Testing the Absolute Surrogate Method via ^{157}Gd(^{3}He,α)

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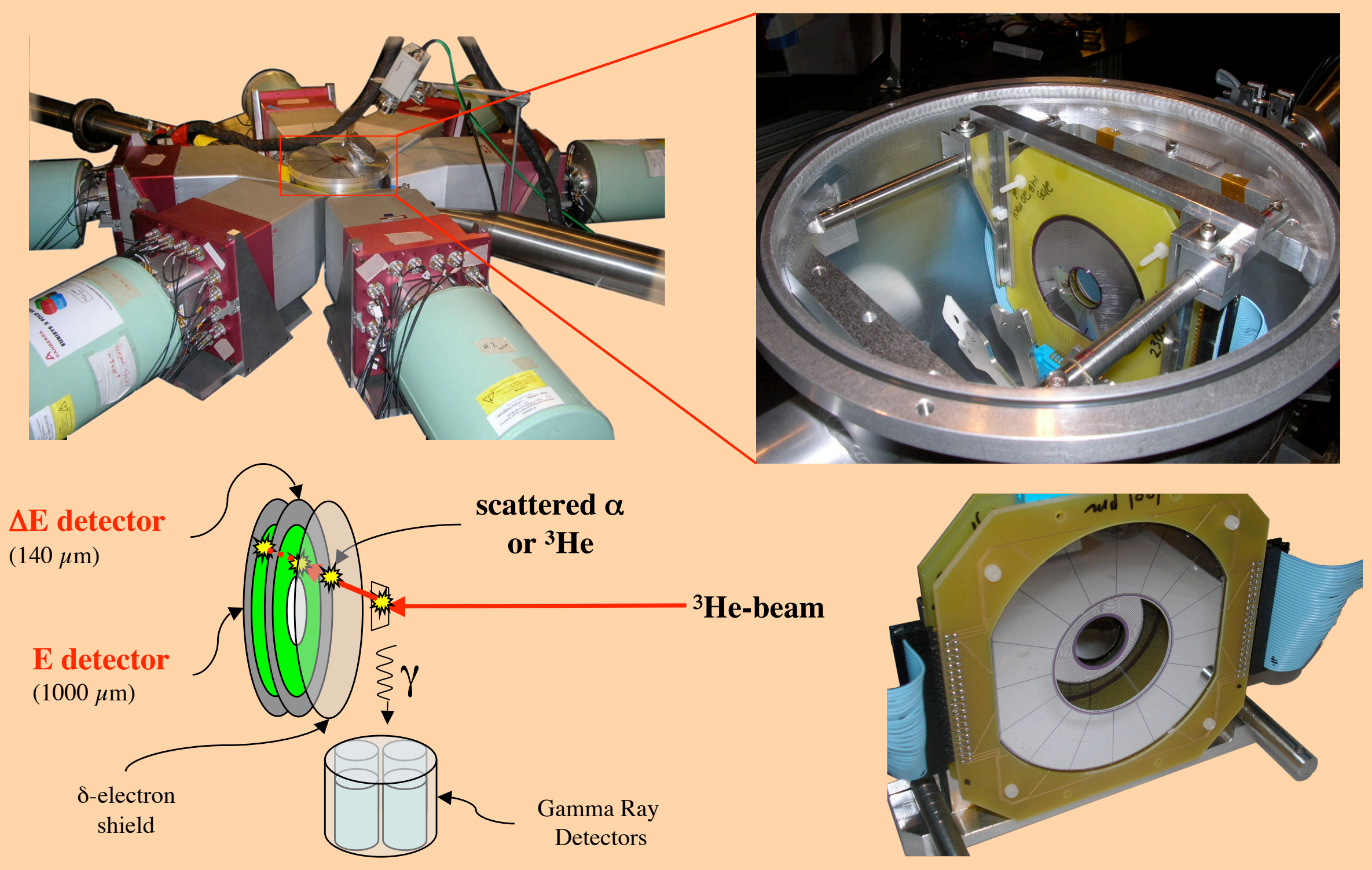
Neutron cross sections on unstable nuclei are difficult, if not impossible to measure directly. Indirect methods, such as the absolute surrogate method, may therefore be used to determine neutron cross-sections using charged particle reactions on stable nuclei. By measuring exit channel probabilities on equivalent compound nuclei, combined with calculated neutron-induced compound nucleus formation cross sections from optical models, (n,xnγ) cross sections can be determined. This study is the first attempt using STARS-LiBerACE at LBNL's 88-inch Cyclotron to test the absolute surrogate method using gamma rays to determine (n,γ) and (n,2n) cross sections.

The Experiment

Setup



Details

- **Beam:** ^{3}He from the 88" Cyclotron (42 MeV, >4 days)
- **Target:** ^{157}Gd (99.2%, ~1.1 mg/cm2)
- **Reactions:** ^{157}Gd(^{3}He,^{3}He'), (^{3}He,α) as surrogates for ^{155,156}Gd(n,x)
- **Why?**

Originally meant to be half of a future two-part surrogate ratio experiment to determine the ^{153}Gd(n,γ) cross section. However, because gadolinium has well-studied neutron cross section due to its use in control rods, it is a good candidate for testing the **absolute** surrogate method.

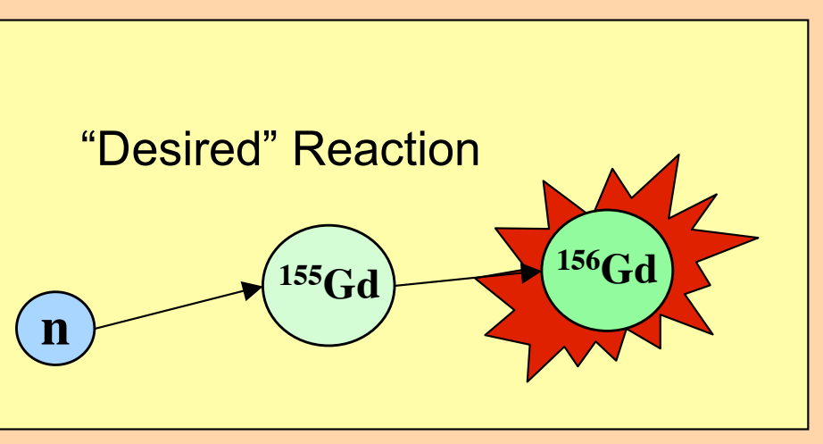
Theory

$$\sigma_{\alpha\chi}(E) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E,J,\pi)\ G_{\chi}^{CN}(E,J,\pi)$$

σ_α^{CN}: formation cross sections calculated using optical models

G_χ^{CN}: branching ratios are very difficult to calculate and results are strongly model-dependent

"Desired" Reaction

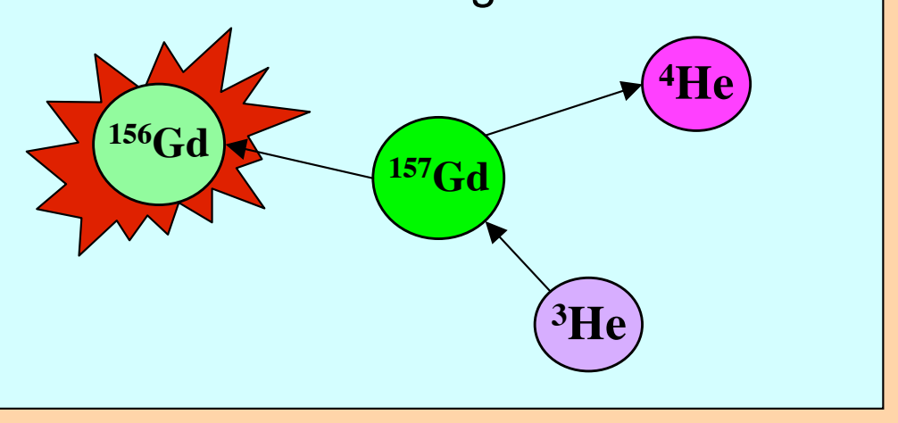


$$P_{\delta\chi}(E) = \sum_{J,\pi} F_{\delta}^{CN}(E,J,\pi)\ G_{\chi}^{CN}(E,J,\pi)$$

F_δ^{CN}: theoretically determined direct reaction probabilities

G_χ^{CN}: these are the same branching ratios for the "desired" reaction above

Surrogate Reaction



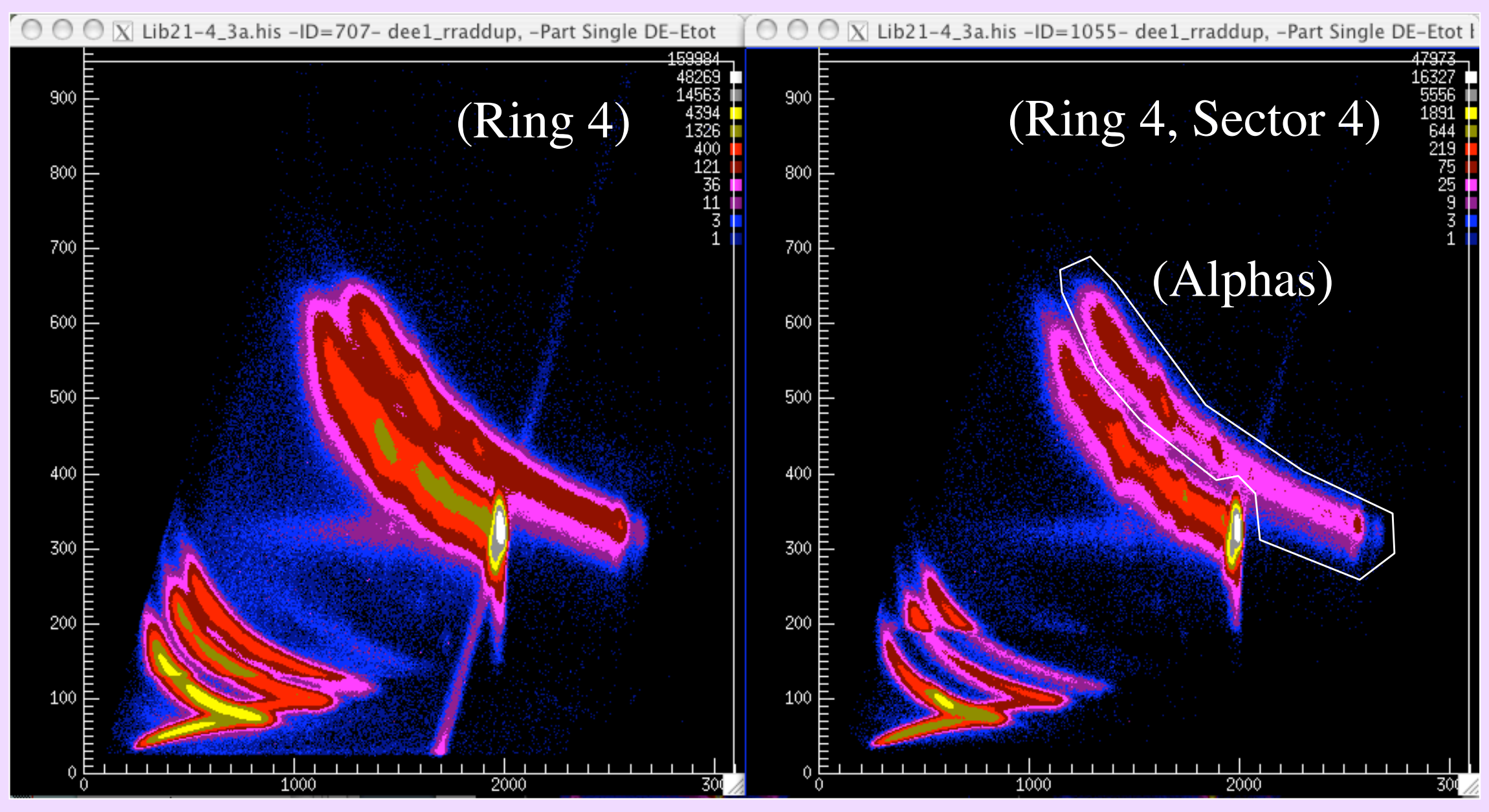
If branching ratios are J$^\pi$ independent:
(Weisskoff-Ewing limit)

$$\sigma_{\alpha\chi} = \sigma_\alpha^{CN}\ P_{\delta\chi}$$

The Analysis

Particle Identification

①



Normal dE vs. (dE+E) plot

Sector 4 dE vs. (dE+E) plot with raytrace and sector match

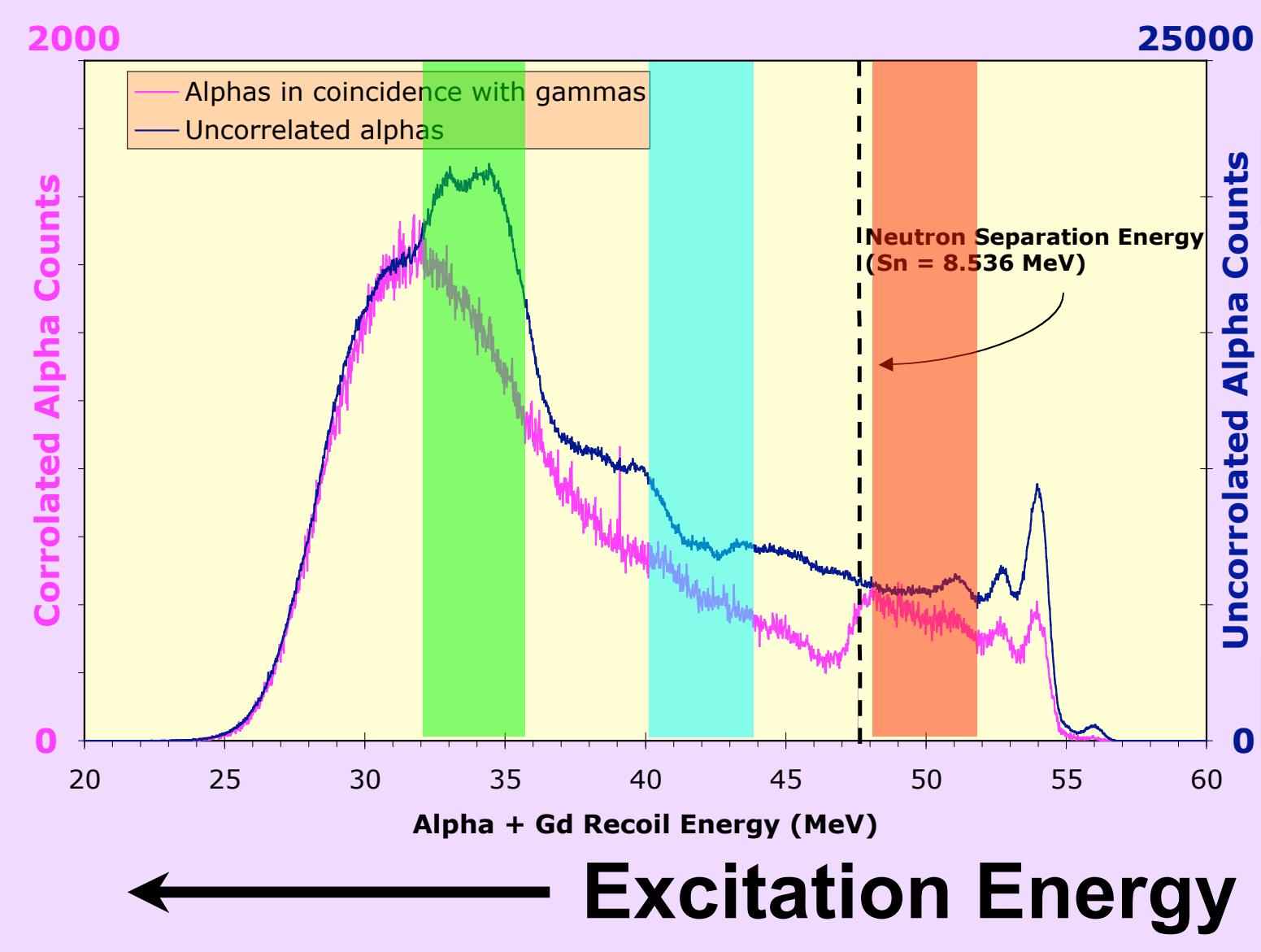
Data analysis involves several steps:

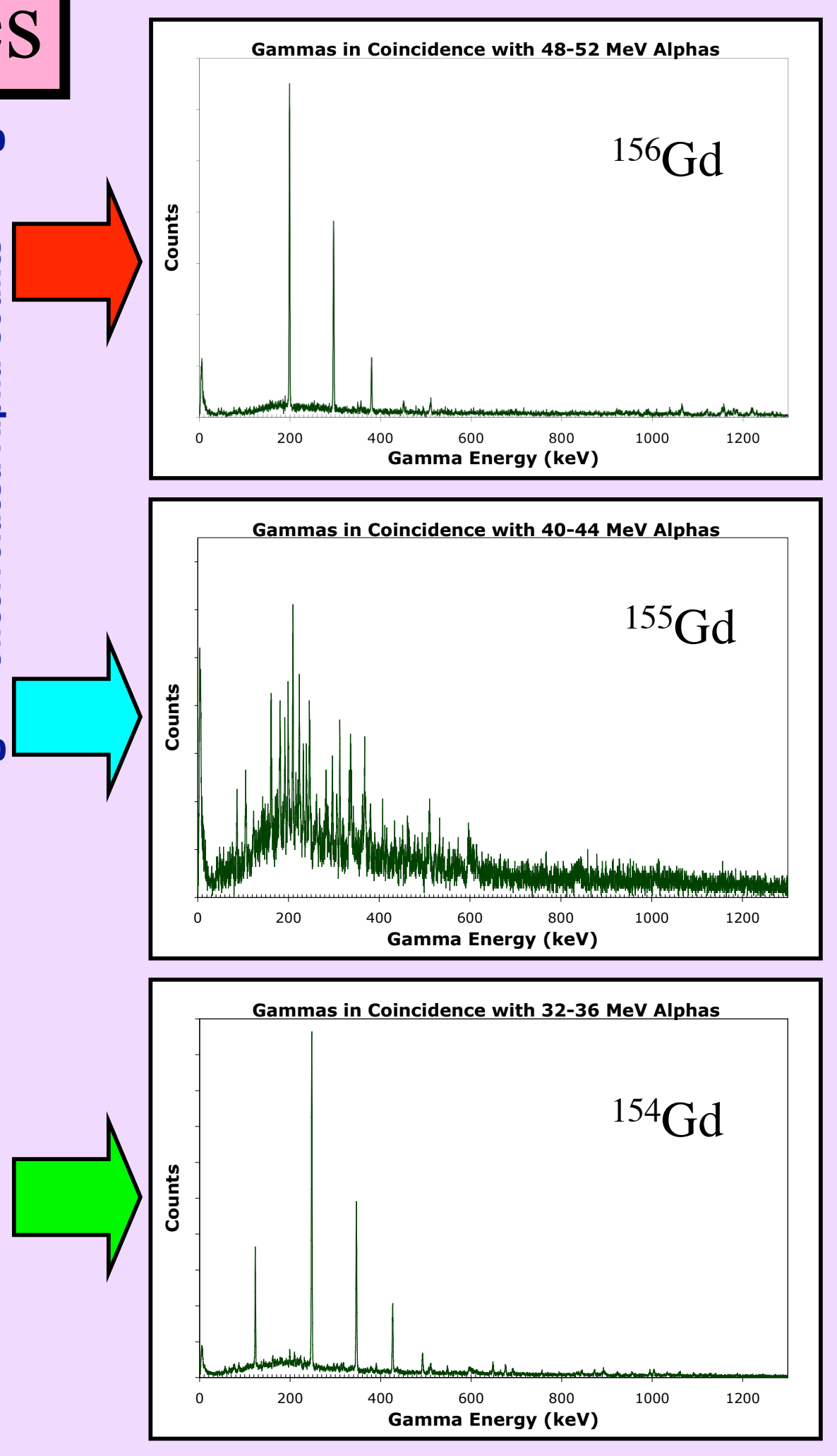
① Alpha particles are distinguished from ^{3}He and other nuclei by plotting the energy loss of charged particles in a telescoped silicon detector and making "banana" gates.

② Gammas in coincidence with alphas are analyzed as a function of Gd excitation energy. We can then gate on discrete lines corresponding to specific ^{154,155,156}Gd nuclei to select the reaction of interest.

Alpha/Gamma Coincidences

②





③ Assuming gamma cascades from highly-excited nuclei proceed through low-level transitions similarly, the probability of a (^{3}He,αγ) reaction **above** the neutron separation energy can be calculated as the ratio of the intensity of a low-level yrast gamma transition (divided by the total number of alphas) to the intensity of the same transition immediately **below** the separation energy (where the probability of decay by anything other than gamma emission is zero).

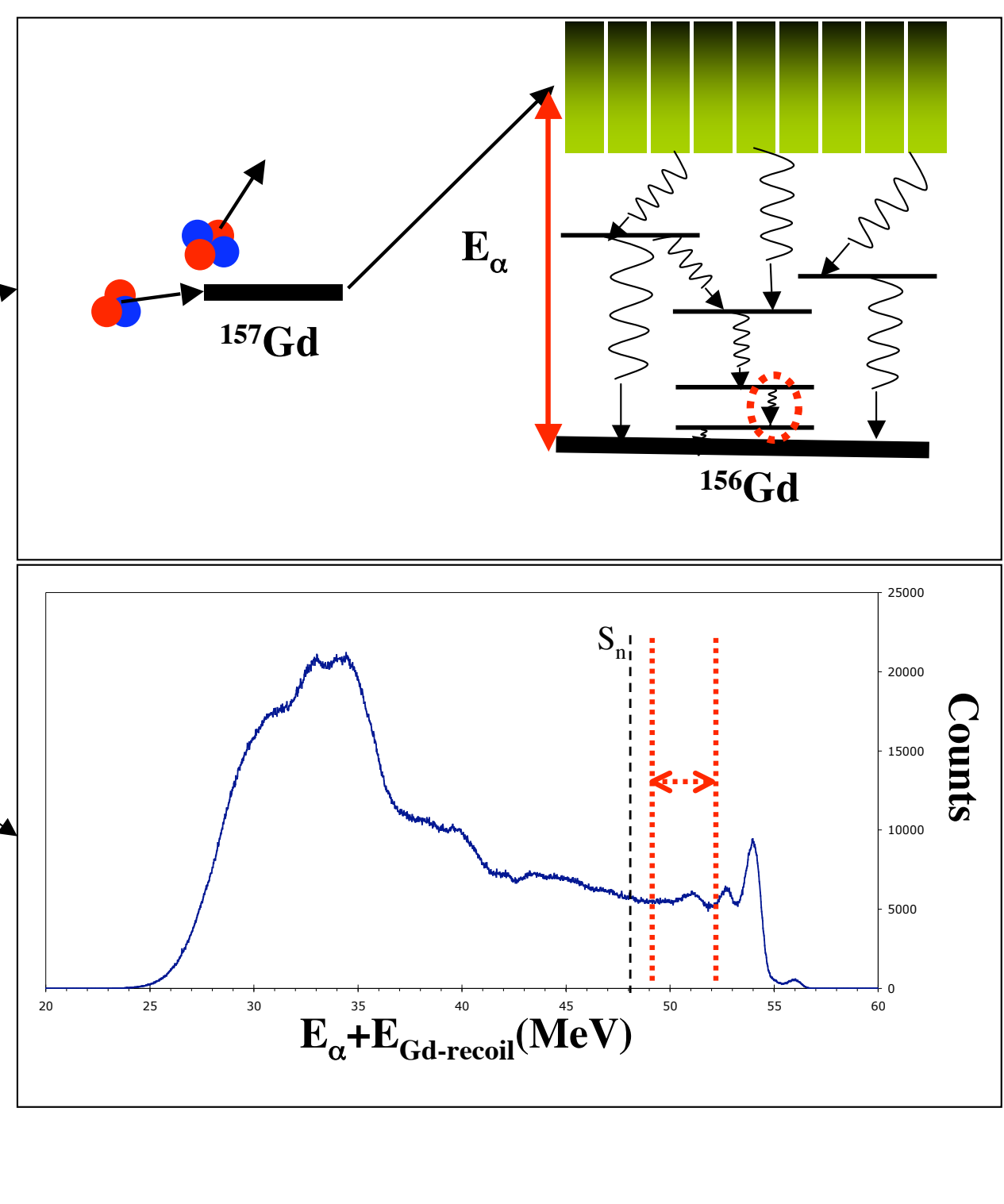
Exit Channel Detection Efficiency

③

$$P_{^3He,\alpha\gamma}(E_{ex}) = \frac{N_{\alpha\gamma}(E_{ex})}{\varepsilon_{\alpha\gamma} N_\alpha(E_{ex})}$$

$$\varepsilon_{\alpha\gamma} = \frac{\sum_{i=1} N_{\alpha\gamma}^i}{N_\alpha}$$

(@ E$_{ex}$=negative high level density)

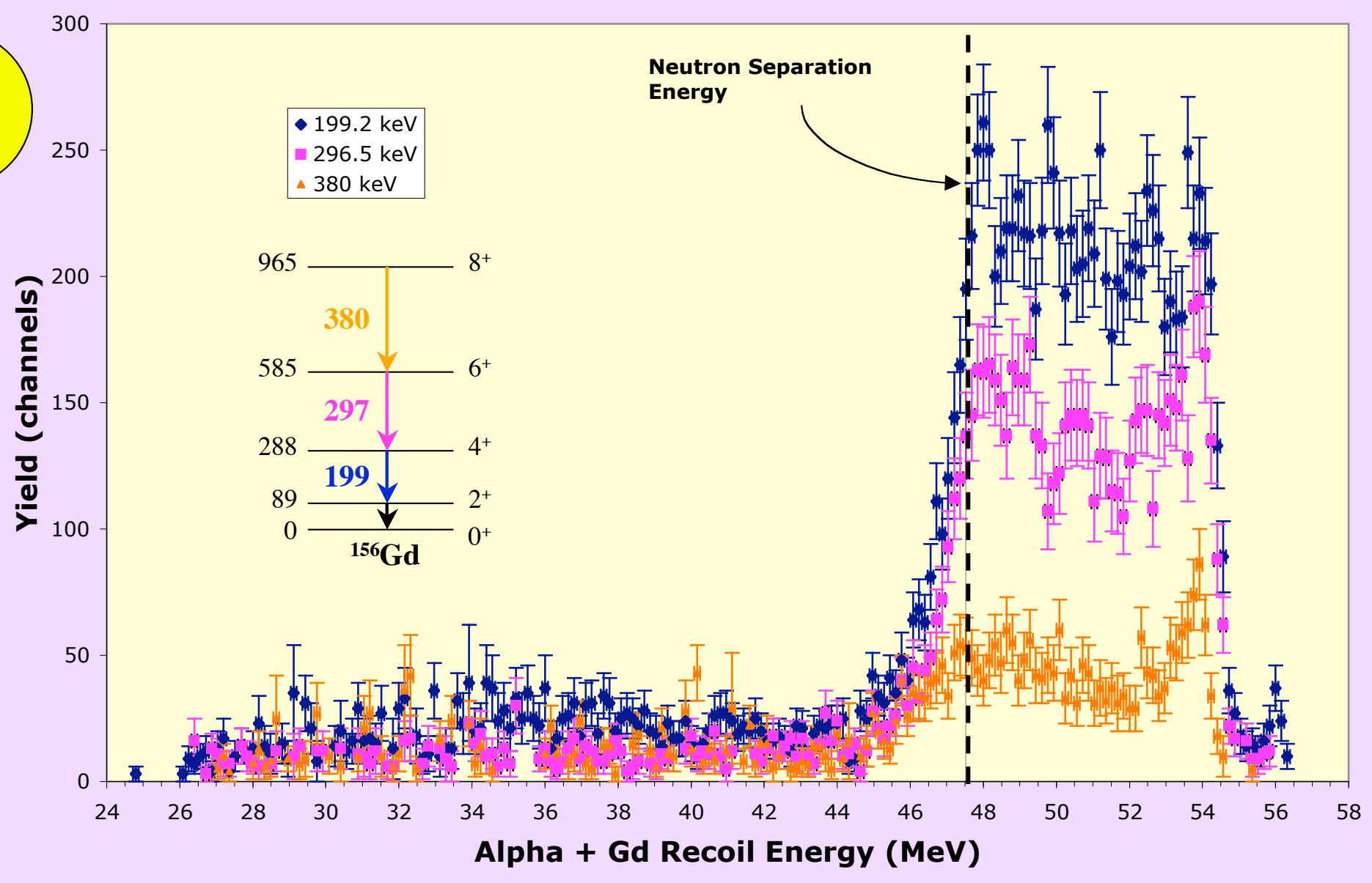


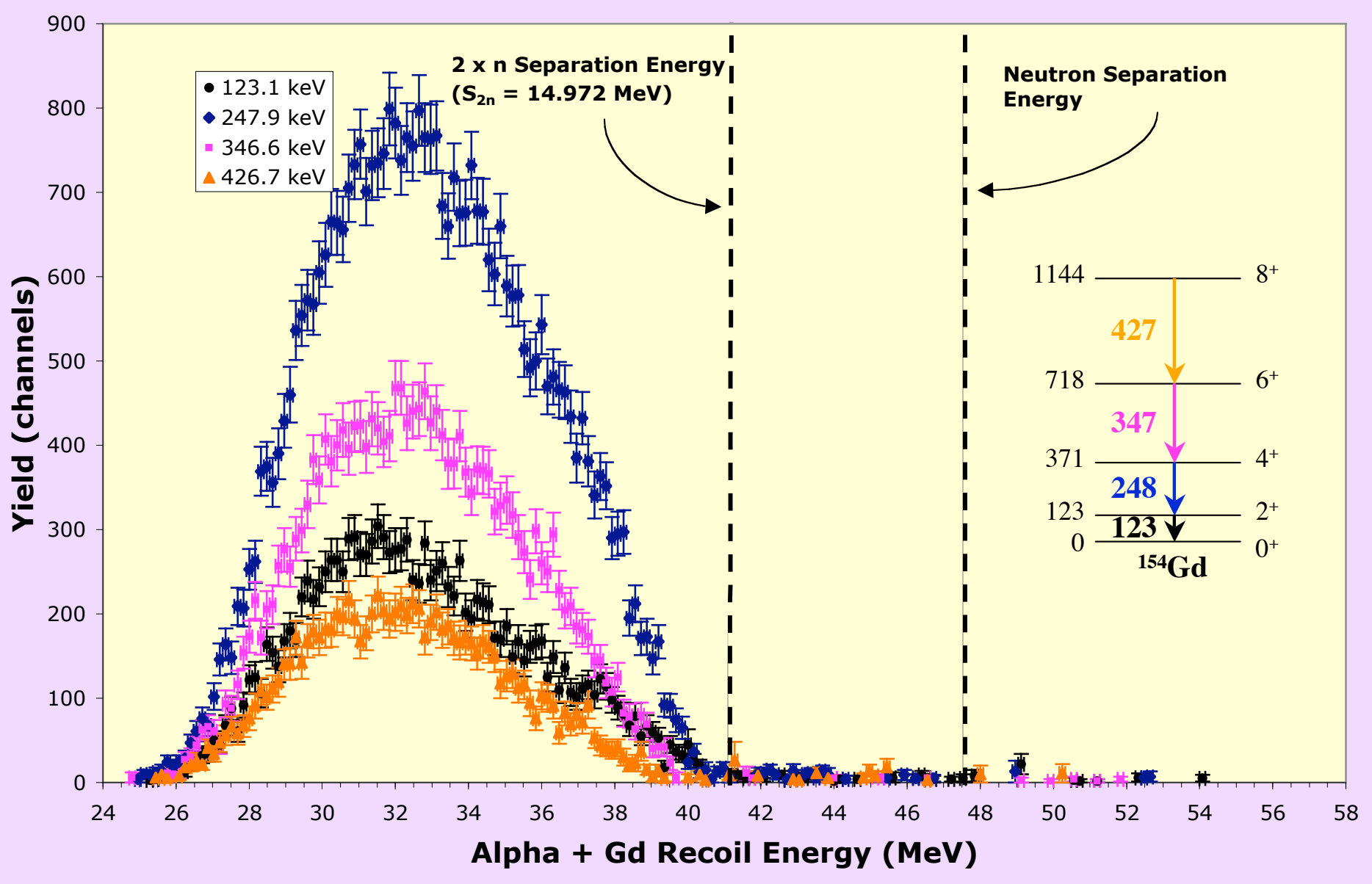
For ^{157}Gd(^{3}He,α)^{156}Gd:
199 keV ($4^+ \to 2^+$): $\varepsilon_{p\text{-}\gamma}$ = 0.49%
297 keV ($6^+ \to 4^+$): $\varepsilon_{p\text{-}\gamma}$ = 0.30%
380 keV ($8^+ \to 6^+$): $\varepsilon_{p\text{-}\gamma}$ = 0.09%
SUM: $\varepsilon_{p\text{-}\gamma}$ = 0.88%

④ Examples of yrast gamma ray intensities for the γ and 2n exit channels are shown below. Exit channel probabilities can be multiplied by neutron-absorption entrance channel cross sections (from optical models) to obtain ^{156}Gd(n,γ) and ^{156}Gd(n,2n) cross sections.

Example Gamma Intensities

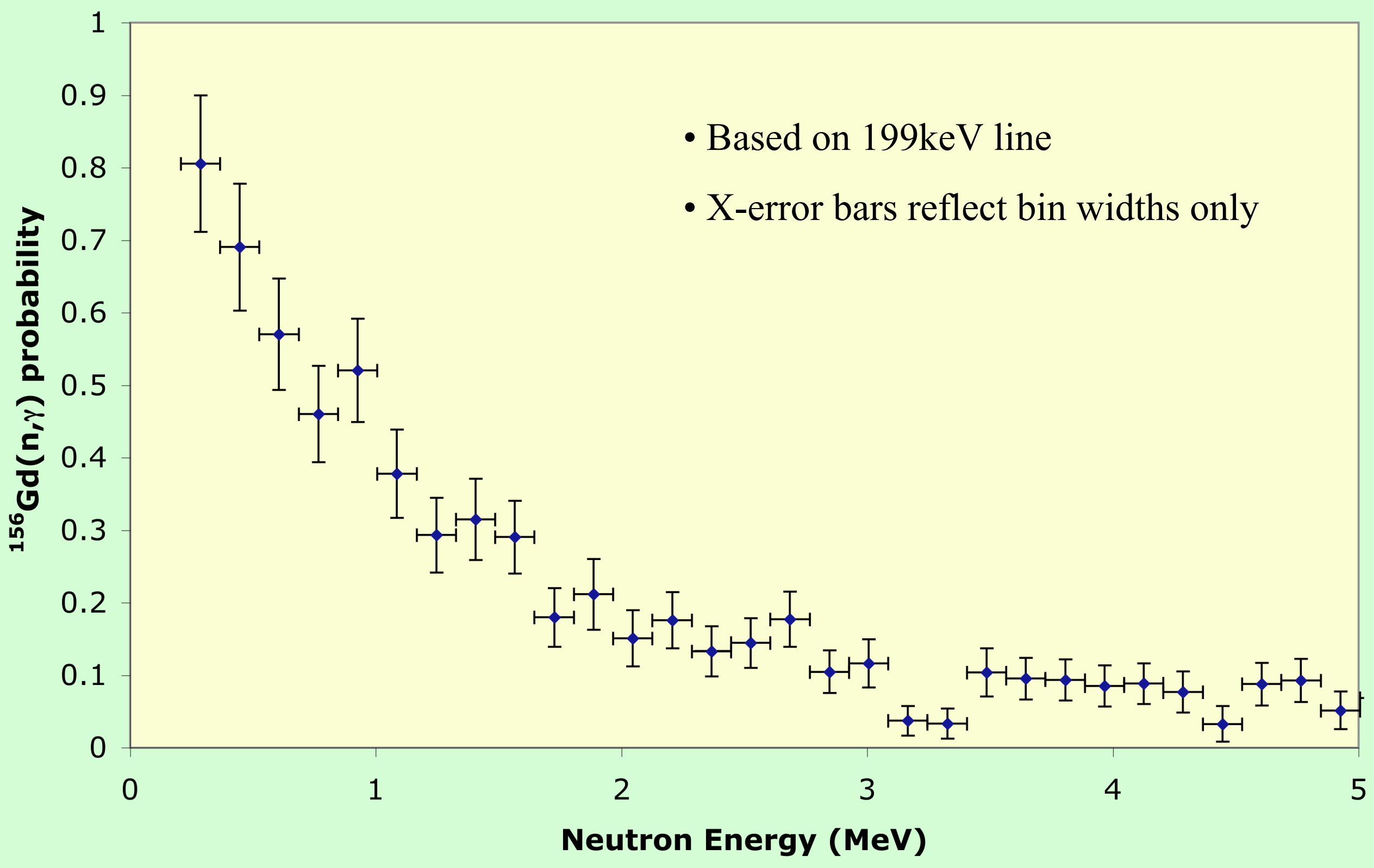
④





The Results

Gamma Exit Channel Probability



Conclusions

At present, we have not been able to reproduce the known neutron cross sections of ENDF evaluations or STAPRE calculations. While the general low-energy shape of the exit channel probability is correct, the absolute magnitude is high by a significant factor. Furthermore, we observed a low, but significant gamma-only emission intensity at high excitation energies, where the (n,γ) cross section should drop to zero. Results for the (n,2n) cross section are similar, but are also affected by significant carbon and oxygen target contamination for which we have yet to compensate.

It is unclear if these results reflect a failure of the absolute surrogate method, non-ideal experimental conditions, or reactions from target impurities. We are continuing to scrutinize the results to identify the cause of the discrepancies.

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