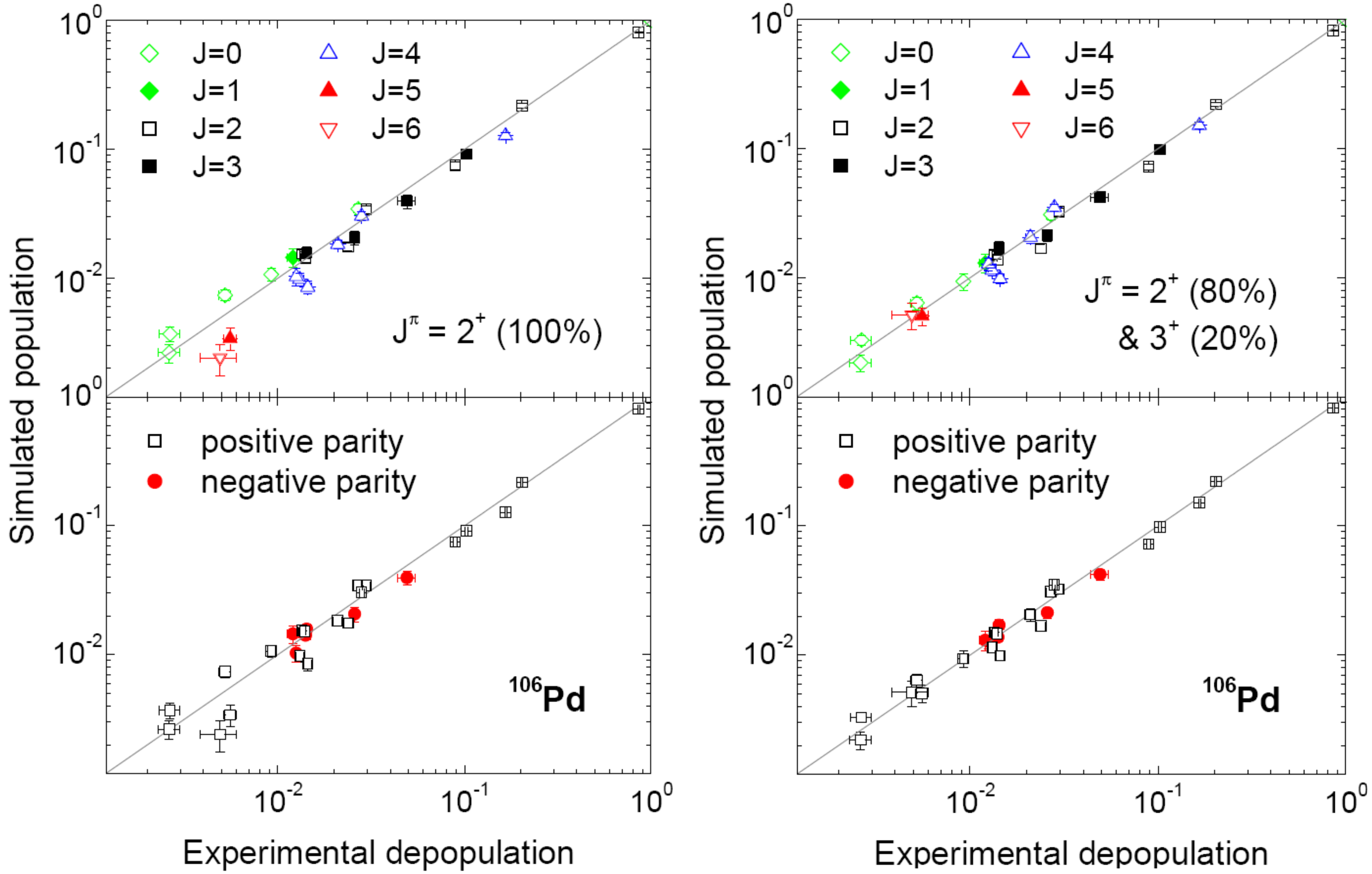
Statistical Model Selection Example

Model dependence of the total capture state width Γ_γ^{tot}

^{105}Pd(n,γ)	E1-PSF*	M1-PSF	ρ(E,J)	Γ_γ^{tot}
	Brink-Axel	SP	CTF	410±47
	Brink-Axel	SF	CTF	352±42
	KMF	SP	BSFG	201±14
	KMF	SF	BSFG	172±12
Best fit →	GLO	SP	BSFG	156±8
	GLO	SF	BSFG	126±8
	Experiment (Mughabghab, 2006)			148±10

*GDER parameters from Dietrich and Berman, ADNDT **38**, 199 (1988).

Comparison of ^{105}Pd(n,γ) simulated $\Sigma\sigma_\gamma$(in) with experimental $\Sigma\sigma_\gamma$(out)



$$\sigma_0=\sigma_\gamma(\mathrm{GS})_{\mathrm{expt}}+\sigma_\gamma(\mathrm{GS})_{\mathrm{calc}}=20.3\pm0.3\ \mathrm{b}+1.4\pm0.3\ \mathrm{b} = 21.7\pm0.5\ \mathrm{b}$$

$$\sigma_0(\text{Mughabghab, 2006})=21.0\pm1.5\ \mathrm{b}$$

Determination of σ_0 for ^{104}Pd(n,γ)^{105}Pd

If minimal experimental data is available σ_0 can be calculated with DICEBOX independently for each observed level feeding.

PSF		**LD**			**Level Feeding(%)**		
E1	**M1**	**ρ(E,J)**	**GDER**	**E_{crit}(keV)**	**280**	**306**	**344**
GLO	SP	BSFG	Dietrich	350	23(9)	4.3(13)	10(3)
KMF	SP	BSFG	Herman	350	26(9)	4.1(12)	10(3)
				Average	**24(9)**	**4.2(12)**	**10(3)**
				σ_γ^{expt} (b)	0.145(13)	0.040(8)	0.099(18)
				σ_0 (b)	**0.60(23)**	**0.95(35)**	**0.99(35)**
				Average	**0.77(17) b**		

Mughabghab, 2006 0.65(30) b

Pd σ_0 results*

Reaction	σ_0(literature) (barns)	σ_0(this work) (barns)
^{102}Pd(n,γ)^{103}Pd	1.6±0.2	1.1±0.4
^{104}Pd(n,γ)^{105}Pd	0.65±0.30	0.77±0.17
^{105}Pd(n,γ)^{106}Pd	21.0±1.5	21.7±0.5
^{106}Pd(n,γ)^{107}Pd	0.30±0.03	0.36±0.10
^{108}Pd(n,γ)^{109}Pd	7.6±0.5	7.2±0.5
^{108}Pd(n,γ)^{109}Pd^{m}	0.185±0.010	0.185±0.011
^{110}Pd(n,γ)^{111}Pd	0.70±0.17	0.34±0.10

* Submitted to Physical Review C.

Future Directions

- The EGAF database will be expanded to include activation data in collaboration with the IAEA CRP *Reference Database for Neutron Activation Analysis*.
- Total thermal radiative neutron cross sections σ_0 will be derived from EGAF data for all isotopes.
- The EGAF σ_0 values will be compared with literature values and new evaluated σ_0 values will be included in EGAF.
- Capture γ-ray spectra will be compared with DICEBOX calculations to find input parameters that best reproduce the continuum shape.
- EGAF will be extended to include continuum γ-rays.
- DICEBOX calculations will be extended to use the thermal parameters for calculations at higher neutron energies.
- ENDF format γ-ray libraries will be generated in collaboration with LLNL.