J^{π} from (n,γ) Measurements and Statistical Model Calculations

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(n,γ) E=Thermal Data Considerations

- Thermal (n,γ) data are usually incomplete except for light (Z<20) isotopes. Beware of papers that normalize γ-ray intensities to $\Sigma I\gamma(GS)=100$.
- Primary γ-rays are mainly E1 or M1. E2 γ-rays are much weaker

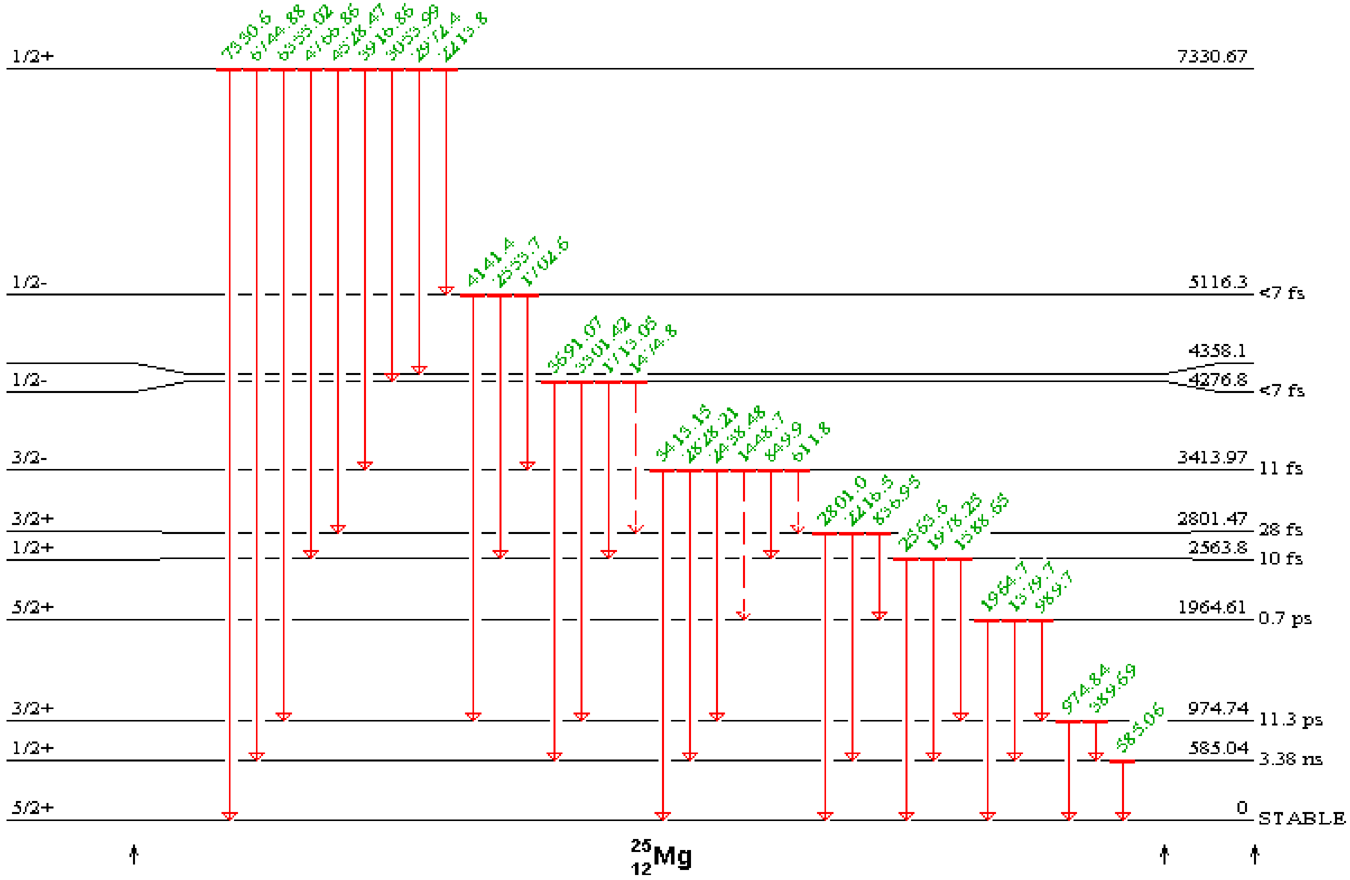
^{209}Bi(n,γ): 4604.7(4^-,5^-) $\rightarrow$ 433.5(7^-) I_γ=30% [E2]

It is improbable that the strongest primary γ-ray is E2. Most likely J^π(433.5)=6^- and the J^π assignments of low-lying levels in ^{210}Bi are incorrect.

- Statistical model calculations can provide important information about spin assignments.

Low-Z Data

The decay schemes of low-Z isotopes are often complete.



Cross section balance for $^{24}Mg(n,\gamma)^{25}Mg$

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	

High-Z Data

^{105}Pd(n,γ)^{106}Pd Level Feedings

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	

For Z≥20 measured neutron capture γ-ray decay schemes are generally incomplete due to unresolved continuum γ-rays.

σ_0=21.0±1.5 b (Mughabghab)

σ_γ(primary γ-rays)=0.55 b

σ_γ(secondary γ-rays, observed)=20.3 ±0.3 b

σ_γ(secondary γ-rays, statistical =1.4 ±0.3 b

σ_0=21.7±4 b

^{105}Pd(n,γ)^{106}Pd level feeding cross sections calculated from EGAF data.

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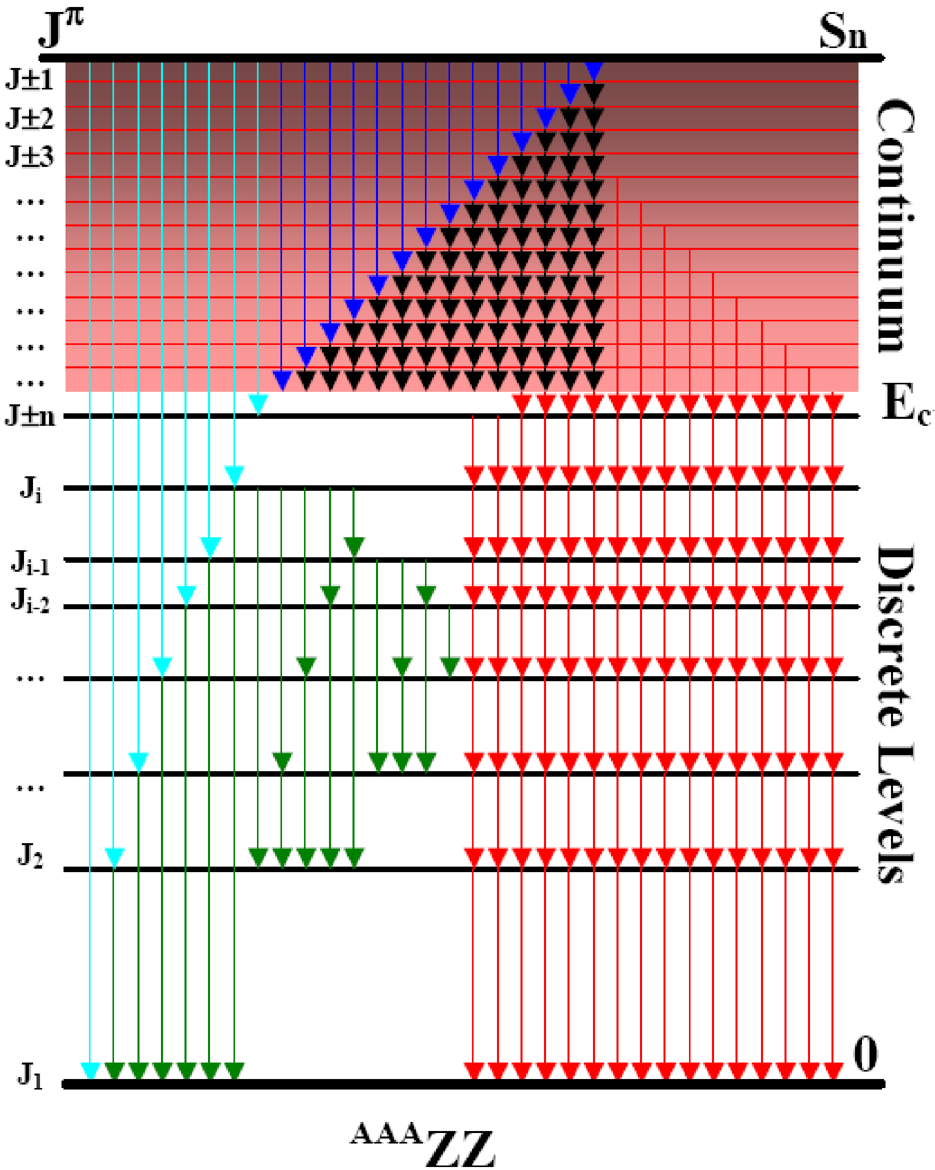
Statistical Model Calculations



The (n,γ) continuum feeding is statistical so it can be calculated if

1. σ_γ deexciting levels below a cutoff energy E_{crit} is complete. ↓
2. Primary σ_γ populating the levels below E_{crit} from the capture state is complete. ↓
3. J^π of levels below E_{crit} are well known.
4. Level density $\rho(E>E_{crit},J)$ is known.
5. Photon strength $f(E_\gamma)$ deexciting levels above E_{crit} is known ↓↓

DICEBOX Calculations

DICEBOX is a Monte Carlo code by F. Becvar and M. Krticka. It generates complete simulated neutron capture decay schemes constrained by known nuclear properties and statistical models.

A. Discrete primary and secondary σ_γ data from EGAF
B. J^π data for $E<E_{crit}$ from Reaction Input Parameter Library (RIPL)
C. Level density models
   1. Constant temperature (CT)

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

   2. Back-shifted Fermi (BSF) model

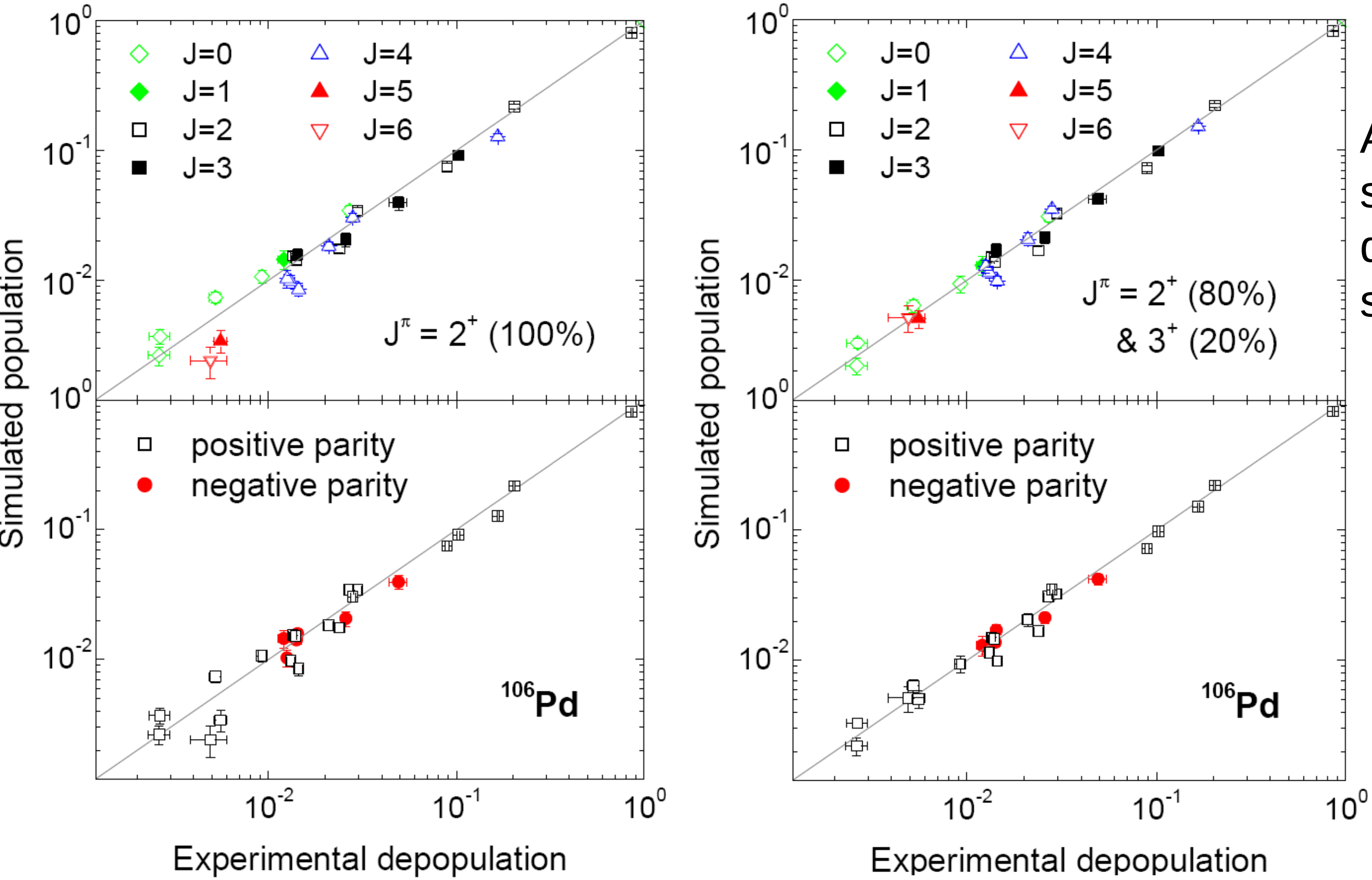
$$\rho(E,J) = f(J)\frac{\exp\left(2\sqrt{a(E-E_1)}\right)}{12\sqrt{2}\sigma_c a^{1/4}(E-E_1)^{5/4}}$$

D. El Photon Strength

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

   1. Brink-Axel (BA)
   2. Kadmenski, Markushev, Furman (KMF) for spherical nuclei
   3. Kopecky *et al* generalized Laurentian (GLO), temperature dep.
E. M1 Photon Strength
   1. Single Particle (SP), *$f^{(E1)}/f^{(M1)}$=5-7 or $f(M1)=1.2\times10^{-8}$ MeV^{-3}*
   2. Spin-Flip (SF), *Laurentzian resonance ≈8.5 MeV, Γ_{SF}≈4 MeV*

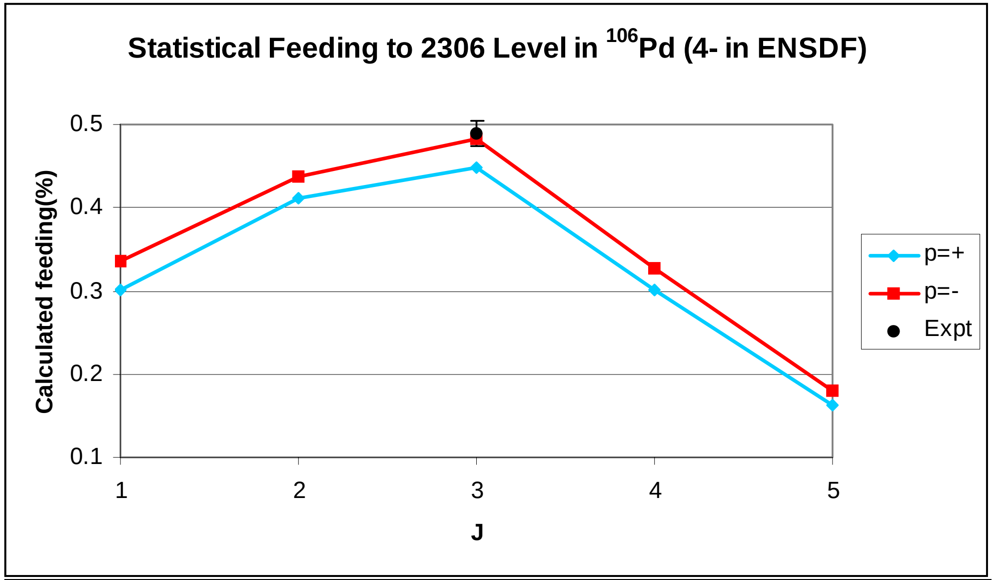
Population/Depopulation Plot



Admixture of capture state J^π values determined by least-squares fit.

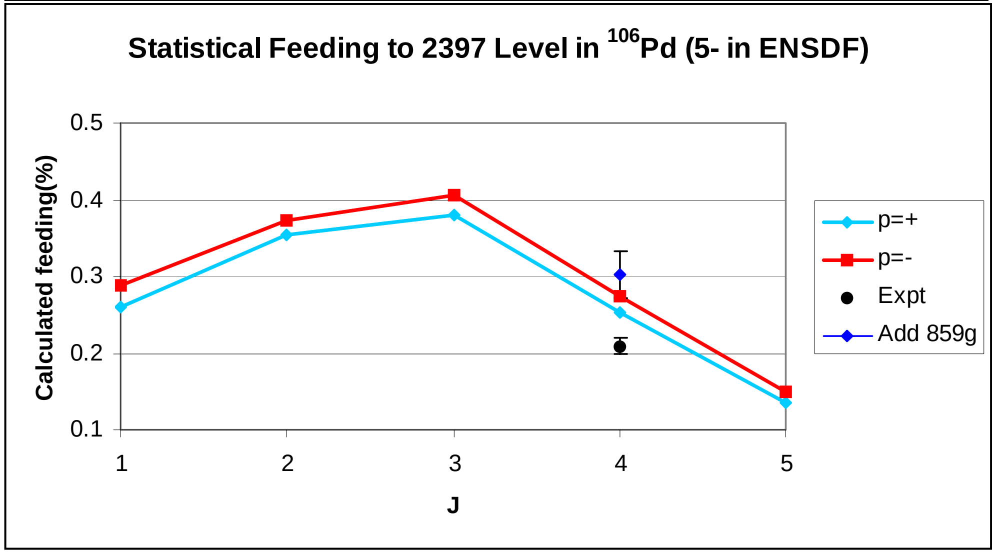
Significant deviations from the line can be indications of problems with input RIPL nuclear structure data. Either J^π or γ-ray branching may be wrong.

Data Problems: J^{π} Errors



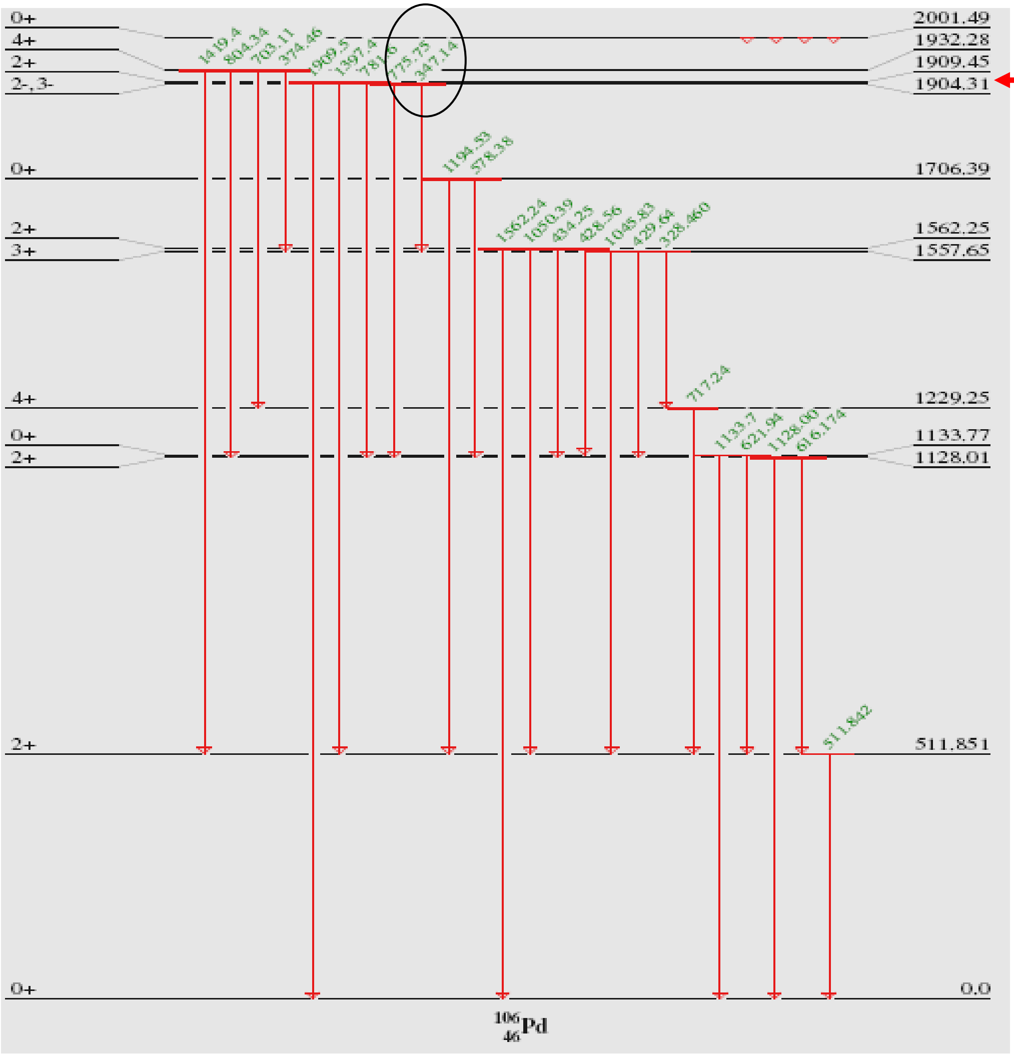
Statistical model calculations can be used to constrain J^{π} values.

2306-keV level feeding is consistent with $J^{\pi}=3^{-}$ not $J^{\pi}=4^{-}$ adopted in ENSDF on basis of $\gamma\gamma(\theta)$.



2397-keV level feeding is consistent with $J^{\pi}=4^{-}$ when additional γ-ray is placed. Assignment of $J^{\pi}=5^{-}$ in ENSDF is based on L=(5) in (p,t).

Level Scheme Errors



Mistaken level assignment

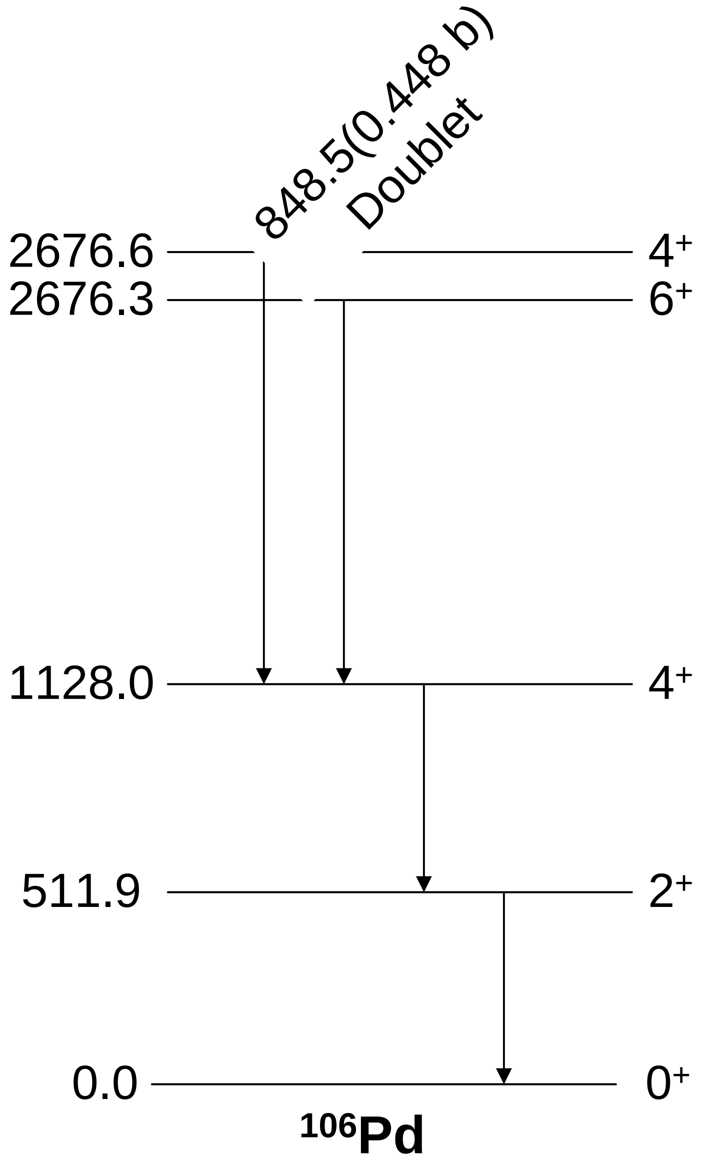
1904.3 keV level assigned using the Ritz principal.

$\sigma_\gamma(1904)_{expt}$=0.12 b
$\sigma_\gamma(1904)_{DICEBOX}$=1.13 b

Reassigning placement of the 347- and 776-keV γ-rays to deexcite the 1909.4-keV level gives

$\sigma_\gamma(1909)_{expt}$=0.62 b
$\sigma_\gamma(1909)_{DICEBOX}$=0.83 b

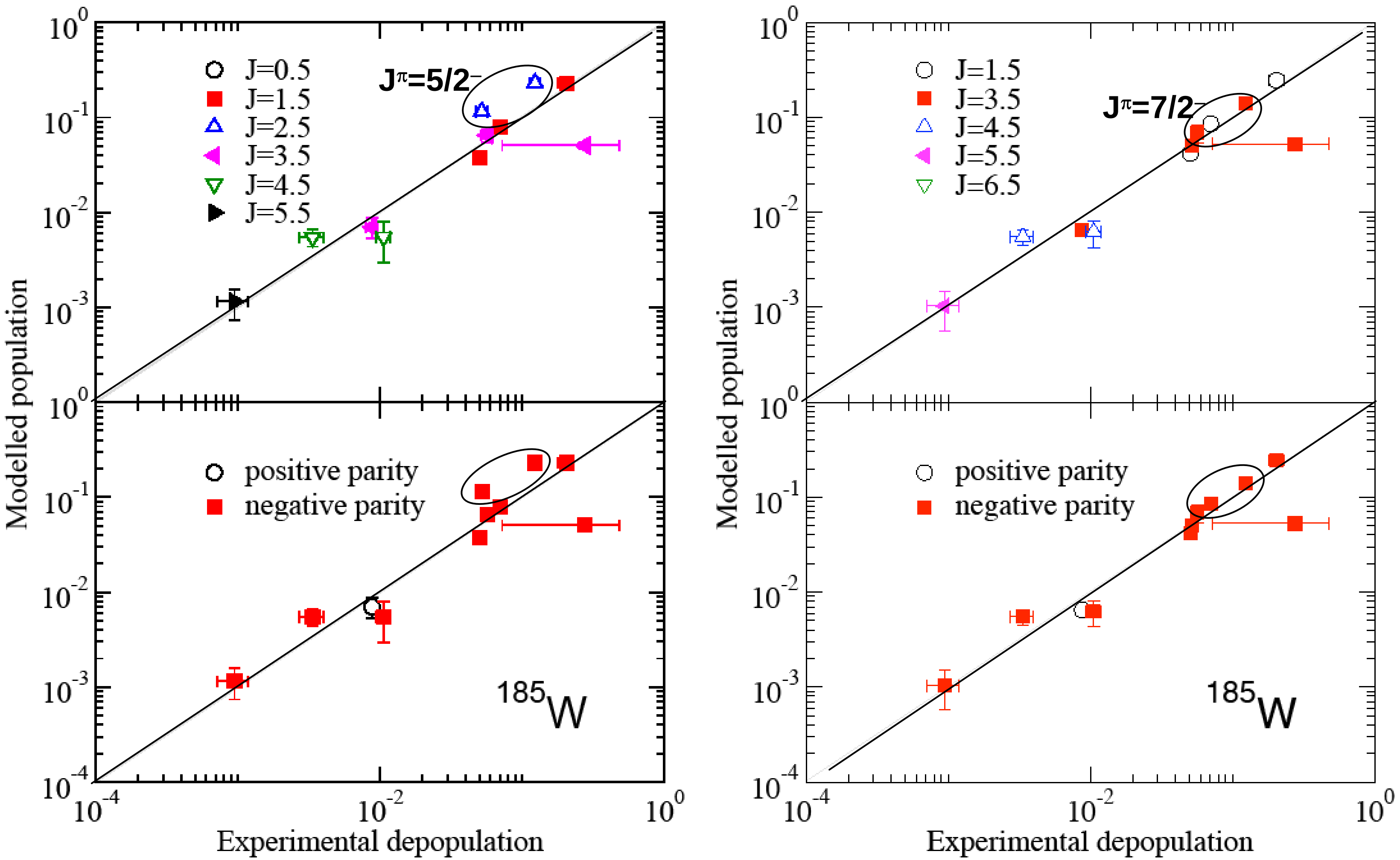
Resolving γ-ray Doublets



Doublet cross section ($\sigma_{848.5\gamma}$=0.448 b) populating the 4^+ and 6^+ can be divided based on DICEBOX calculation.

Eg (keV)	Transition	Calculated cross section (barns)
848.6	$4^+ \rightarrow 4^+$	0.345±0.022
848.3	$6^+ \rightarrow 4^+$	0.103±0.022

DICEBOX Population/Depopulation plot for $^{184}W(n,\gamma)^{185}W$ data. Levels at 66- and 188-keV have $J^{\pi}=5/2^{-}$ in ENSDF. Statistical model calculations indicate that both levels are more consistent with $7/2^{-}$. Many other "definite" J^{π} values in ^{185}W must be revised.



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^{185}W J^{π} Justifications

Level	J^{π}(ENSDF)	ENSDF J^{π} justification	New J^{π}
0.0	$3/2^-$	Atomic beam	$3/2^-$
23.5	$1/2^-$	$1/2^-$,$3/2^-$ (n,γ), DWBA	$3/2^-$
65.9	$5/2^-$	L=3 in (d,t),(d,p), M1+E2 to $3/2^-$	$7/2^-$
		$\alpha(L)_{exp}$=10(2), 11(3). $\alpha(L)_{M1}$=2.11, $\alpha(L)_{E2}$=16.6	
		$\alpha(M)_{exp}$=3.5(15). $\alpha(M)_{M1}$=0.48, $\alpha(M)_{E2}$=4.2	
		ICC(65.9γ) is also consistent with E2	
93.3	$3/2^-$	L=1 in (d,t),(d,p)	$3/2^-$
173.7	$7/2^-$	M1+E2 to $5/2^-$, E2 to $3/2^-$(GS)	$7/2^-$
187.9	$5/2^-$	L=3 in (d,t),(d,p), γ-ray to $1/2^-$	$7/2^-$

J=L+1/2 appears to be favored in (d,t),(d,p) reactions

Conclusions

- Statistical model calculations provide an important check of J^{π} assignments
- "Definite" J^{π} assignments may be wrong
- New publications using statistical J^{π} arguments are coming
- Simple statistical arguments should be used by evaluators when adopting J^{π} values.
- An evaluator code for doing statistical calculations would be useful.