Systematics of Low-Energy Photon Strengths

Richard B. Firestone
Lawrence Berkeley National Laboratory, Berkeley, CA 94720

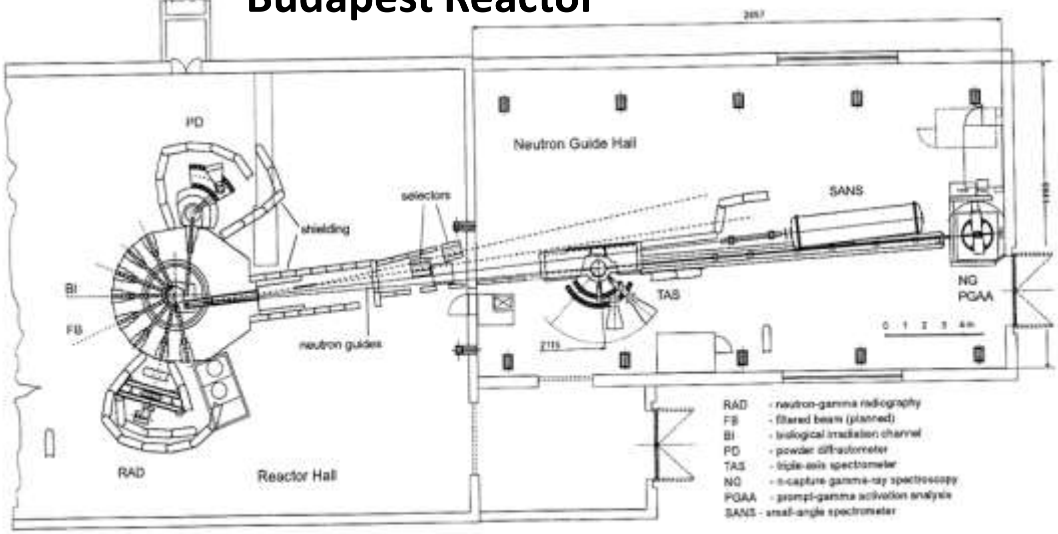
4th Workshop on Nuclear Level Density and Gamma Strength
Oslo, May 27 - 31, 2013

Outline of this presentation

1. Measurement of primary γ-ray cross sections
2. Determination of photon strengths
3. Systematics of photon strengths
4. Low-energy enhancement of photon strength in the molybdenum isotopes
    a. Evidence of low-energy photon strength enhancement for thermal neutron capture to ^{96}Mo
    b. Parity considerations
    c. A new formulation of M1 strengths
    d. Quantitative explanation of the low-energy photon strength enhancement in Mo isotopes.

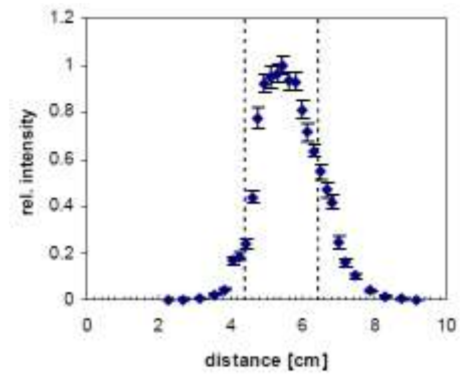
Prompt γ-ray Measurements

Budapest Reactor

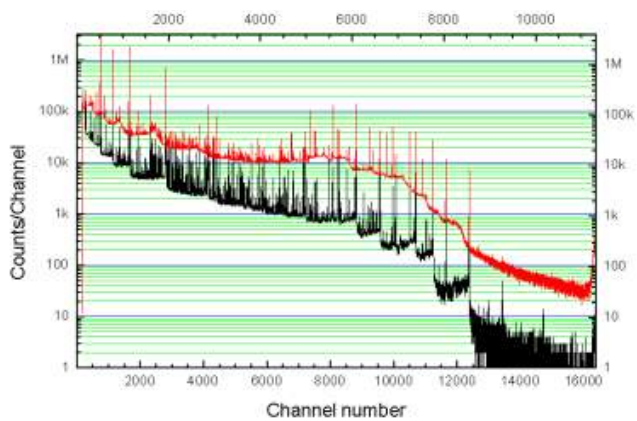


Budapest and FRM II (Garching) Reactors

Guided, curved neutron beam. Prompt γ-rays were measured ≈30 m from the reactor wall in a low background counting area.



Measured beam profile



HPGe: Compton suppressed γ-ray spectrum for CCl_4

Efficiency: <1% for E=0.5-6 MeV, <3% for 6-10 MeV

<u>Budapest</u>

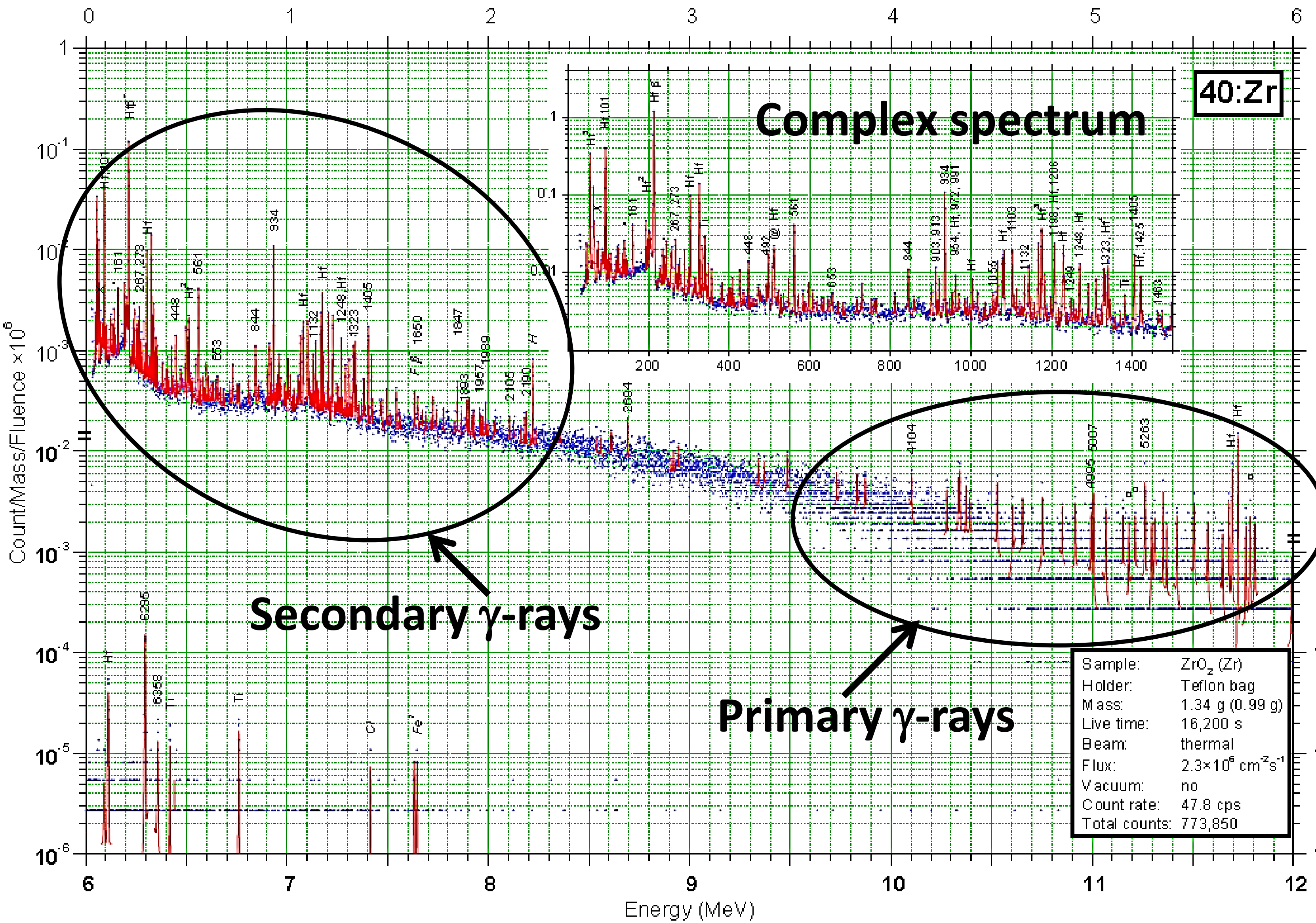
Thermal flux: 2×10^{6} $cm^{-2}s^{-1}$.

Cold flux: 5×10^{7} $cm^{-2}s^{-1}$

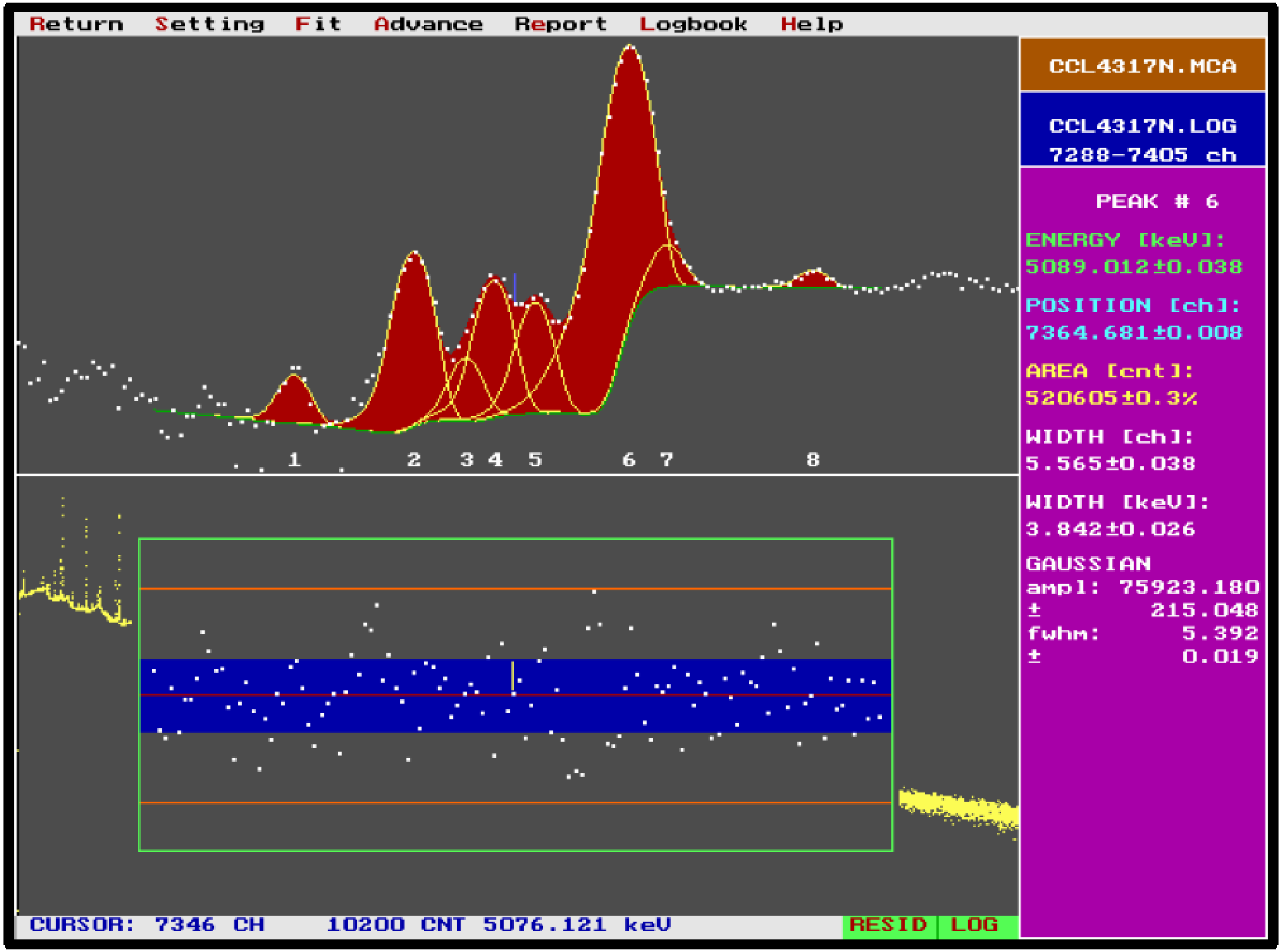
<u>FRM II</u>

Cold flux: 2×10^{10} $cm^{-2}s^{-1}$

Typical Prompt γ-ray Spectrum



Data Analysis – Hyperment-PC



Internal Cross Section Calibration

Thermal γ-ray cross sections were determined using internal standards of known composition. For 1/v isotopes this measurement is independent of neutron energy. For non-1/v isotopes g-factor corrections were made.

1. **Stoichiometric compounds** containing elements with well-known cross sections: **B, H, N, Cl, S, Na, Ti, Au**

   e.g. KCl, $(CH_2)_n$, $Pb(NO_3)_2$, GdB_6, Tl_2SO_4

2. **Homogenous mixtures**

   Aqueous solutions and mixed powders (TiO_2)

3. **Activation products** with well-known decay P_γ

   ^{19}F, ^{28}Al, ^{100}Tc, ^{235}U

Original measurements were performed on all stable elemental targets with Z=1-83, and on the selected radioactive targets ^{99}Tc, and ^{129}I.

New measurements are being performed on enriched isotopic targets.

Evaluated Gamma-ray Activation File (EGAF)

The data discussed in this talk are published in the report of an IAEA CRP EGAF and were published in

Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis, R.B. Firestone, et al, 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, edited by G.L. Molnar (Kluwer Publishers, 2004).

New measurements are being performed by the international EGAF collaboration at the Budapest and Garching FRM II reactors. A partial list of collaborators includes. Others are welcome to join us.

LBNL- R.B. Firestone, M.S. Basunia, A.M. Hurst, A.M. Rogers
LLNL - B. Sleaford, N.C. Summers, J.E. Escher, L.A. Bernstein
Budapest - T. Belgya, L. Szentmiklosi **Julich** - M. Rossbach, C. Genreith
Garching - Zs. Révay, P. Kudejova **Prague -** M. Krtička, F. Bečvář
Oslo - S. Siem, M. Guttormsen, A. Larsen, F. Giacoppo
S.Africa - M. Wiedeking **S. Korea –** H. Choi **Jordan -** K. Abusaleem
Ohio State U. – D. Turkoghu, **UC Berkeley -** K. van Bibber, B. Goldblum

Determination of Primary γ-ray photon strengths

Photon strengths: $f(E_\gamma) = P_\gamma \Gamma_\gamma / (d_0 \cdot E_\gamma^3)$

E_γ= primary γ-ray energy (MeV) – EGAF, ENSDF

Γ_γ = capture state width (eV) – Atlas*

d_0 = average level spacing at S_n (eV) – Atlas*

For EGAF thermal capture data, $P_\gamma = \sigma_\gamma / \sigma_0$

σ_γ = primary γ-ray cross section (b) – EGAF, ENSDF

σ_0 = total radiative neutron cross section (b) – Atlas*

$f(E_\gamma)$ should be averaged over many transitions, P-T dist

For Average Resonance Capture (ARC) data, P_γ per 100 neutron captures may be measured or can be calculated with statistical model codes.

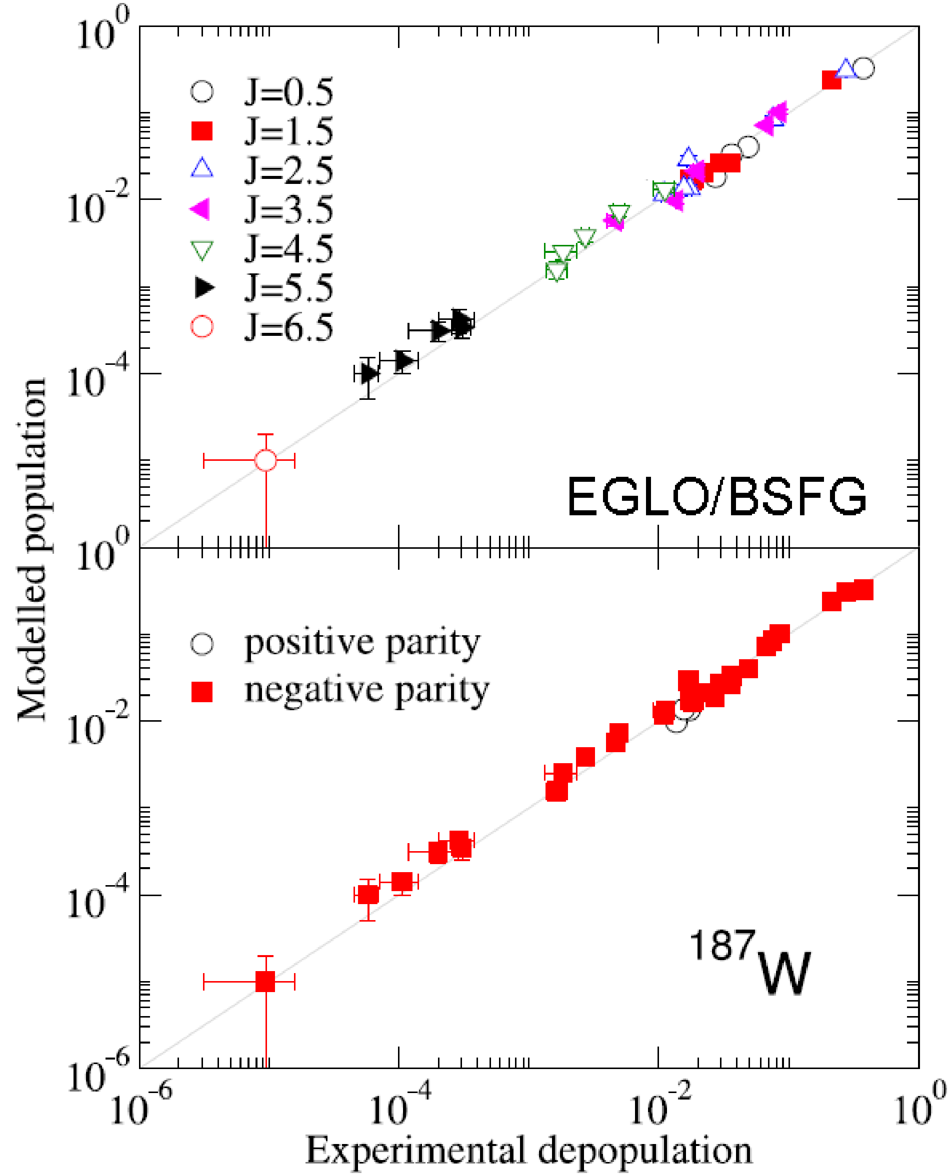
$f(E_\gamma)$ already averaged over many initial levels, p-capture

*Atlas of Neutron Resonances, S Mughabghab (2006)

DICEBOX Statistical Model Calculations

DICEBOX* assumes that the level scheme is completely determined below an excitation energy E_{crit}.

It calculates simulated level schemes above E_{crit} based on various statistical models assuming Porter-Thomas transition probability distributions. The DICEBOX calculated feedings to levels below E_{crit} can be renormalized to the experimental depopulation of these levels. Population/depopulation plots are used to indicate agreement between DICEBOX and experiment.

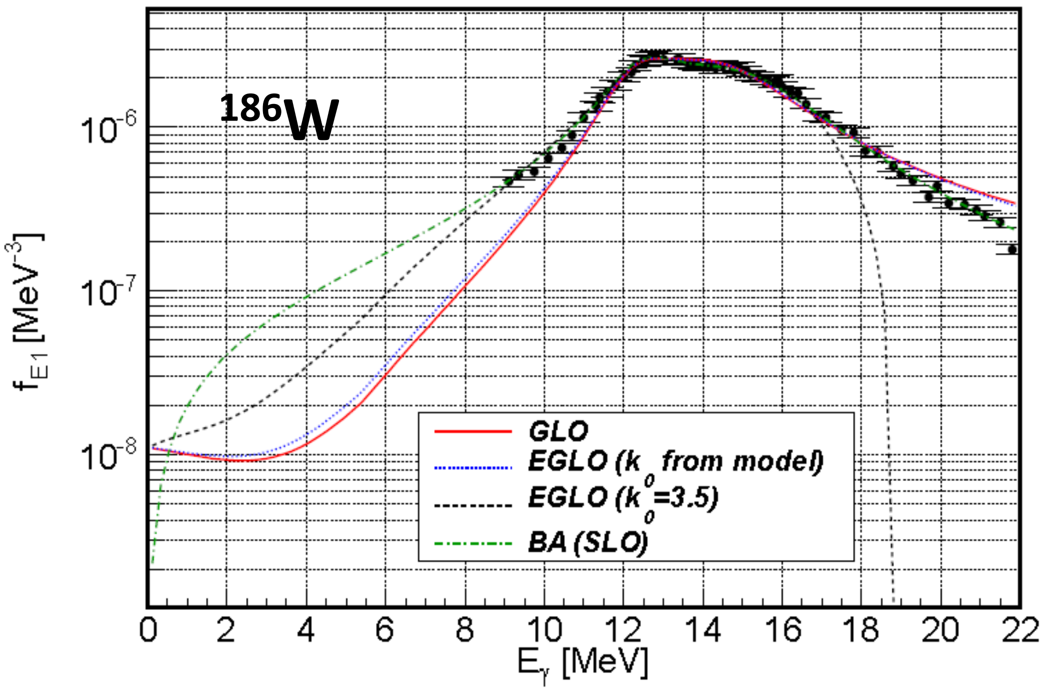


Excellent agreement with EGAF over 5 orders of magnitude and J^{π}=1/2-13/2 is obtained for $^{186}W(n,\gamma)^{187}W$.

Relies mainly on secondary γ-rays

*F. Becvar and M. Krticka, Prague

Photon Strength Functions



E_{G_1} [MeV]	Γ_{G_1} [MeV]	σ_{G_1} [mb]	E_{G_2} [MeV]	Γ_{G_2} [MeV]	σ_{G_2} [mb]
12.68	2.71	268.0	14.68	3.62	395.0

Various photon strength functions have been proposed that differ significantly <10 MeV.

- E1 only
- Based on GDR
- Independent of level energy

Standard Laurentzian Brink-Axel (BA)

$$f_{\mathrm{BA}}^{(E1)}(E_\gamma) = \frac{1}{3(\pi\hbar c)^2} \cdot \sum_{i=1}^{i=2} \frac{\sigma_{G_i} E_\gamma \Gamma_{G_i}^2}{(E_\gamma^2 - E_{G_i}^2)^2 + E_\gamma^2 \Gamma_{G_i}^2}$$

Generalized Lorentzian (GLO)

$$f_{\mathrm{GLO}}^{(E1)}(E_\gamma, \Theta) = \sum_{i=1}^{i=2} \frac{\sigma_{G_i}\Gamma_{G_i}}{3(\pi\hbar c)^2} \left[F_K \frac{4\pi^2\Theta^2\Gamma_{G_i}}{E_{G_i}^5} + \frac{E_\gamma \Gamma_{G_i}(E_\gamma,\Theta)}{(E_\gamma^2 - E_{G_i}^2)^2 + E_\gamma^2 \Gamma_{G_i}^2(E_\gamma,\Theta)} \right]$$

Nuclear temperature dependence

$$\Theta = \sqrt{(E_{\mathrm{ex}} - \Delta)/a},$$

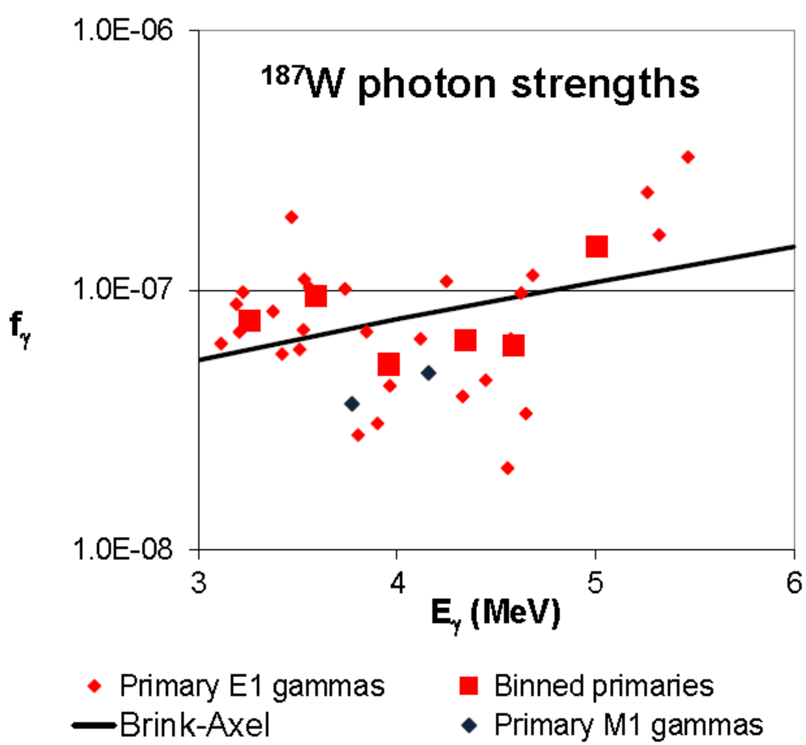
And $\Gamma_{G_i}(E_\gamma, \Theta) = \frac{\Gamma_{G_i}}{E_{G_i}^2}(E_\gamma^2 + 4\pi^2\Theta^2).$

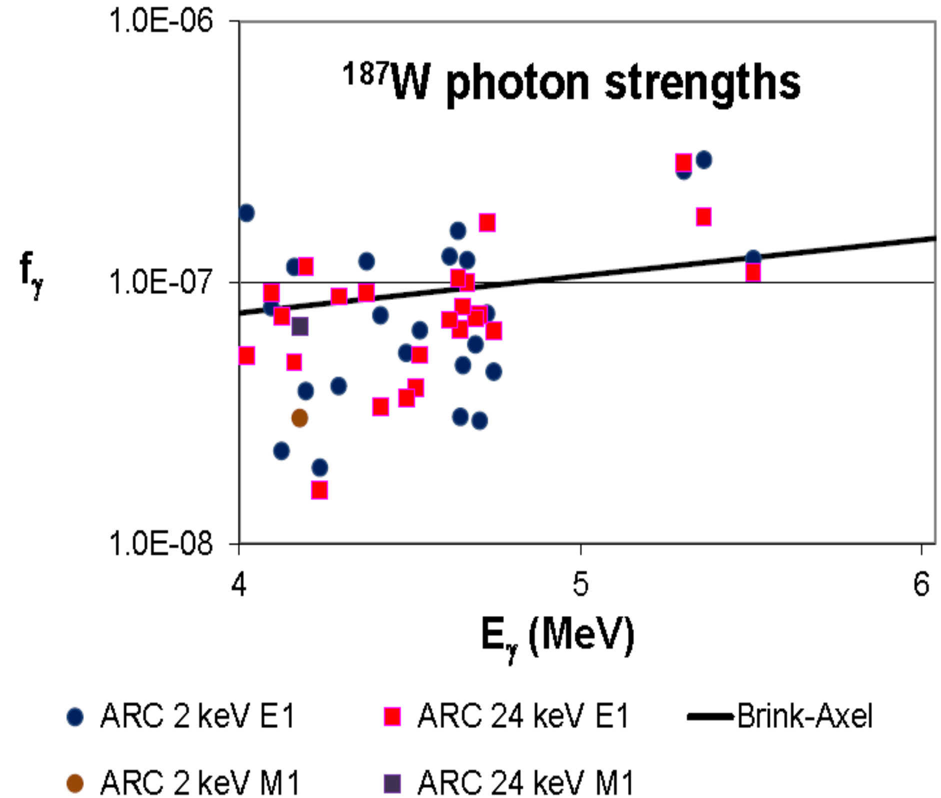
Enhanced Generalized Laurentzian (EGLO)

$$\Gamma'_{G_i}(E_\gamma, \Theta) = \left[k_0 + (1 - k_0)\frac{(E_\gamma - E_0)}{(E_{G_i} - E_0)} \right] \Gamma_{G_i}(E_\gamma, \Theta)$$

$$E_0 = 4.5 \ \mathrm{MeV}$$

^{186}W Photon Strengths

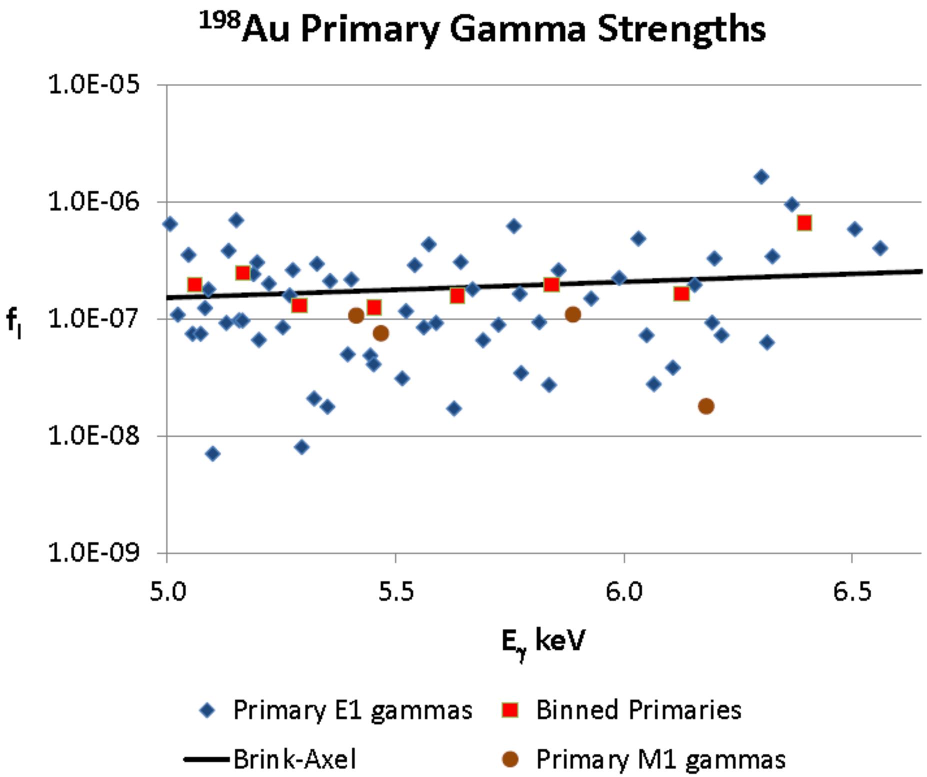


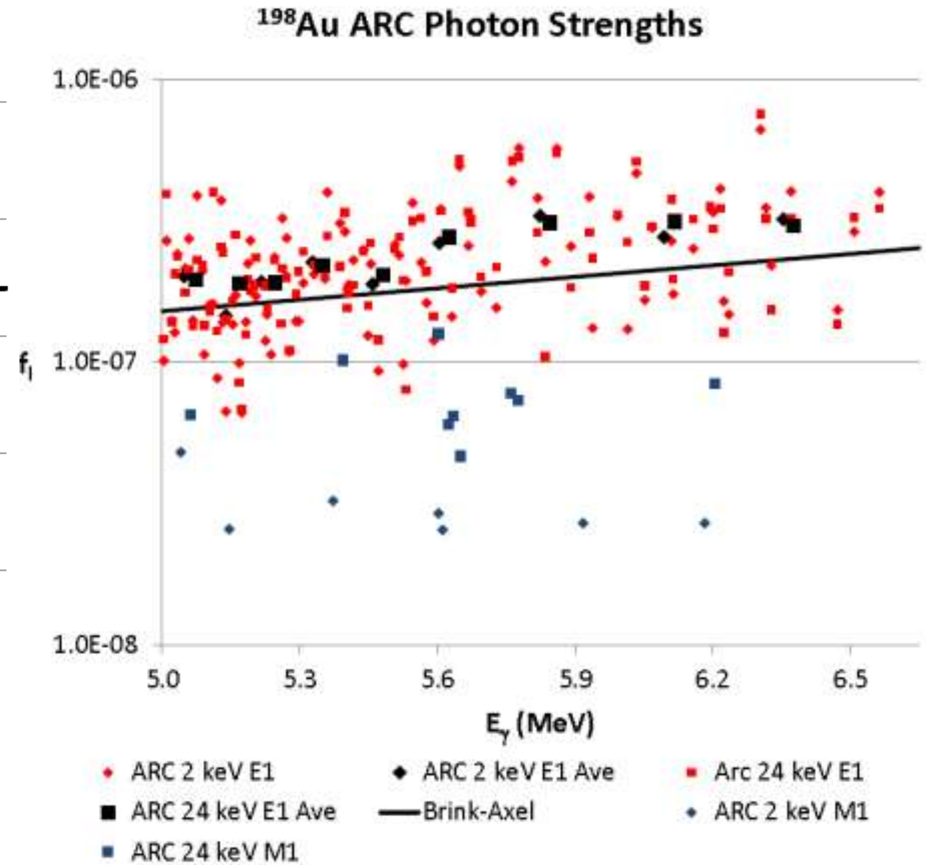


Average f_γ(EGAF)/f_γ(BA)=0.98

Average f_γ(2 keV)/f_γ(BA)=0.86
Average f_γ(24 keV)/f_γ(BA)=0.84

^{198}Au Photon Strengths



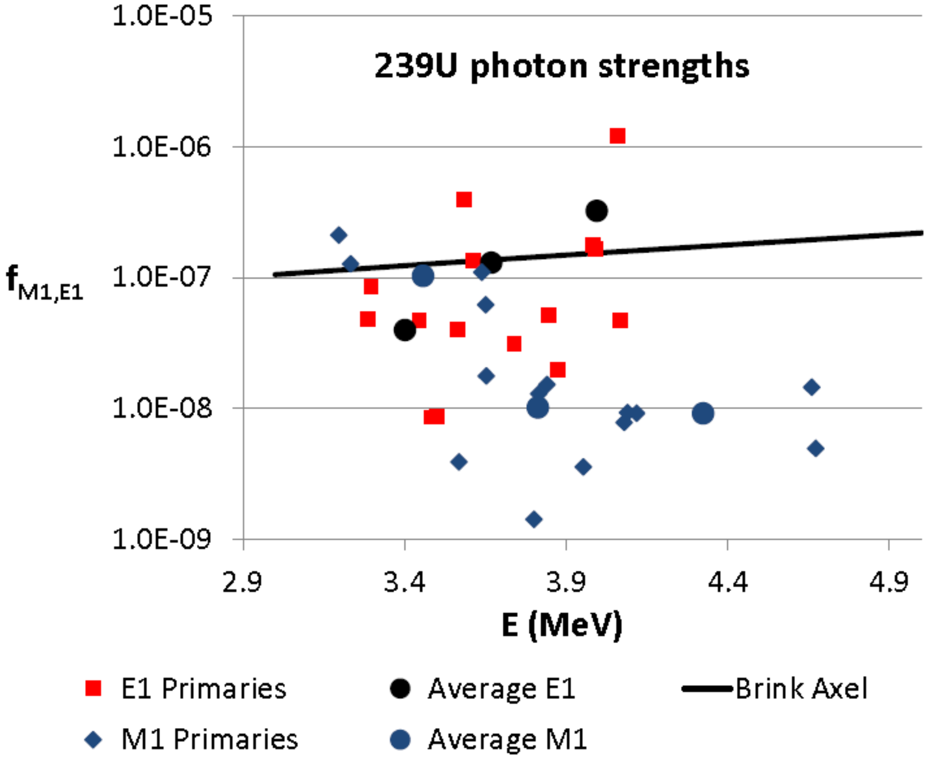


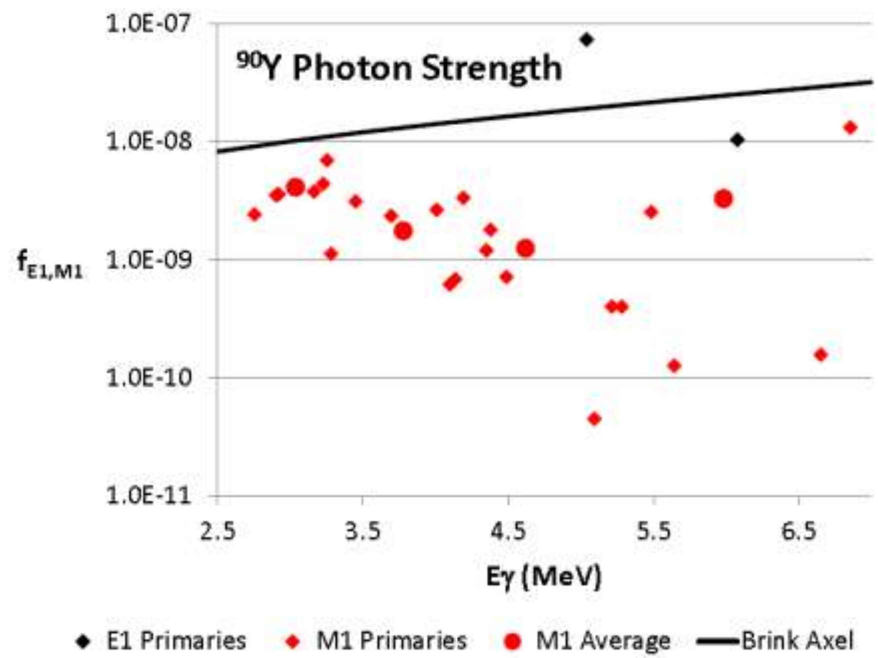
Average f_γ(EGAF)/f_γ(BA)=1.10

Average f_γ(2 keV)/f_γ(BA)=1.18

Average f_γ(24 keV)/f_γ(BA)=1.22

^{238}U and ^{90}Y Photon Strengths





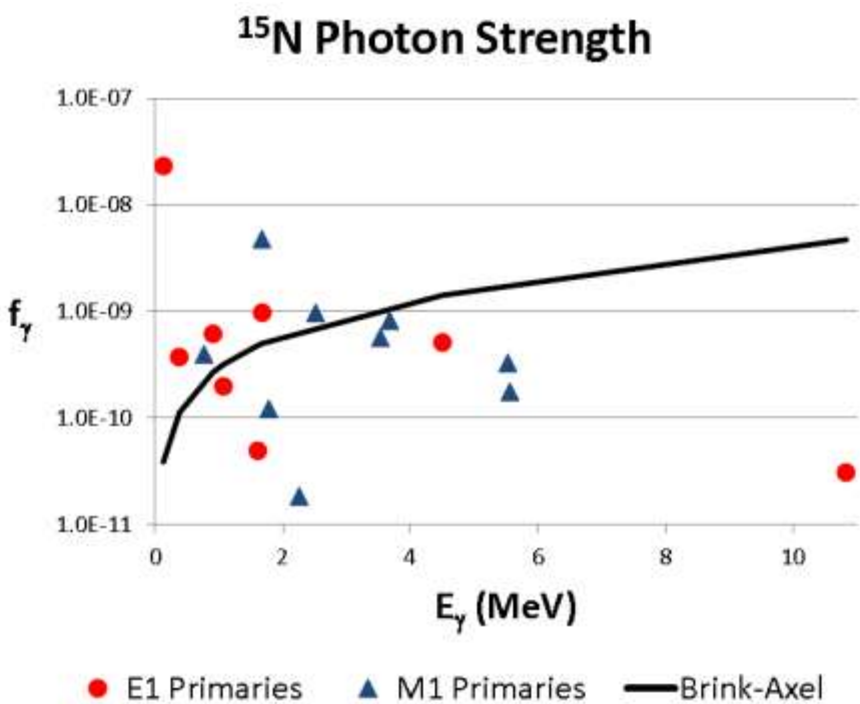
Average f_γ(EGAF)/f_γ(BA)=1.16

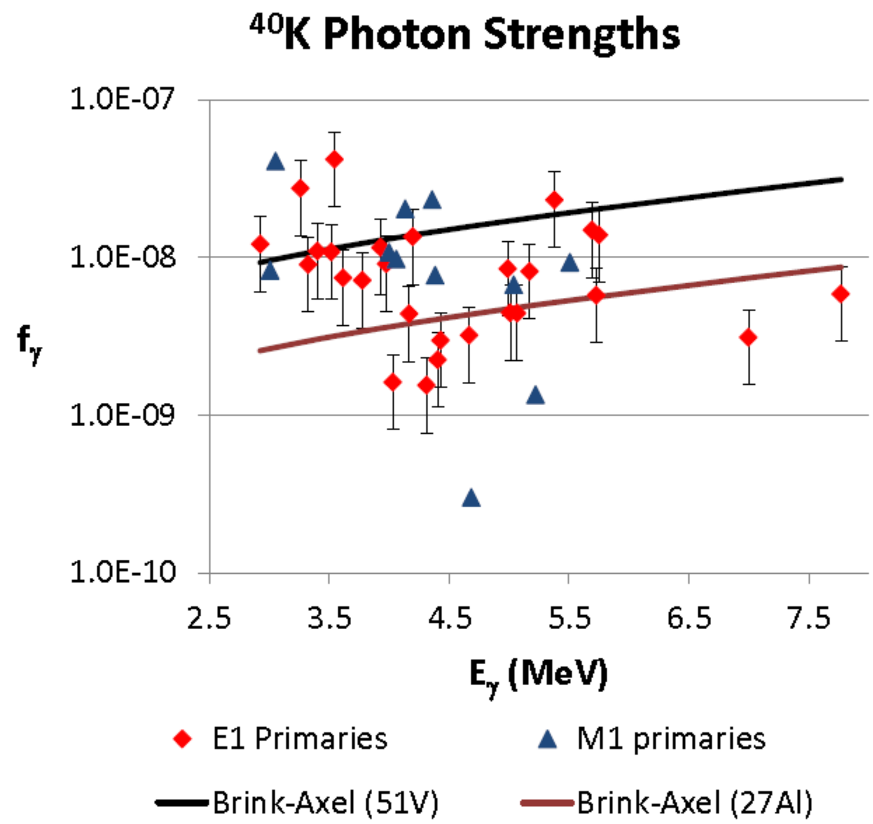
2 E1 γ–rays, consistent with BA

E1 transitions are consistent with Brink-Axel.

M1 transitions strength increases to E1 strength at low energies.

Light Element Photon Strength



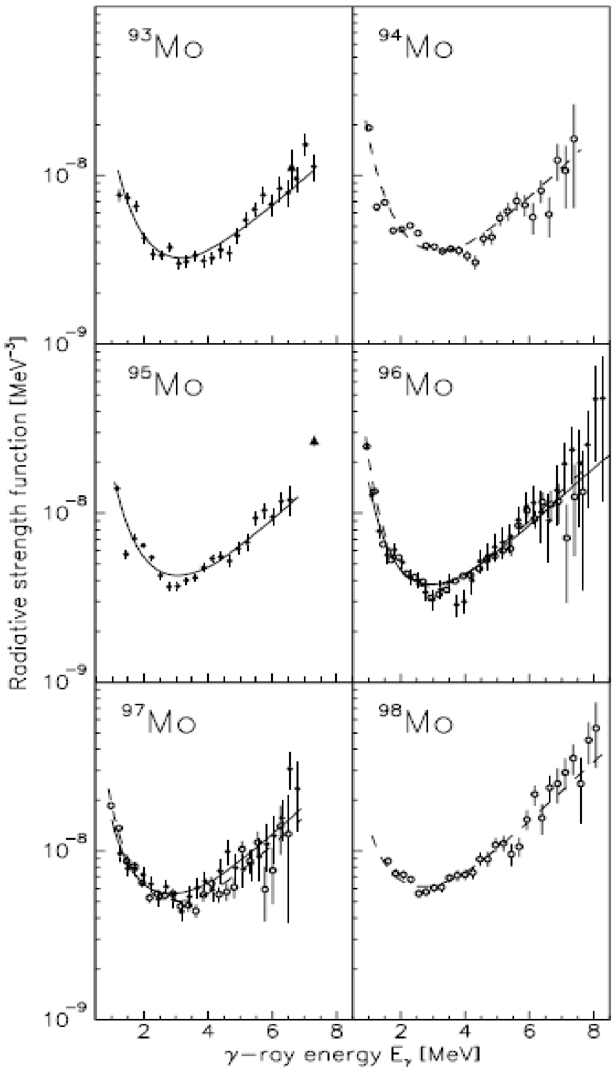


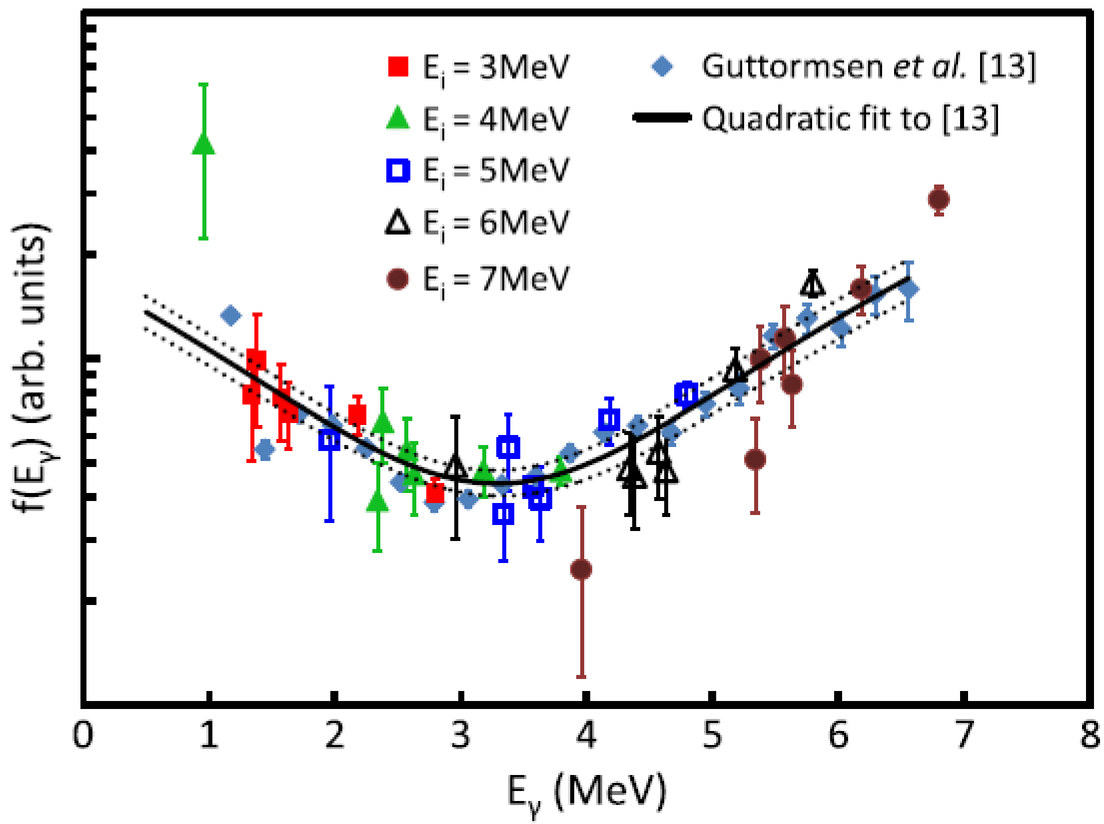
Average f_γ/f_γ(BA)=0.88
Neglecting extreme values

M1 and E1 strength are comparable

Average f_γ/f_γ(BA-^{27}Al)=2.31
Average f_γ/f_γ(BA-^{51}V)=0.64

Low-energy Photon Strength Enhancement: E_γ<4 MeV

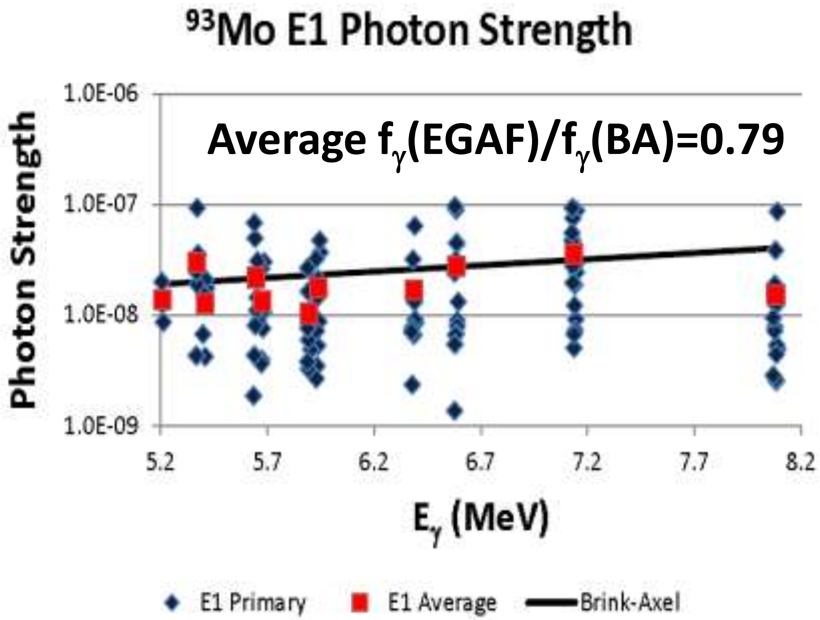


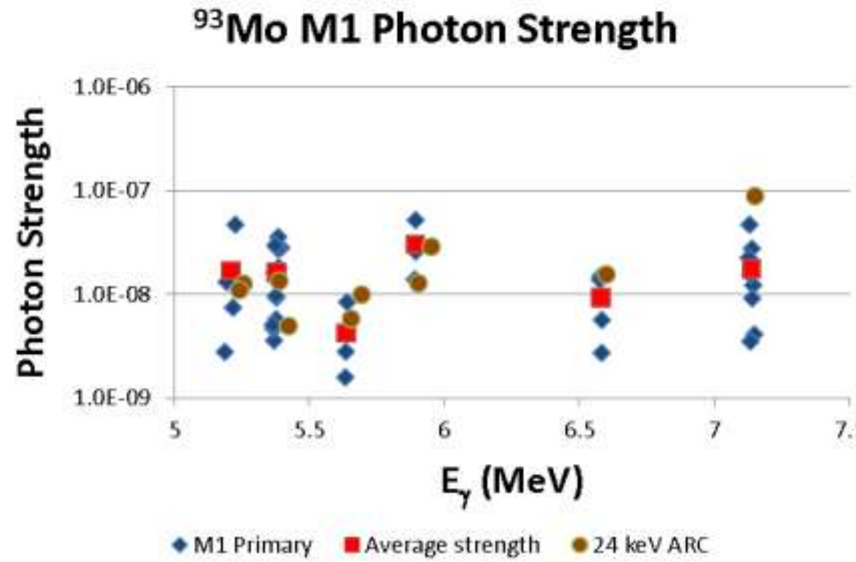


M. Wiedeking et al, Phys. Rev. Lett. 108, 162503 (2012)

M. Guttormsen et al, Phys. Rev. C71, 044307(2005)

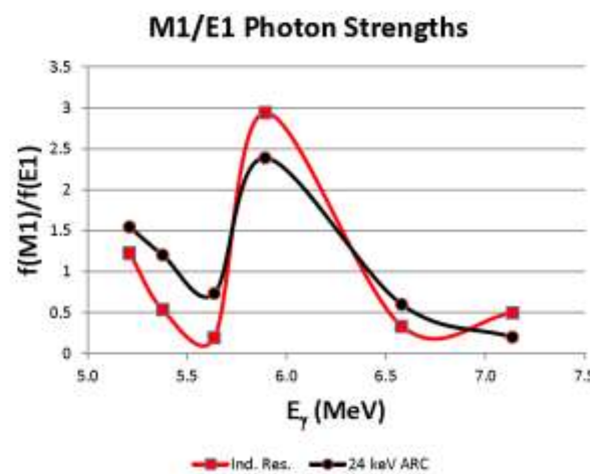
^{93}Mo Photon Strength





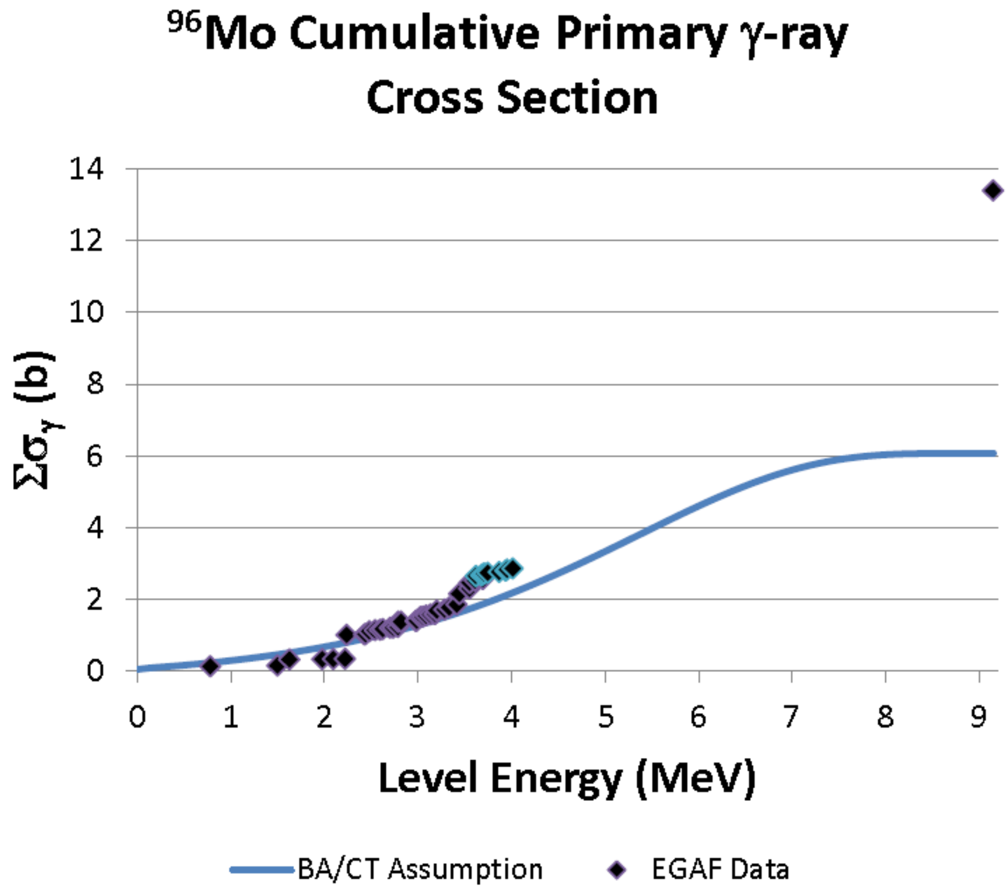
Primary γ-ray data deexciting 29 individual resonances in ^{93}Mo between 0.3-23.9 keV*.

- E1 Photon strength consistent with Brink-Axel
- M1 photon strength is variable and sometimes stronger than E1.
- M1 strength is dependent on final state



*O.A. Wasson and G.G. Slaughter, Phys. Rev. C8, 297 (1973).
24±2 keV ARC – K. Rimawi and R.E. Chrien, Phys. Rev. C15, 1271 (1977).

$^{95}Mo(n,\gamma)$ E=Thermal



<u>Standard Statistical Model</u>

S_n=9154 keV, J^π=3+, σ_0=13.4 b

D_0=81 eV, Γ_γ=162 meV

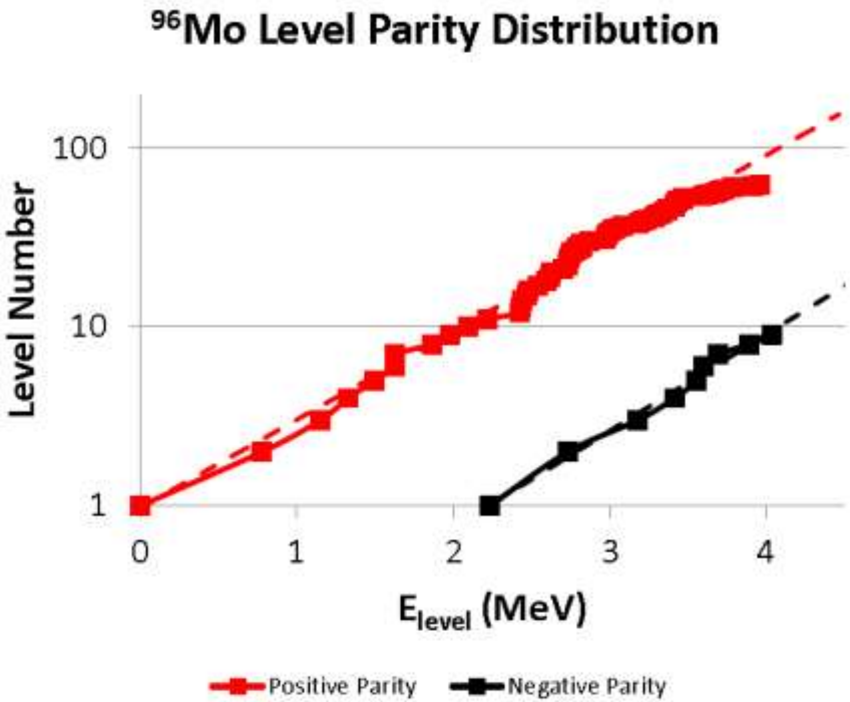
The calculated cumulative primary γ-ray cross section falls short of experiment and the total radiative cross section, 13.4 b, for ^{95}Mo.

- E1: f(Brink-Axel)
- M1: f(BA/7)
- CTF level density

Evidence of additional photon strength to levels above 3-4 MeV

Excess photon strength for low-energy primary gammas

Parity Corrections



Dotted line shows expected exponential fit to the level distribution.

*Phys. Rev. C67, 015803 (2003).

No negative parity levels below 2.2 MeV.

For ^{95}Mo(n,γ), 27 primary γ-rays are M1, 3 are E1, and 2 are E2.

We can apply the systematic parity correction to the statistical model as described by Al-Qurashi et al*.

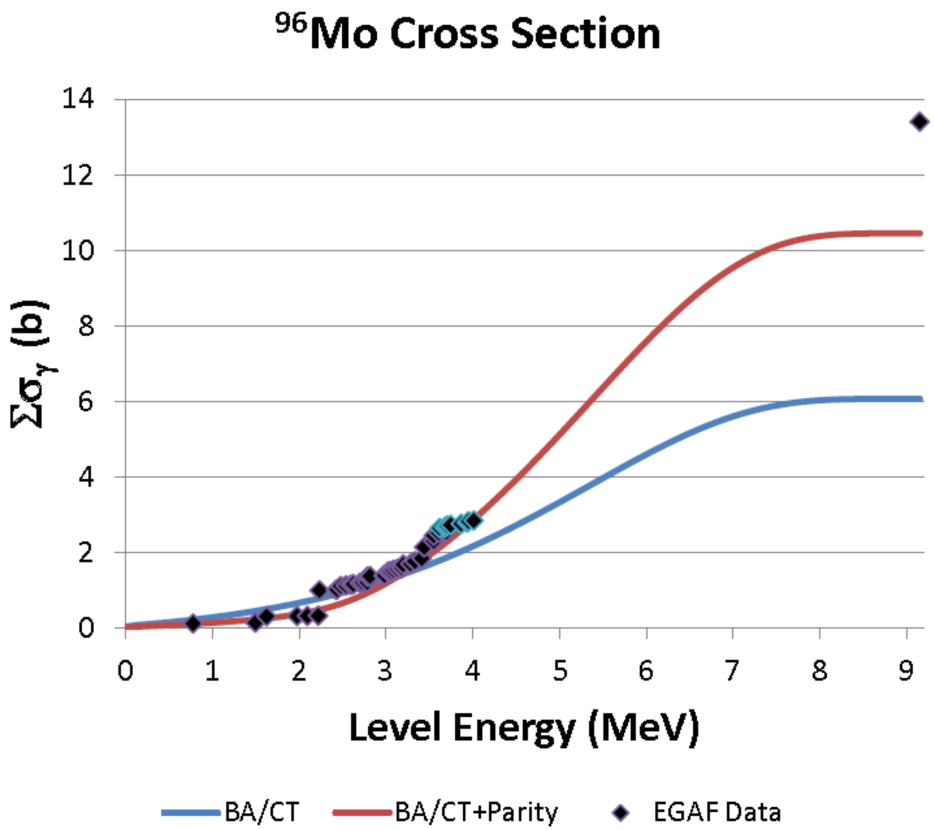
$$\pi(u) = \frac{\rho_+(u)}{\rho_+(u)+\rho_-(u)} = \frac{1}{2}\left(1 + \frac{1}{1+\exp[c(u-\delta_p)]}\right)$$

Where

c=3 MeV^{-1}, u=level energy,

$\delta_p = a_0 + a_1/A^{a2}$, a_0=1.34, a_1=75.22, and a_2=0.89

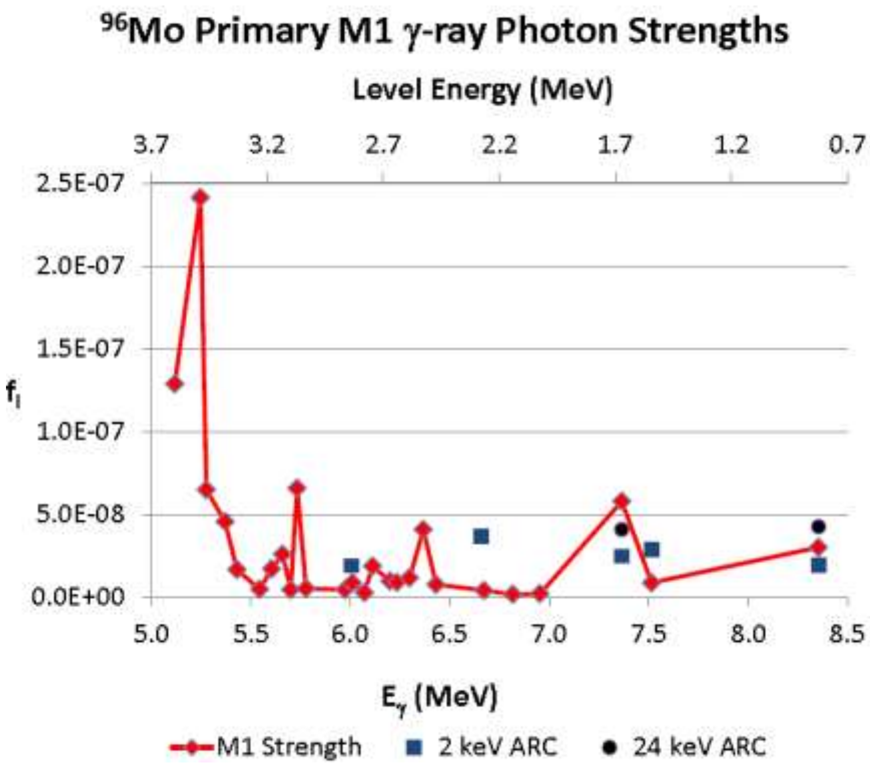
BA/CTF/Parity Correction



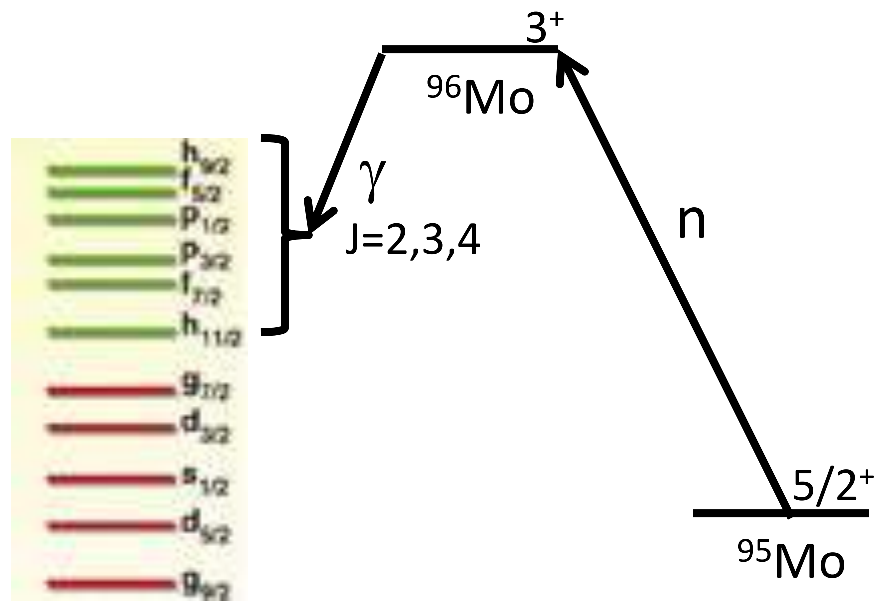
Parity correction is consistent with cumulative experimental cross section up to 4 MeV, but falls short of the total cross section.

More photon strength is needed populating levels above 4 MeV

M1 Photon Strength



In ^{96}Mo the M1 primary γ-ray strength increases for transitions to levels above 3.5 MeV.



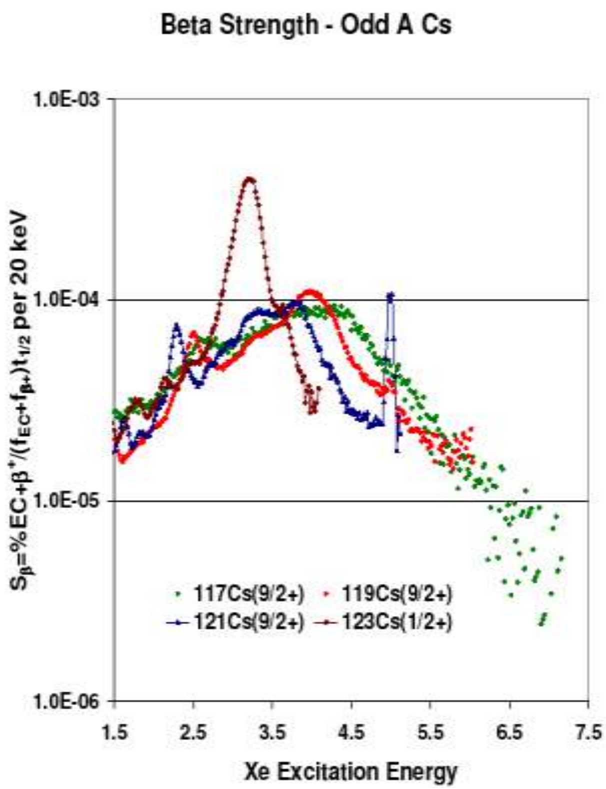
Strong M1 transitions are associated with Shell gaps near 5 MeV.

e.g. spin flip transitions ($h_{11/2} \rightarrow h_{9/2}$)

Direct (n,γ) reactions favor populating single particle states.

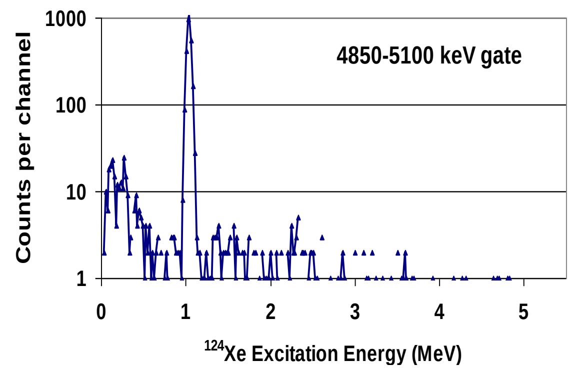
60% of ^{95}Mo(n,γ) cross section is direct (Mughabghab Atlas)

Beta Decay Strength Functions

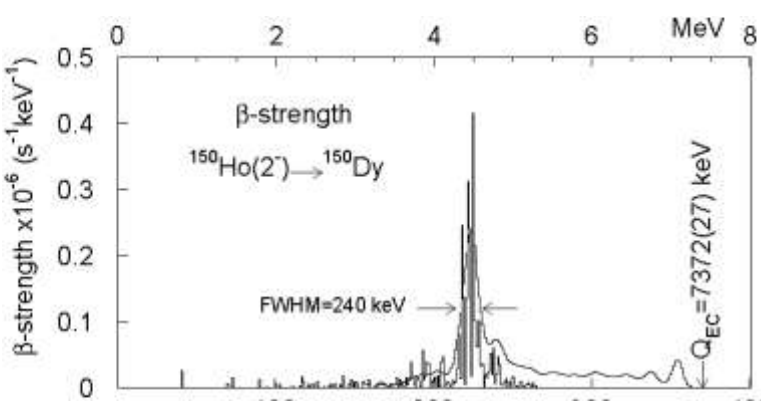


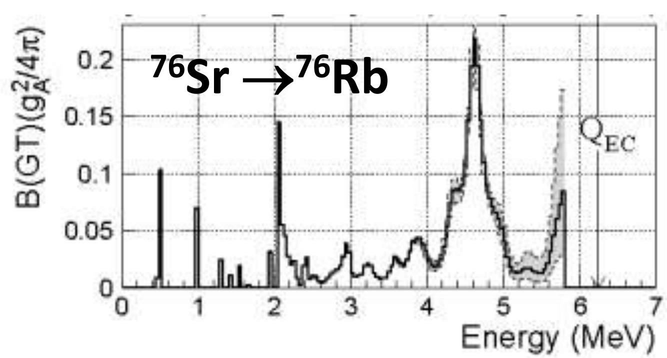
Total Absorption Spectroscopy (TAS) gives the β-decay strength function which is analogous to the M1 γ-ray strength function.

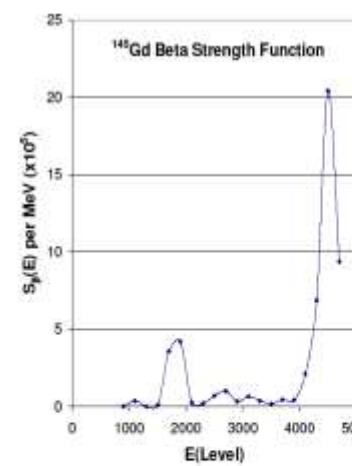
- Strength strongly peaked at 4-5 MeV
- No GT(M1) giant resonance



Gate on 5 MeV level excitation shows decay by γ-ray to GS







M1 Resonance Photon Strength Function

Assume that the M1 photon strength is defined by a Laurentzian resonance with parameters

E_{res}=4.5 MeV, Γ_{res}=0.5 MeV, σ_{res}=0.5 mb

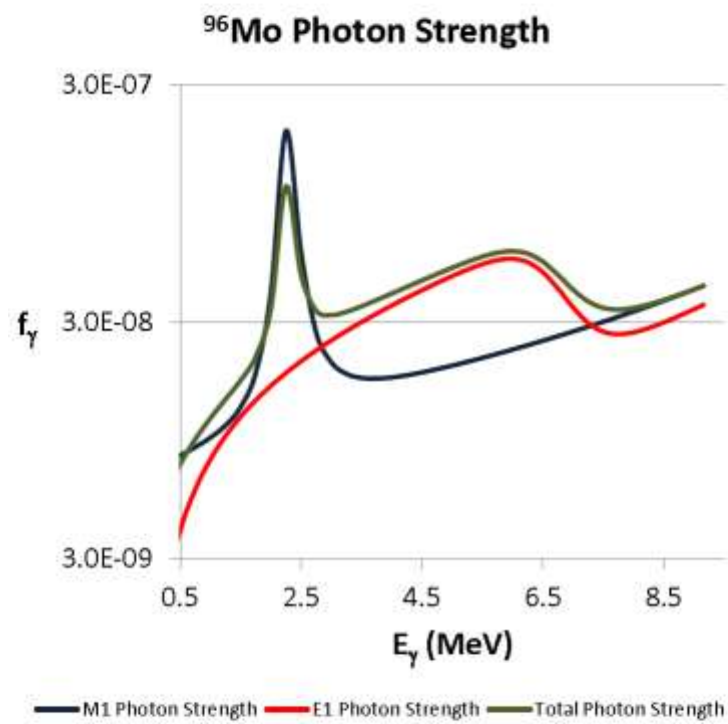
Such that

$$f_{M1} = \frac{1}{3(\pi\hbar c)^2} \frac{\sigma_{res} E_{res} \Gamma^2{}_{res}}{[E_\gamma{}^2 - (E_{level} - E_{res})^2]^2 + (E_\gamma \cdot \Gamma_{res})^2} + f^0{}_{M1}$$

where $f^0{}_{M1}=f_{BA}/7$

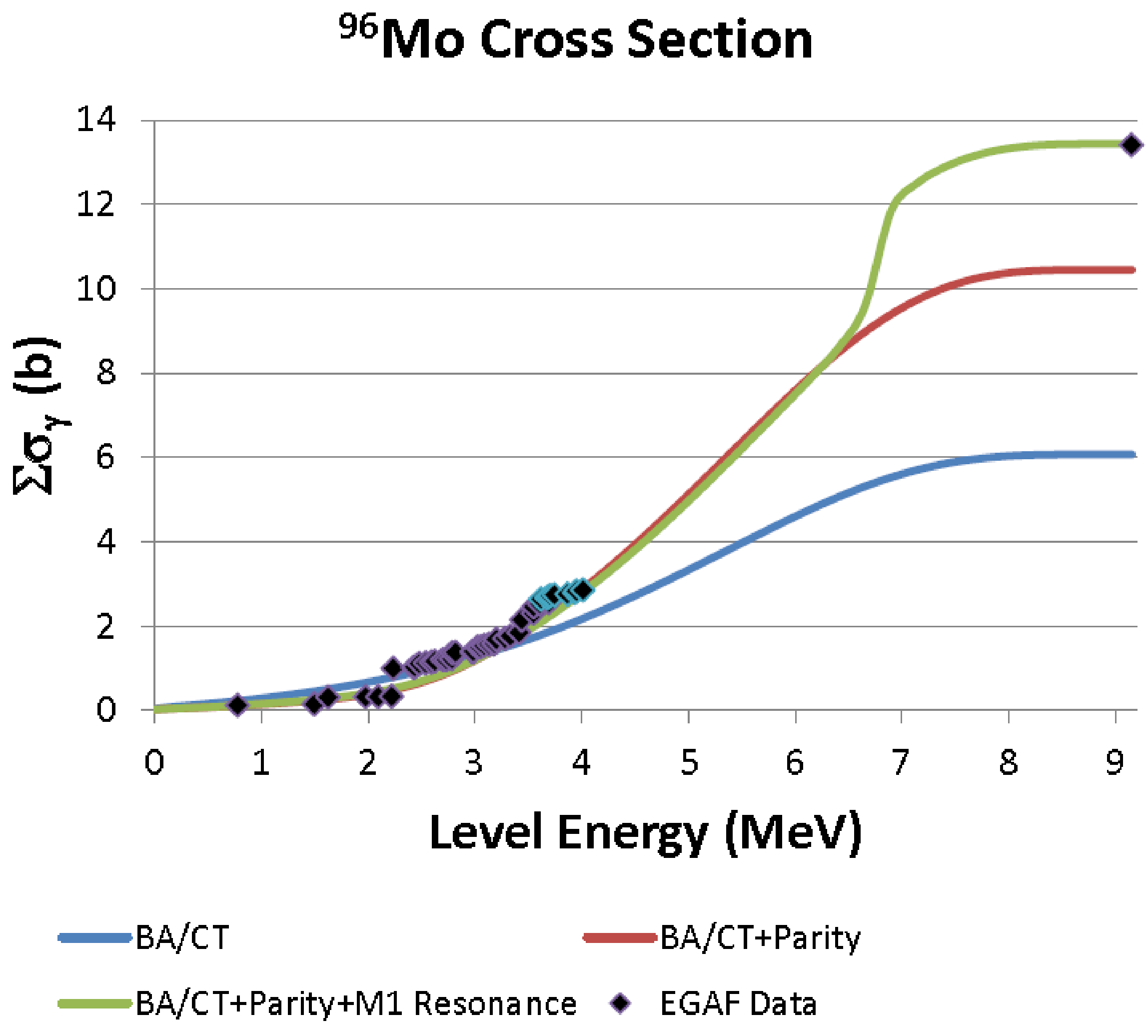
The M1 resonance is presumed to Be composed of single-particle neutron states coupled with the $\pi f_{5/2}$ proton state to give 2^+, 3^+, 4^+ final states.

Choice of resonance parameters is Arbitrary, designed to be consistent with the total cross section.



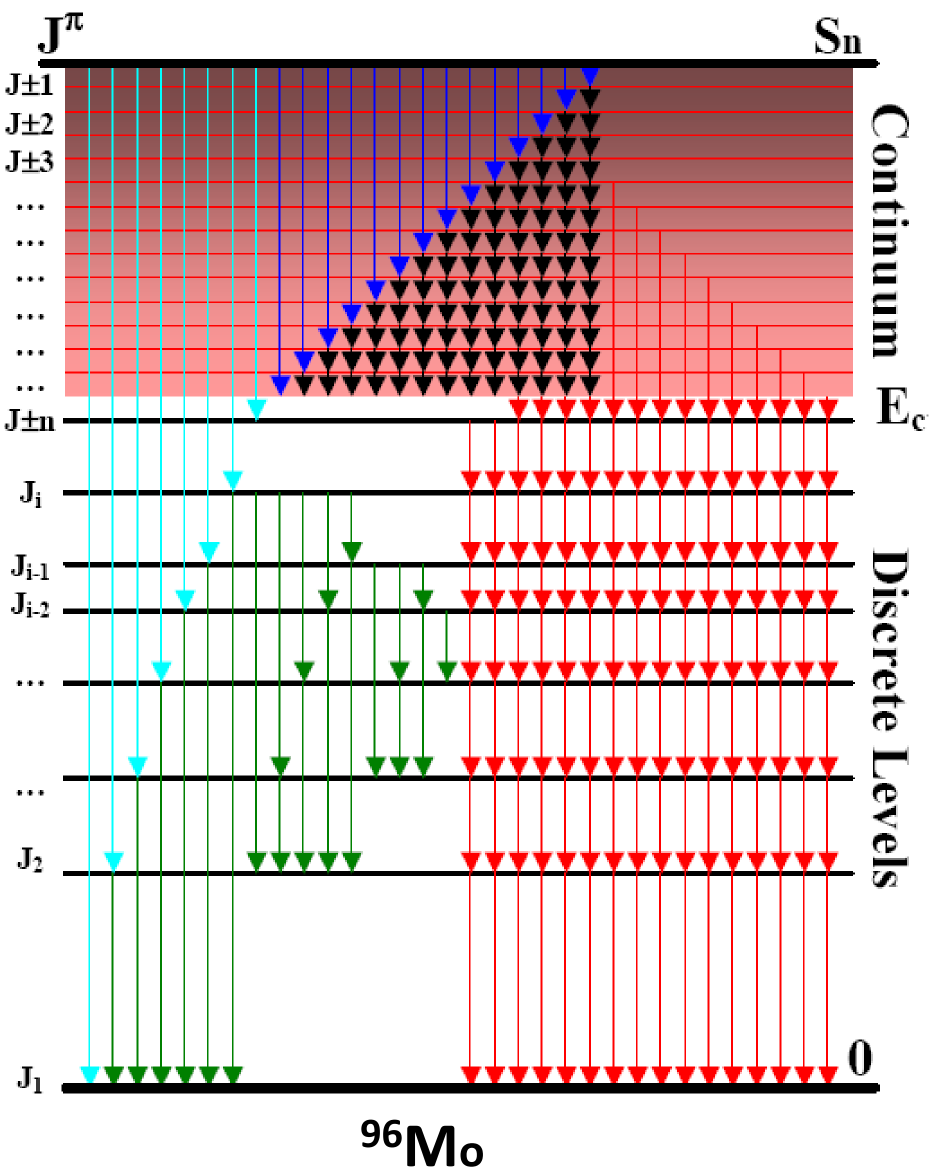
^{95}Mo(n,γ) E=Thermal

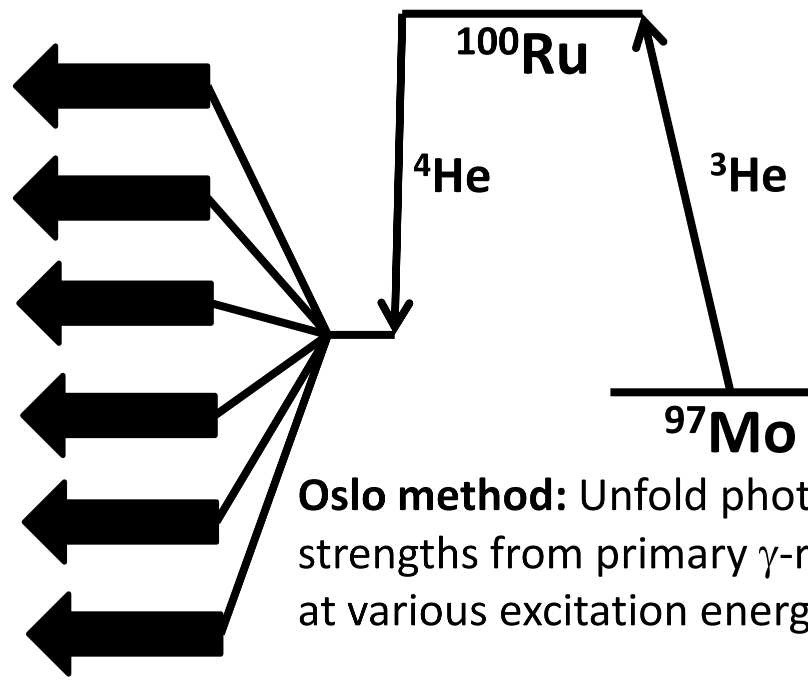
E1: Brink Axel, M1; 4.5 MeV Resonance; CTF level density



Consistent with experimental σ_0.

Application of an M1 Resonance to Oslo Method





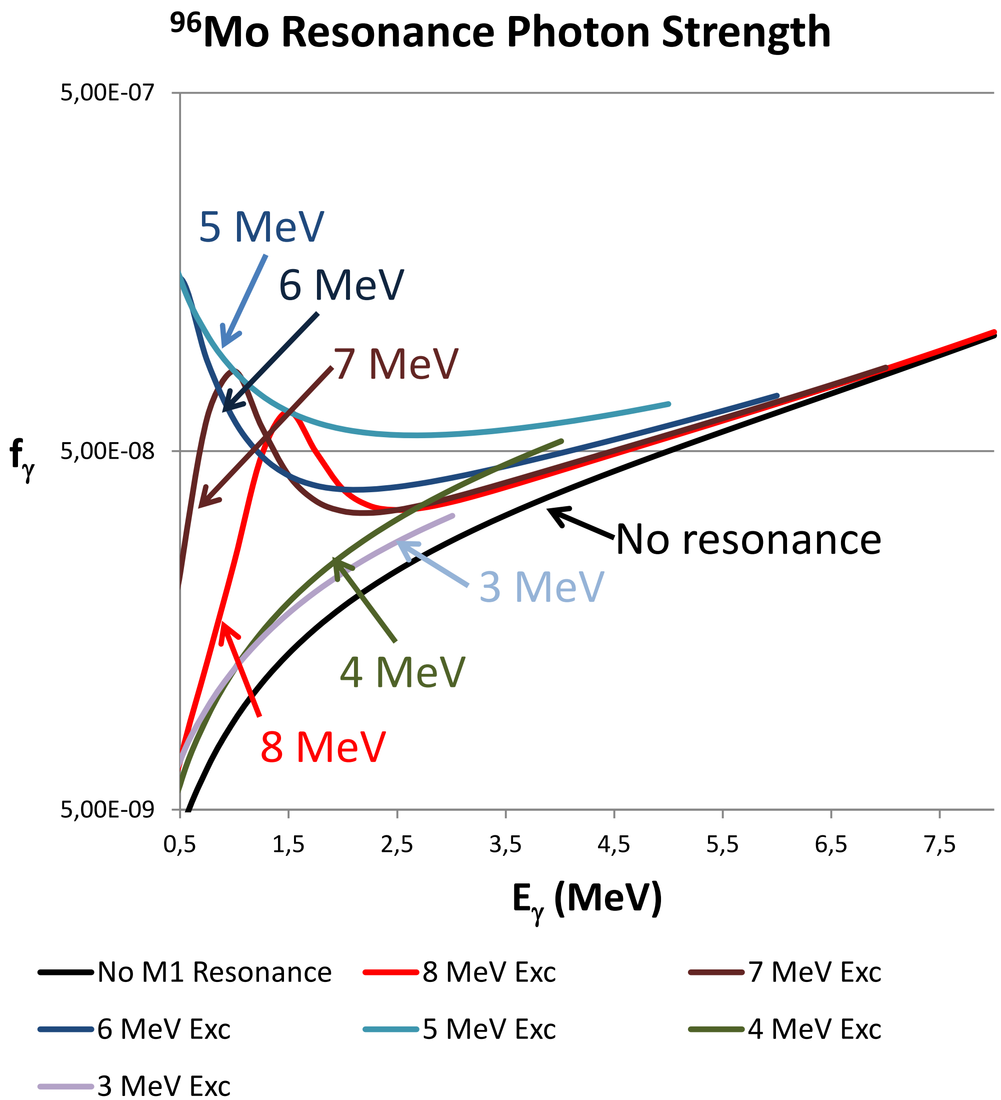
Oslo method: Unfold photon strengths from primary γ-rays at various excitation energies.

Assumption: Photon strengths are only properties of γ-ray energies.

M1 Resonance: Photon strengths are dependent on both the γ-ray energy and level excitations.

Photon strengths vary with (^{3}He,α) excitation energy in ^{96}Mo.

Primary Photon Strength vs Excitation Energy

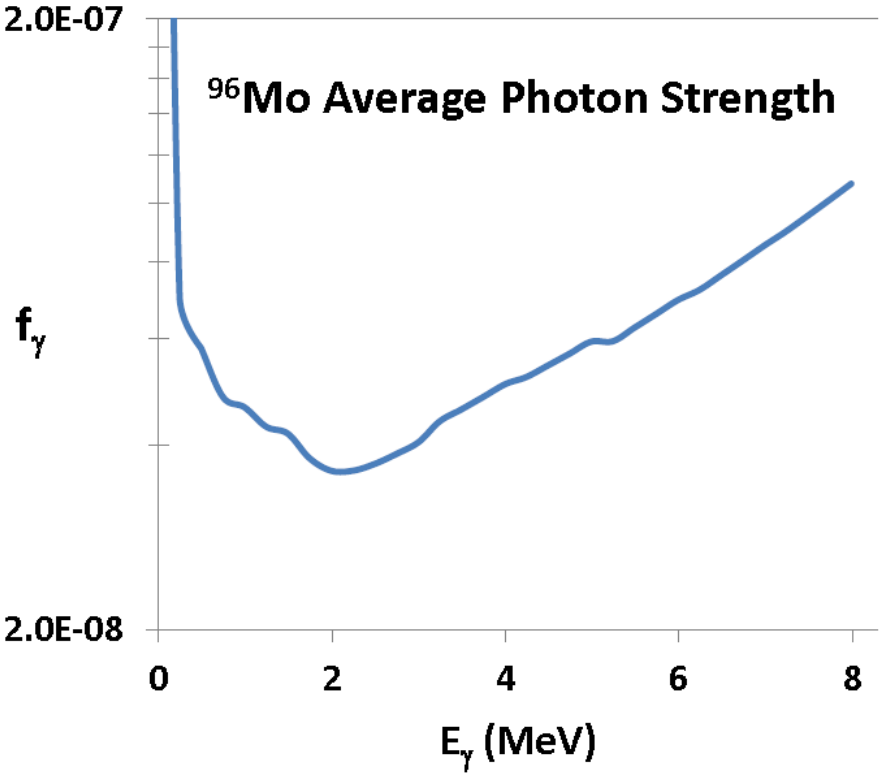


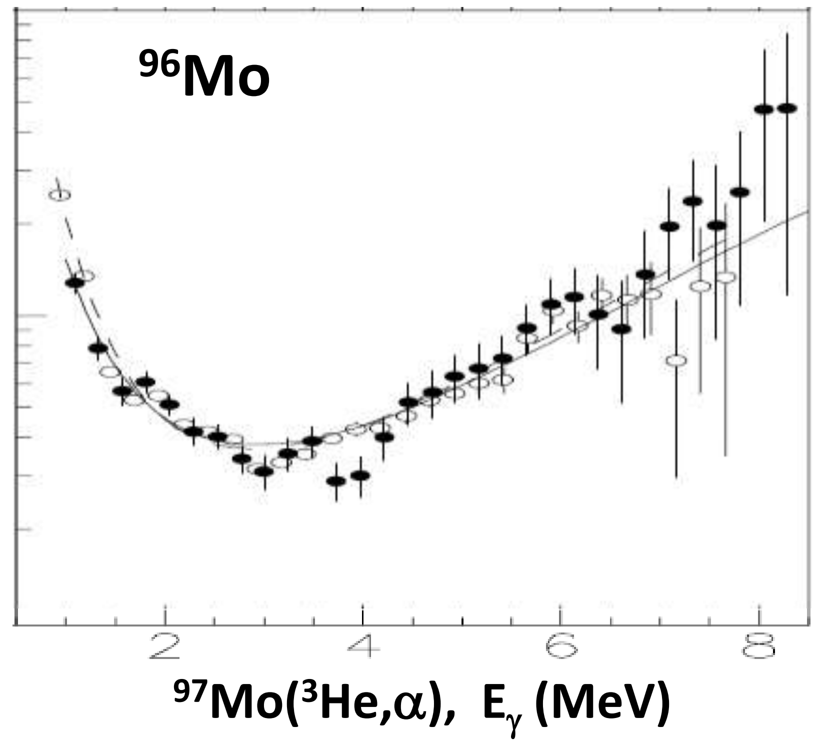
Assumptions

- E_{res}=4.5 MeV, Γ_{res}=0.5 MeV, σ_{res}=0.5 mb
- Parity correction for entry level excitation

The photon strengths vary dramatically with excitation energy.

Unweighted average photon strength





^{96}Mo average 3-8 MeV (^{3}He,α) photon strength calculated assuming a 4.5 MeV M1 resonance is very comparable to Guttormsen *et al.* experimental results.

Conclusions

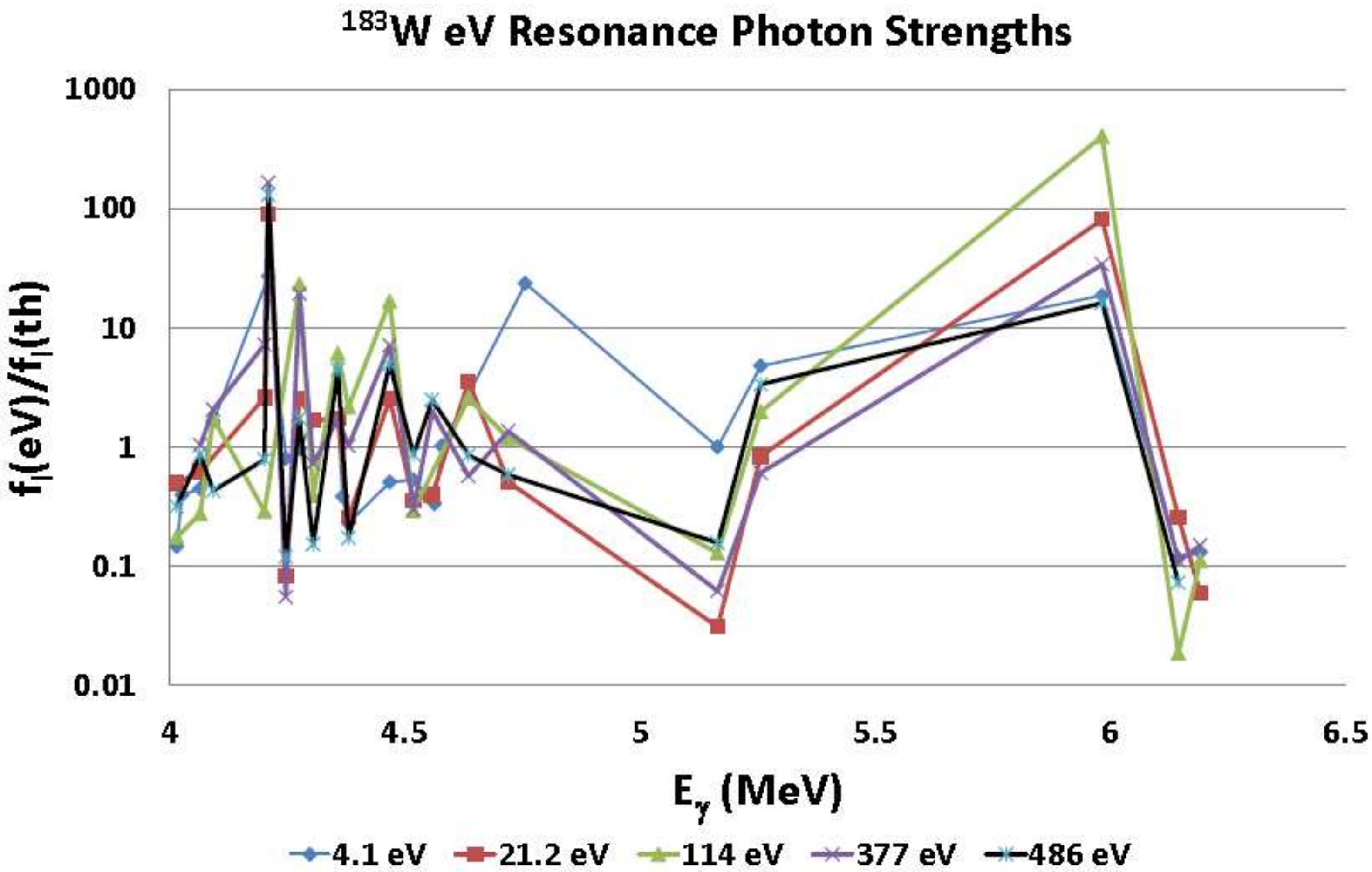
What we have learned

- Measurement of primary γ-ray E1, M1 strengths in thermal and average resonance (n,γ) reactions is a powerful tool for understanding photon strengths.
- E1 strengths are can be described by the Brink-Axel approximation.
- M1 strengths are dominated by "simple" nuclear structure considerations and can be stronger than E1 strengths.

What we need to learn

- What is the "true structure" of the M1 shell resonance?
- Are there other M1 resonances?
- Are there also E1 resonances?
- Are E2 and M1+E2 transitions important?
- Can the Oslo Method be adapted to uncover the M1 resonances?

^{183}W eV Resonances



Correlated decay of adjacent resonances in ^{183}W. To be discussed at the Oslo 2015 Workshop.

Thank you for your attention