Failure of the Gross Theory of Beta Decay in Neutron Deficient Nuclei

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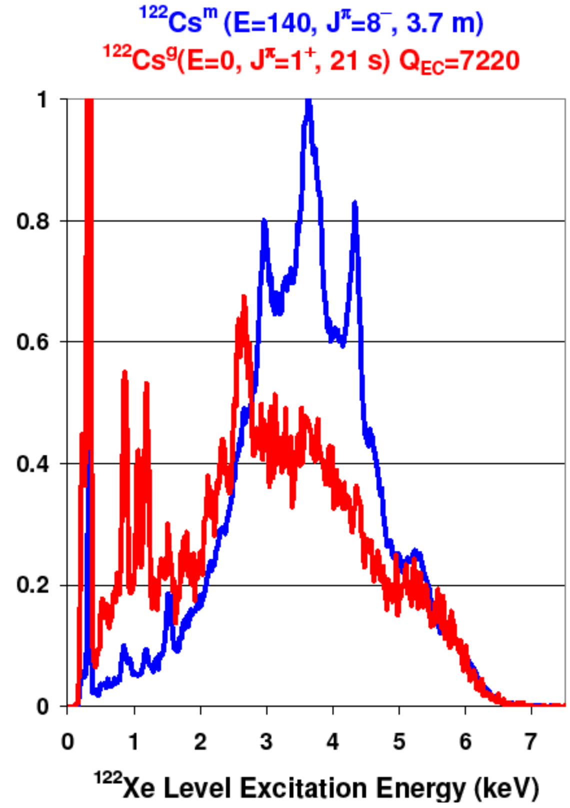
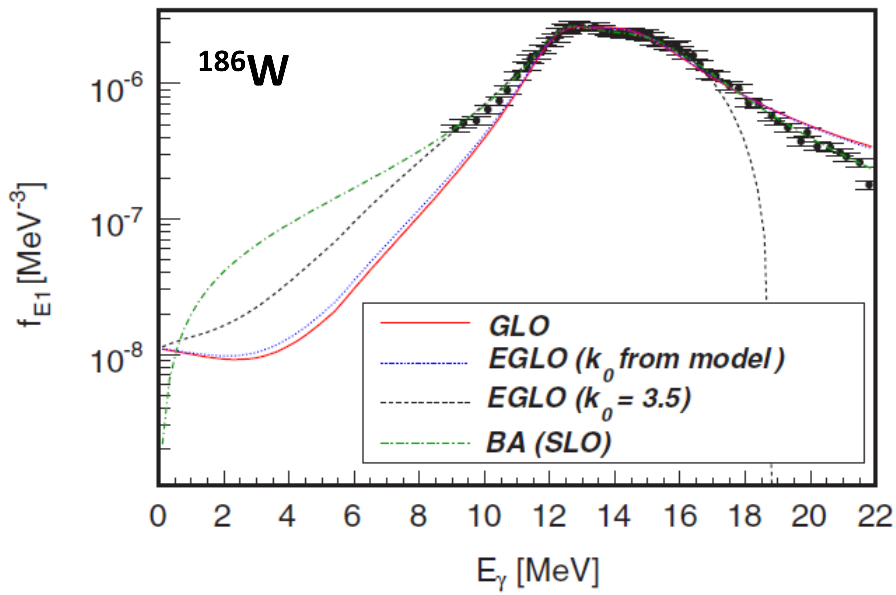


Fifteenth International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics
CGS15

Photon Strength Statistical Models

<u>Gamma Rays</u>

E1: Brink-Axel and variations; based on the shape of the Giant Dipole Resonance (GDR).

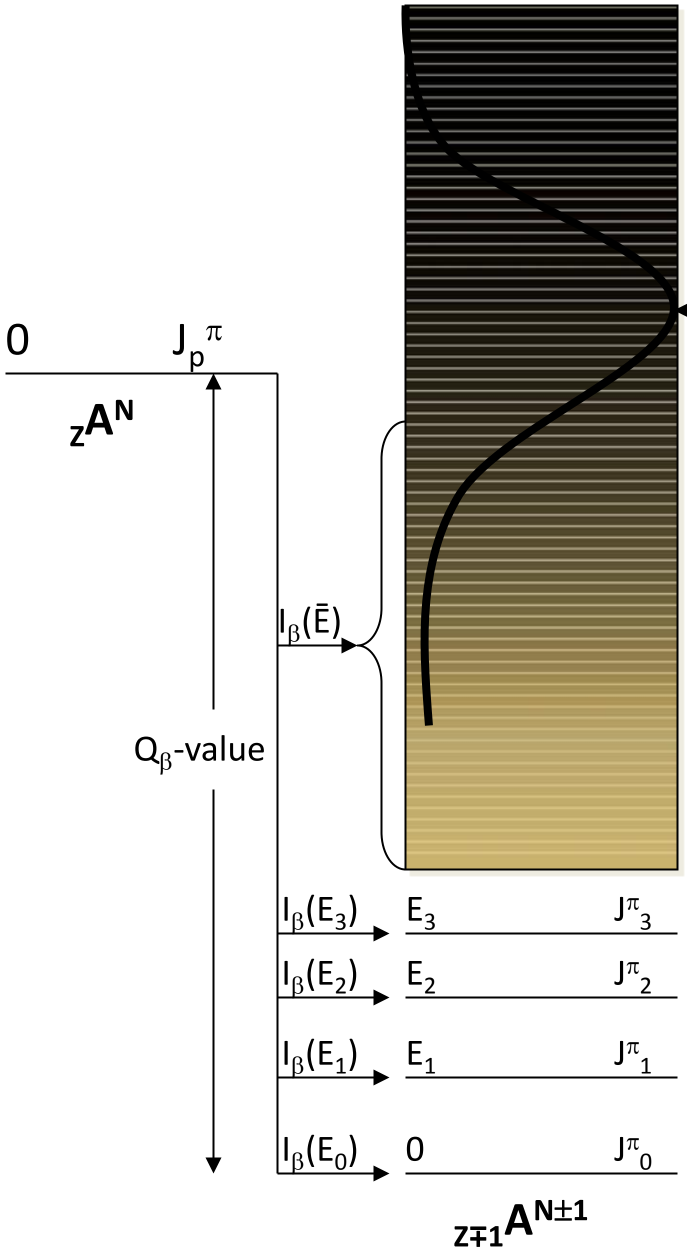


- Verified by photonuclear data *above the neutron separation energy*
- *Uncertain below the neutron separation energy S_n*
- ***Photon strength measured below S_n cannot reliably be compared to Brink-Axel.***

M1: No statistical model is available.

- *Single particle and scissors models may be applicable at low energies*
- *Success of Brink-Axel above S_n, where E1 is dominant, suggests that **M1 strength is very weak at high energies**.*

Beta Decay Statistical Model



Gross theory of β-decay*

Giant Gamow-Teller Resonance (GT)

β-strength function $S_\beta(E)$ increases with E_{level}

$$S_\beta(E) = \frac{\rho(E)}{f(Q_\beta - E)t_{1/2}^{ave}} \text{ (continuum levels)}$$

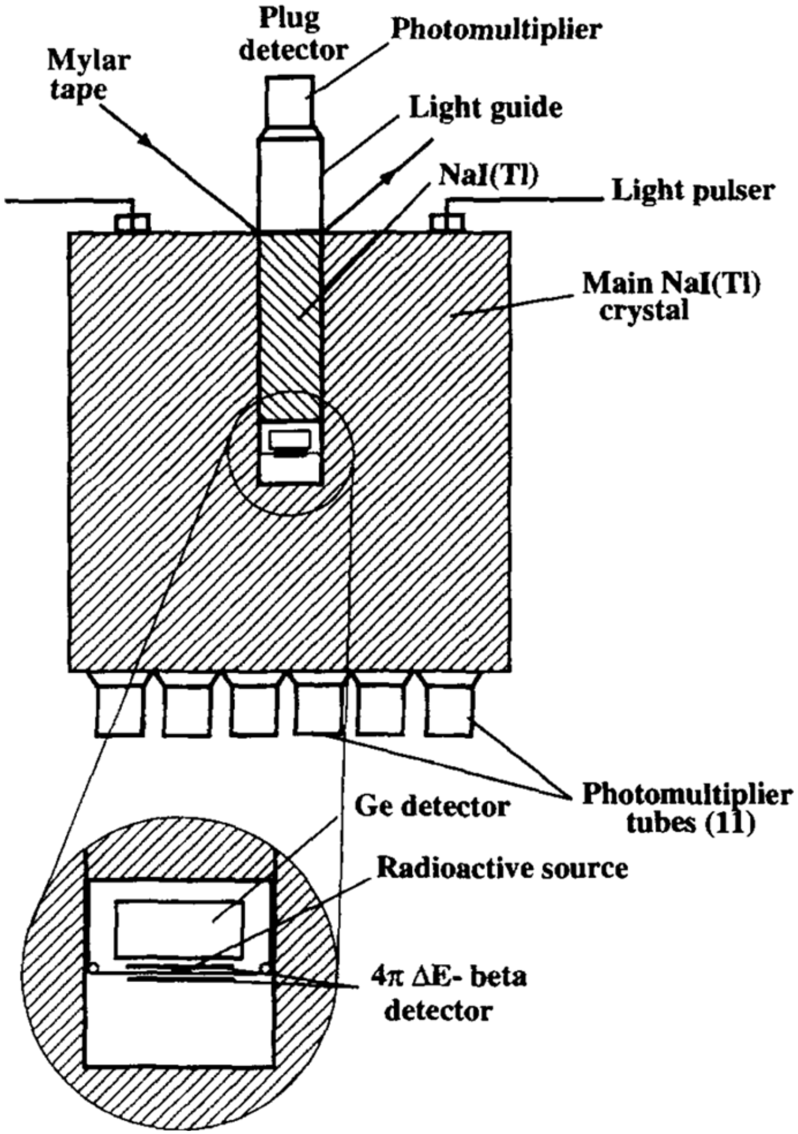
$$S_\beta(E) = \frac{I_\beta(E)}{f(Q_\beta - E)t_{1/2}} \text{ (individual levels)}$$

$S_\beta(E)$ is predicted by GT to increase with level excitation energy due to

- Increased level density
- GT resonance

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

LBNL Total Absorption Spectrometer (TAS)*



Measurement of β-strength with TAS

The TAS detector consisted if

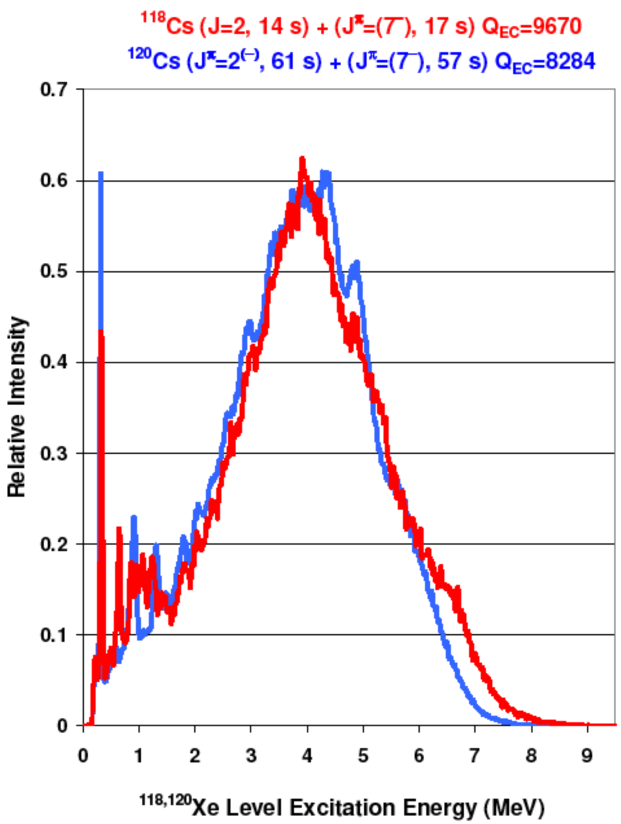
- 36×36 cm NaI(Tl) well detector with a 4×15 cm plug detector for measuring the sum γ-ray energy following decay.
- 1.6×1 cm Ge x-ray detector
- Two 1.8×0.1 Si beta detectors

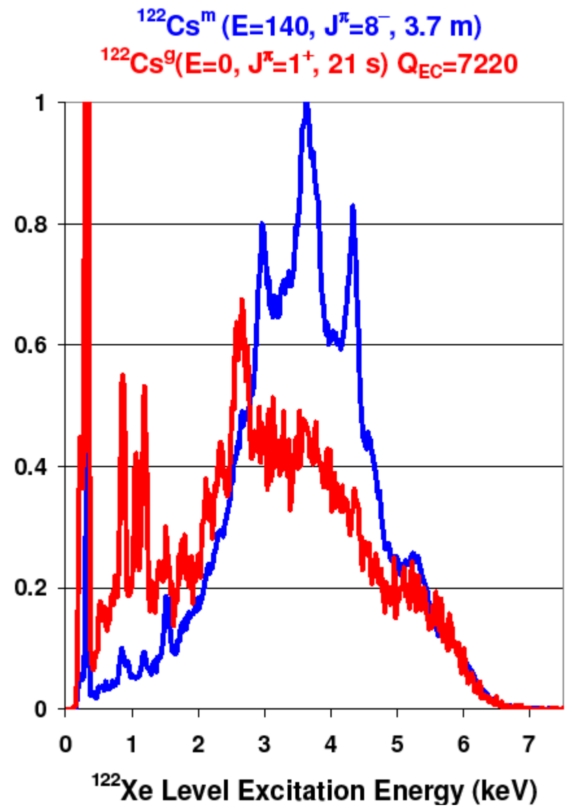
The only TAS experiment at the LBNL SuperHILAC was performed in 1990. A ^{28}Si beam bombarded a ^{nat}Mo target to produce the isotopes $^{117-121}$Xe, $^{117-124}$Cs, and $^{122-124}$Ba.

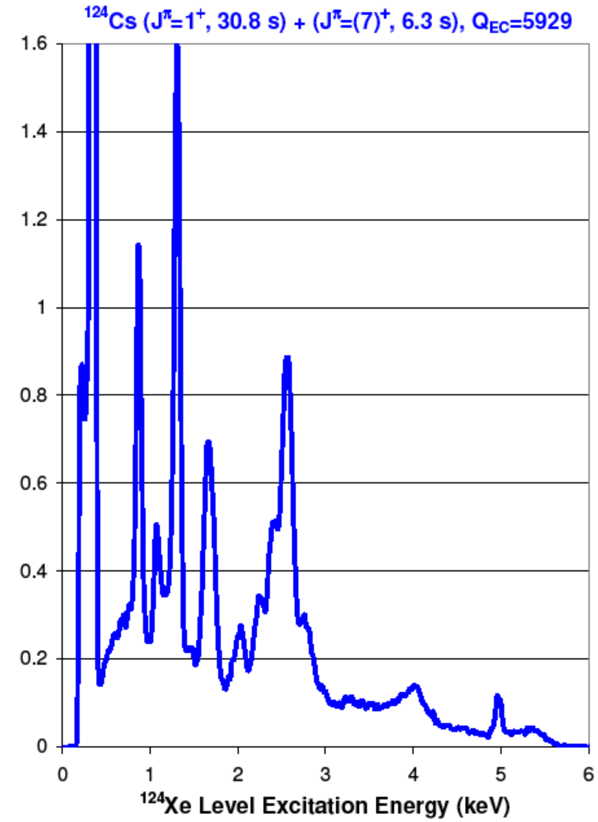
- A identification by OASIS mass separator
- Z identification by coincident EC x-rays

* Designed by J.M. Nitschke, TAS was moved to GSI shortly after this experiment and now lies in pieces in Berkeley.

TAS Spectra Even-A Cs Isotopes

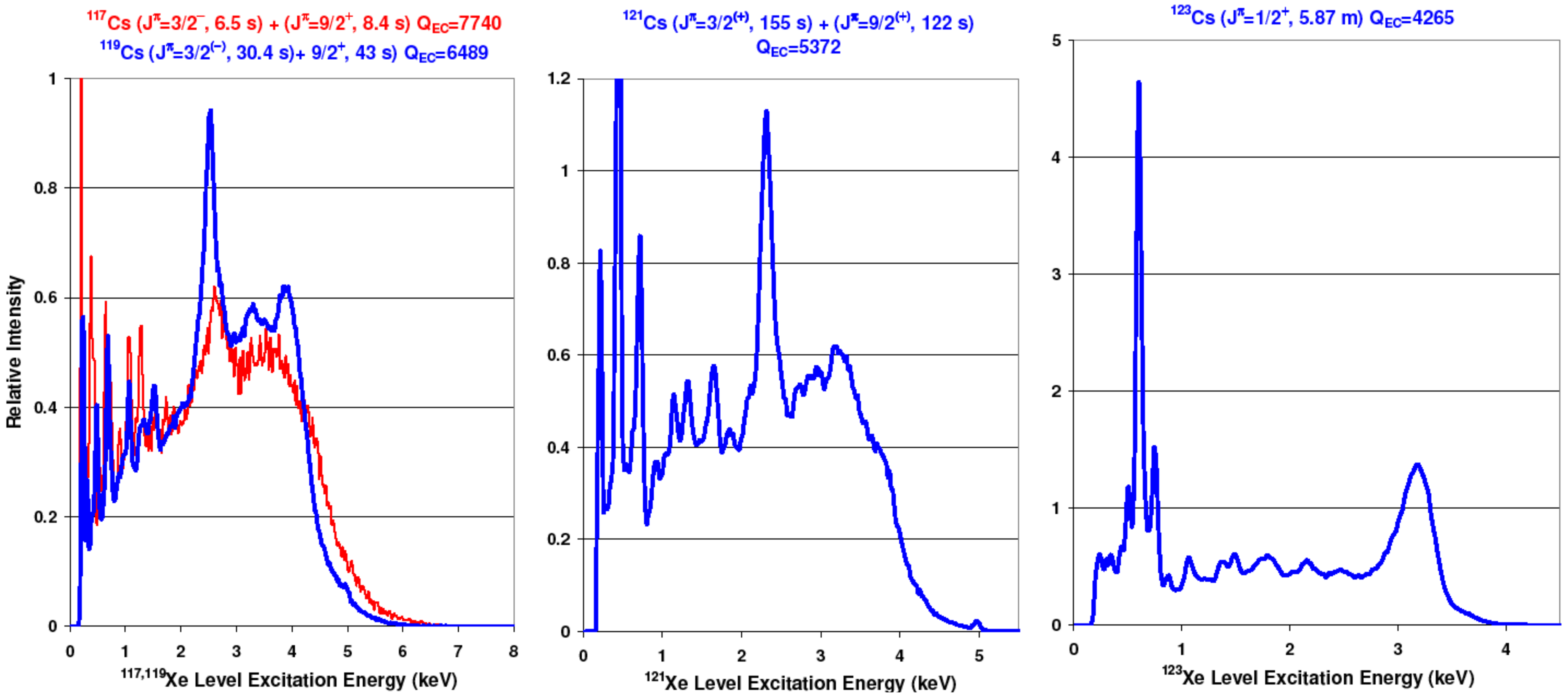






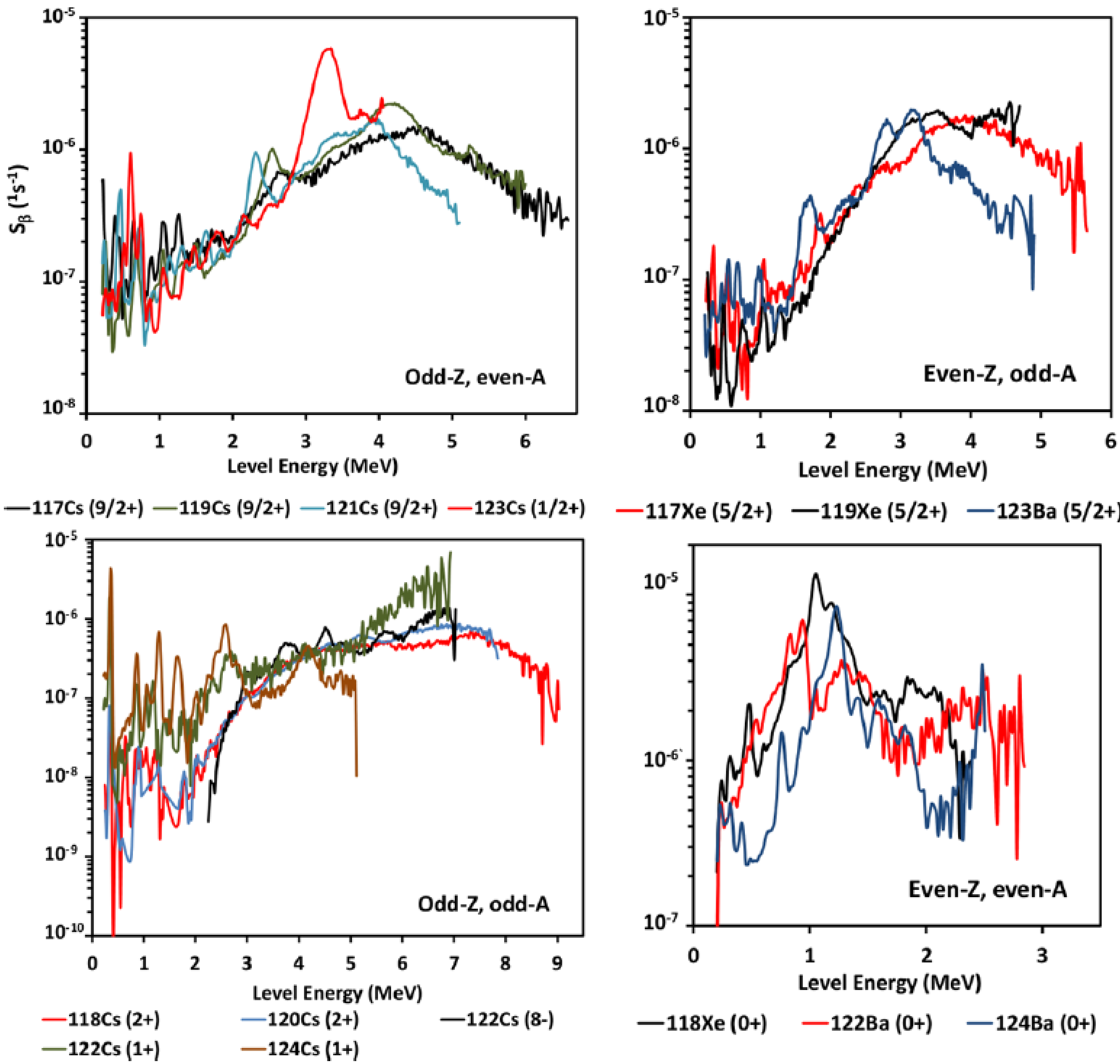
Typical spectra for $^{118\text{-}124}$Cs decays. The TAS γ-ray spectra correspond to β-decay feeding intensities after correction for the detector response and EC/EC+β^+ ratio. Total detection efficiency ranged from 95% (0.3 MeV) to 55% (5 MeV).

TAS Spectra Odd-A Cs Isotopes



Typical spectra for $^{117\text{-}123}$Cs decays.

Photon Strength Functions



The 19 keV binned experimental strengths are comparable for each group of nuclides.

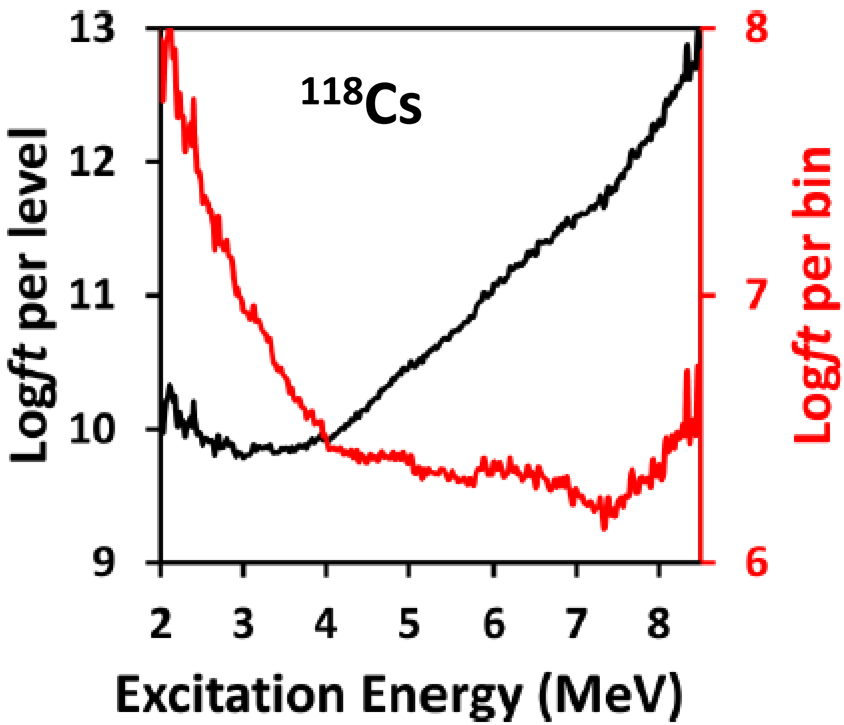
$$S_\beta(E) = {}^1\!/_{f t_{1/2}(E)}$$

Note that the strength falls off dramatically above

- 1 MeV: even-Z, even-N
- 3-4 MeV: even-Z, odd-N
- 4-5 MeV: odd-Z, even-N
- 7-8 MeV: odd-Z, odd-N

These results contradict the simple predictions of Gross Theory.

Log*ft* Variation

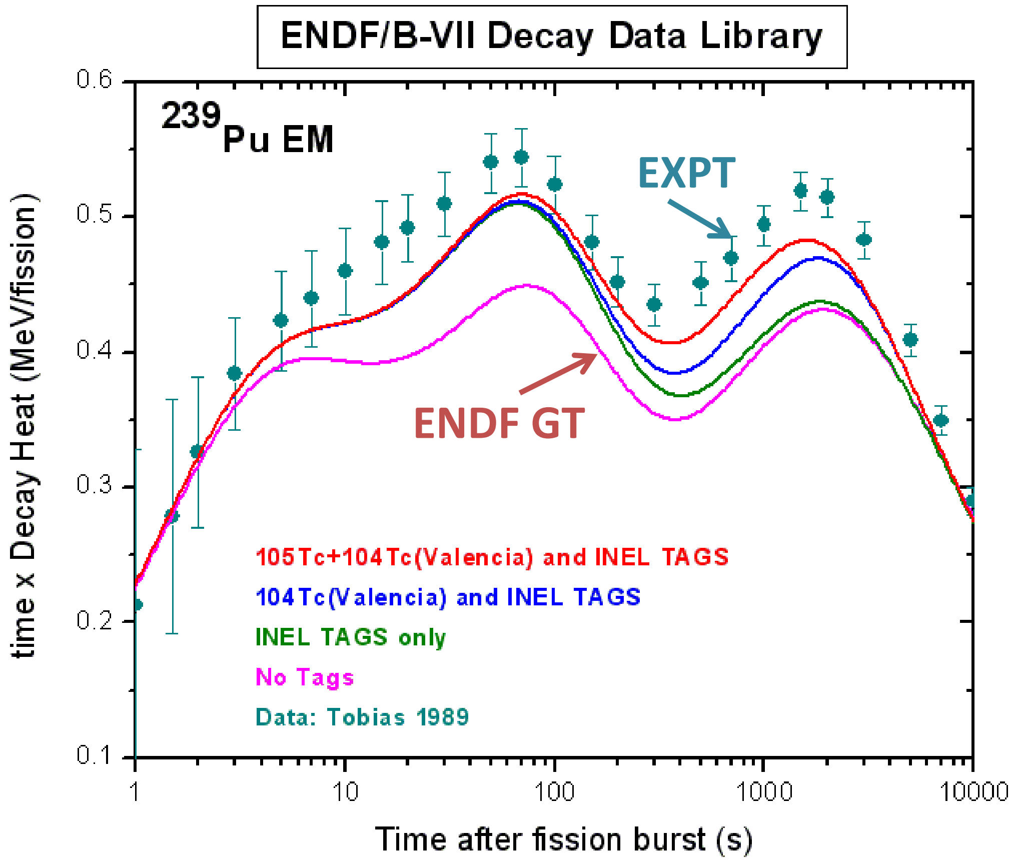


The average log*ft* per 19 keV energy bin increases rapidly above 7 MeV to log*ft*≈6.5 at 8.5 MeV.

Correcting for the level density, the average log*ft* per level increases rapidly above 3 MeV to log*ft*≈13 at 8.5 MeV.

These results disagree with predictions from Gross Theory

Decay Heat and Total Absorption γ-ray data



Decay heat calculations are dramatically improved by replacing ENDF Gross Theory based data with TAGS measurements from INEL (Greenwood *et al**) and Valencia (Algora *et al*#).

* NIM A, 317 (1992)

J. Korean Phys. Soc. 59,1479 (2011).

Poor agreement of the Gross Theory of β-decay with TAS and decay heat data cast doubt on the validity of this theory!

A Shell Model Approach to β-decay

The $ft_{1/2}$ value is defined as

$$ft_{1/2} = {}^{6144}/_{|M|^2}$$

where

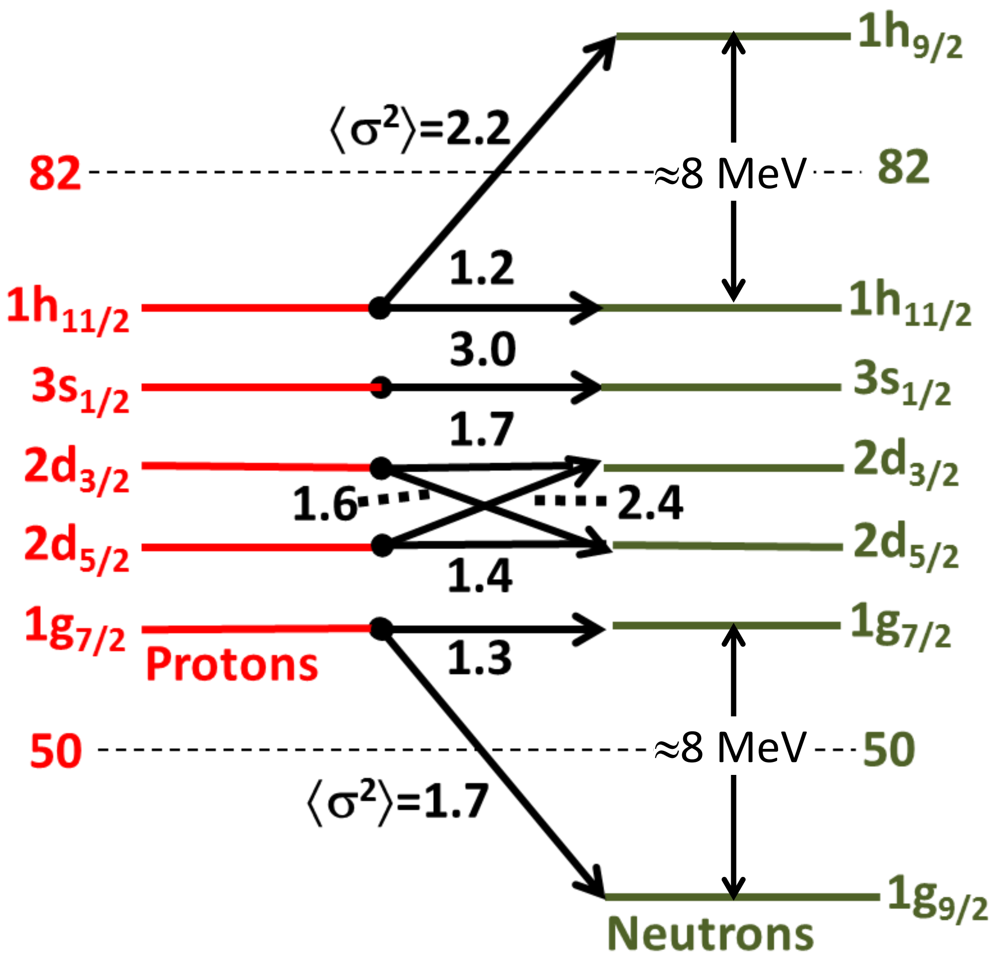
$$|M|^2 = \left|\int 1\right|^2 + \left(\frac{C_A}{C_V}\right)^2 \left|\int \sigma\right|^2$$

For mirror transitions, $\left|\int 1\right|^2 = 1$, and for $0^+ \rightarrow 0^+$ transitions, $\left|\int 1\right|^2 = 2$,
From the Shell Model

$$\left|\int \sigma\right|^2 = \left[\frac{j+1}{j}\right]^{\pm 1} \quad j_i = j_f = l \pm 1/2$$

$$\left|\int \sigma\right|^2 = \left[\frac{l + 1/2 \mp 1/2}{2l+1}\right]^{\pm 1} \quad j_i = \mathrm{l} \mp \frac{1}{2}, \qquad j_f = l \pm 1/2$$

Shell Model …..



Fast Shell Model transitions available in the $4\pi\hbar$ oscillator shell to Xe, Cs, and Ba.

For light isotopes $|C_A/C_v|$=1.24 and the superallowed β-decays give

$0^+ \to 0^+$, T=1: $ft_{1/2}$ = 3072
Mirror, T=1/2: $ft_{1/2} \approx$ 4000-6000

Hypothesis: *If the superallowed β-decay to low-lying levels dominates the β-decay of light isotopes, then similar strength should be observed to low-lying levels in heavier isotopes.*

- *Strength mixed to lower levels*
- *No strength to higher levels*

For heavier nuclei we can define

$$\overline{ft_{1/2}} = \sum_{E=0}^{Q_{EC}} \left[S_\beta(E)\right]^{-1}$$

Results from LBNL TAS Data

^{A}Z	J^{π}	$t_{1/2}$ (s)	Q_{EC} [a] (keV)	GS Feeding	Isomer[b] J^{π},$t_{1/2}$	$[\sum S_{\beta}(E)]^{-1}$ ($\equiv \overline{ft}$)
^{117}Xe	$5/2^+$	61	6251	10%[c]		5900
^{117}Cs	$9/2^+$	8.4	7690		$3/2^+$,6.5 s	5800
^{118}Xe	0^+	216	2892	12%[c]		2800
^{118}Cs	2^+	14	9670		7^-,17 s	10000
^{119}Xe	$5/2^+$	348	4971	16%[d]		6200
^{119}Cs	$9/2^+$	43	6489		$3/2^+$,30.4 s	5300
^{120}Xe	0^+	2400	1581	38%		7100
^{120}Cs	2^+	61.3	8284		7^-,57 s	9700
^{121}Xe	$5/2^+$	2400	3771	28%		10800
^{121}Cs	$9/2^+$	122	5445		$3/2^+$,155 s	7600
^{122}Cs	1^+	21.2	7070[e]	37%		5400
^{122}Cs	8^-	222	7210[e]			9900
^{122}Ba	0^+	117	3540	13%[f]		3400
^{123}Cs	$1/2^+$	353	4205	33%		5500
^{123}Ba	$5/2^+$	162	5389	12%[c]		9100
^{124}Cs	1^+	30.9	5930	34%		12800
^{124}Ba	0^+	660	2642	17%[f]		5900

Comparison of Xe, Cs, and Ba decays with superallowed/mirror decays

For isotopes with the largest Q_{EC} values, where most of the shell model β-strength is energetically accessible we find

Odd-Z, even-N Cs isotopes: $\overline{ft_{1/2}} = 5300 - 5800, \quad |M|^2 = 1.1 - 1.2$

Odd-Z, odd-N Cs isotopes: $\overline{ft_{1/2}} = 5400 - 10000, \quad |M|^2 = 0.6 - 1.1$

Even-Z, odd-N Xe isotopes: $\overline{ft_{1/2}} = 5900 - 6200, \quad |M|^2 = 1.0$

For mirror β-decays, $|M|^2 = 1.0 - 1.5$

Even-Z, even-N Xe,Ba isotopes: $\overline{ft_{1/2}} = 2800 - 3400, \quad |M|^2 = 1.8 - 2.2$

For 0+→0+ β-decays, $|M|^2 = 2.0$

The LBNL TAS measurements yield total beta strengths consistent with the strengths of superallowed/mirror decays in lighter isotopes.

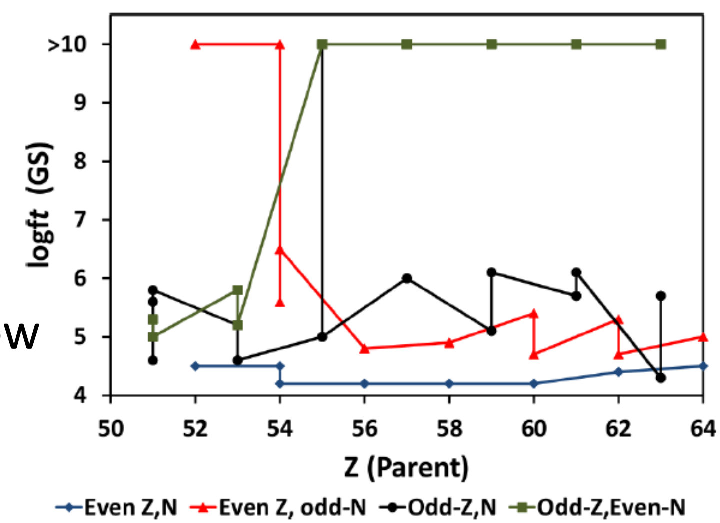
Calculation of half-lives near the proton drip line

Gross Theory is often used to calculate the half-lives of nuclei far from stability. Can the TAS β-strength data obtain similar results?

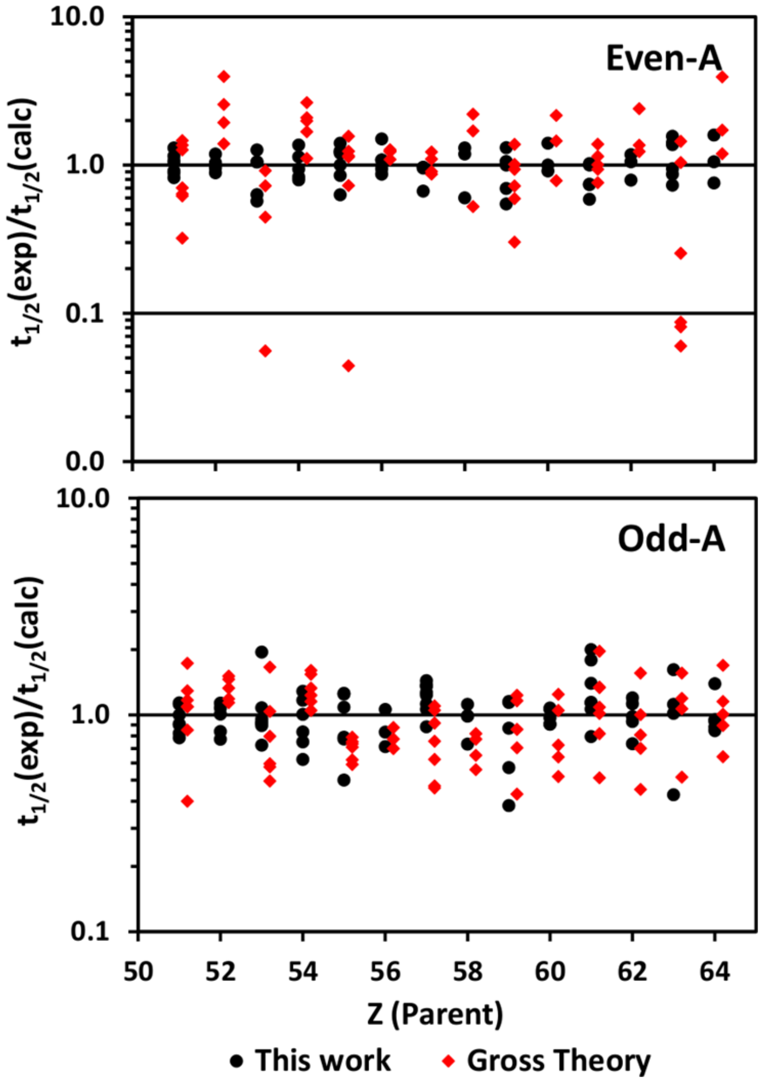
Assumption 1: The measured β-strengths from ^{117}Xe, ^{117}Cs, ^{118}Cs, and ^{122}Ba can be used as standard b-strength templates for all odd-even, odd-odd, and even-even neutron deficient isotopes with N<82 and Z=50-64.

Assumption 2: An additional parameter is needed for the strong β-strength to low lying levels. (note that this feeding is also needed for the Gross Theory model).

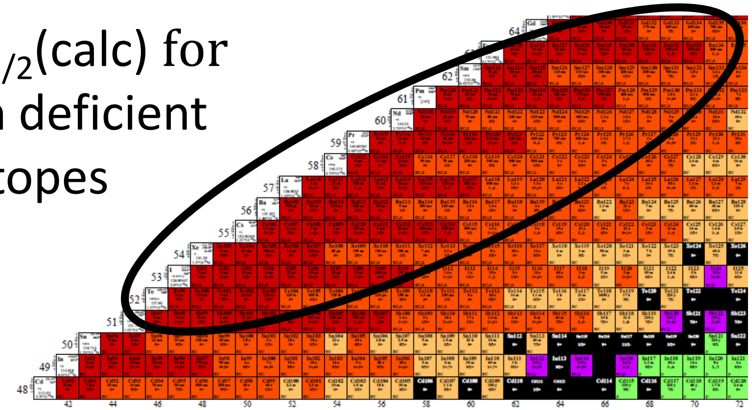
For odd-N or odd-Z isotopes the $ft_{1/2}$ to low lying levels varies with the Shell Model configuration of the GS.



Comparison of TAS Strength and Gross Theory Half-life Calculations



$t_{1/2}$(expt)/$t_{1/2}$(calc) for 143 neutron deficient Z=51-64 isotopes



<u>TAS β-strength</u>

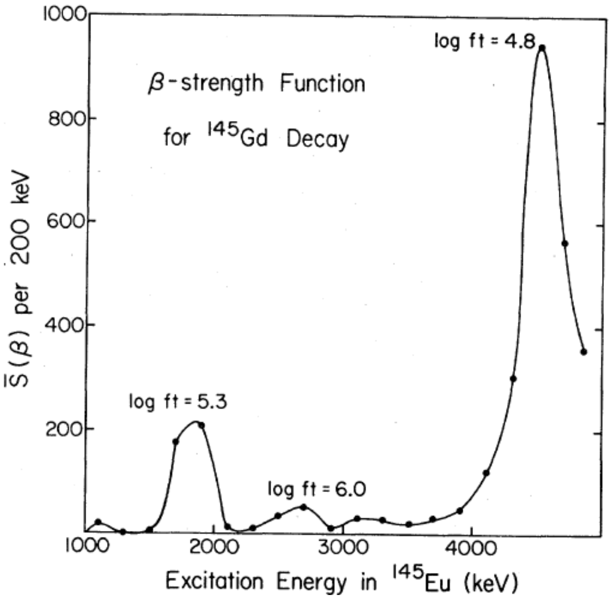
χ^2/f=1.0 assuming a theoretical uncertainty of **20%** for all isotopes.

<u>Gross Theory β-strength*</u>

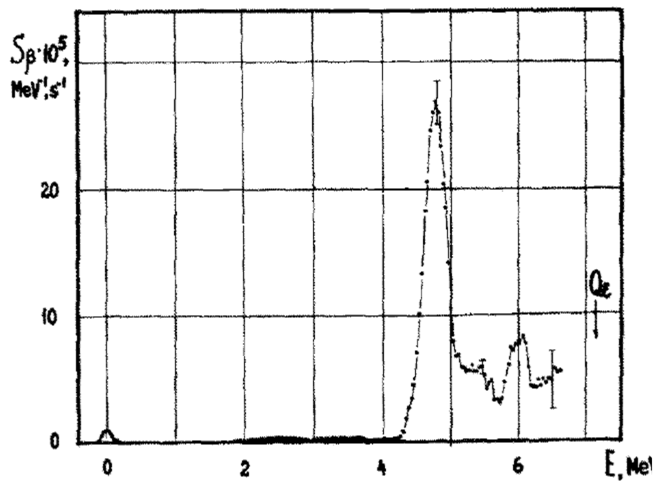
χ^2/f=1.0 assuming a theoretical uncertainty of **33%** for odd-A nuclei and **73%** for even-A nuclei.

*Nuclear Data Center JAEA, 2013

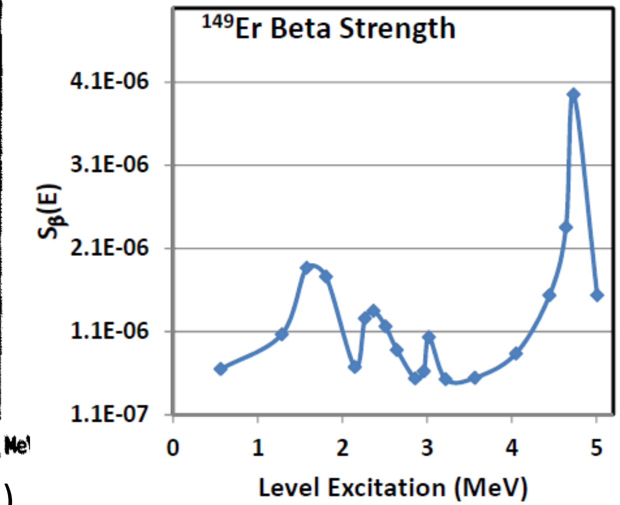
Application of template method to heavier isotopes



Firestone et al, PRC25, 527(1982)
Q_{EC}=5068, $\overline{ft_{1/2}}$=39,000



Alkhazov et al, NPA 438, 482 (1985)
Q_{EC}=6546, $\overline{ft_{1/2}}$=10,000

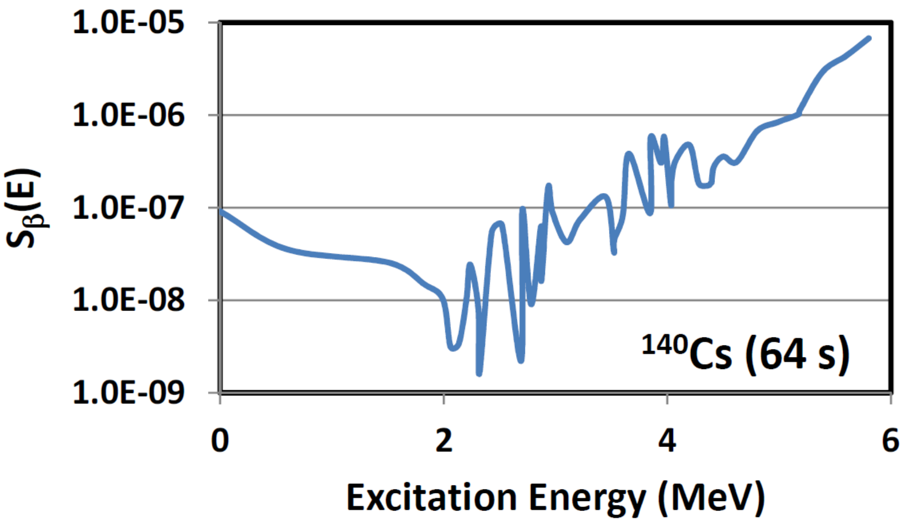


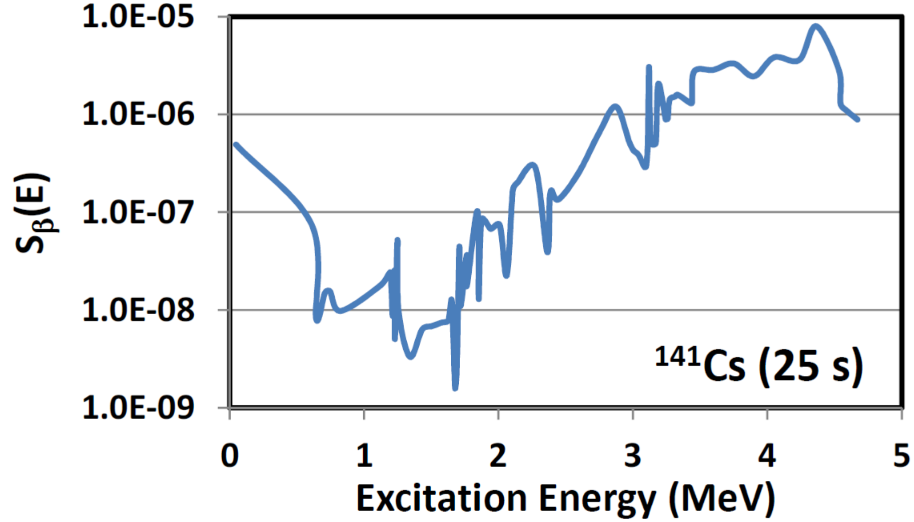
Firestone et al, PRC39, 219 (1988)
Q_{EC}=7920, $\overline{ft_{1/2}}$=13000

N=81: The only allowed decay channel open is the $\pi h_{11/2} \rightarrow \nu h_{9/2}$ spin flip transition. Single particle $\overline{ft_{1/2}}$=2900 is much lower than observed values.

Missing strength at higher excitations? Higher energy template needed?

Neutron Rich Cs Isotopes





$\overline{ft_{1/2}} = 25,000$ $\overline{ft_{1/2}} = 18,000$

Data from INEL Total Absorption Gamma Spectrometer (TAGS)*

Experimental β-strengths do not peak within experimental energy window. These data would be incomplete templates for extrapolation to heavier Cs isotopes.

*R.G. Helmer et al, NIMA 339, 189 (1994).

Calculation of Cs Half-lives

1. Extrapolate standard $S_\beta(E)$ to higher energies with a broad peak at 7 MeV with $S_\beta(E)_{max}= 2.5\times10^{-5}$, 1 MeV fwhm for odd- and even-A Cs isotopes
2. Calculate half-life
   - $t_{1/2} = c\sum_{E=0}^{Q_{EC}}({}^{1}/_{S_\beta(E)})$: c(^{140}Cs)=0.29, c(^{141}Cs)=0.23

   The reason for renormalization of $S_\beta(E)$ is unknown.

Isotope	J^π	$t_{1/2}$(expt)	$t_{1/2}$(calc)	$t_{1/2}$(GT)
^{142}Cs	0^-	1.684(14) s	3.9 s	3.3 s
^{143}Cs	$3/2^+$	1.791(7) s	1.9 s	3.1 s
^{144}Cs	$1^{(-)}$	0.994(6) s	0.97 s	1.6 s
^{145}Cs	$3/2^+$	0.587(5) s	0.51 s	1.2 s
^{146}Cs	1^-	0.321(2) s	0.36 s	0.68 s
^{147}Cs	$(3/2^+)$	0.230(1) s	0.24 s	0.27 s
^{148}Cs		0.146(6) s	0.13 s	0.16 s
^{149}Cs		>50 ms	101 ms	94 ms
^{150}Cs		>50 ms	47 ms	85 ms

For the $^{144-148}$Cs calculations

This work: χ^2/f=1 for $\Delta t_{1/2}$=9%

Gross Theory: χ^2/f=1 for $\Delta t_{1/2}$=37%

Conclusions

- β-strength measurements with the LBNL TAS spectrometer for neutron deficient Xe, Cs, and Ba isotopes are inconsistent with predictions of the Gross Theory of β-decay
- Total β-strengths for neutron deficient isotopes are consistent with shell model predictions.
- Half-lives of neutron deficient isotopes can be calculated with good accuracy using measured TAS templates.
- Total β-strengths for neutron rich isotopes are consistent with decay across shell gaps
- Half-lives of neutron rich isotopes may be calculated with good accuracy using TAS templates that are extrapolated to higher energies
- ***Lessons from β-strength analysis should apply to M1 γ-rays.***