Neutron Capture Experiments with DANCE

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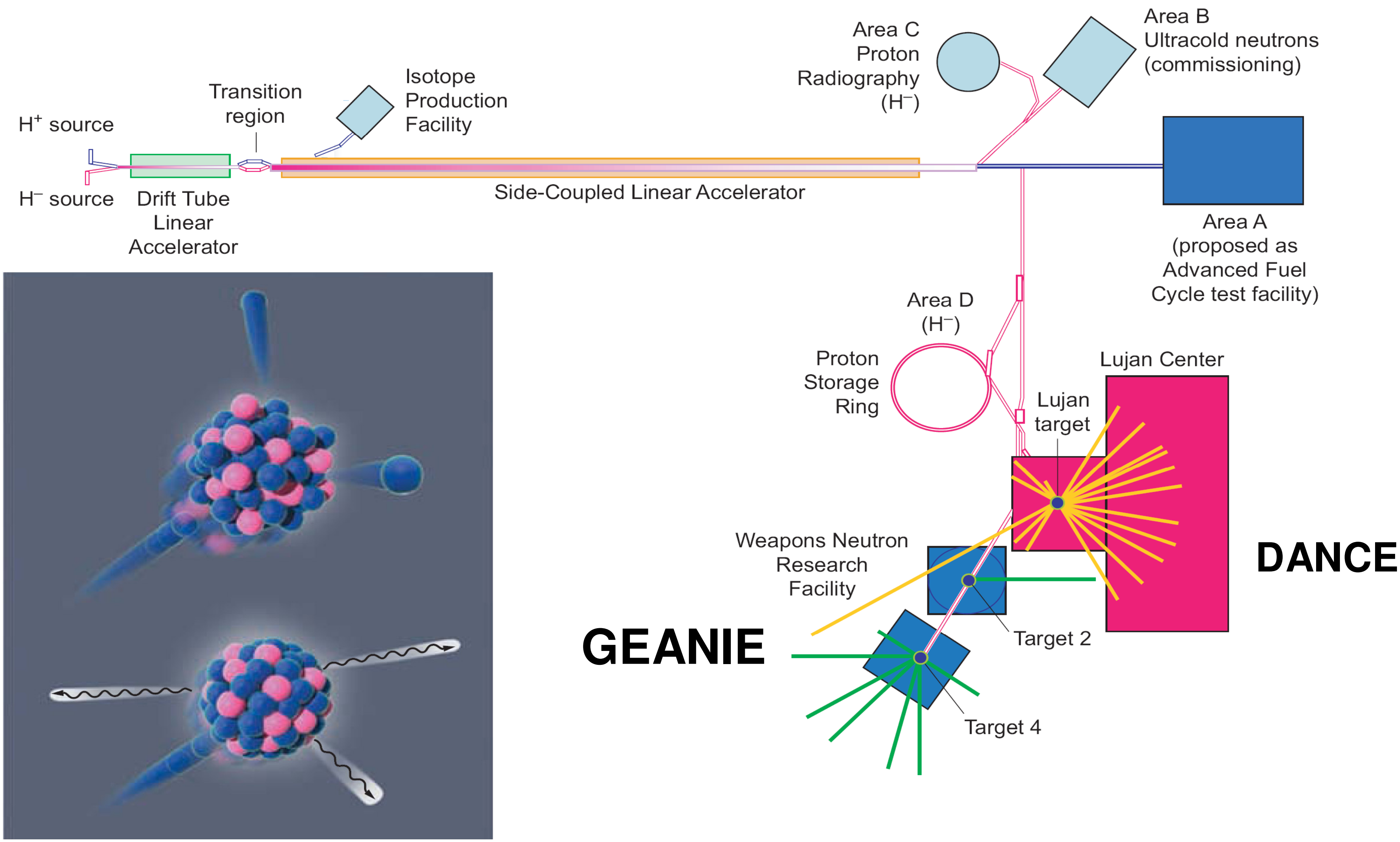
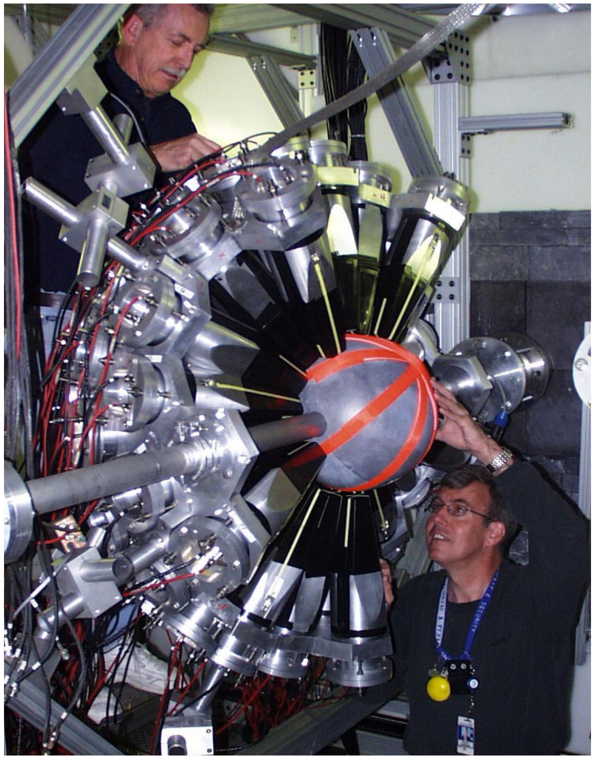
LANSCE User Facility

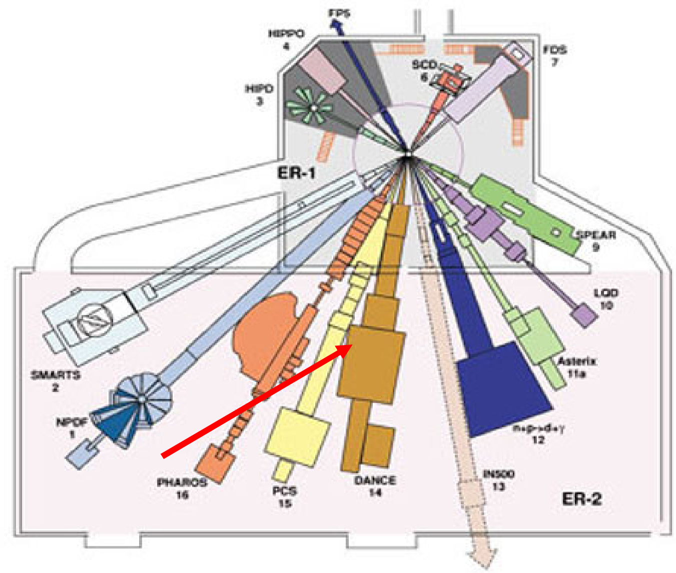


Neutron-capture using DANCE array at LANSCE

n – beam



DANCE is composed of 160 BaF_2 detectors covering ~4π.



DANCE is located on Flight Path 14 at the Lujan Center.

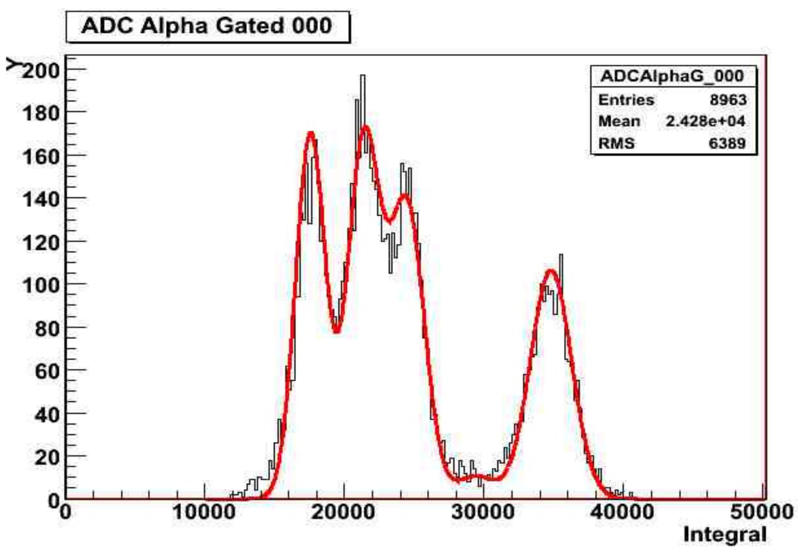
The neutron-capture of ^{94,95}Mo, and ^{152,154,156,157,158,160,nat}Gd are measured using the DANCE array and the high granularity of the array was used to extract multiplicity and γ-ray energy distributions.

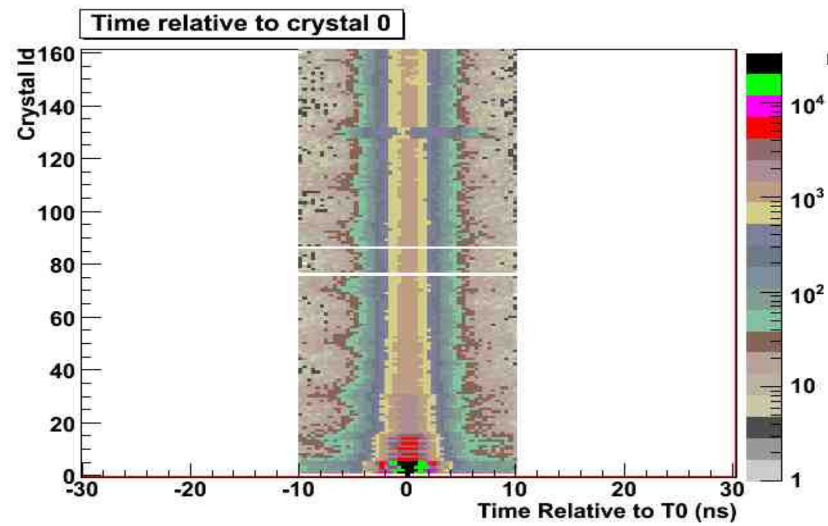
Calibration

- **Gamma Energy**
- **Time**
- **Neutron Energy**

Gamma Energy Calibration

- Standard sources as ^{88}Y, ^{22}Na, ^{60}Co
- Gain shifts are corrected with Ra alpha decay energy for each crystal





Time Calibration

- Average time difference between the crystal and the reference crystal

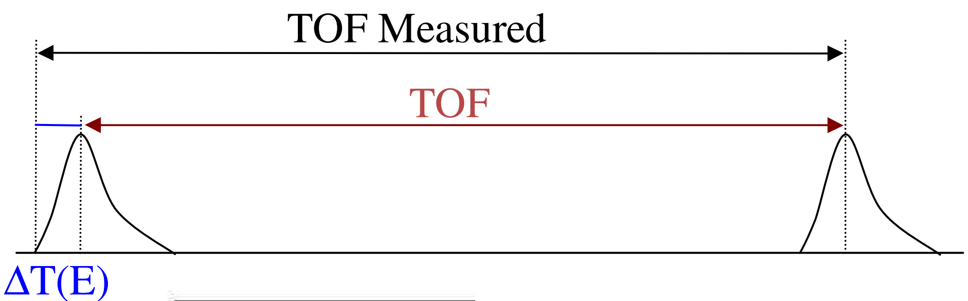
Calibration

Neutron Energy Calibration

- Flight Path Length
- ΔT determination

$$T_j = a_j L + \Delta T_j + \Delta T_0 \qquad \text{where} \quad a_j = 72.29/\sqrt{E}$$

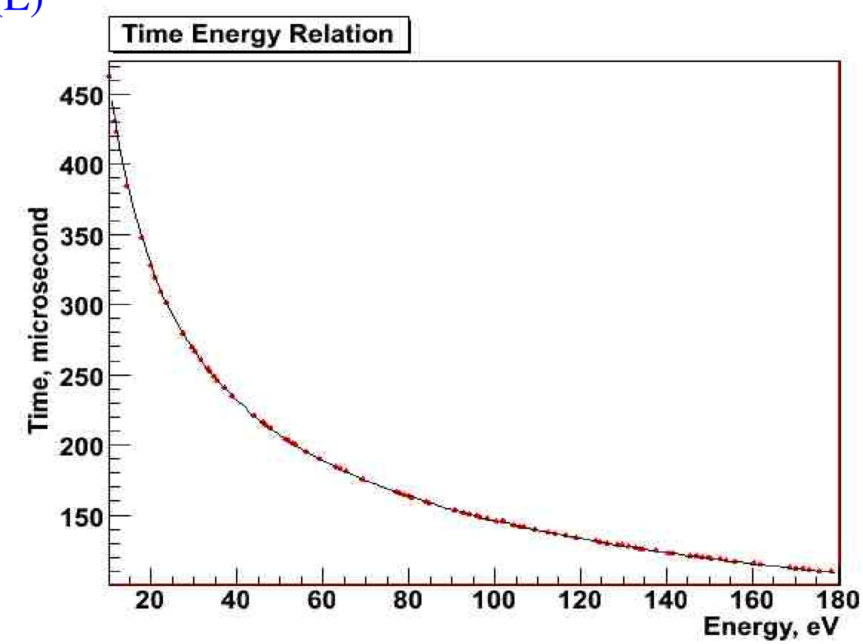
$$T_j = a_j\left(L + \frac{\Delta T_j}{a_j}\right) + \Delta T_0 = a_j L_{eff} + \Delta T_0$$

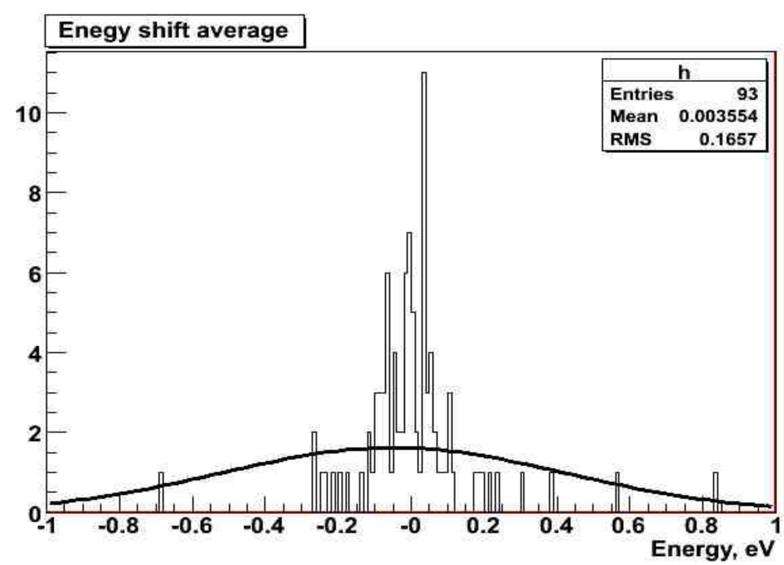


Fitting L_{eff} and ΔT_0 as parameter:

L_{eff} = 20.312 ± 0.162 meter

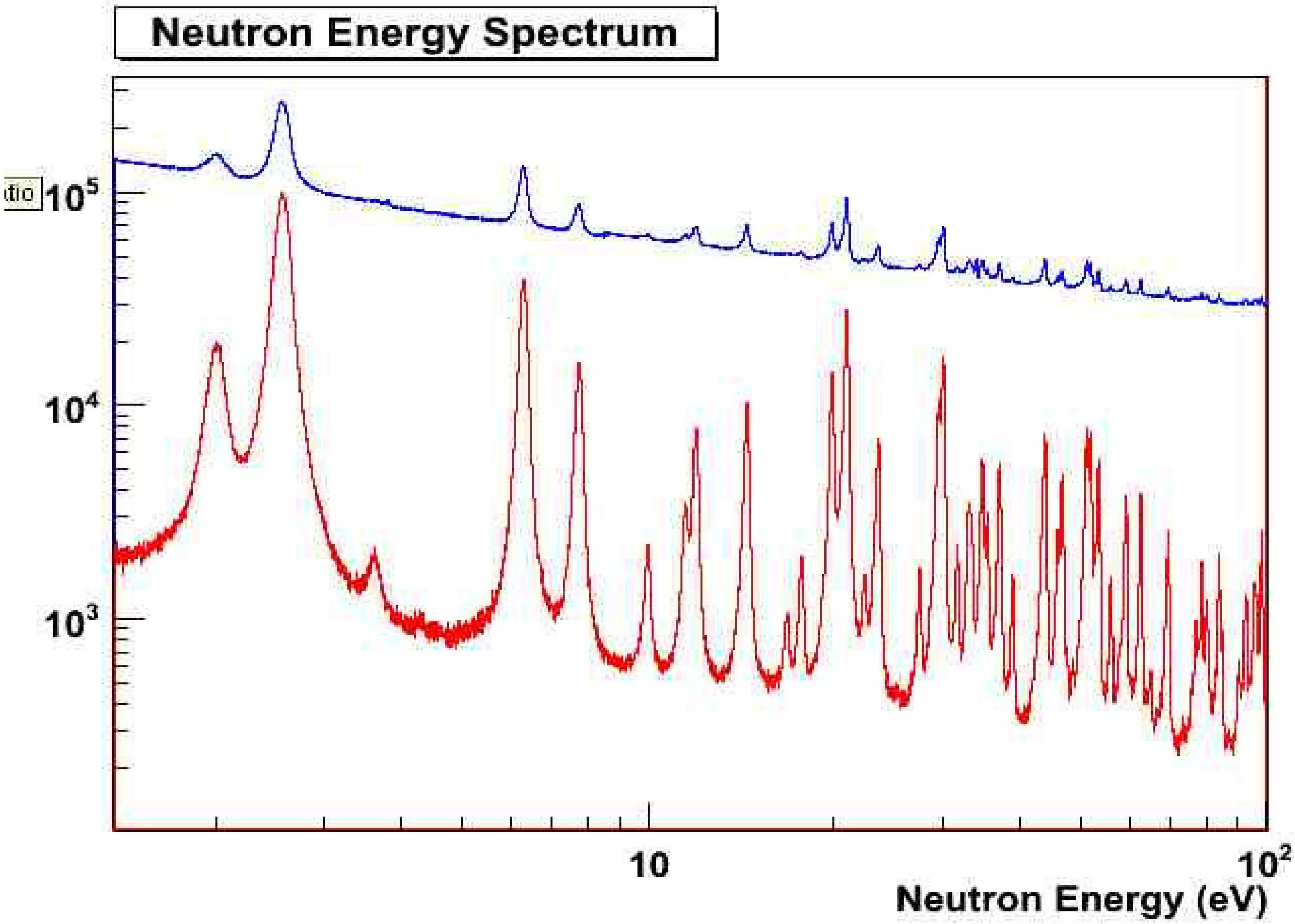
ΔT_0 = 550 ns





Gating

With proper gating we can significantly improve signal to noise ratio

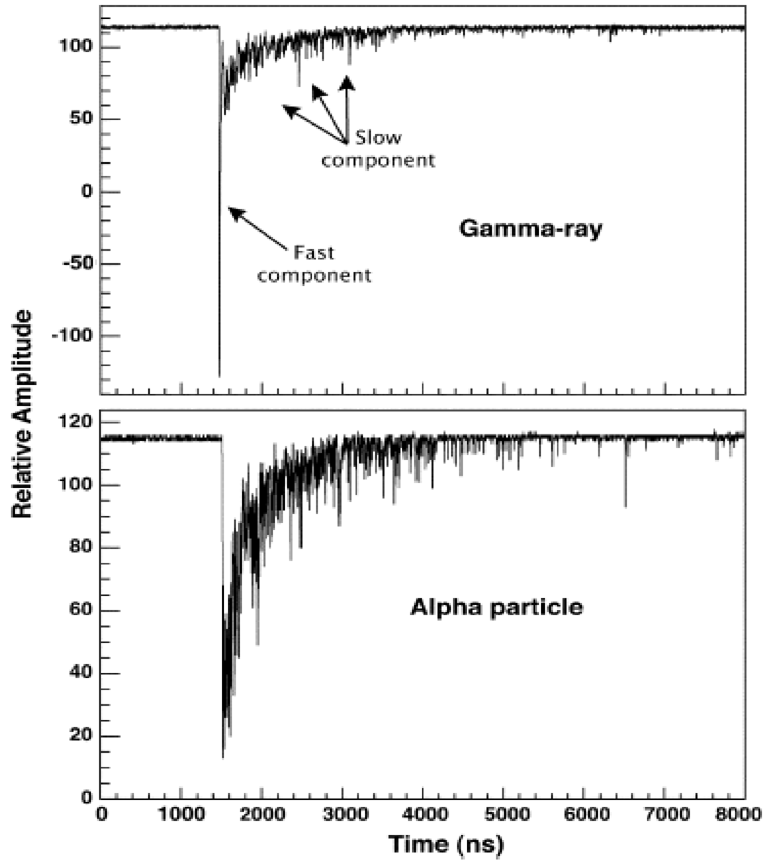


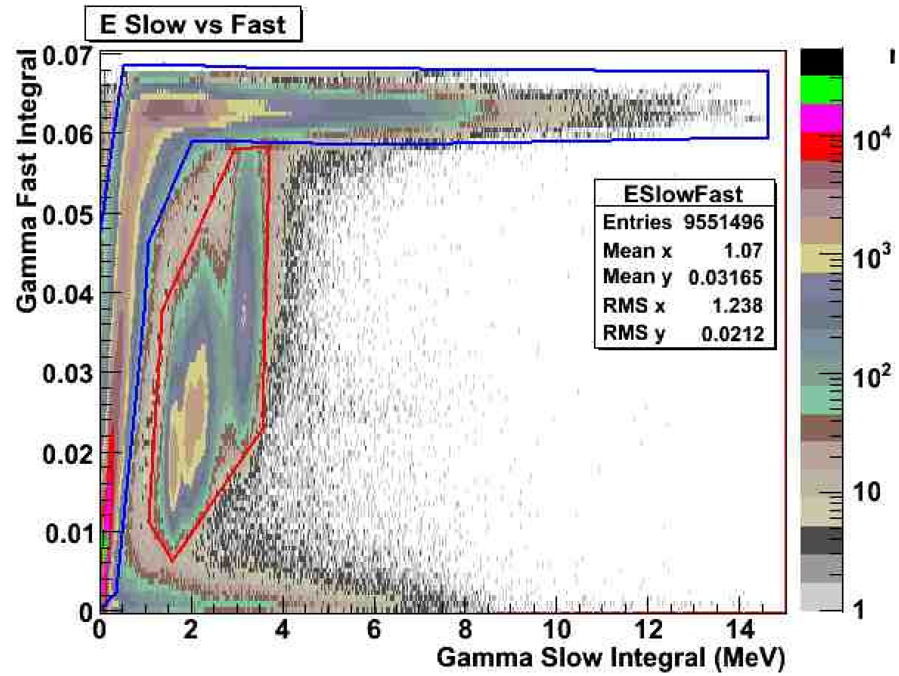
Ungated Spectra
- $M \geq 1$
- Q Gate is not applied

Gated Spectra
- $M \geq 3$
- Q Gate = 4-9 MeV

Gating

- Particle identification

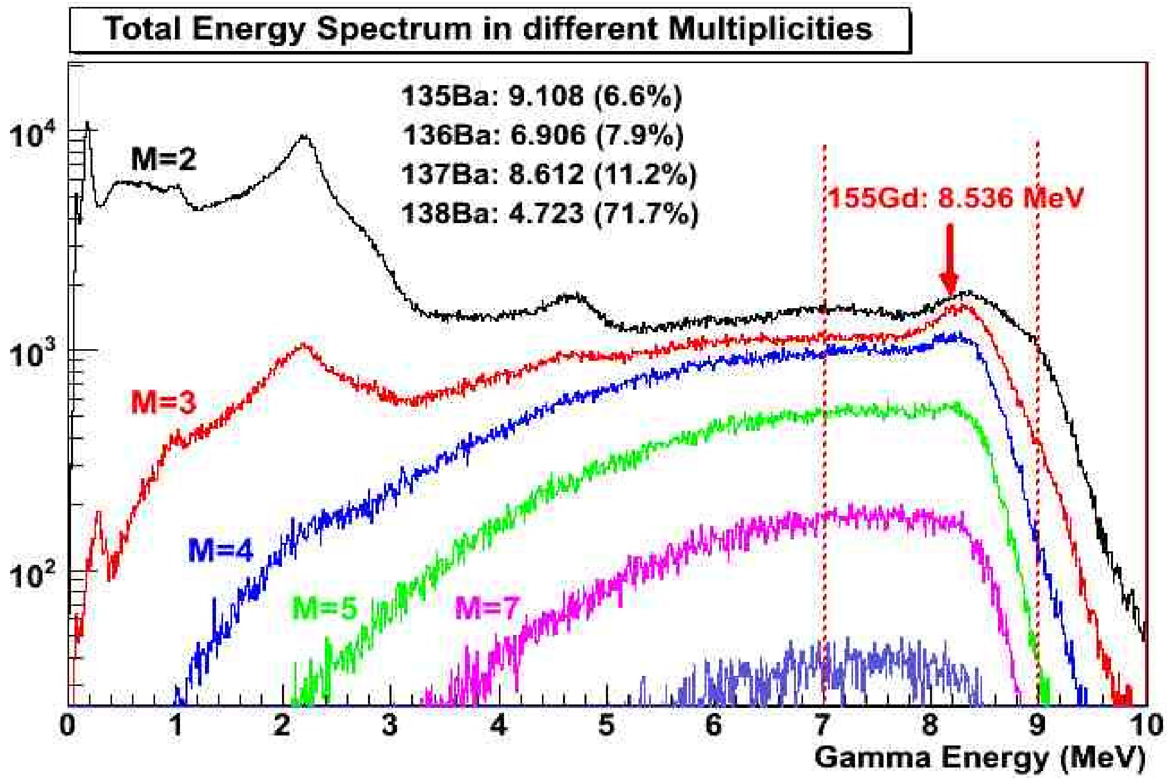




Gating

- Multiplicity Selection
- Q-Gate Selection

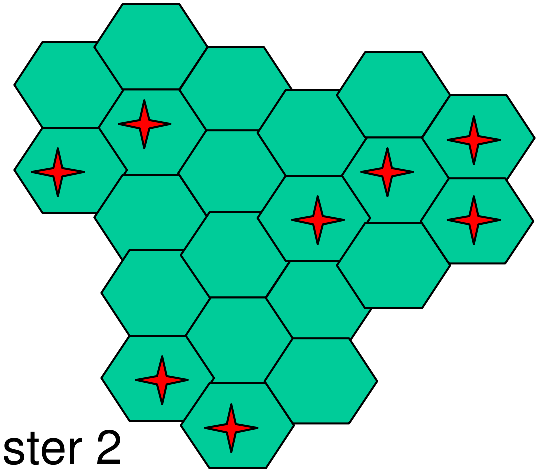
Background Reduces
Signal to Noise Ratio Increases



Q-gate = 7.0-9.0 MeV

$M \geq 3$

DANCE Cluster Multiplicity, Total Energy cuts



High efficiency of the DANCE calorimeter is useful for identifying signals due to different total energy of different isotopes.

Isotopes	Q-value (MeV)
^{152}Gd	6.2
^{154}Gd	6.4
^{155}Gd	8.5
^{156}Gd	6.3
^{157}Gd	7.9
^{158}Gd	5.9
^{160}Gd	5.6

Example:
The array multiplicity is 8 and the cluster multiplicity is 3.

Performed two different cuts:

$\Sigma E_\gamma = 4 - 6.5$ MeV ^{152,154,156,160}Gd

$\Sigma E_\gamma = 6.8 - 9$ MeV ^{155,157}Gd

Target materials

Isotope	Percent compositions in Gd targets							
	^{nat}Gd target	^{155}Gd	^{156}Gd	^{158}Gd	^{152}Gd	^{154}Gd	^{157}Gd	^{160}Gd
^{152}Gd	0.20 %	0.03%	0.01%	0.1%	**42.49 %**	0.05 %	<0.01 %	<0.01 %
^{154}Gd	2.18 %	0.63%	0.11%	0.1%	4.38 %	**67.34 %**	<0.01 %	0.02 %
^{155}Gd	14.80 %	**91.74%**	1.96%	0.96%	15.93 %	21.11 %	0.08 %	0.22 %
^{156}Gd	20.46 %	5.12%	**93.79%**	1.7%	13.91 %	5.65 %	0.09 %	0.37 %
^{157}Gd	15.65 %	1.14%	2.53%	3.56%	7.82 %	2.24 %	**99.7 %**	0.27 %
^{158}Gd	24.84 %	0.94%	1.20%	**92.0%**	9.56 %	2.32 %	0.12 %	0.92 %
^{160}Gd	21.87 %	0.40%	0.41%	1.82%	5.91 %	1.29 %	<0.01 %	**98.2 %**

All targets are made with highly enriched samples and approximately 1 mg/cm^2.

Data Analysis

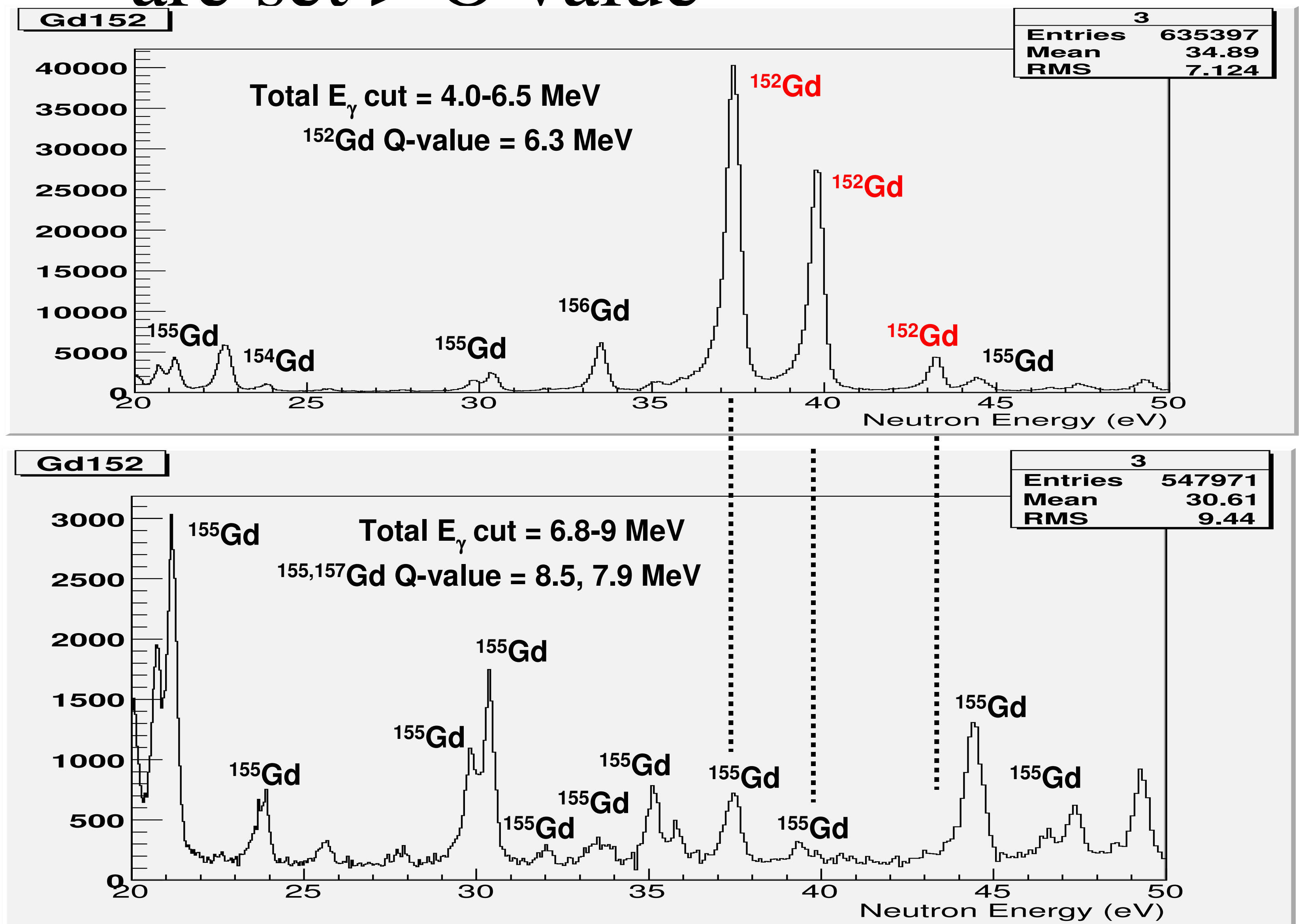
On-Line

- The DANCE raw data rate can exceed 1 Terabyte per hour depending on the target material.
- Extract and record only the most fundamental information out of each waveform
- The data rate is reduced to ~1 Mbyte/sec
- DAQ requires 40ms to read out the digitizers, extract the waveform and store reduced waveform and time information in central Midas server

Off-Line

- Extraction of Parameters from Each Crystal
  - *Back.Subtracted Integrals, T0*
- Construction of Physics Events
  - *Cluster and Crystal Multiplicity*
- Calibration of Raw Signals to Produce Physics Quantities
  - *Obtain real physics quantities*
- Particle identification and background subtraction
  - *Pure capture events are separated*
- Obtaining Final Results
  - *Many results can be obtained*

No ^{152}Gd resonances when gates are set > Q value



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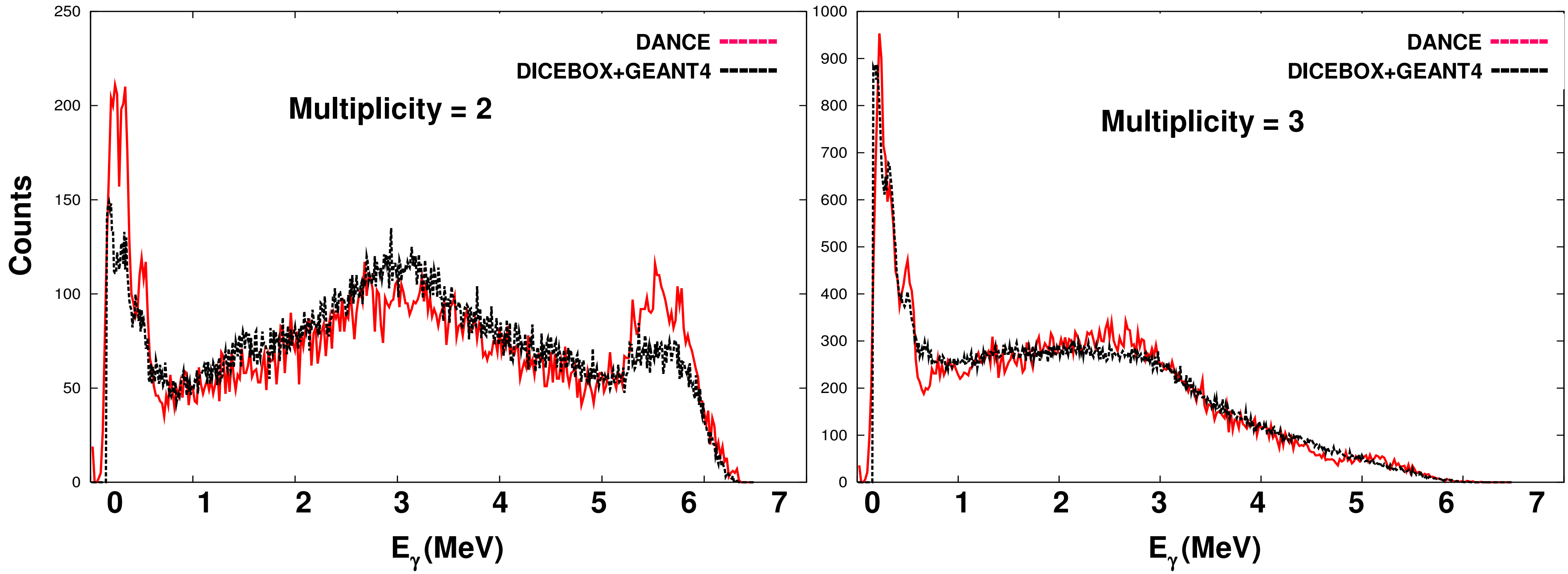
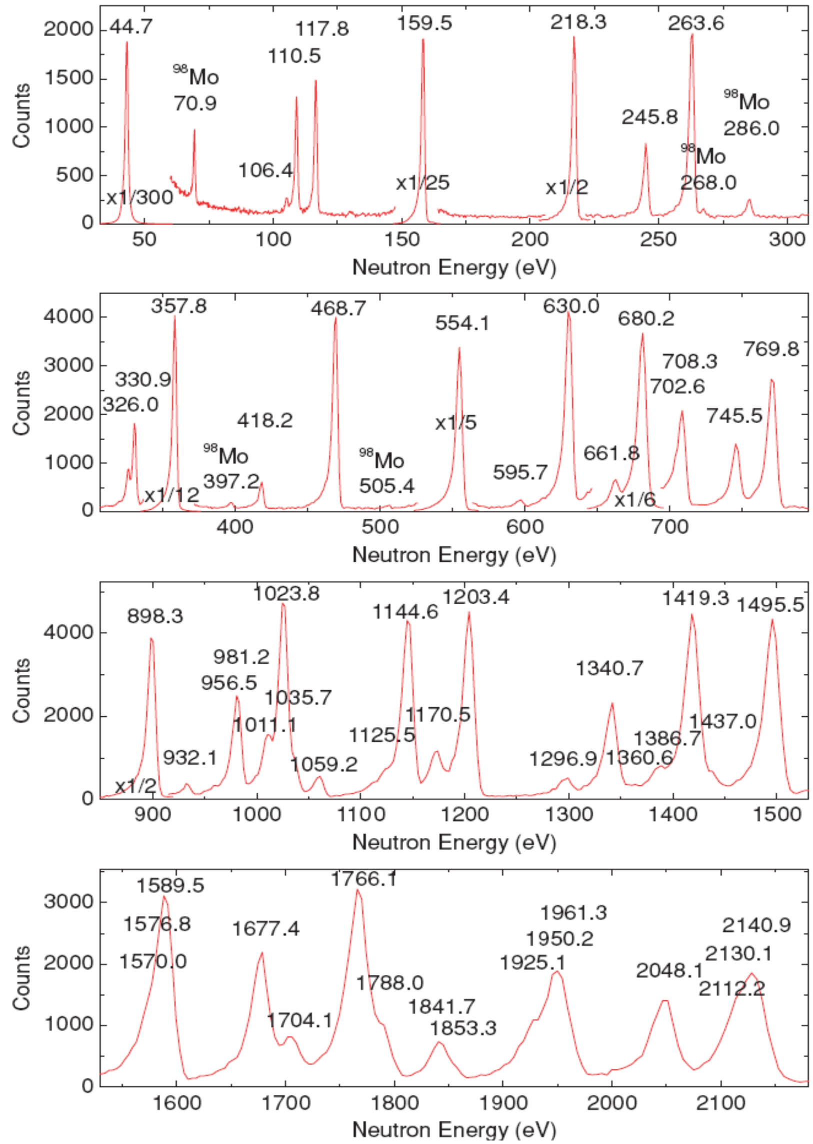
Comparison between DANCE data and simulation

Neutron energy gate is set around well-separated s-wave ^{152}Gd resonance at E_n = 39.3 eV.



This is for one well-separated resonance. The gamma-ray spectral shape is sensitive to parameters of the level density and the PSF. Requiring simultaneous fit to all M at once is essential.

Neutron resonances in the $^{95}Mo(n,\gamma)^{96}Mo$ reaction



$^{94,95}Mo + n$

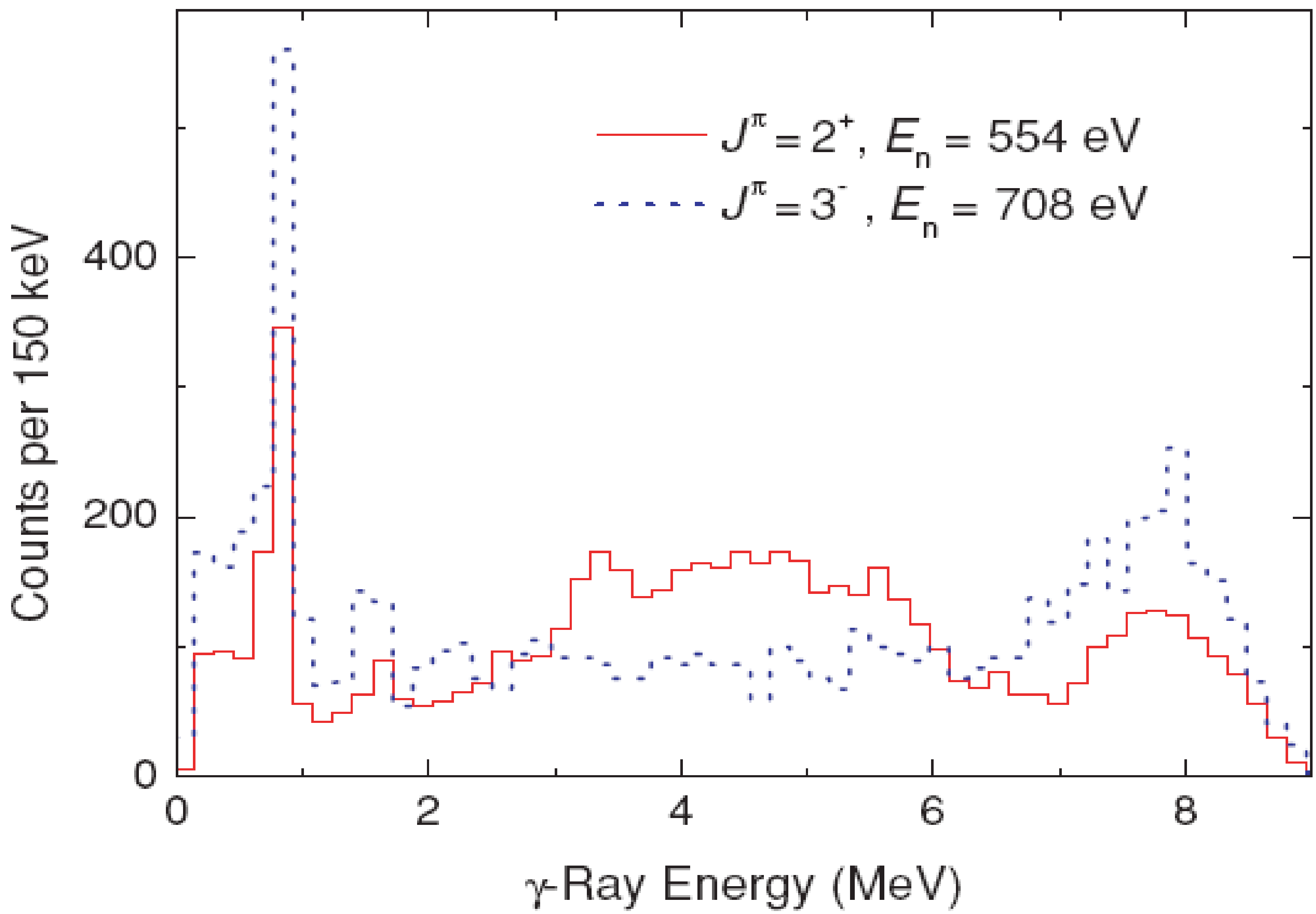
TABLE I. Summary of DICEBOX simulations of average multiplicities $\langle M_J \rangle$ for s- and p-wave resonances in $^{94,95}Mo + n$ systems: the predicted expectation values $E[\langle M_J \rangle]$ and the residual Porter-Thomas uncertainties.

Quantity	$\langle M_J \rangle$					
J	1/2	3/2	1	2	3	4
^{94}Mo, s waves	3.25(4)					
^{94}Mo, p waves	3.03(15)	3.07(15)				
^{95}Mo, s waves				3.90(4)	4.23(4)	
^{95}Mo, p waves			3.30(8)	3.68(10)	4.00(12)	4.30(14)

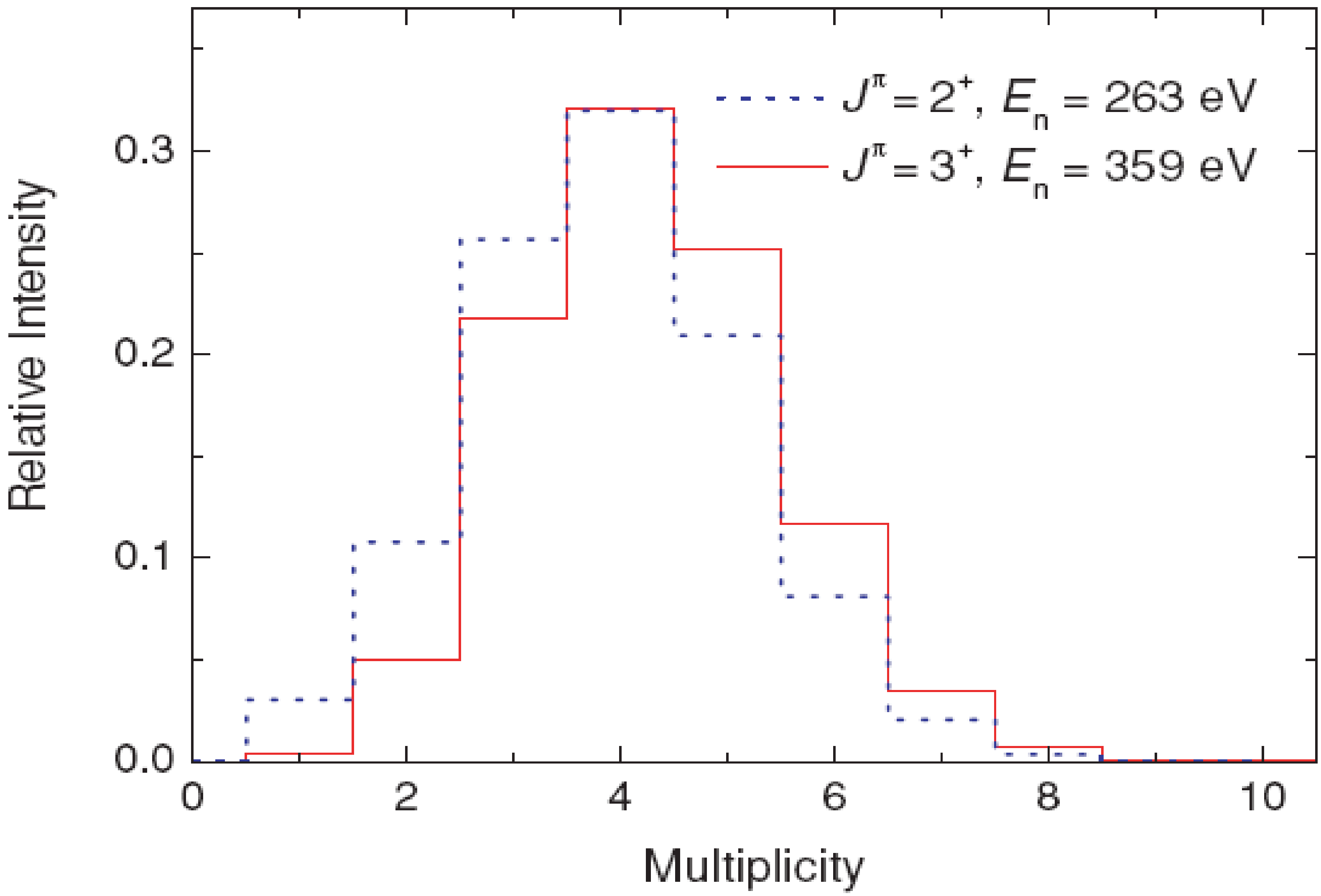
TABLE II. Isotopic composition for the targets used in the measurements. The amount of isotope is listed as the percentage of the target material.

Target	Isotope abundances						
	^{92}Mo	^{94}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
^{94}Mo	0.73	91.59	5.35	1.11	0.37	0.65	0.20
^{95}Mo	0.26	0.63	96.47	1.45	0.46	0.63	0.15

Measured γ-ray energy spectra for an s-wave resonance in the $^{95}Mo(n,\gamma)^{96}Mo$



Multiplicity distributions for s wave resonances in the $^{95}Mo(n,\gamma)^{96}Mo$



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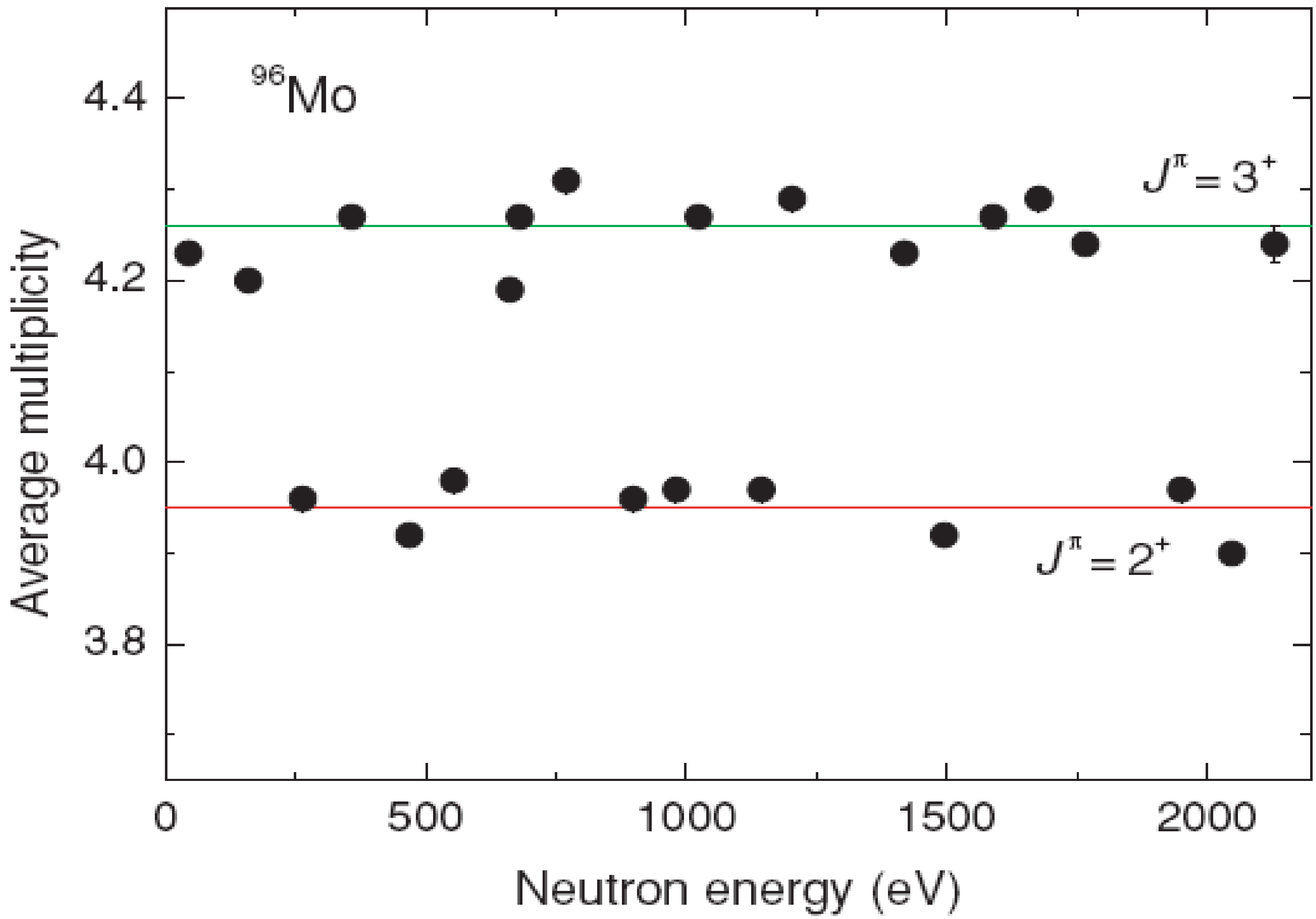
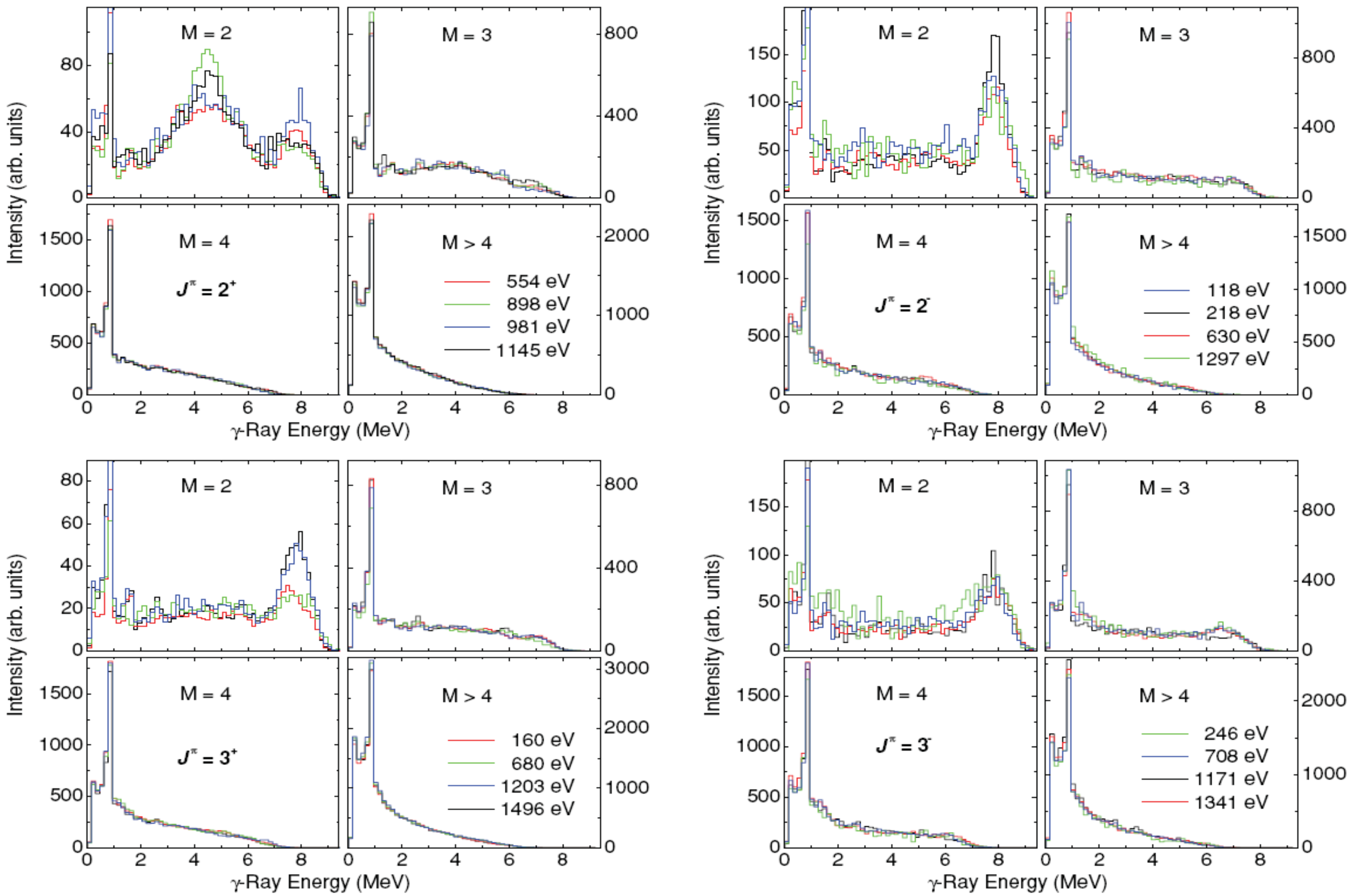
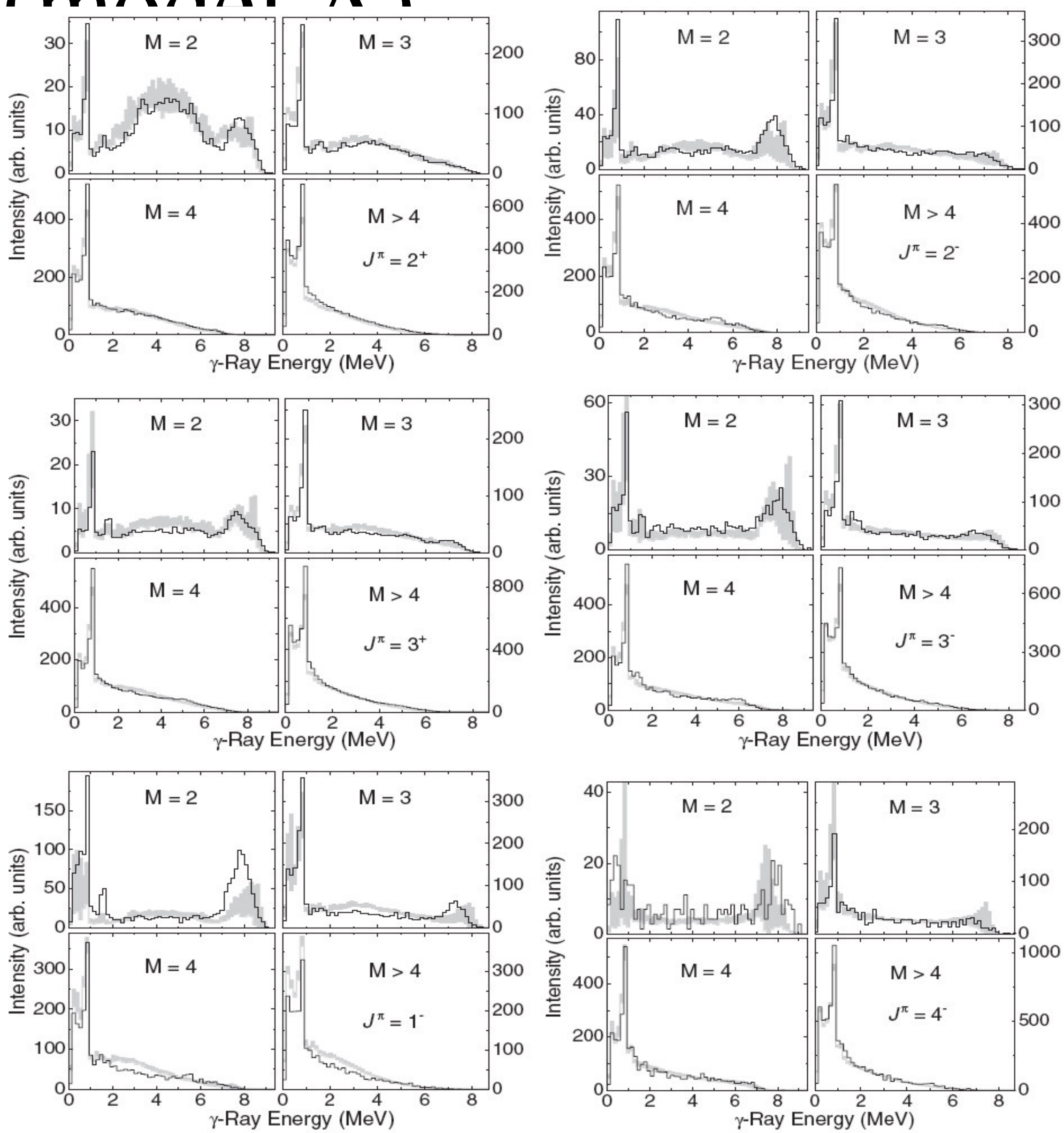
Average multiplicities of s wave resonances from $^{95}Mo(n,\gamma)^{96}Mo$ reaction



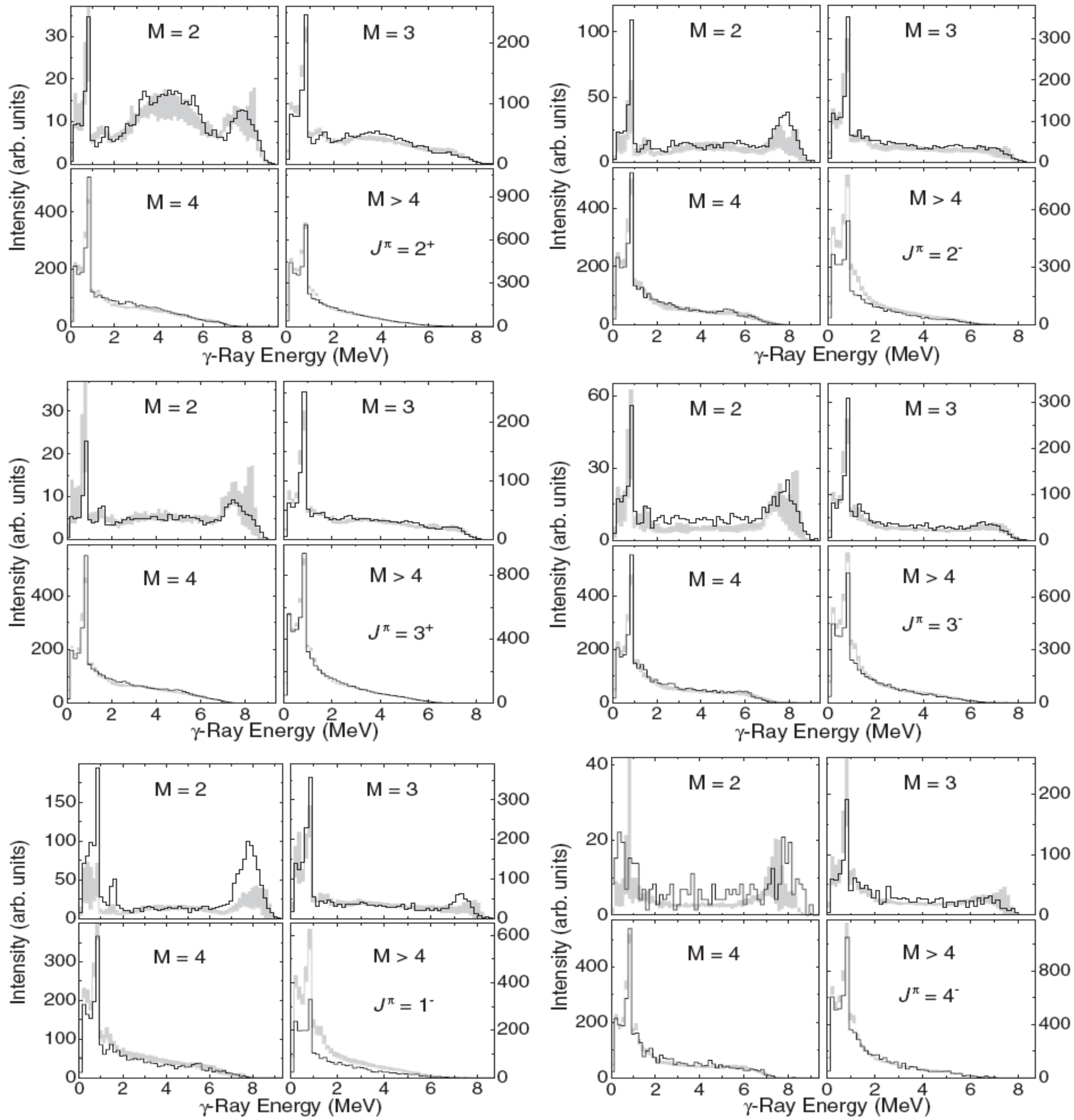
Experimental MSC spectra in different resonances



Comparison of simulated MSC spectra with experimental data (model A)



Comparison of simulated MSC spectra with experimental data (model B)



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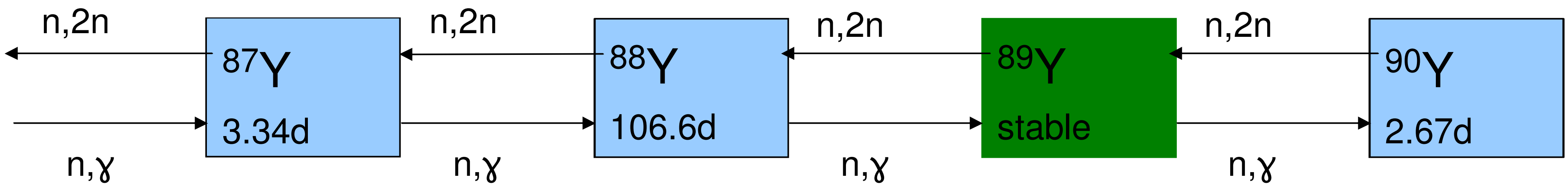
Improved Measurement of Y for Stewardship Science Academic Alliance



•Radchem detector – $^{87}Y/^{88}Y$ = 1/2 $\sigma(n,2n)\Phi_n$, where Φ_n – neutron fluence above 11.6 MeV threshold for $^{88}Y(n,2n)$ reaction.

•But: The isotopic ratio $^{87}Y/^{88}Y$ is altered by (n,γ) reactions, ultimately we want to measure all these with DANCE as precisely as we can.

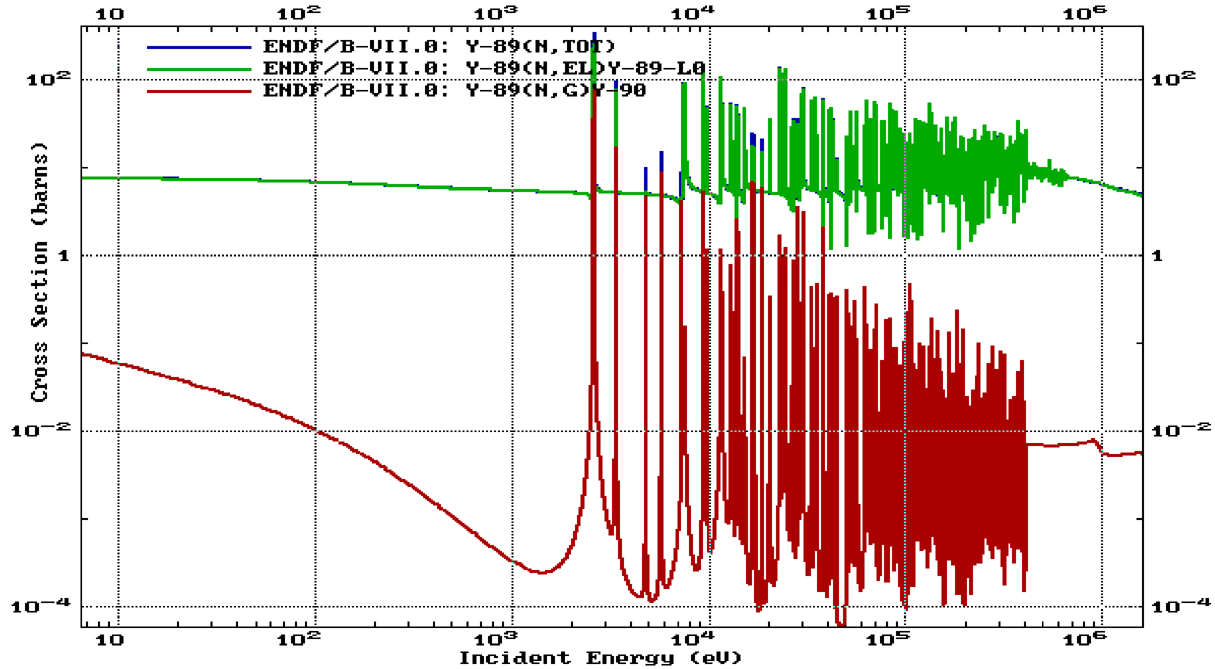
•No Data for cross section of $^{87}Y(n,\gamma)$ and $^{88}Y(n,\gamma)$ in ENDF/B, JENDL, and JEFF.

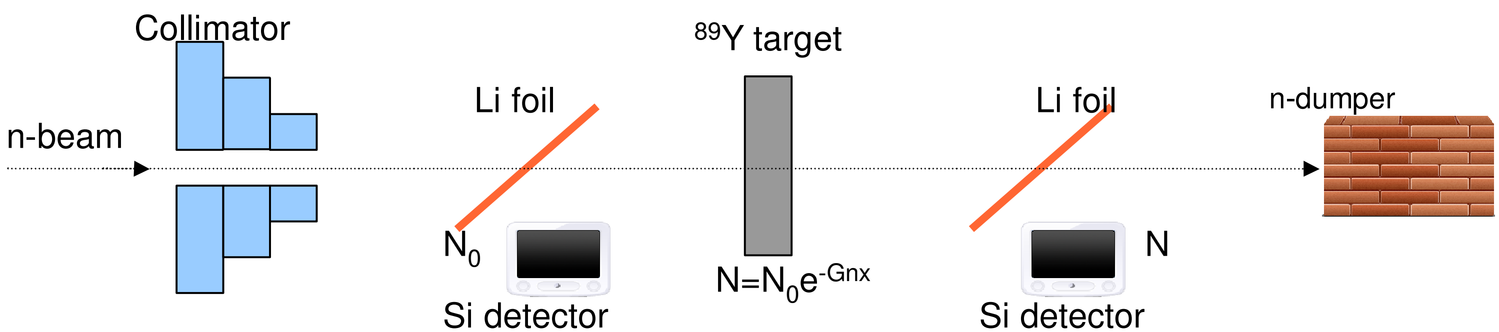
•In the long run we plan to measure $^{88}Y(n,\gamma)$ cross section.

•Both ^{87}Y and ^{89}Y are odd-even nuclei – cross section of $^{89}Y(n,\gamma)$ will allows to constrain model calculations for nuclei we can not measure with DANCE, for example $^{87}Y(n,\gamma)$

Evaluated Cross Section Data for ^{89}Y(n,g)

- Different evaluations of ^{89}Y(n,γ) provide data with differencies of up to 10^1-10^2 times at 1 keV
- Ratio ^{89}Y(n,el)/^{89}Y(n,γ) = 10^2-10^4
- Improved data is needed
- 6 orders of magnitude in cross section – run thin and thick targets to span this range
- ^{89}Y(n,tot) was measured via transmission experiment

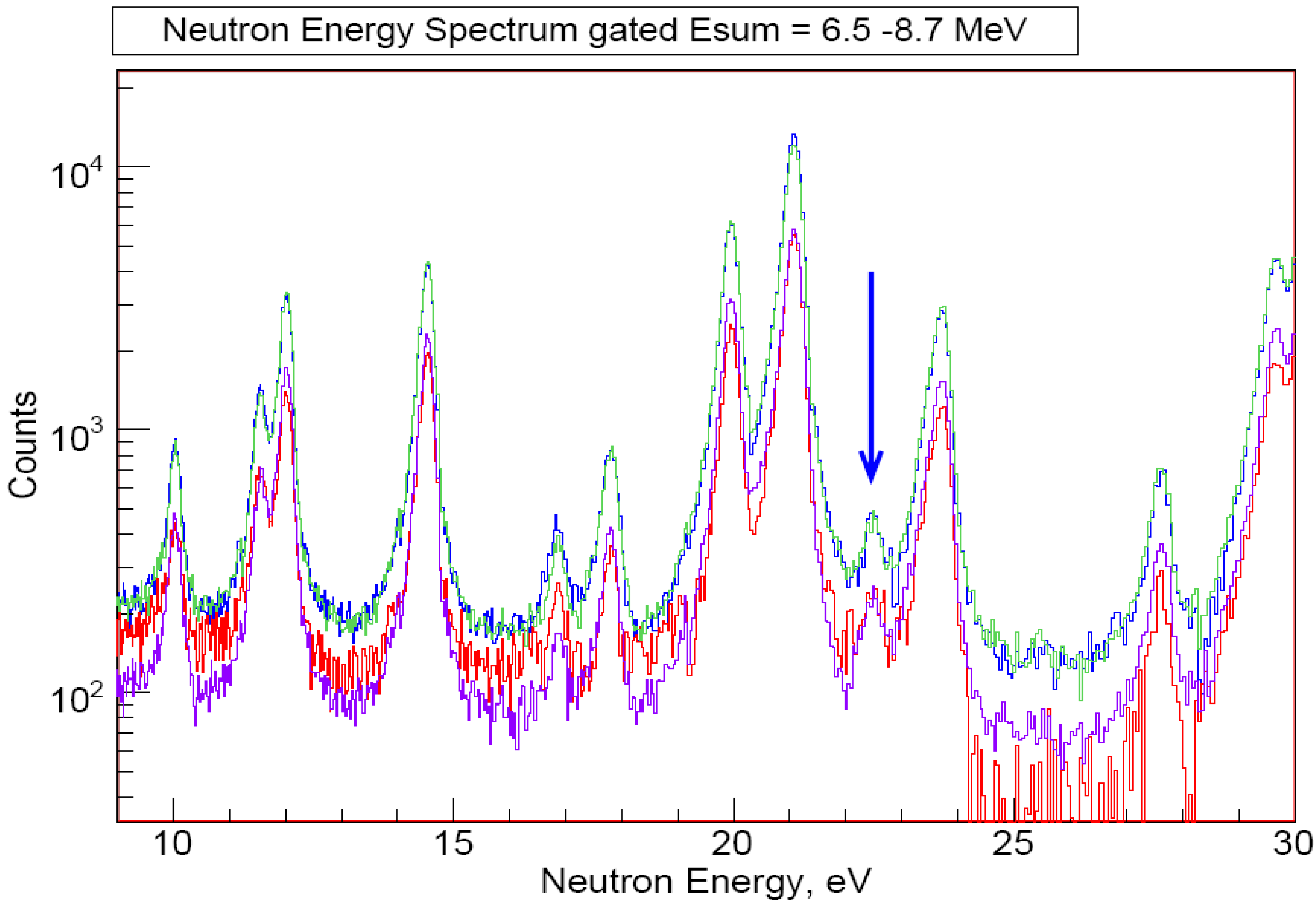




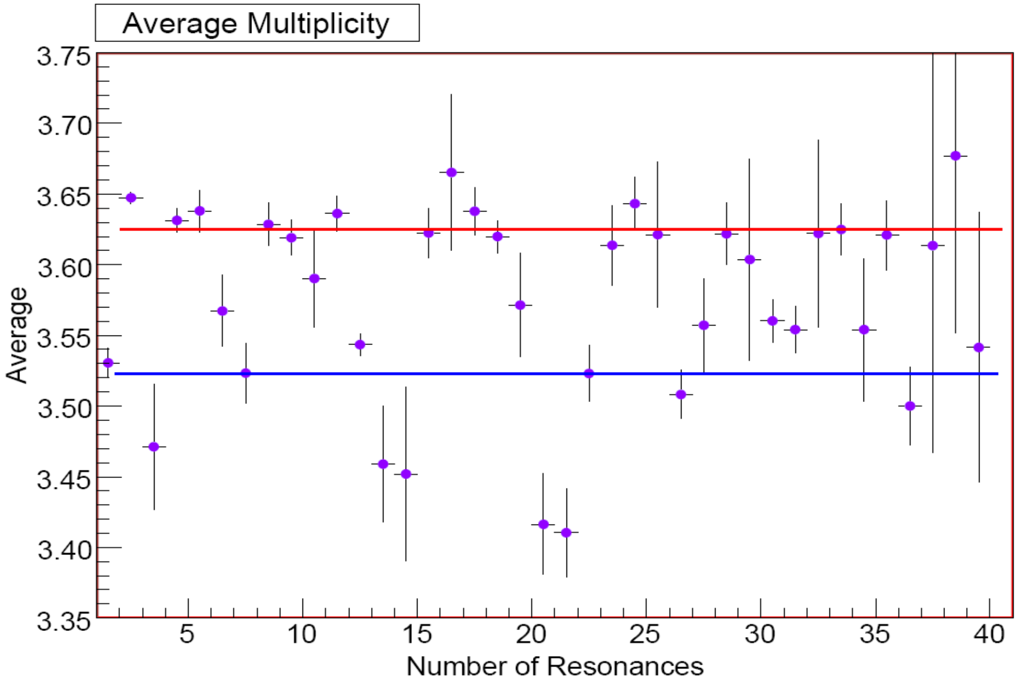
Conclusions on $^{89}Y(n,\gamma)$ experiment

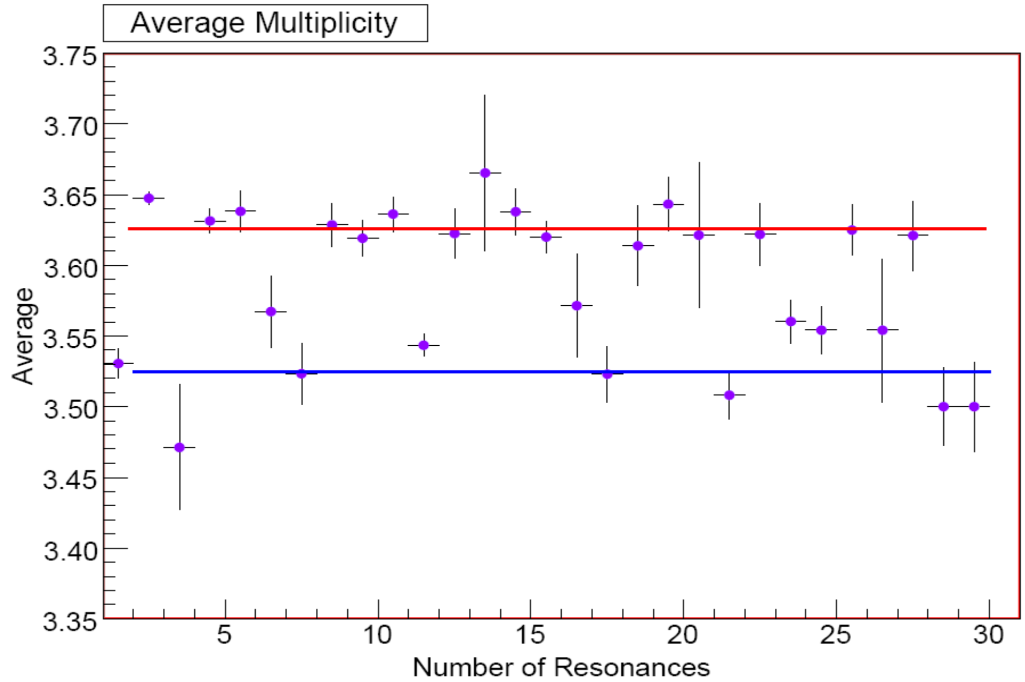
- **DANCE data was taken for 11.5 days of production beam time**
- **3 different ^{89}Y targets were exposed: 1 mil, 5 mil, 25 mil**
- **Additional targets were measured for neutron flux determination, neutron scattering background, and contamination in ^{89}Y target: ^{197}Au, ^{nat}Pb, ^{208}Pb ^{nat}Fe, ^{181}Ta**
- **Neutron flux was determined using the ^{197}Au experimental data (4.9 keV) as a reference**
- **Neutron beam was corrected for attenuation + neutron capture yield was corrected for self shielding (blackness of resonances) + 1 resonance was corrected for pileup**
- **Cuts on E_{sum} and Multiplicity were made for cross section data**
- **DICEBOX/GEANT4 simulations are to be done to justify efficiency of [E_{sum},M] cuts**
- **Cross section of $^{89}Y(n,\gamma)$ was calculated in the energy range E_n=10 eV – 300 keV**
- **Error bars vary: 10-20% in $E_n=10^1-10^2$ eV, 10% at resonances, 50-80% between resonances, 20-50% in $E_n=2\cdot10^4-3\cdot10^5$ eV**

Experimental neutron capture spectra



Spin Determination





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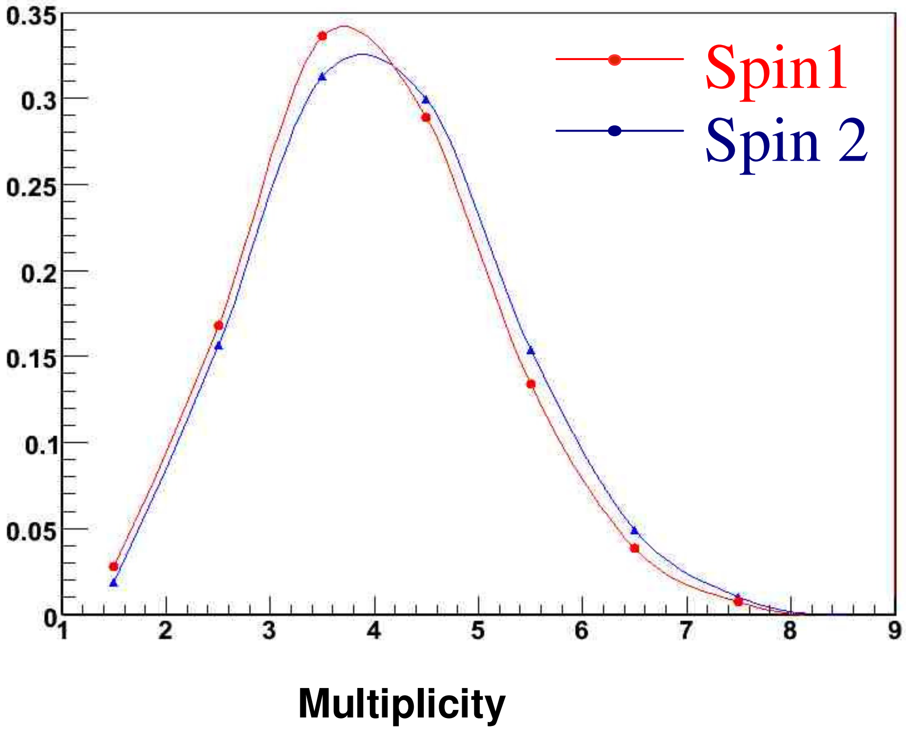
Previous Methods



- Average Multiplicity

  Successfully defined the spins of the ^{94,95}Mo

  (*S.A. Sheets et al. Phys.Rev.C 76, 064317*)

$$\overline{M} = \frac{\sum_i M_i \cdot Y_i}{\sum_i Y_i}$$

- Spin Separation

  More advanced method

  Separate unresolved resonances

  Determined Spins of ^{147}Sm

  (P. Koehler et al. Phys.Rev. C76, 025804)

The Method

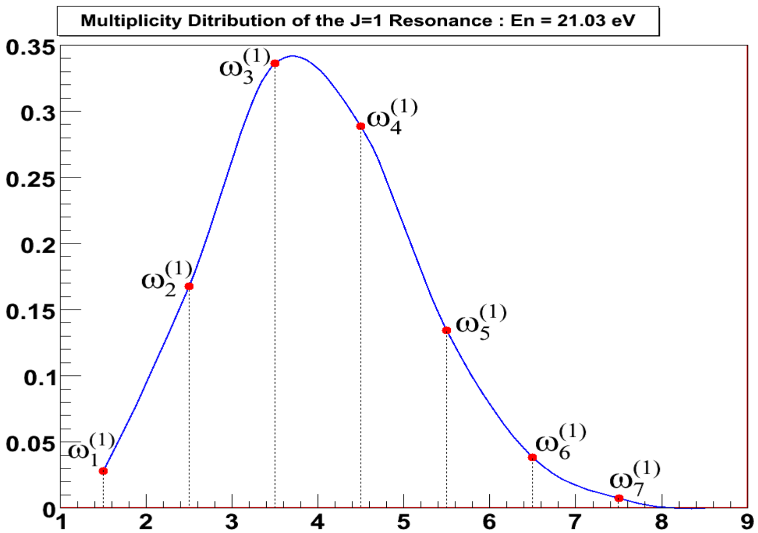
- **High segmentation of the detector gives an advent to sort events by γ-ray multiplicity**

$$Y_{total}(E) = Y_1(E) + Y_2(E) + \ldots + Y_{max}(E)$$

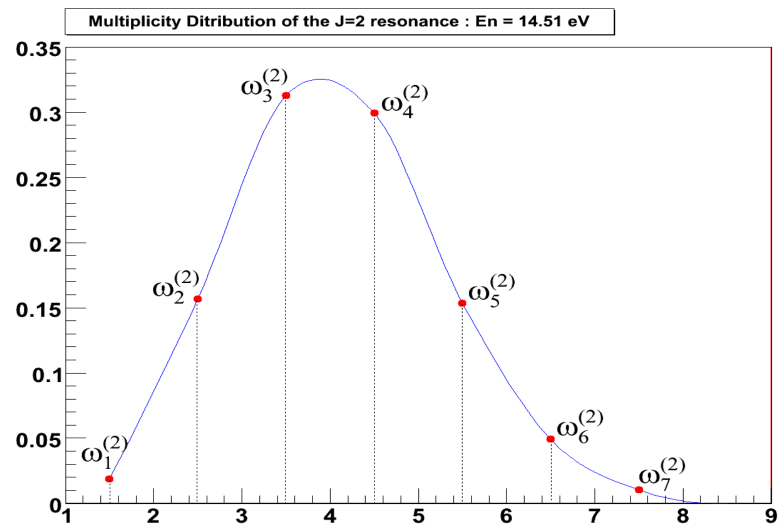
- **Normalization of the yields to the total gives the multiplicity distribution**

$$\omega_1^{(J)} + \omega_2^{(J)} + \ldots + \omega_{max}^{(J)} = 1$$

Distribution of the $J = 1$ resonances



Distribution of the $J = 2$ resonances



The Method

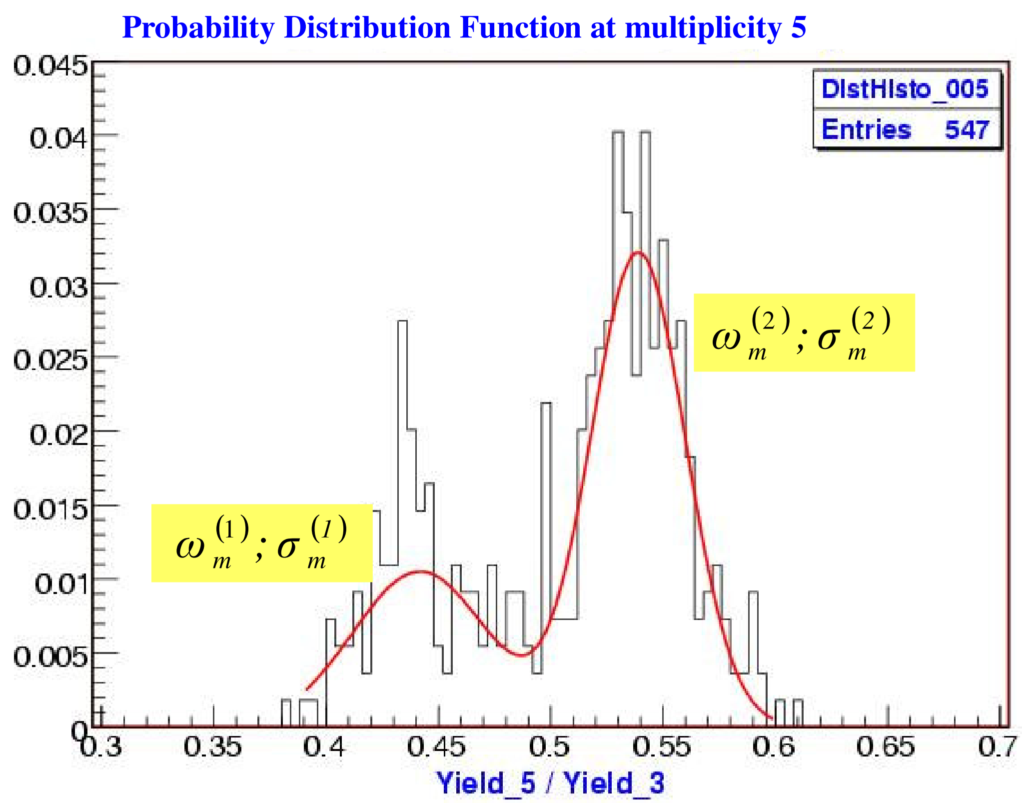
- The $\omega_m^{(J)}$ are not exactly the same for all resonances, they are distributed around the mean value
- The Distribution Function is a Double Gaussian

- The widths of the Gaussian are determined by the PT distribution and the experimental errors

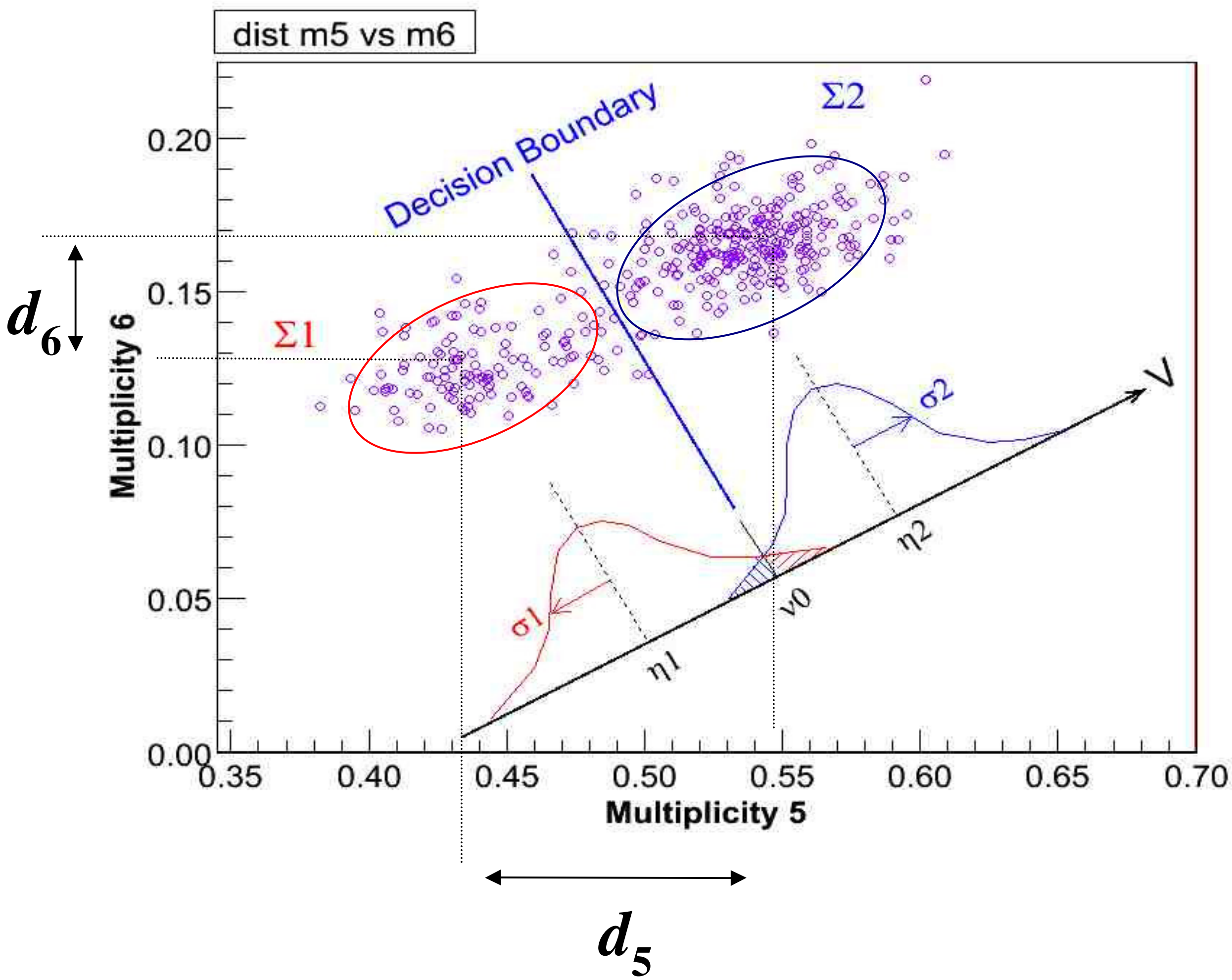
$$\sigma_m^2 = \sigma_{PT}^2 + \sigma_{Exp.}^2$$

- The distance between the two distributions

$$d_m = \omega_m^{(1)} - \omega_m^{(2)}$$



Example in Two Dimension



Distance between the clusters

$$D = \sqrt{d_5^2 + d_6^2}$$

$$D \geq d_5 \quad \text{and} \quad D \geq d_6$$

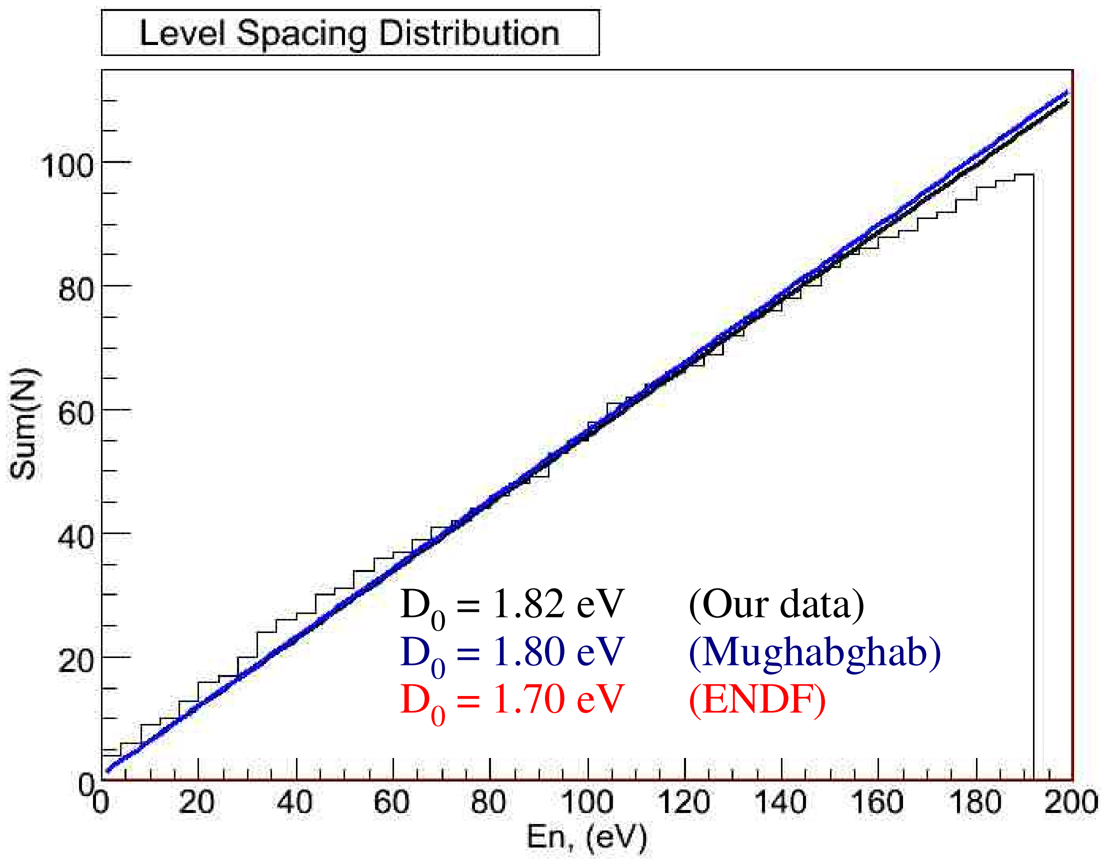
Thus a projection of the distribution into V axis gives more separation

Problem is to find an axis V that maximizes separation of the clusters and the threshold value v_0 that minimizes error

$$h(Y) = V^T \cdot Y + v_0$$

h(Y) is called a linear discriminant function

Average Level Spacing



Average level spacing for each spin group is obtained

$$D_{0,1} = 4.9 \text{ eV}$$
$$D_{0,2} = 2.9 \text{ eV}$$

Consistent with a (2J+1) level density law