Evaluation with EGAF Thermal Neutron Capture Data

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Collaborators

Budapest Reactor: Zs. Revay and T. Belgya
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EGAF Database

EGAF – **E**valuated **G**amma-ray **A**ctivation **F**ile developed at LBNL in collaboration with researchers at the Budapest Reactor and the IAEA.

- Precision measurements of thermal neutron γ-ray cross sections σ_γ for all elements with Z=1,83,92 except He and Pm.
- Determination of thermal total radiative neutron cross sections σ_0 for selected nuclei.

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), **2007ChZX**; 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:

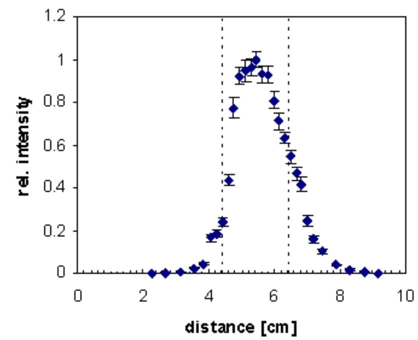
http://ie.lbl.gov/ng.html

IAEA CRP "Reference Database for Neutron Activation Analysis". Addition of activation data to EGAF from the IAEA/k0 database, DDEP. ENSDF, Budapest, and other sources.

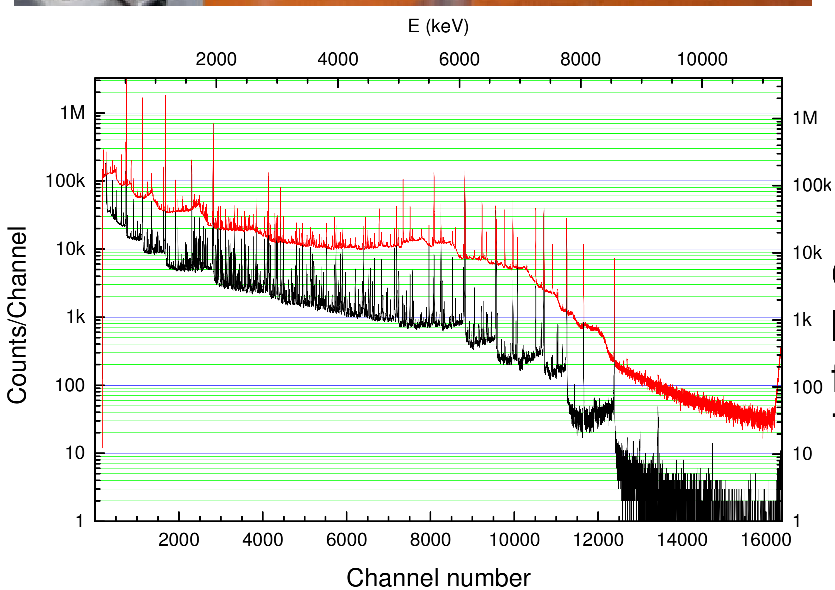
Budapest Prompt Gamma-ray Facility

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

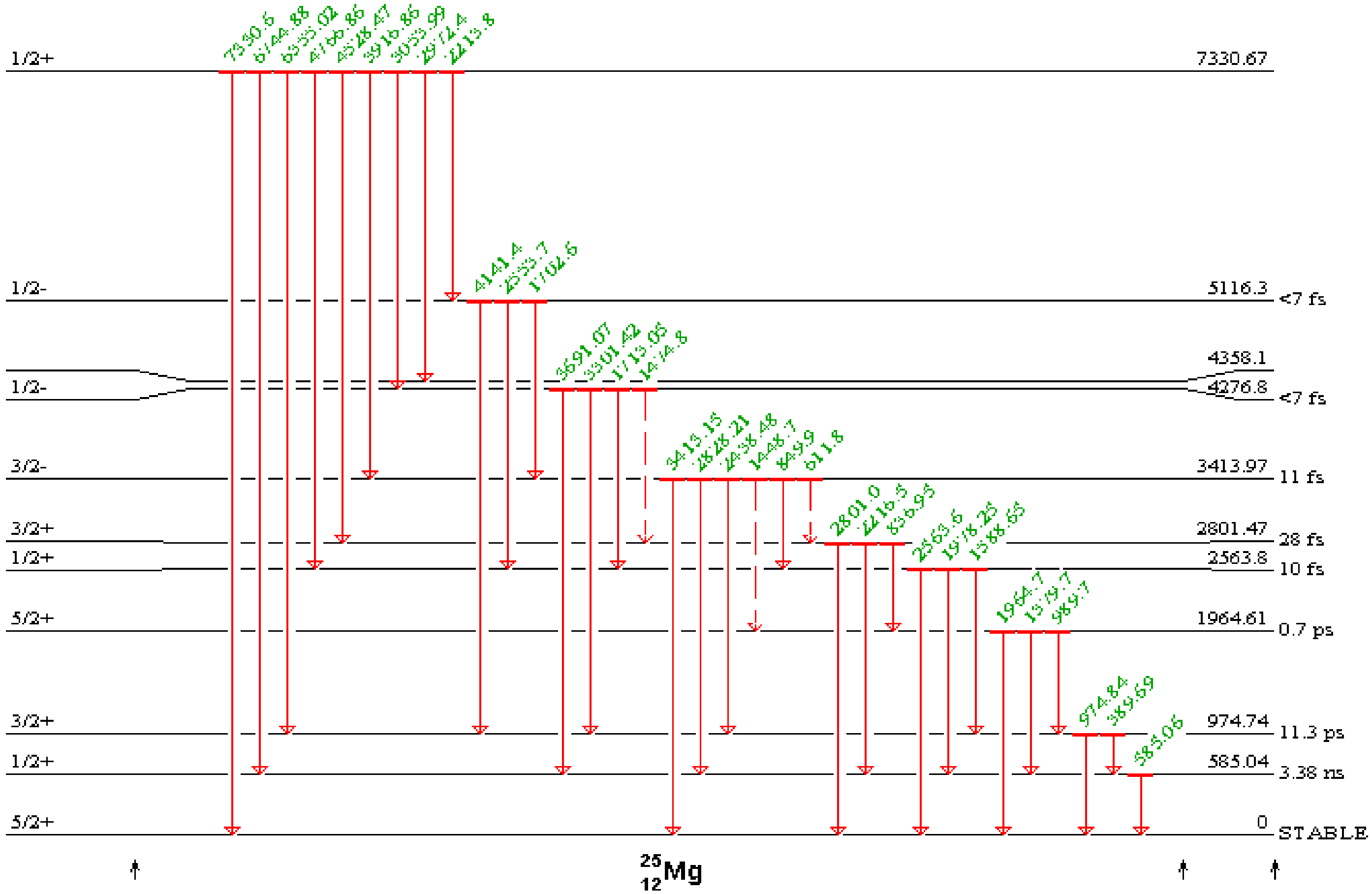
- Stoichiometric compounds of well-known compostion containing elements with well-known cross sections
  e.g. H,N,Cl,S,Na,Ti,Au, $\rightarrow$ KCl,$(CH_2)_n$,$Pb(NO_3)_2$,Tl_2SO_4

- 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

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 – $^{24}Mg(n,\gamma)^{25}Mg$

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	

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
$^{10}B(n,\alpha)$	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).

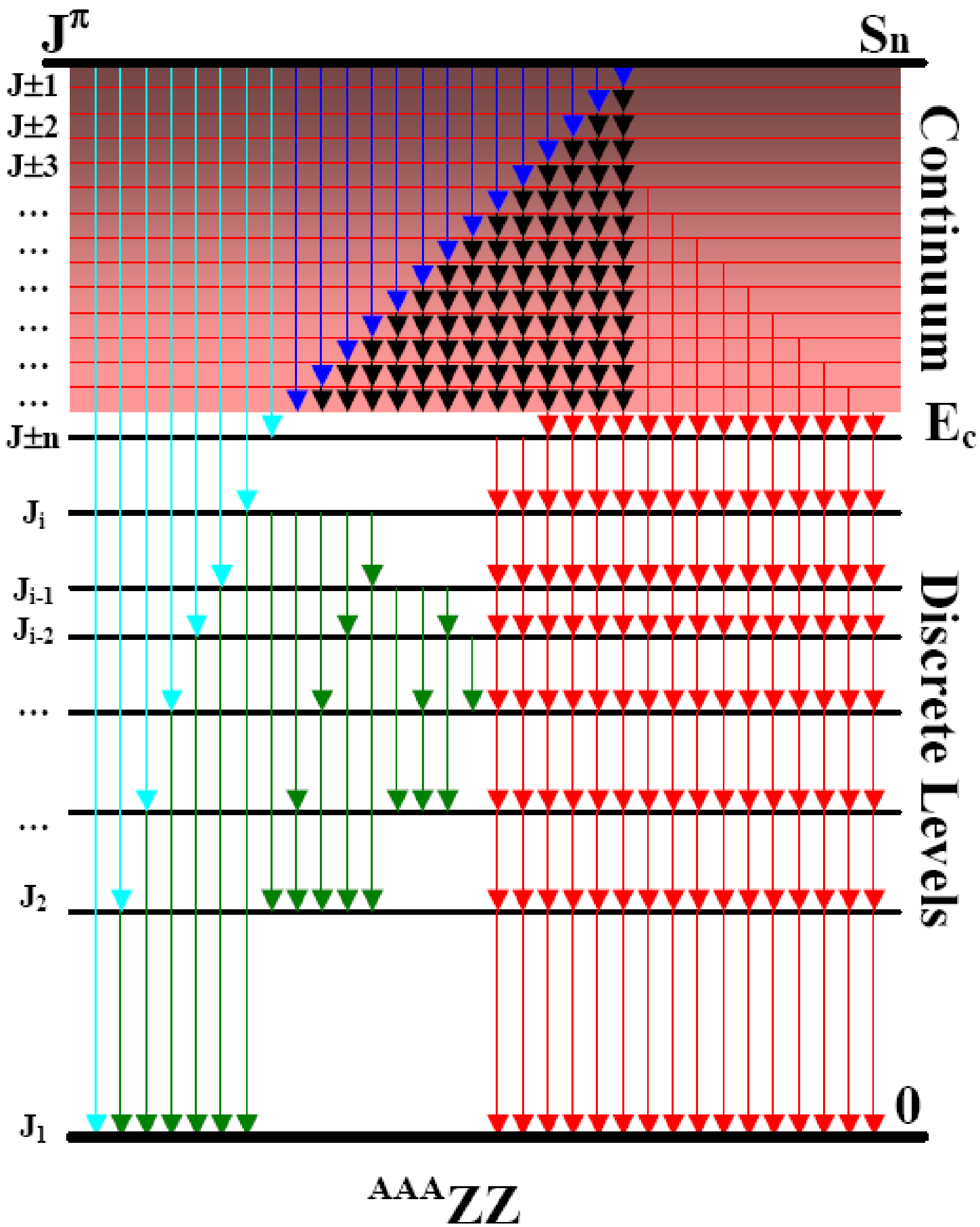
Statistical Model Calculations

For heavier nuclei, e.g. $Z \geq 20$, neutron capture decay schemes are not usually complete due to unresolved continuum decay.

The continuum decay can be calculated if the level densities and γ-ray transition probabilities can be represented as average nuclear properties that vary randomly.

- **DICEBOX** – Monte Carlo statistical model code developed by F. Becvar and M. Krticka (Prague).
- Thermal total radiative neutron cross sections σ_0 can be determined using EGAF data and DICEBOX calculations.
- Simple statistical considerations can be used to determine nuclear structure information from (n,γ) data.

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.

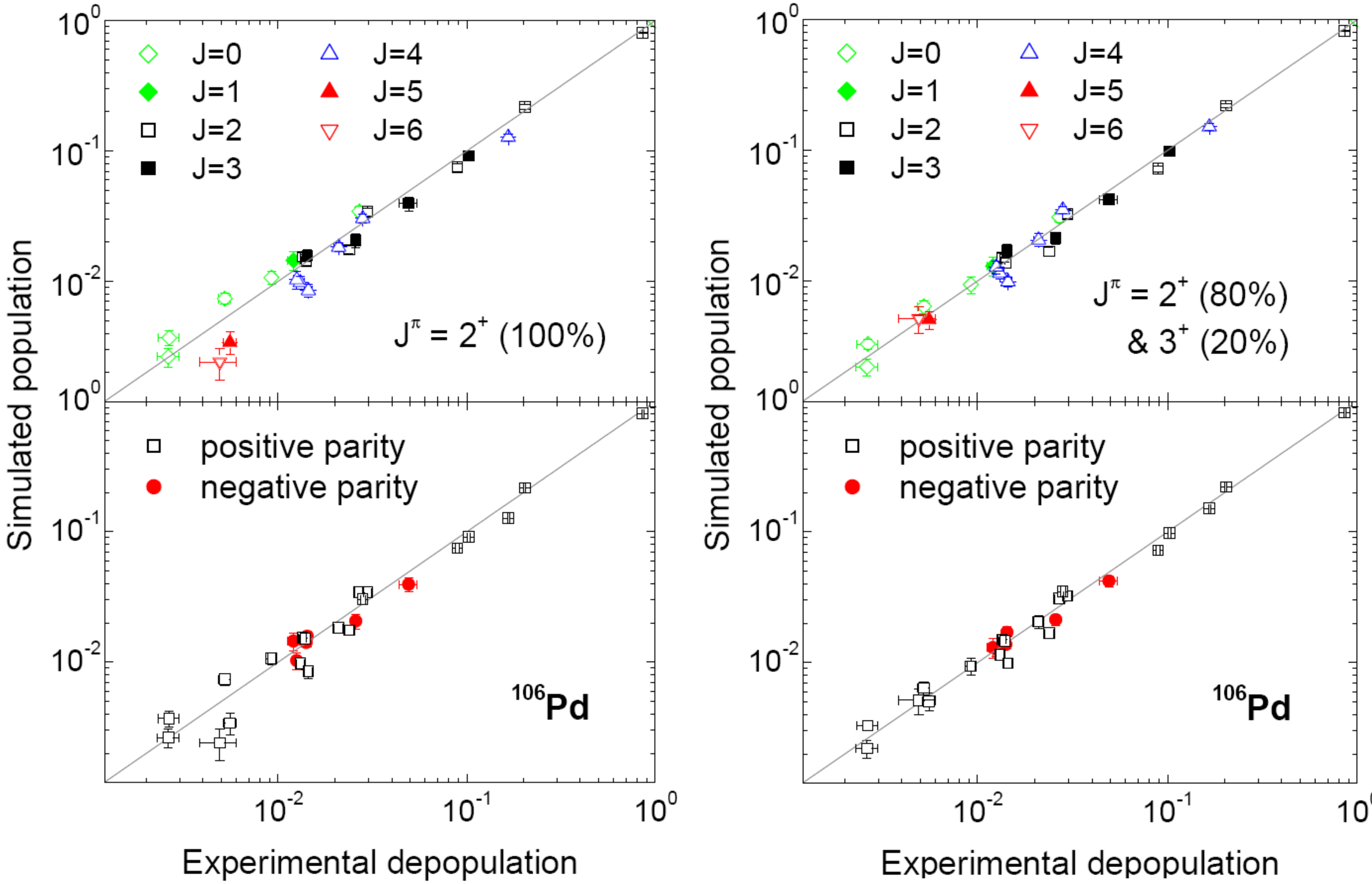
b) All levels and γ-rays above E_{crit} are generated randomly from level density and PSF models

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.

Comparison of ^{105}Pd(n,γ)^{106}Pd DICEBOX $\Sigma\sigma_\gamma$(in) with Experimental $\Sigma\sigma_\gamma$(out)



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

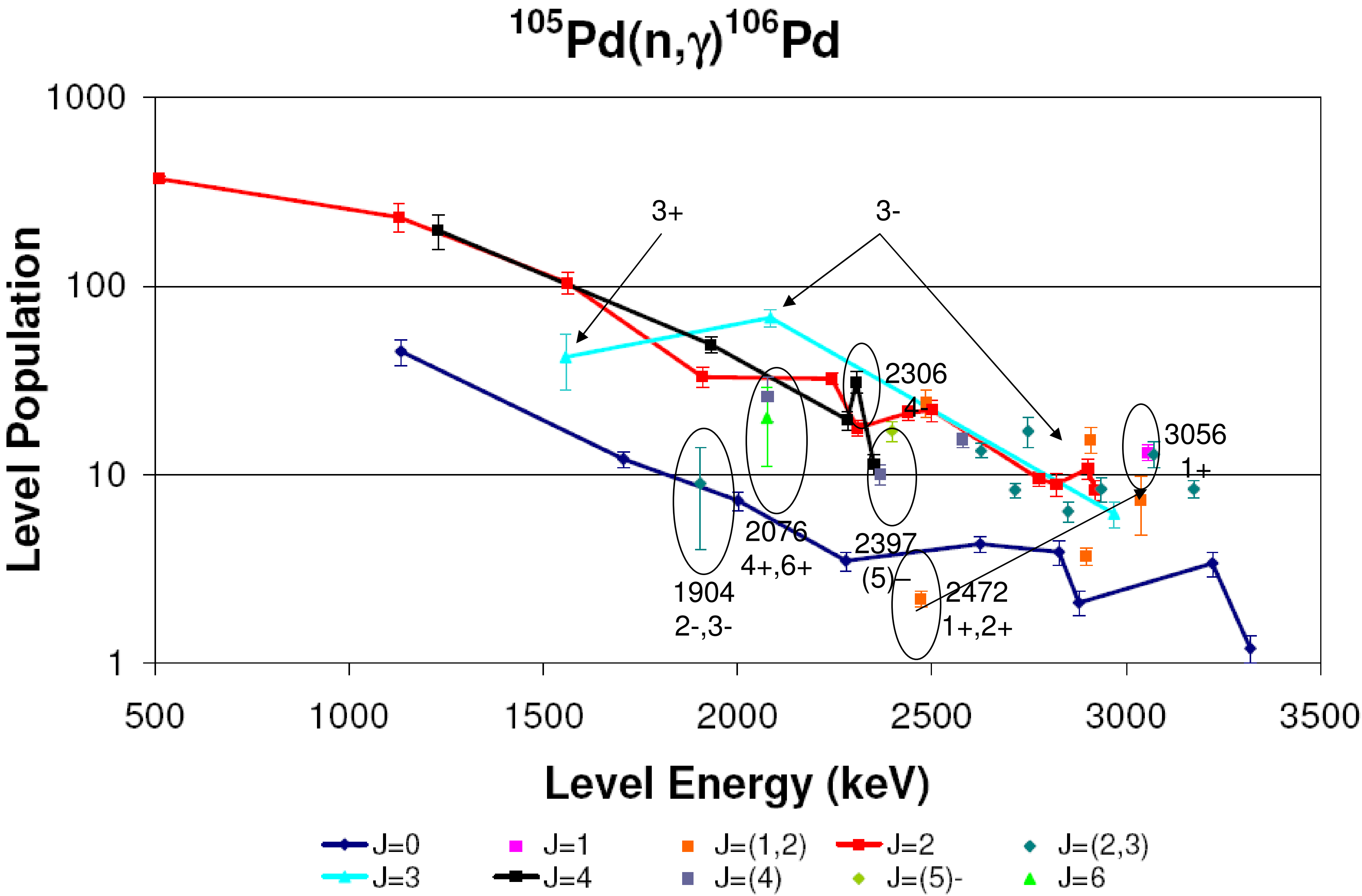
σ_0(Mughabghab, 2006)$=21.0\pm1.5$ b

Pd σ_0 results*

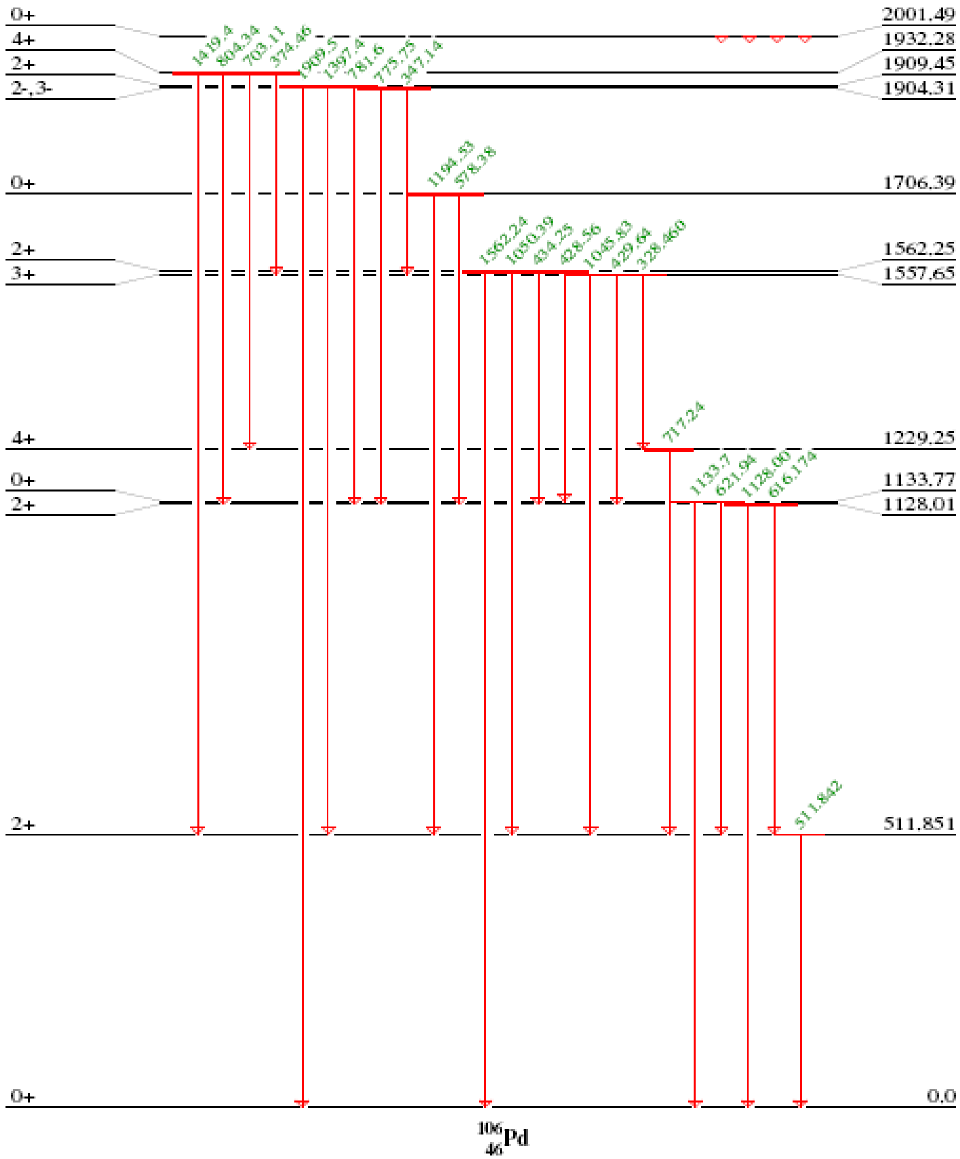
Reaction	σ_0(literature) (barns)	σ_0(this work) (barns)
$^{102}Pd(n,\gamma)^{103}Pd$	1.6±0.2	1.1±0.4
$^{104}Pd(n,\gamma)^{105}Pd$	0.65±0.30	0.77±0.17
$^{105}Pd(n,\gamma)^{106}Pd$	21.0±1.5	21.7±0.5
$^{106}Pd(n,\gamma)^{107}Pd$	0.30±0.03	0.36±0.10
$^{108}Pd(n,\gamma)^{109}Pd$	7.6±0.5	7.2±0.5
$^{108}Pd(n,\gamma)^{109}Pd^m$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

* Submitted to Physical Review C.

Graphical Statistical Analysis



1904-keV Level [2+,3+ in ENSDF]

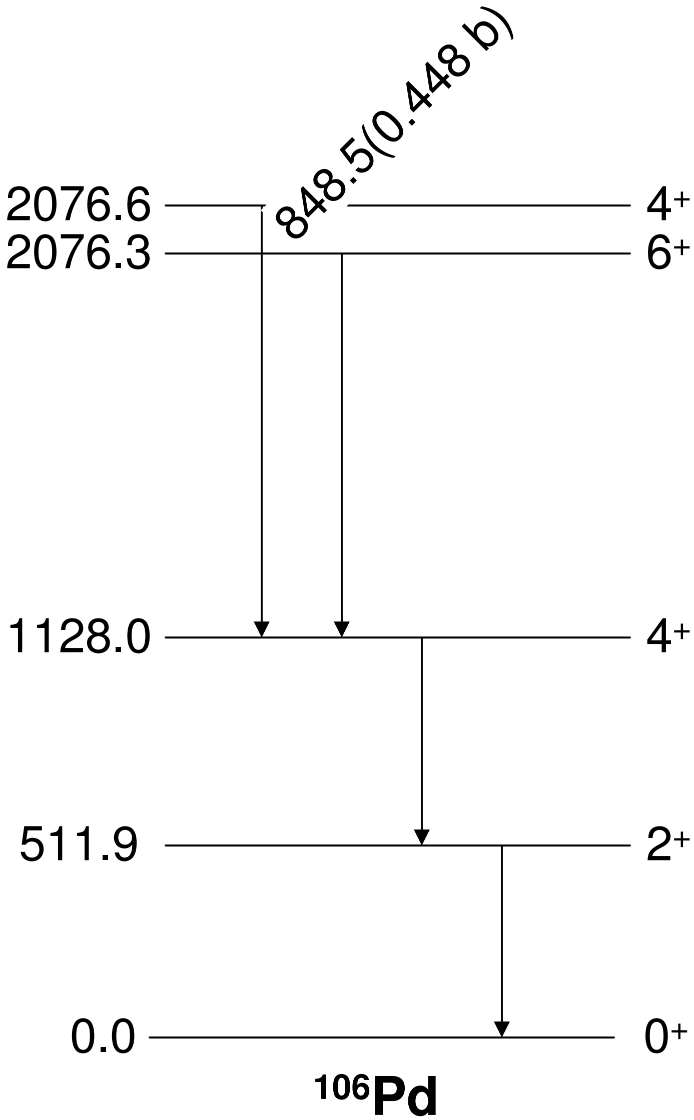


Wrong level placement

The 1904.3 keV level was assigned by the Ritz principal. It has $\sigma_{\gamma}(out)_{expt}$=0.12 b, which is much less than $\sigma_{\gamma}(out)$=1.13 b predicted by DICEBOX calculations.

The 347- and 776-keV γ-rays deexciting the 1904.3 keV level can also be placed from the 1909.3 keV level giving $\sigma_{\gamma}(out)_{expt}$=0.62 b, which is consistent with 0.83 b predicted by DICEBOX for that level.

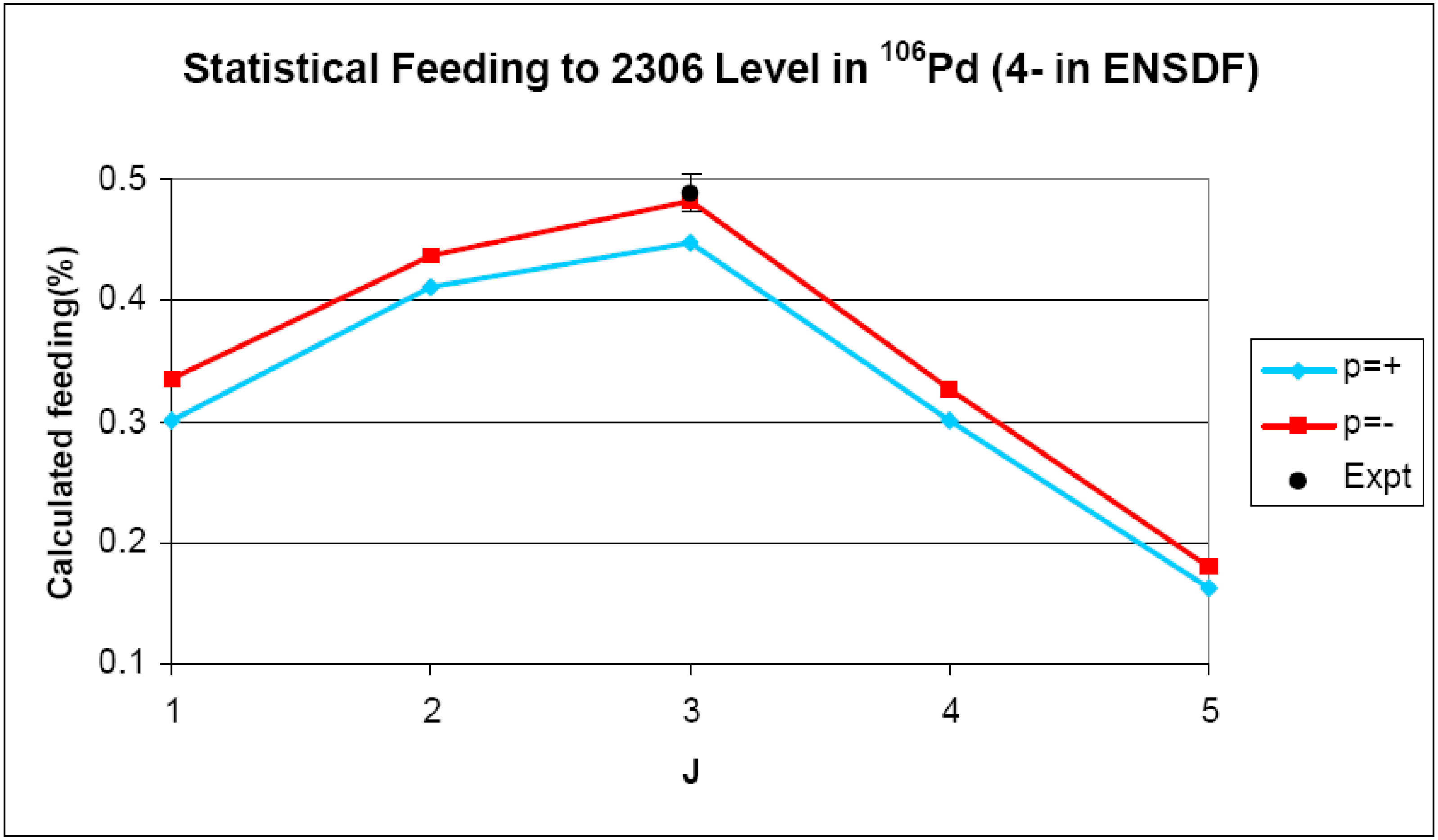
2076.5-keV 4^++6^+ Doublet



848.5 keV doublet can be resolved from calculated population of 4^+ and 6^+ levels using either the graphical trend for 4+ levels or statistical model calculations.

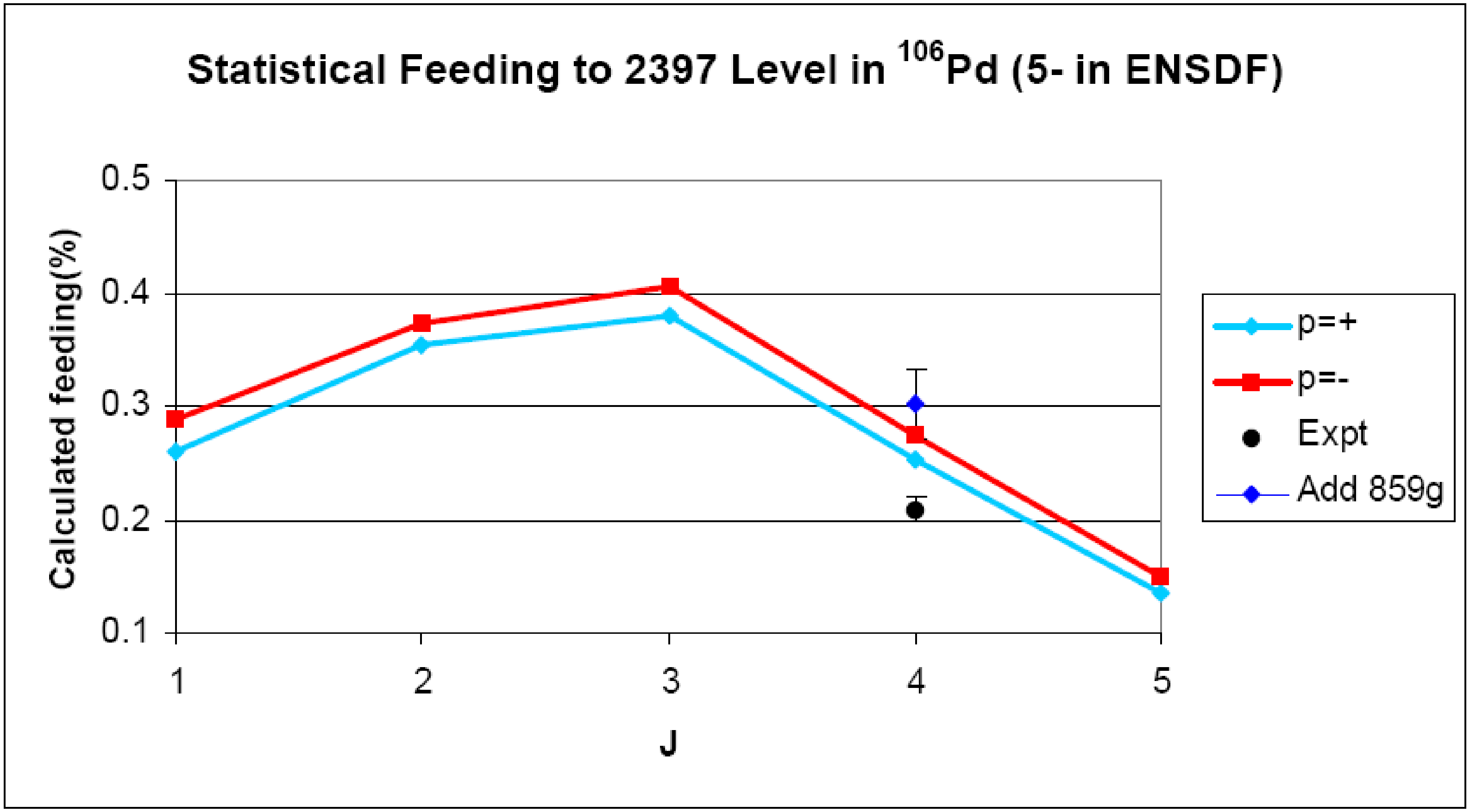
	E_γ	Transition	Cross Section
1.	848.5 keV	$4^+ \rightarrow 4^+$	0.345±0.022 b
2.	848.5 keV	$6^+ \rightarrow 4^+$	0.103±0.022 b

2306-keV level



J$^{\pi}$ consistent with 3-. Previous assigment based on solely on the interpretation of $\gamma\gamma(\theta)$ data appears to be incorrect..

2397-keV level



J$^{\pi}$ consistent with 4-. Previous value base on L=(5) from (p,t) may be include contamination from 2401 keV level (3-). Addition of unplaced 859-keV γ-ray to 1557.7-keV (3+) level improves fit to 4-. Parity was determined by E1+M2 γ-ray to 4+ level.

2472-keV [1+,2+] and 3056 [1+] Levels

2472 – $J^{\pi}=1^{+},2^{+}$ in ENSDF is assigned from L=2 in $^{105}Pd(5/2^{+})$(d,p), γ-ray to 0^{+}.

Weak population in thermal $^{105}Pd(n,\gamma)$ is inconsistent $J^{\pi}=2^{+}$ assignment

Weak population in average resonance capture is consistent with J^{π}=1+, 5+.

∴ $J^{\pi}(2472)=1^{+}$

3056 – $J^{\pi}=1^{+}$ in ENSDF is assigned from $\gamma\gamma(\theta)$

Log*ft*=5.7 from 1^{+} and γ-ray deexcitation to $J^{\pi}=0^{+}$ suggest $J^{\pi}=1^{+},2^{+}$

Strong population in thermal 105Pd(n,g) is consistent with J=2,3

Strong population in average resonance capture indicates $J^{\pi}=2^{+},3^{+}$

∴ $J^{\pi}(3056)=2^{+}$

ENSDF Recomendations

1. Define a new (n,γ) normalization NR that normalizes the γ-ray intensities to cross sections as follows

   $$NR=\sigma_\gamma/(I_\gamma^{EGAF}\times f_{AB})$$

   where σ_γ^{EGAF} is the elemental cross section from EGAF and f_{AB} is the isotopic abundance.

2. The ENSDF (n,γ) normalization factor BR (intensity per 100 neutron captures) can then be calculated as follows

   $$BR=(100\times NR)/\sigma_0$$

   where σ_0 can be taken from Mughabghab (2006MuZX).