Deviations from the Statistical Model in Capture γ-ray and EC/β^+-decay Data

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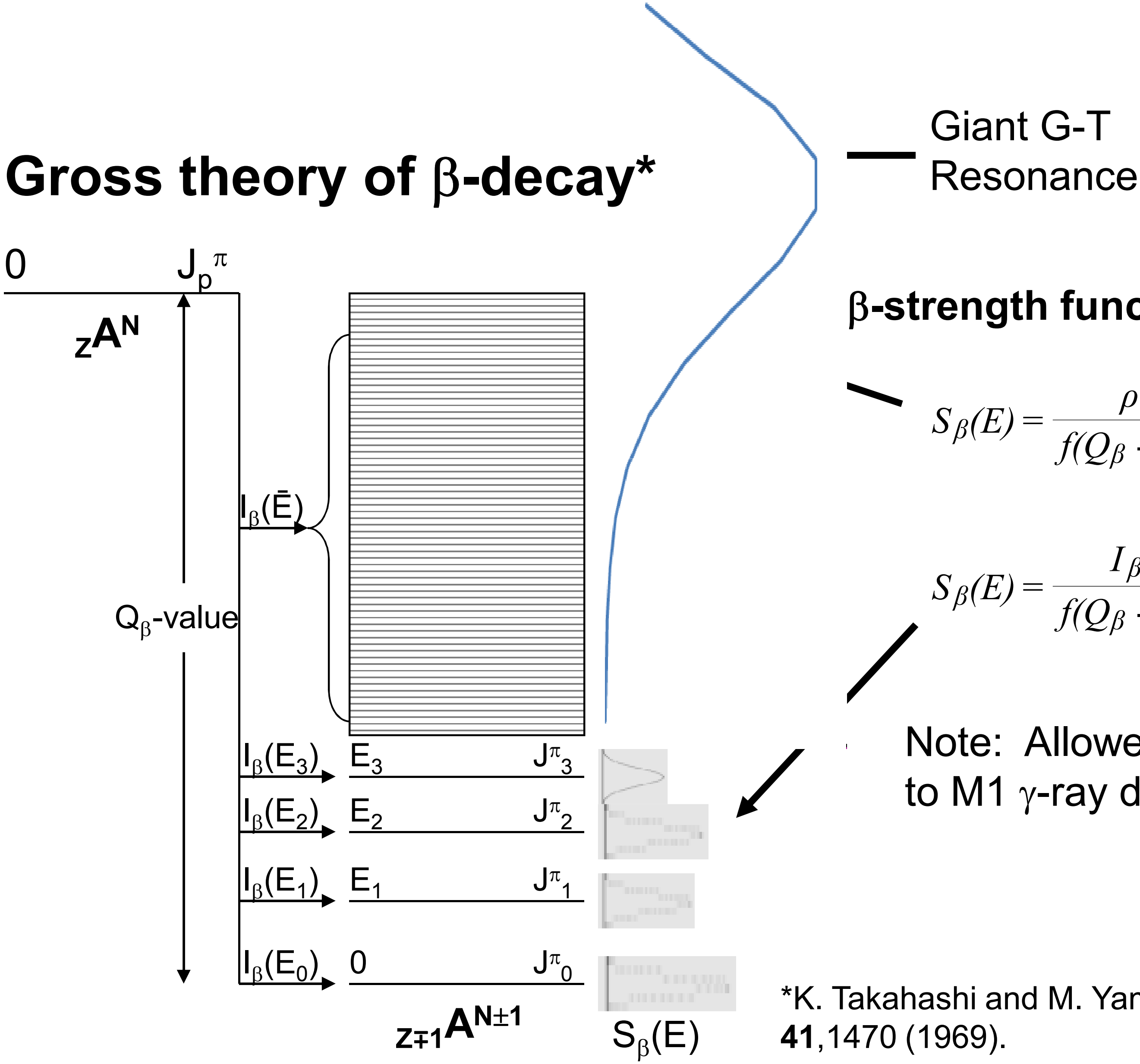
Outline

1. **Beta decay statistical properties**
    - Gross theory of beta decay
    - Total Absorption Spectrometer (TAS) studies
    - Evidence of nuclear structure effects
2. **Average resonance neutron capture**
    - Single particle M1, E2 strength
    - M1+E2 mixing rations
3. **Hypothesis –** Allowed β-decay, M1 and E2 transitions are dominated by nuclear structure properties.

Caveat: This presentation is based on preliminary, unpublished work and the data analysis is still in progress

Statistical Model of β-decay

Gross theory of β-decay*



β-strength function $S_\beta(E)$*

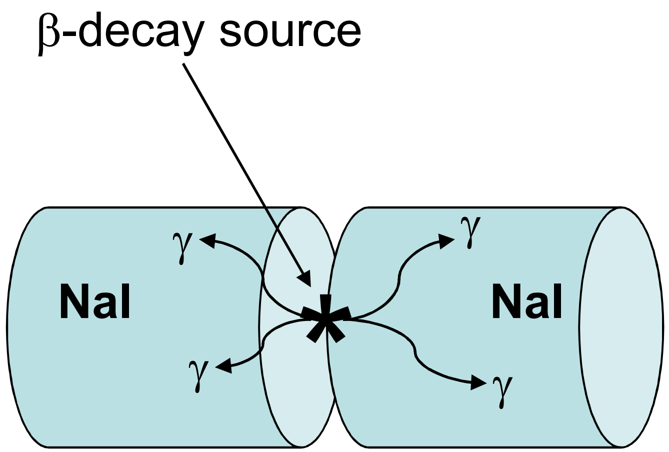
$$S_\beta(E) = \frac{\rho(E)}{f(Q_\beta - E)t_{Ave}} \text{(continuum levels)}$$

$$S_\beta(E) = \frac{I_\beta(E)}{f(Q_\beta - E)t_{1/2}} \text{(individual levels)}$$

Note: Allowed β-decay is analogous to M1 γ-ray decay.

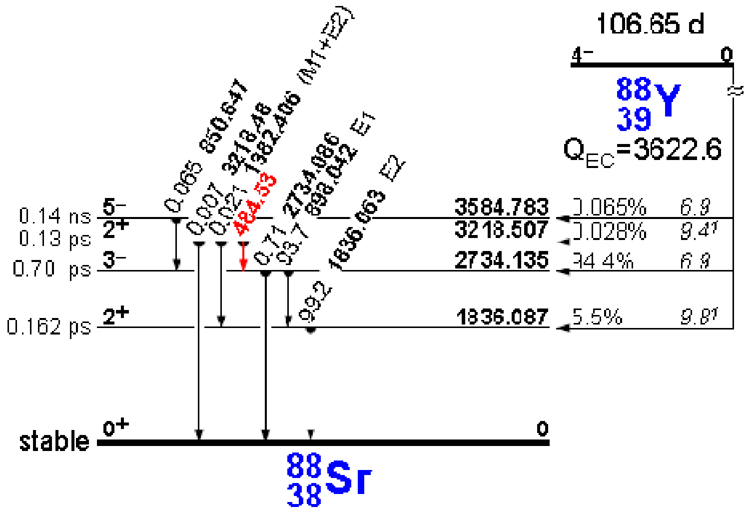
*K. Takahashi and M. Yamada, Progr. Theoret. Phys. **41**,1470 (1969).

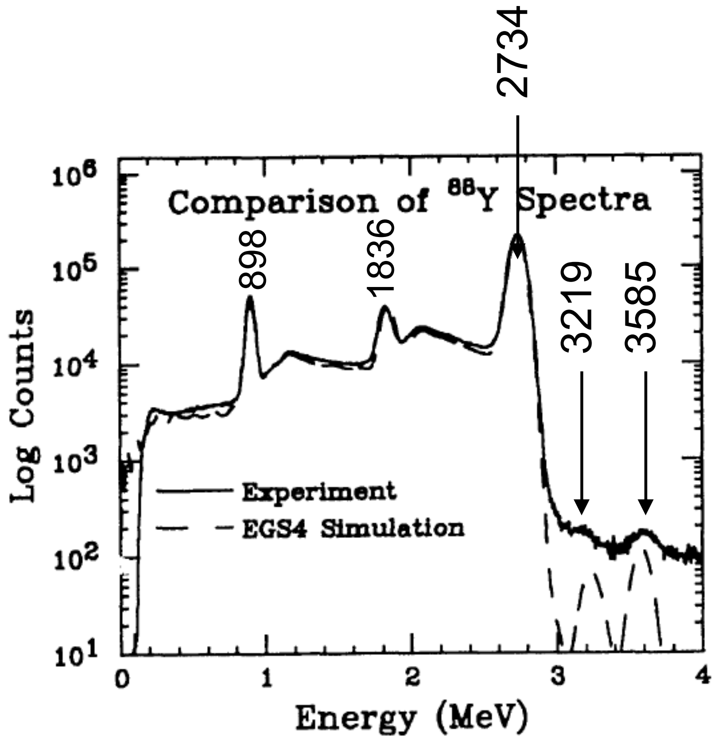
Total Absorption Spectroscopy (TAS)



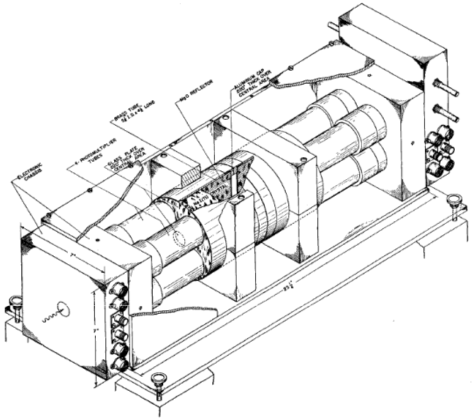
TAS spectrometer measures γ-ray sum spectrum for each β-decay event

The β-strength function can be directly measured by TAS and compared with statistical models after correction for detector response.





TAS Spectrometers

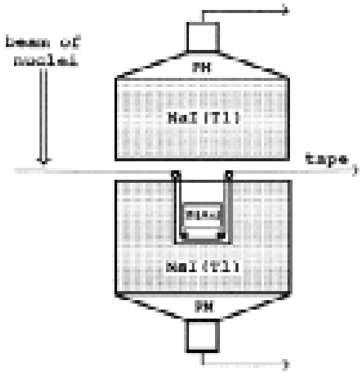


First TAS Spectrometer*: 2-10×13 cm NaI(Tl) detectors, 19% efficiency at 662 keV.

* R.S. Foote and H.W. Koch, Rev. Sci. Instr. **25**, 746 (1954).

Lucretia–Isolde: 38×38 cm NaI(Tl) well detector, 63% photopeak efficiency at 1.33 MeV.

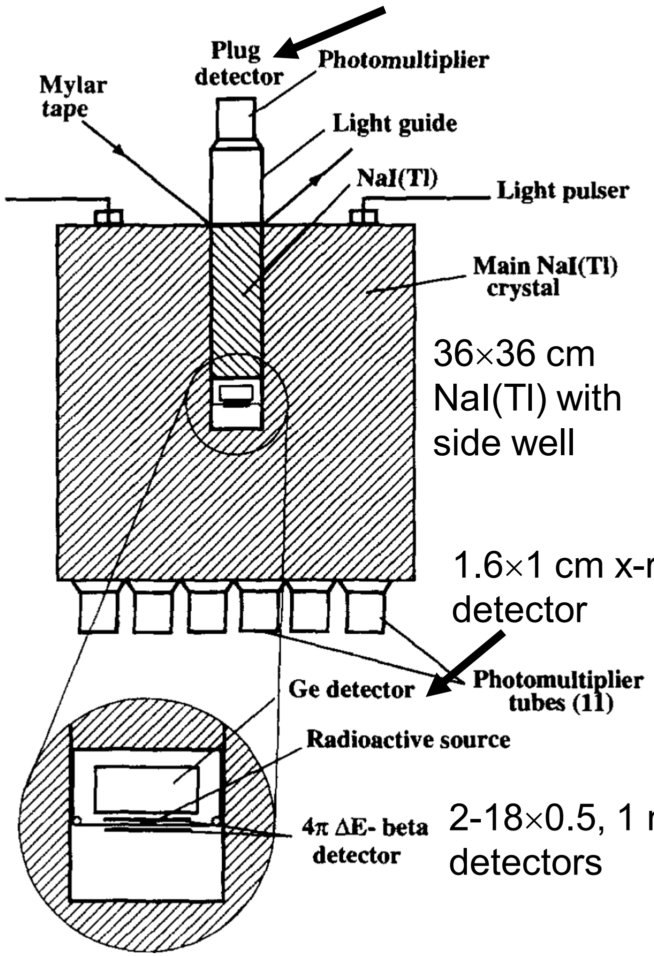
TAGS-INEL: 20×20 vm NaI(Tl) well detector, 99% efficiency at 200 keV.



TAGS-St. Petersburg: 20×11 cm NaI(Tl) + 20×11 cm NaI(Tl) well detector. Si(Au) β–particle detector.

LBNL/GSI TAS Spectrometer

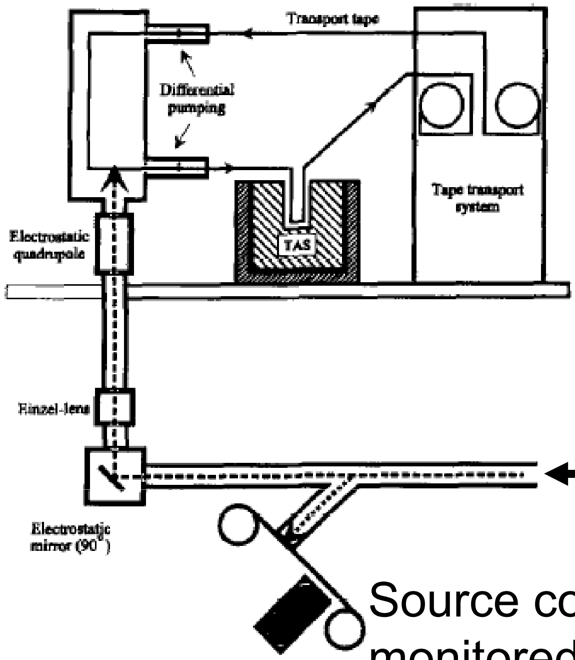
4×15 cm NaI(Tl) plug



36×36 cm NaI(Tl) with side well

1.6×1 cm x-ray detector

2-18×0.5, 1 mm Si β detectors



Reel to reel tape transport system brings the source into the detector well.

OASIS* mass separated beam

Source composition monitored with HPGe

Efficiency

>66% peak @ 0.3-1.5 MeV
>95% total detection @ 0.3-1.5 MeV
>55% peak @ 5 MeV
>89% total detection @ 5 MeV

*J.M. Nitschke, Nuclear Instruments and Methods 206 (1983) 341-351.

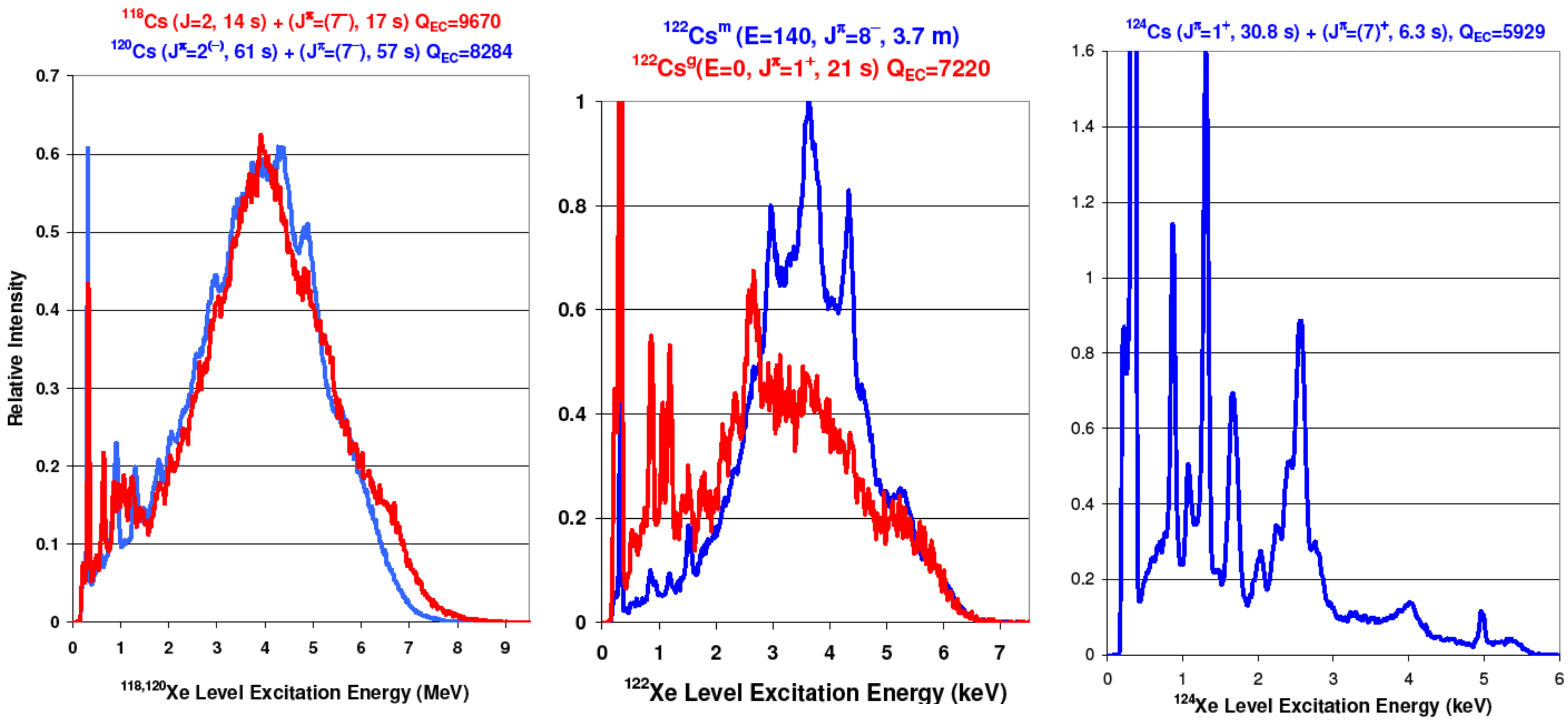
LBNL TAS Measurements

Only one TAS measurement was performed at LBNL in 1990 before it moved to GSI. These unpublished results will be presented here.

- **Collaborators:** J.M. Nitschke*, P.A. Wilmarth†, and R.B. Firestone
- **Reaction:** $^{28}Si(^{nat}Mo,xnyp)$ at LBNL SuperHILAC
- **Isotopes studied:** $^{117-124}Cs$, $^{117-121}Xe$, and $^{121-124}Ba$
- **Measured:** Complete I_β spectra, Q_{EC} values, and S_β and S_γ strengths
- **Tested:** Gross theory of β-decay

*Deceased (1995).
†Oregon Health & Sciences University, School of Dentistry, Portland OR.

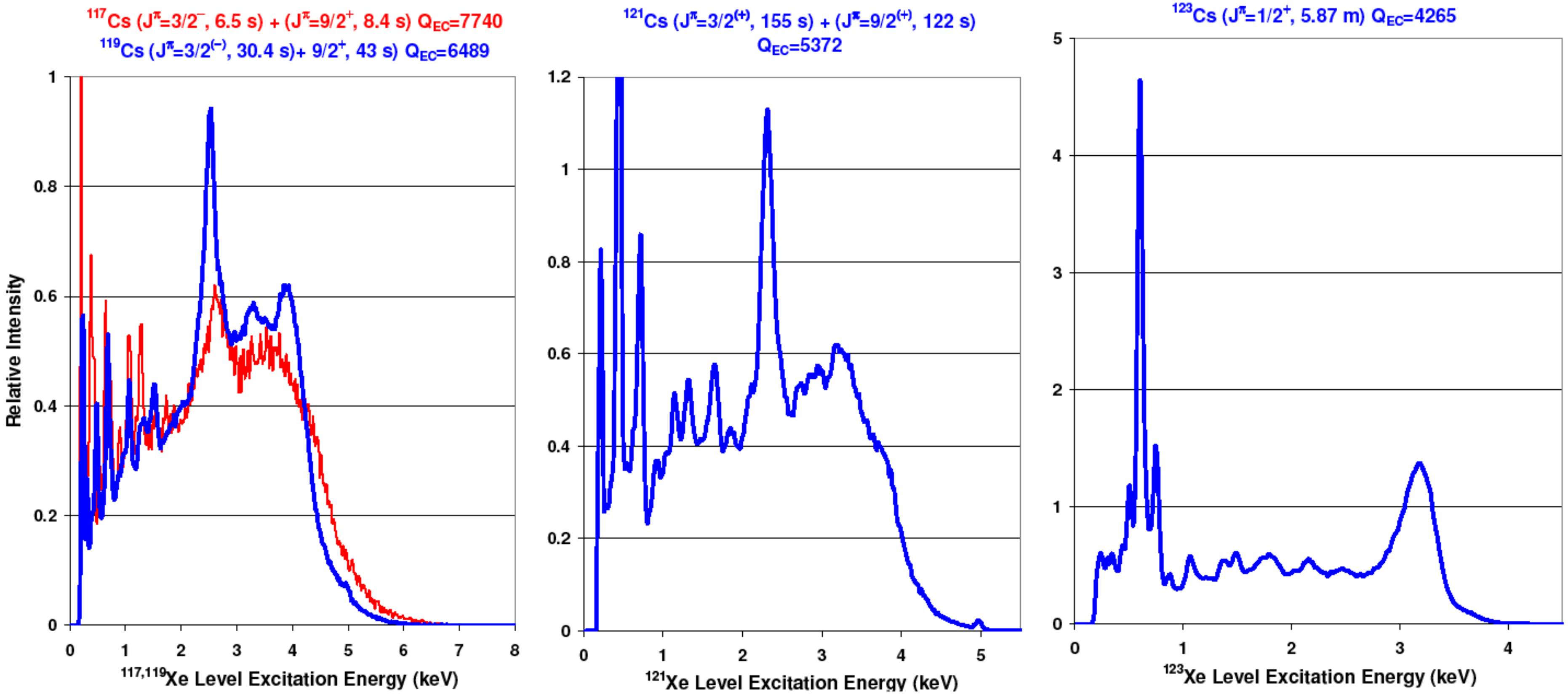
TAS Spectra for Even A Cs Isotopes*



Structure observed in these decay schemes is inconsistent with Gross Theory.

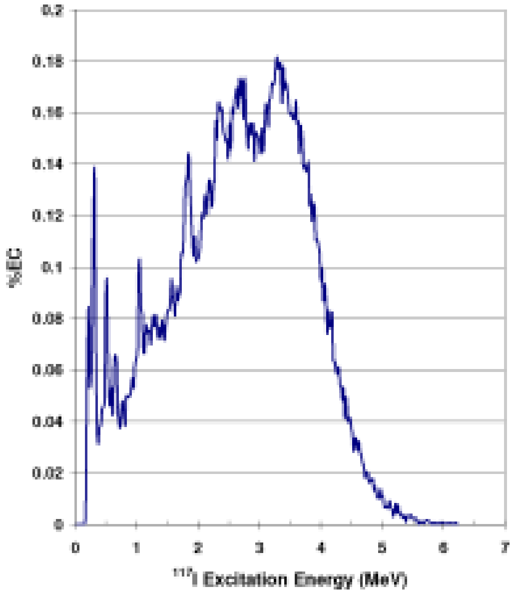
* Uncorrected for the TAS response function.

Odd-A Cs Isotopes

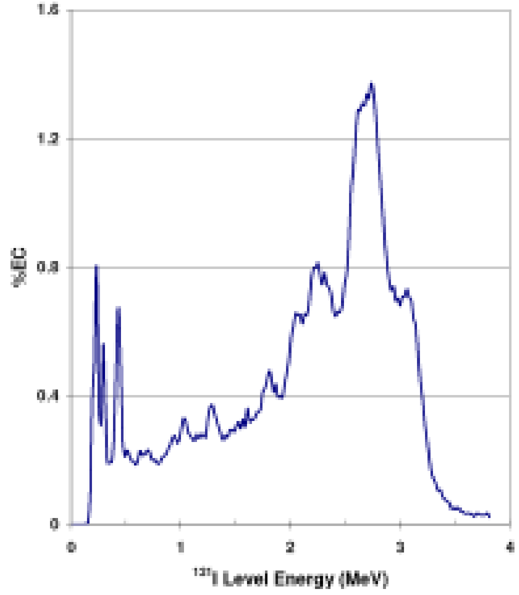


Xe, Ba Isotopes

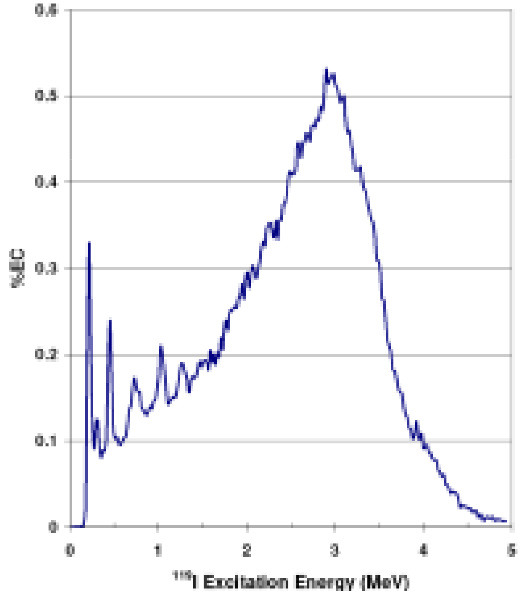
^{117}Xe (J^{π}=5/2+), $t_{1/2}$=61 s, Q_{EC}=6250



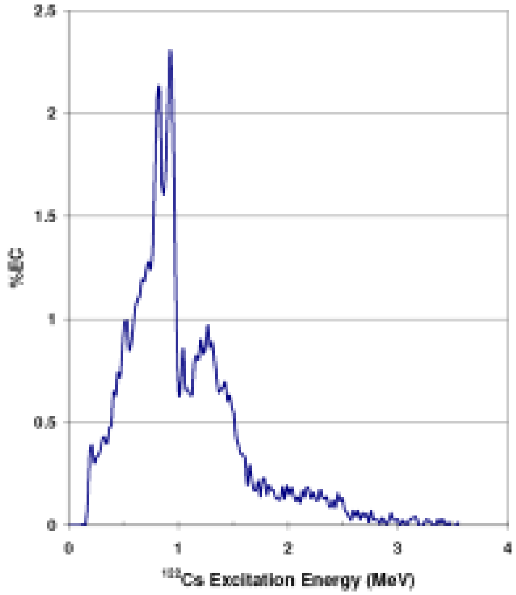
^{121}Xe (J^{π}=5/2+), $t_{1/2}$=40 m, Q_{EC}=3814



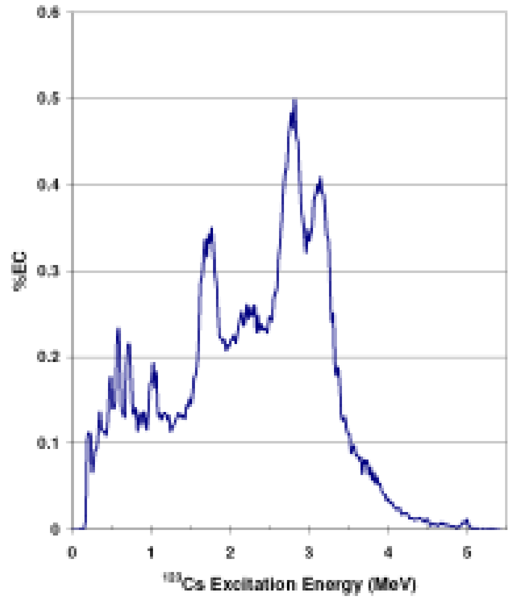
^{119}Xe (J^{π}=5/2+), $t_{1/2}$=5.8 m, Q_{EC}=4970



^{122}Ba (J^{π}=0+), $t_{1/2}$=2 m, Q_{EC}=3530

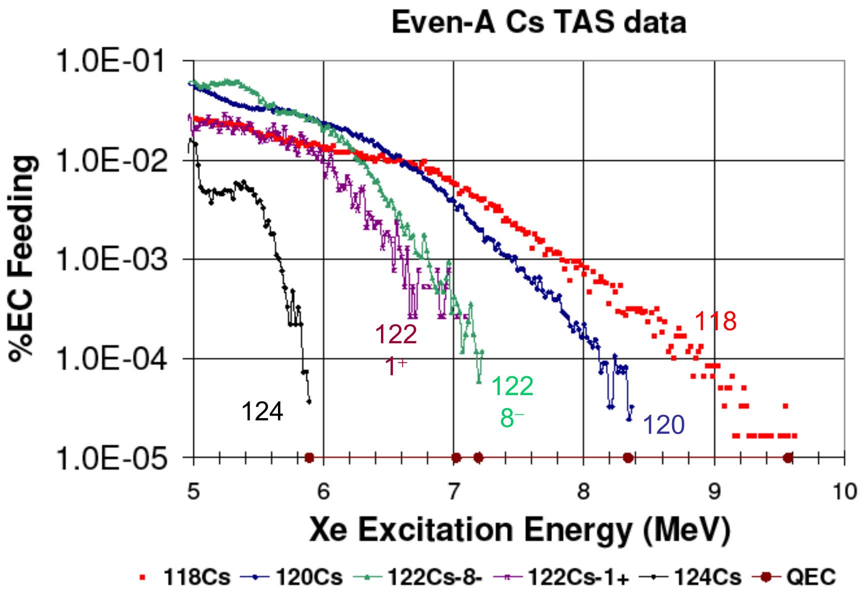


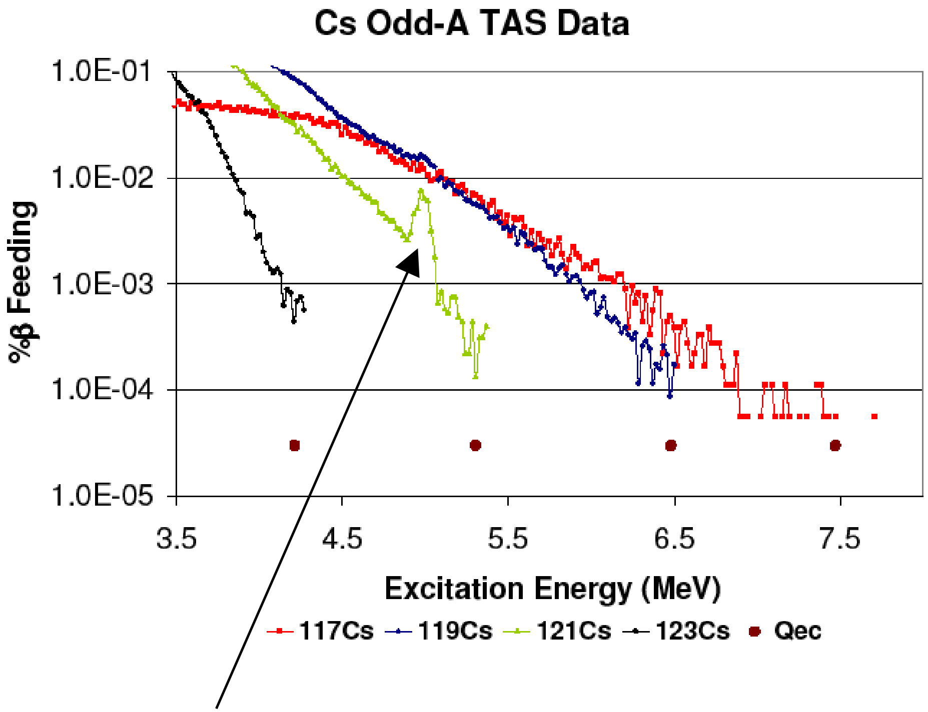
^{123}Ba (J^{π}=5/2+, $t_{1/2}$=2.7 m, Q_{EC}=5340



Q_{EC} Determination

Q_{EC} can be determined by the endpoint of the γ-ray sum spectrum.





Note the high energy resonance with E=5.0 MeV fed in ^{121}Cs decay

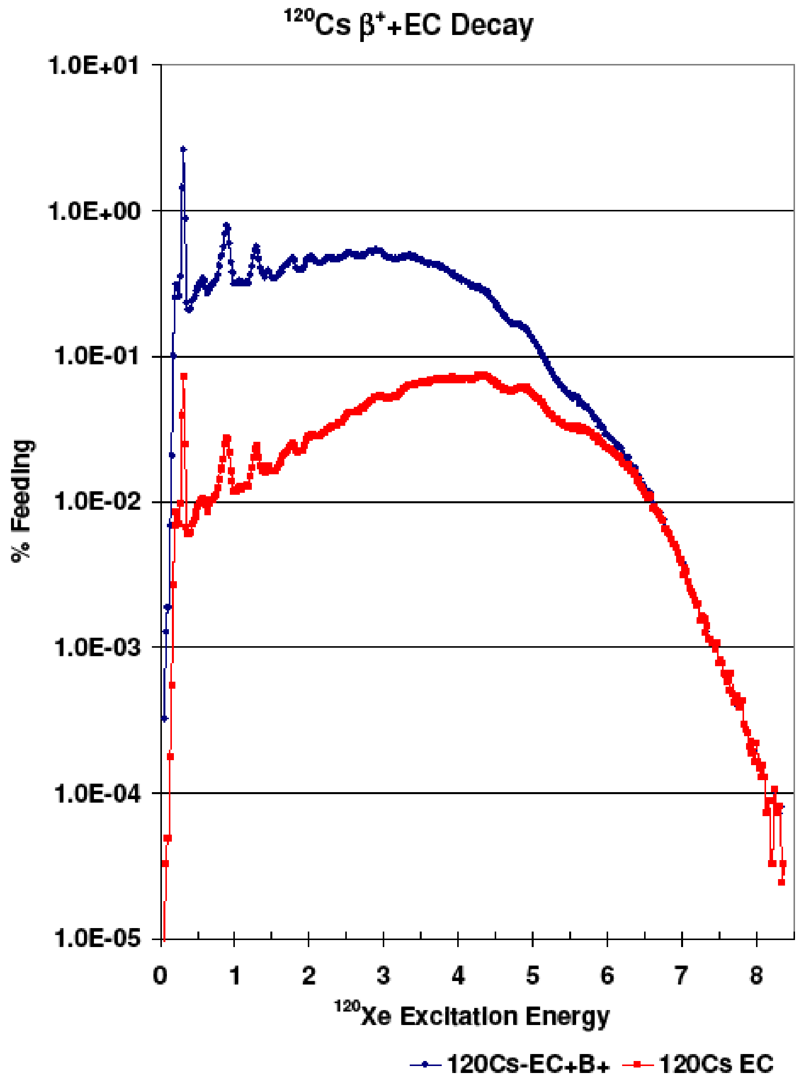
Ba, Cs, and Xe Q_{EC} Results

Isotope	AME (Audi)		TAS
	E	Q_{EC}	
$^{117}Cs(9/2^+)$	0	7740(60)	7470(100)
$^{117}Cs(3/2^-)$	150(80)		
$^{119}Cs(9/2^+)$	0	6489(17)	6480(100)
$^{119}Cs(3/2^+)$	50(30)		
$^{121}Cs(9/2^+)$	0	5372(18)	5300(100)
$^{121}Cs(3/2^+)$	68.5(3)		
$^{123}Cs(1/2^+)$	0	4205(15)	4210(100)

Isotope	AME (Audi)		TAS
	E	Q_{EC}	
$^{118}Cs(2)$	0	9670(16)	9570(100)
$^{118}Cs(7^-)$	100(60)		
$^{120}Cs(2^-)$	0	8284(15)	8340(100)
$^{120}Cs(7^-)$	100(60)		
$^{122}Cs(1^+)$	0	7220(30)	7020(100)
$^{122}Cs(8^-)$	140(30)		7190(100)
$^{124}Cs(1^+)$	0	5929(9)	5890(100)

Isotope	Q_{EC} (keV)	
	AME Audi	TAS
$^{117}Xe\ (5/2^+)$	6250(30)	6220(100)
$^{118}Xe\ (0+)$	2892(22)	2880(100)
$^{119}Xe\ (5/2^+)$	4970(30)	4930(100)
^{120}Xe 0+	1617(21)	1610(100)
$^{121}Xe\ (5/2^+)$	3814(15)	3820(100)
$^{121}Ba(5/2^+)$	6360(140)	6160(100)
$^{122}Ba(0^+)$	3530(40)	3530(100)
$^{123}Ba(5/2^+)$	5389(17)	5340(100)
$^{124}Ba(0^+)$	2542(15)	2650(100)

Absolute EC+β^+ Feedings



TAS measures relative electron capture feedings. To get total EC+β^+ feedings

$$I(EC+\beta^+)_i = I(\gamma)_i(1+\frac{f_{\beta^+}}{f_{EC}})$$

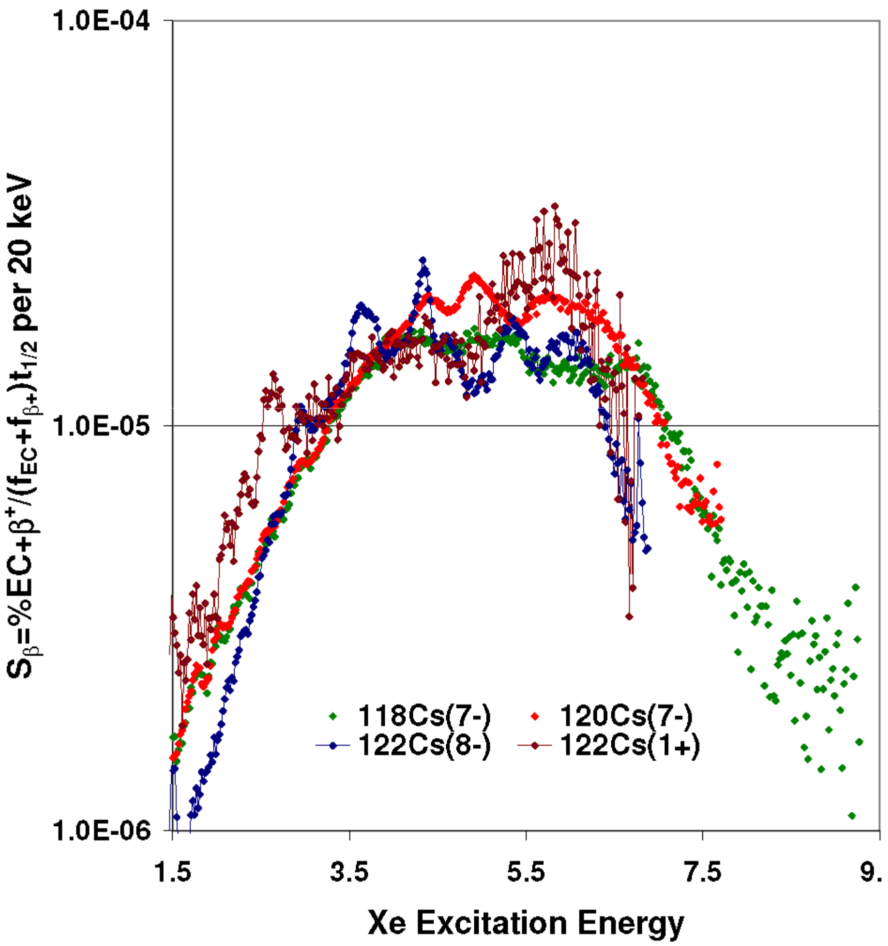
$$\%(EC+\beta^+)_i = 100\times \Sigma_i I(EC+\beta^+)_i$$

The spectrum should be corrected for the detector response function which is not known because the γ-ray spectrum is not known as a function of excitation energy.

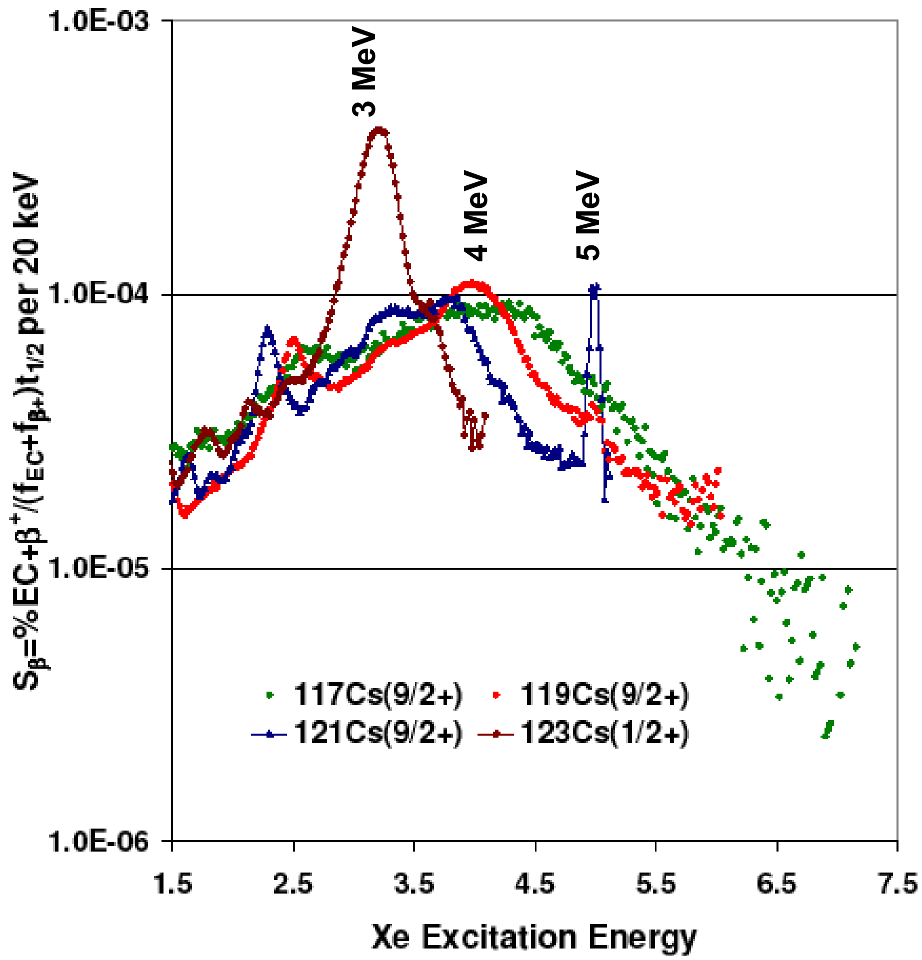
Preliminary attempts to estimate this correction indicate that this only qualitatively affects the following results.

Cs Beta Strength

Beta Strength - Even A Cs



Beta Strength - Odd A Cs



The Cs beta strength declines exponentially above ≈4.5 MeV. This is inconsistent with the statistical model of beta decay.

Nuclear Structure in the β-strength of the Cs isotopes

$\pi g_{9/2} \rightarrow \nu g_{7/2}$ spin-flip transition

Cs isotopes have β_2=0.2-0.3 so this fast spin-flip β-decay transition is expected near ≈4 MeV.

Configuration mixing spreads the β-strength over a wide energy range.

Shell model effects appear to dominate these decays.

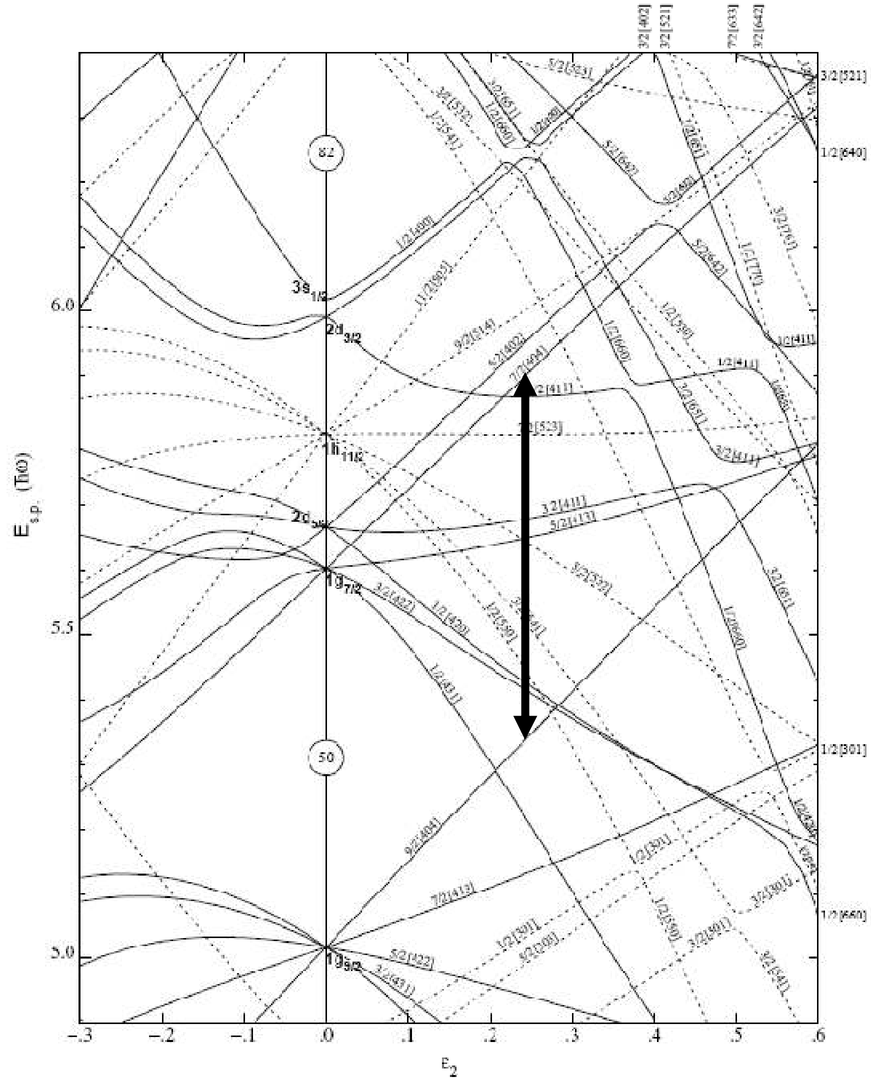
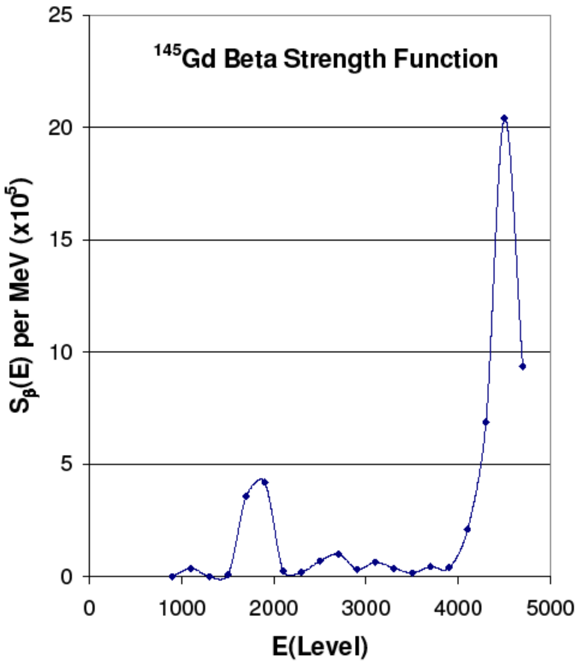
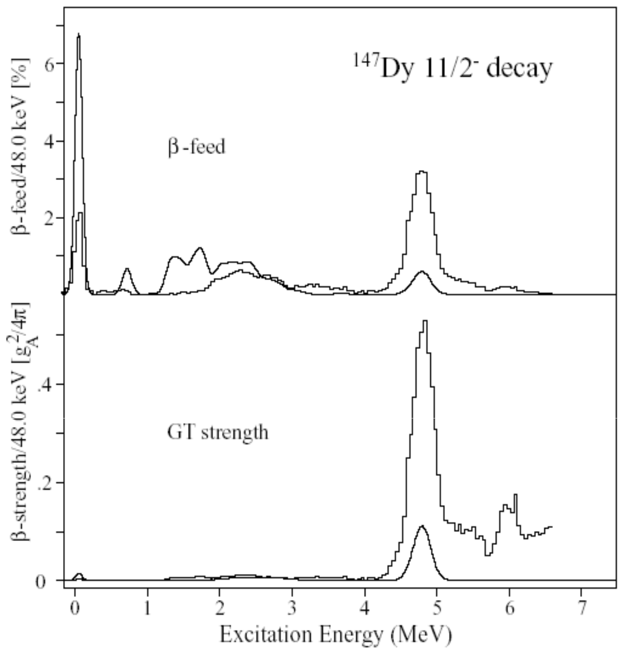


Figure 12. Nilsson diagram for protons, $50 \leq Z \leq 82$ ($\varepsilon_4 = -\varepsilon_2^2/6$).

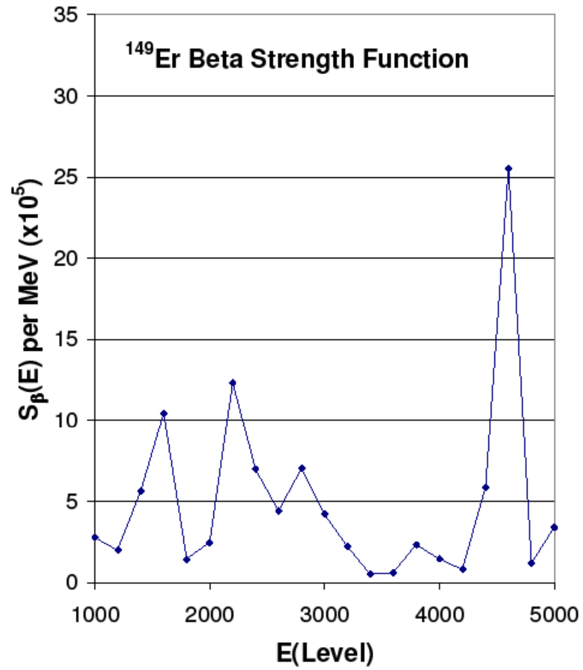
β-strength near theN=82 closed shell



R.B. Firestone *et al,* PRC25, 527(1982)



R. Collatz et al, Z. Phys. A 358, 241(1997)

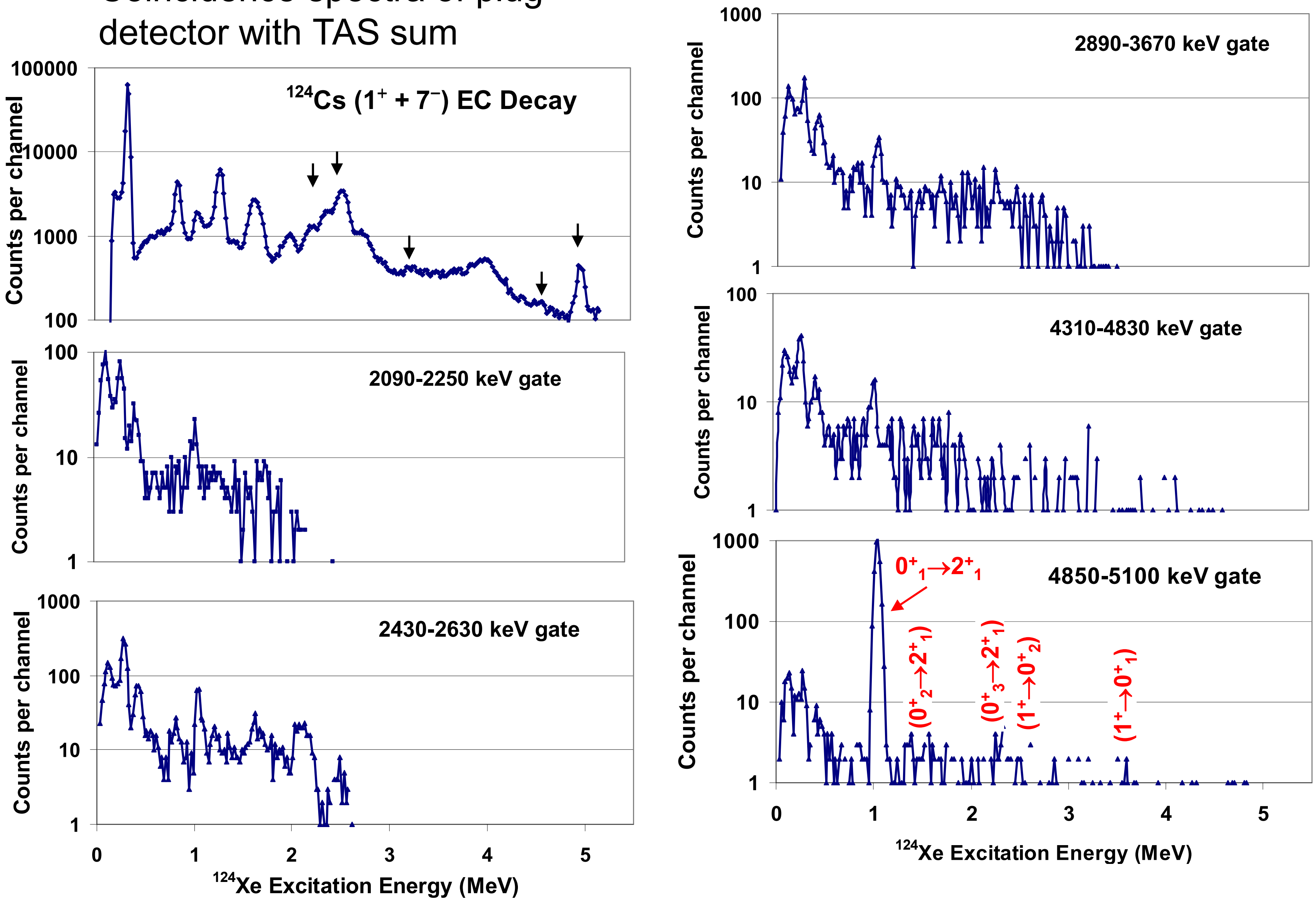


R.B. Firestone *et al,* PRC39, 219(1988)

For the N=81 ^{145}Gd, ^{147}Dy,and ^{149}Er decays the shell model effects are even more pronounced dominated by the $\pi h_{11/2-} \rightarrow \nu h_{9/2-}$ transition.

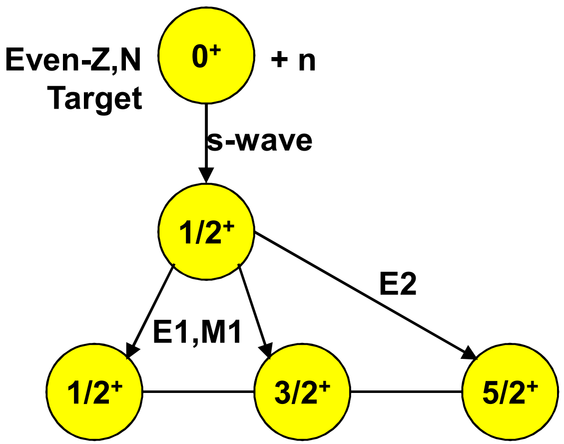
γ-ray Strength Function

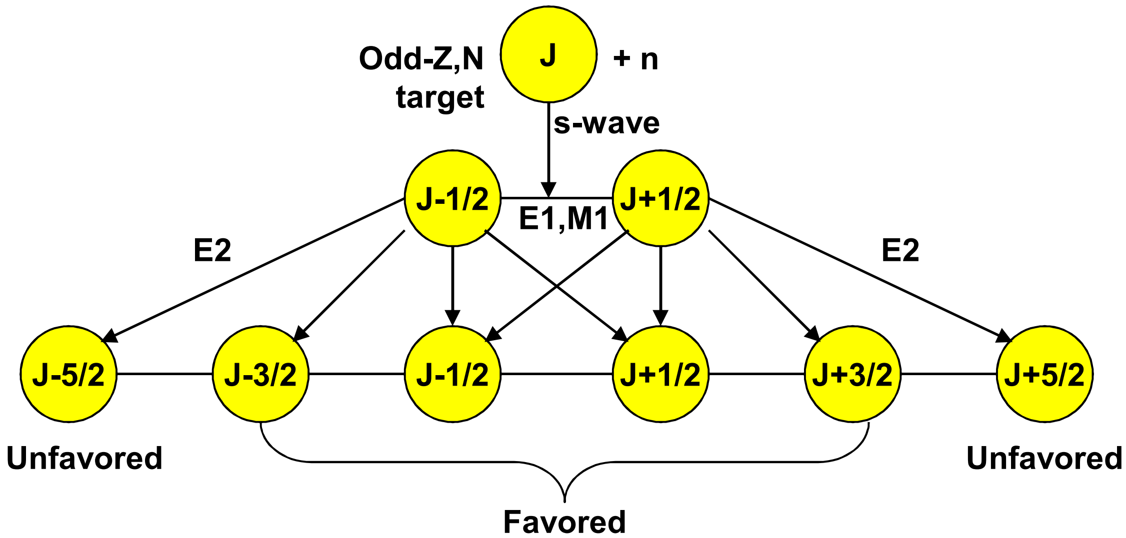
Coincidence spectra of plug detector with TAS sum



Average Resonance Capture ARC: A window to γ-ray strengths

ARC experiments look at primary γ-rays following neutron capture from a narrow resonance region containing many levels. Typical experinents at 2- and 24- keV are performed with filtered beams.





p-wave capture becomes important at 24-keV ARC

Assuming equal population of J$\pm$1/2 levels we expect

$$\frac{B(E1,M1)_{unfavored}}{B(E1,M1)_{favored}} = 0.5$$

Favored/Unfavored B(E1,M1) 2-keV ARC

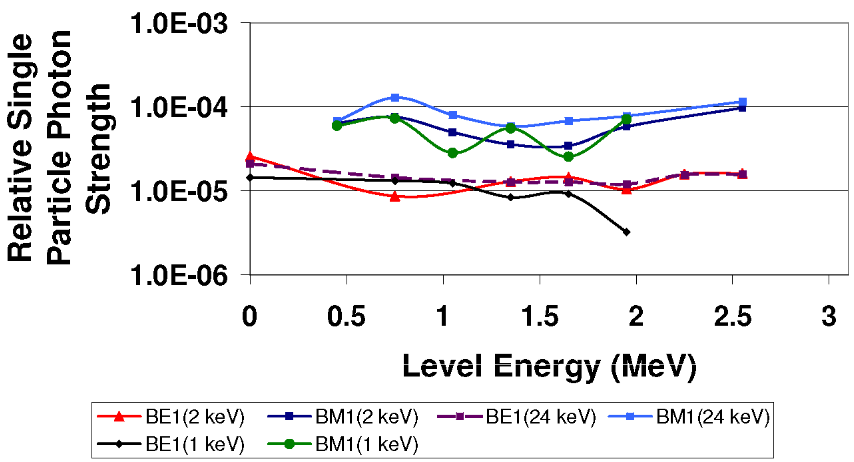
	Fav/UnFav B(E1)	Fav/UnFav B(M1)	J-1/2/J+1/2 B(E1)	J-1/2/J+1/2 B(M1)	J-3/2/J+3/2 B(E1)	J-3/2/J+3/2 B(M1)
^{106}Pd	0.74	0.74	1.00	1.36	0.94	1.05
^{156}Gd	0.55	0.67	0.82	0.71	1.19	
^{162}Dy	0.55	0.50	1.26	1.12	0.86	0.87
^{164}Dy	1.06	0.89	1.10	1.25	1.91	
^{168}Er	0.51	0.53	0.98	1.12	0.78	0.98
^{174}Tb	0.55	1.30	1.21	1.08	1.33	4.32
^{198}Au	0.50		1.13		0.93	0.66

Most examples are consistent with Unfavored/Favored ≈ 0.5.

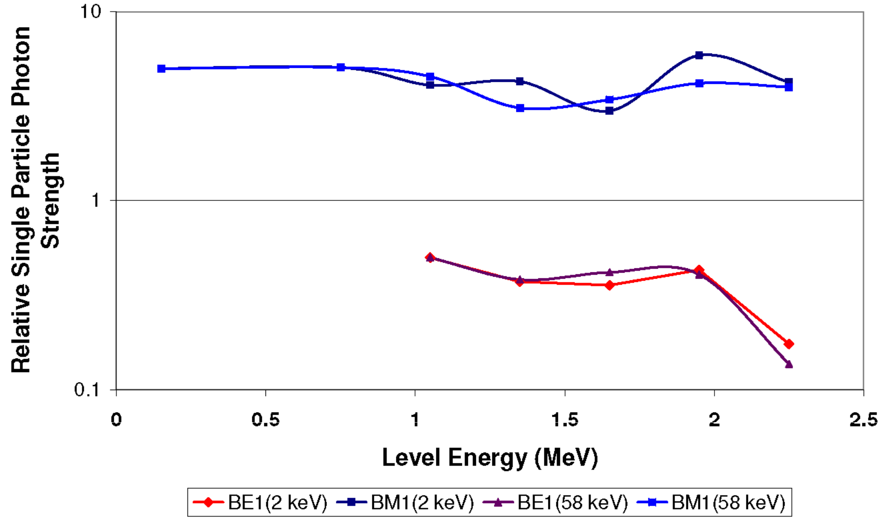
Most anomalies are seen in both the B(E1) and B(M1) ratios

Variation of B(E1,M1) with Final Level Excitation

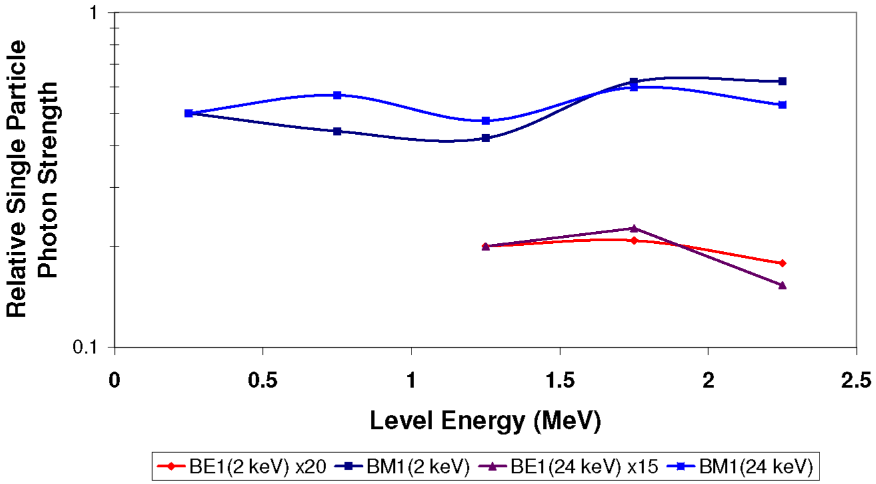
^{157}Gd M1-E1 Primary γ-ray Photon Strengths S_N=6360.6



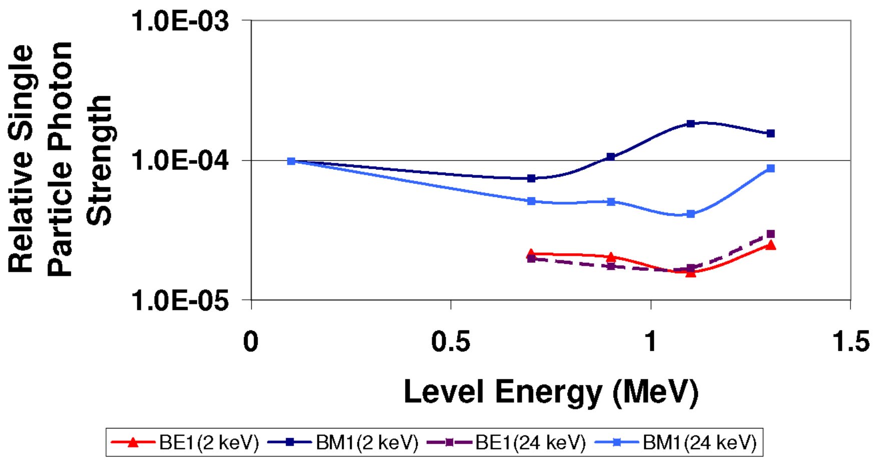
^{162}Dy M1-E1 Primary γ-ray Photon Strengths S_N=8197.0



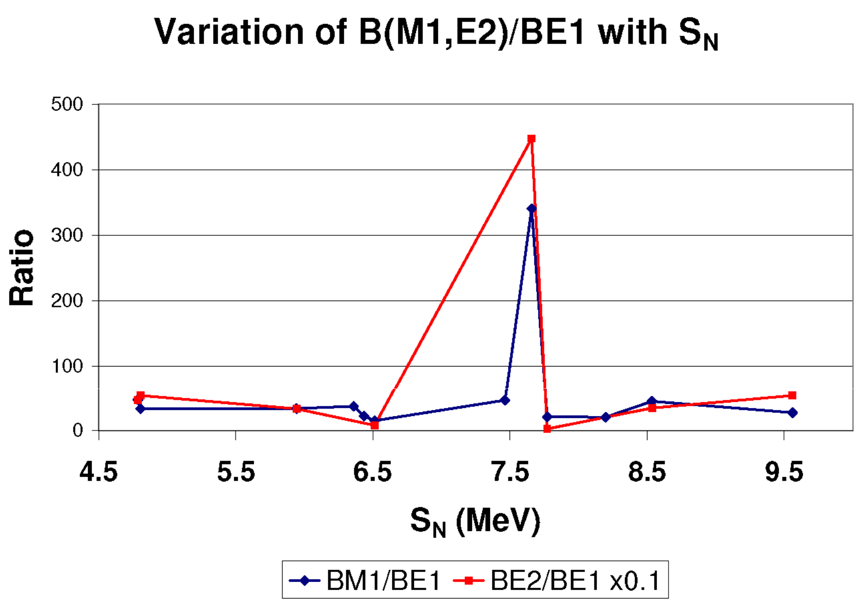
^{168}Er M1-E1 Primary γ-ray Photon Strengths S_N=7771.3

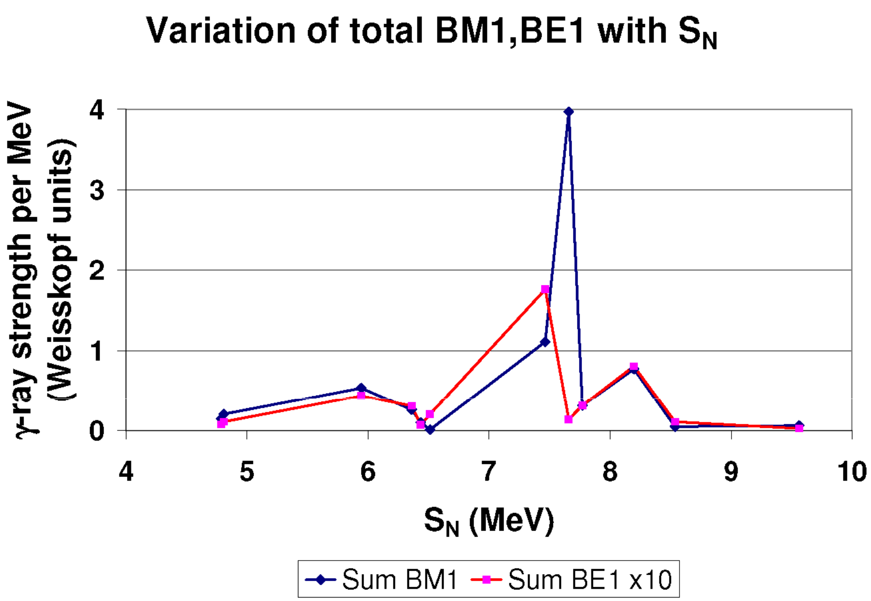


^{239}U M1-E1 Primary γ-ray Photon Strengths S_N=4806.3



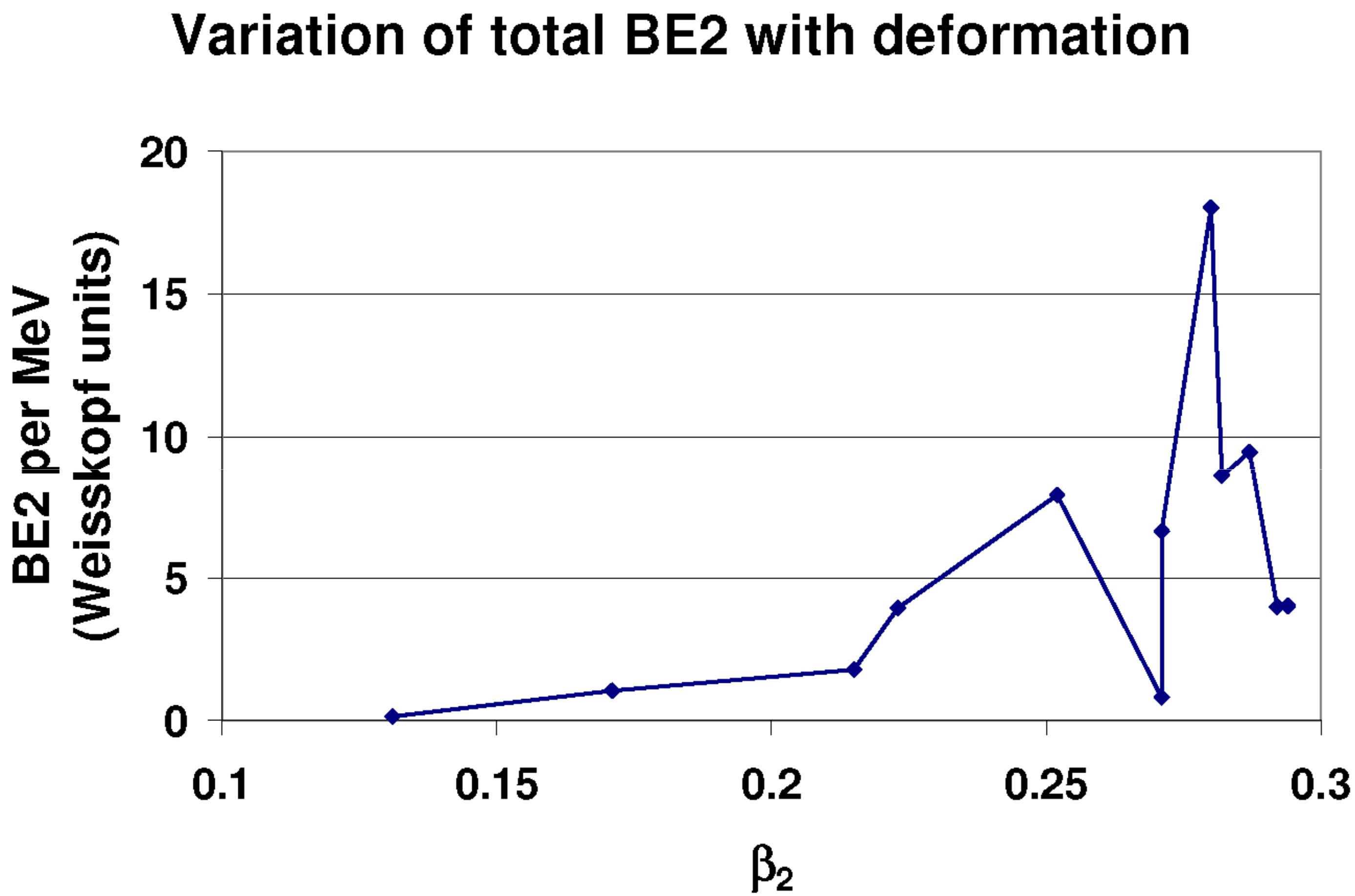
Variation of B(M1,E2,E1) with S_N





Enhanced M1, E2 strength near 7.5 MeV?

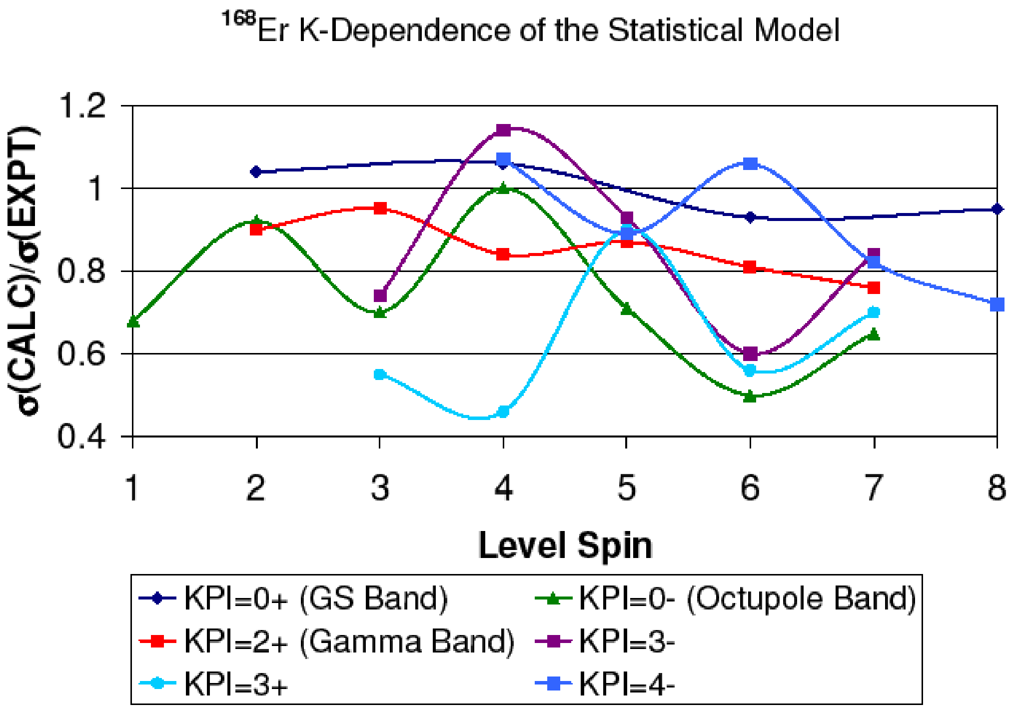
B(E2) Strength



There is a general correlation of B(E2) strength with deformation.

Note that β_2 is a GS deformation

K-Dependence



Comparison of experimental $^{167}Er(n,\gamma)$ thermal neutron capture feedings with DICEBOX calculations.

- Oscillations appear to be due to failure of spin distribution function
- Discrepancies correlated with band assignment

M1+E2 Mixing Ratios

	E_N (ARC) MeV	δ=E2/M1
^{106}Pd	1	1.32
^{106}Pd	2	2.24
^{155}Gd	2	0.81
^{156}Gd	1	0.74
^{156}Gd	2	0.70
^{157}gd	1	1.27
^{159}Gd	2	1.75
^{164}Dy	2	0.52
^{168}Er	2	0.33
^{198}Au	2	1.24
^{233}Th	0	1.39
^{233}Th	2	1.05
^{239}U	2	0.79

M1/E2 mixing rations can be estimated from the measured B(E2) values for pure E2 transitions.

δ_{Ave} = 1.1

- Probably high since only strongest E2 transitions seen
- Consistent with $\delta \approx 0.5$-1 assumed by the nuclear data community

Conclusions

- Nuclear beta decay is dominated by nuclear structure and cannot be interpreted by statistical model calculations
- E1 primary photon transitions are strongly hindered and statistical in nature
- M1,E2 primary photon transitions can have strong single particle strengths distributed over broad energy excitations.
- E2 primary photon transitions retain significant collectivity
- M1 primary photon transitions have significant E2 admixtures
- Nuclear structure effects arising from M1, E2 transitions will be observed as deviations from statistical models in charged particle-gamma reaction experiments.