Lawrence Livermore National Laboratory

Determining the (n, γ) cross section of ^{153}Gd using surrogate reactions

10/23/07

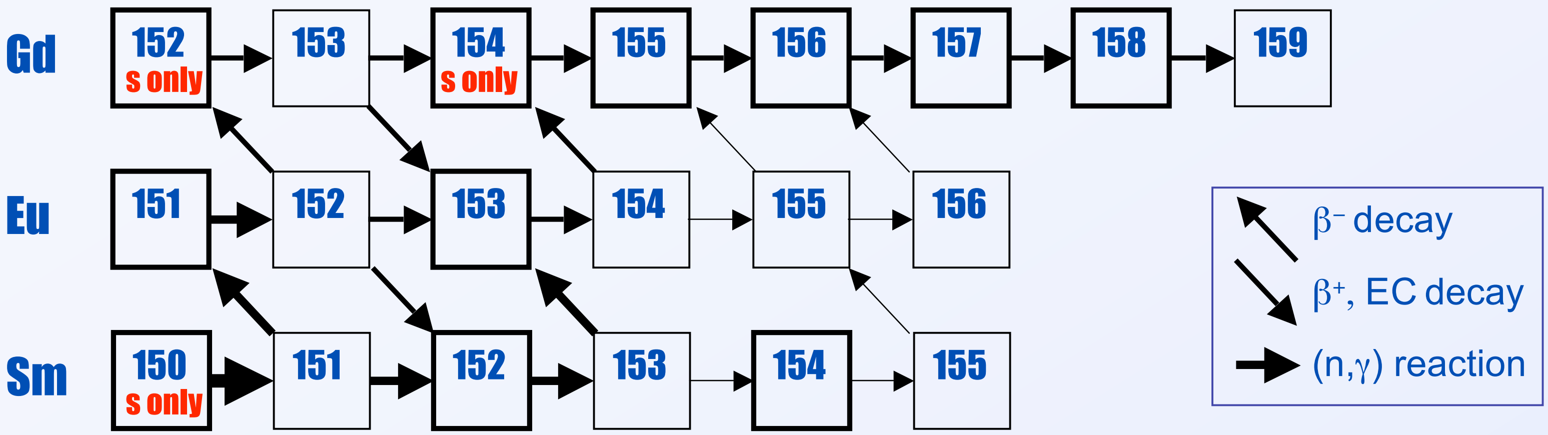
Nicholas Scielzo

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

This work performed under the auspices of the U.S. Department of Energy by
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

UCRL-PRES-235732

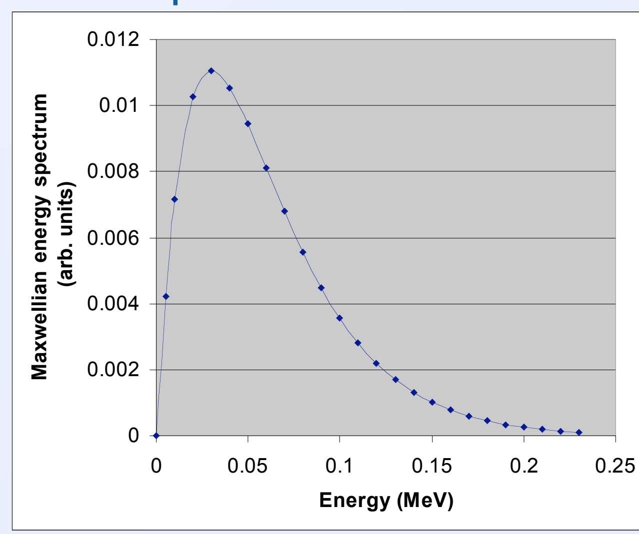
s-process



^{152}Gd and ^{154}Gd cannot be produced by the *r*-process and therefore these abundances can be used to investigate the *s*-process which has typical temperatures of ~30 keV

These abundances are influenced by (n,γ) cross sections at energies 0-200 keV in branch-point nuclei such as ^{153}Gd (for which the time scales for neutron capture and β-decay can be comparable)

temperature kT = 30 keV

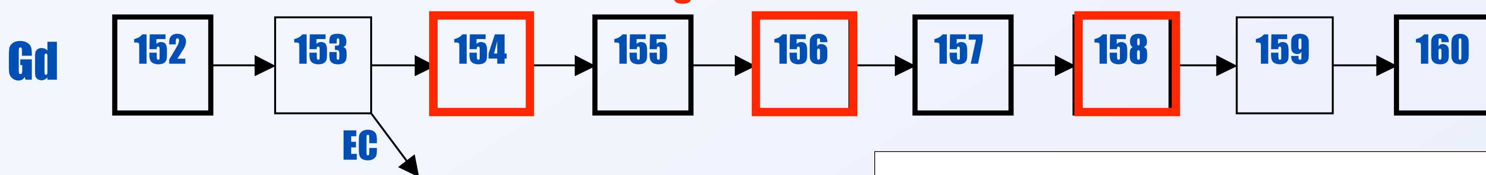


(n,γ) cross section

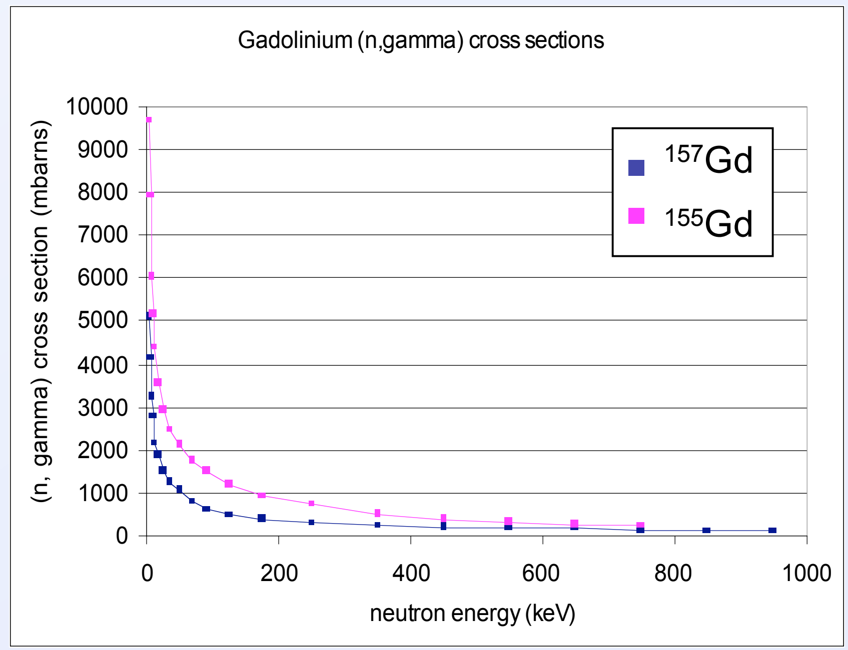
Direct measurements using ^{153}Gd difficult because of radioactivity (with ~100 keV γ-rays in 50% of decays):

1 milligram of ^{153}Gd ⇔ 3.5 Curies ($t_{1/2}$=240 days)

Targets used …



Well-suited for surrogate measurement because of neighboring stable Gd isotopes that can be used as targets for measurement and benchmarks.



Challenges:

small energy range of interest – experimental resolution is critical

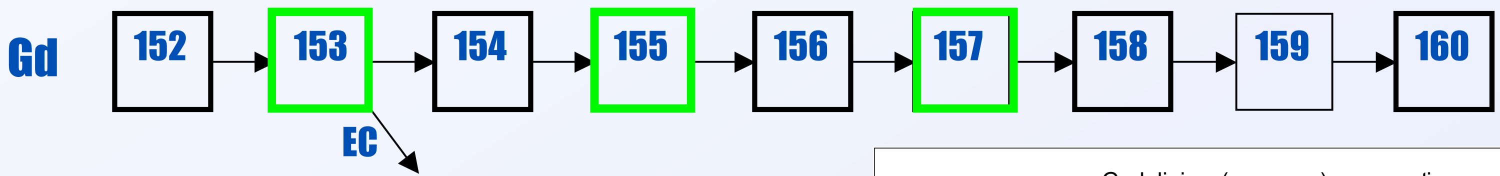
enriched sample of ^{154}Gd is 67% isotopically pure

(n,γ) cross section

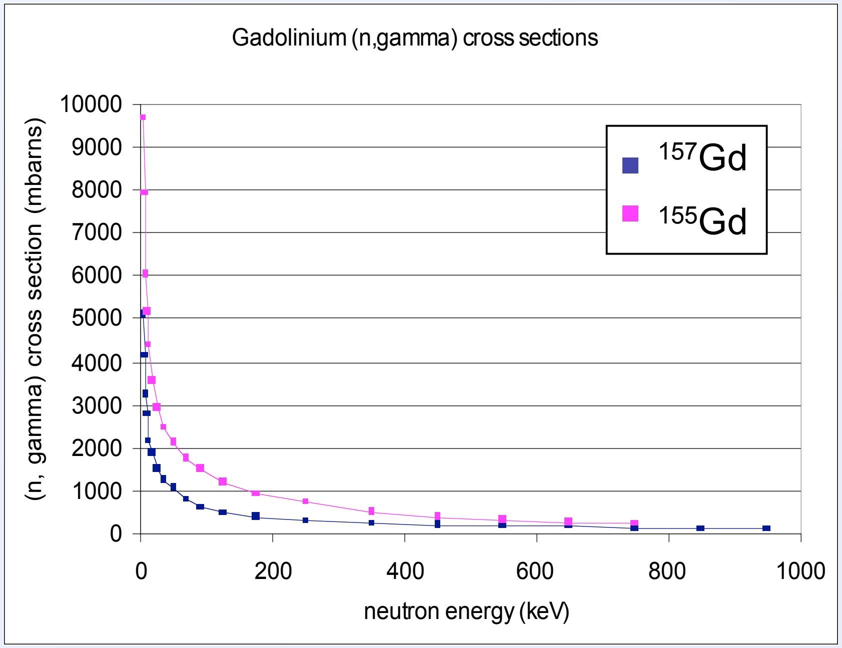
Direct measurements using ^{153}Gd difficult because of radioactivity (with ~100 keV γ-rays in 50% of decays):

1 milligram of ^{153}Gd ⇔ 3.5 Curies ($t_{1/2}$=240 days)

…for (*n*, γ) on these isotopes



Well-suited for surrogate measurement because of neighboring stable Gd isotopes that can be used as targets for measurement and benchmarks.



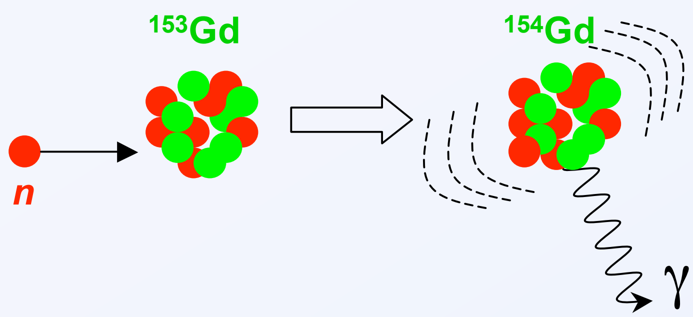
<u>Challenges:</u>

small energy range of interest – experimental resolution is critical

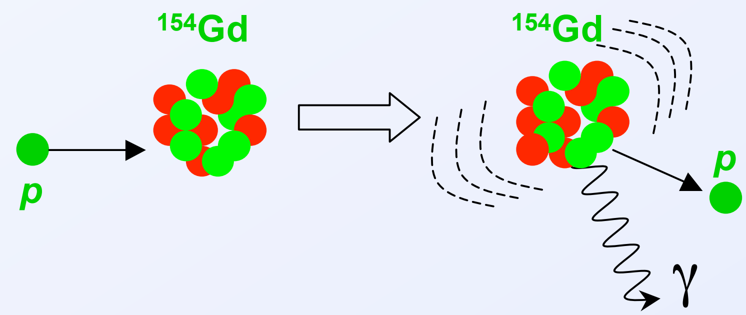
enriched sample of ^{154}Gd is 67% isotopically pure

Surrogate measurement

“Desired” reaction



“Surrogate” reaction



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

$$P_\chi(E)=\frac{N_{p\gamma}(E)}{\varepsilon_\gamma N_p(E)}=\sum_{J,\Pi}F_\alpha^{CN}(E,J,\Pi)\cdot G_\chi^{CN}(E,J,\Pi)$$

We measure this ratio

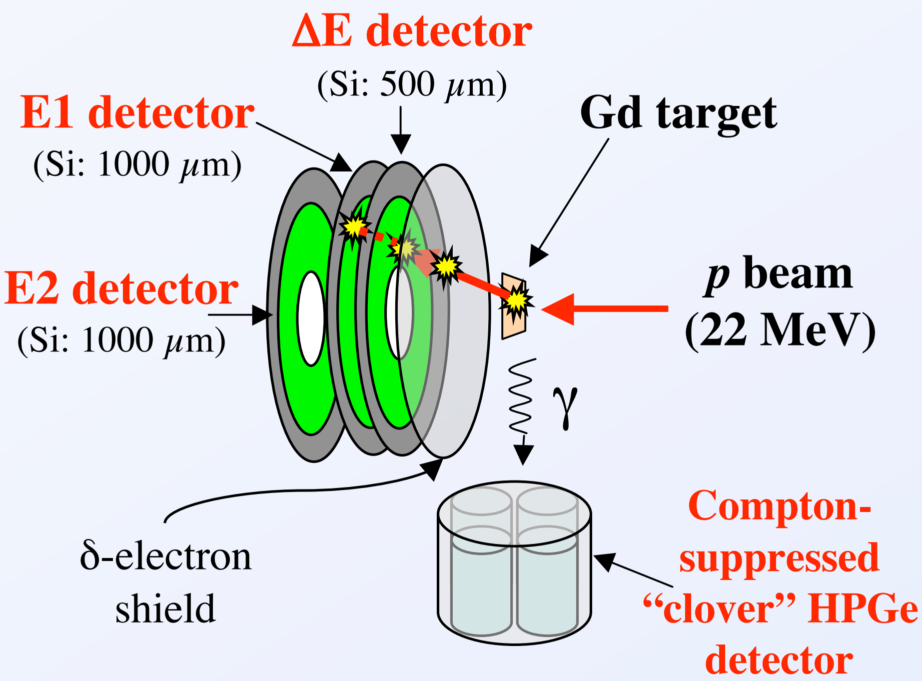
These exit channel probabilities are identical!

Need theory to reconcile differences in σ_α^{CN} and F_α^{CN}

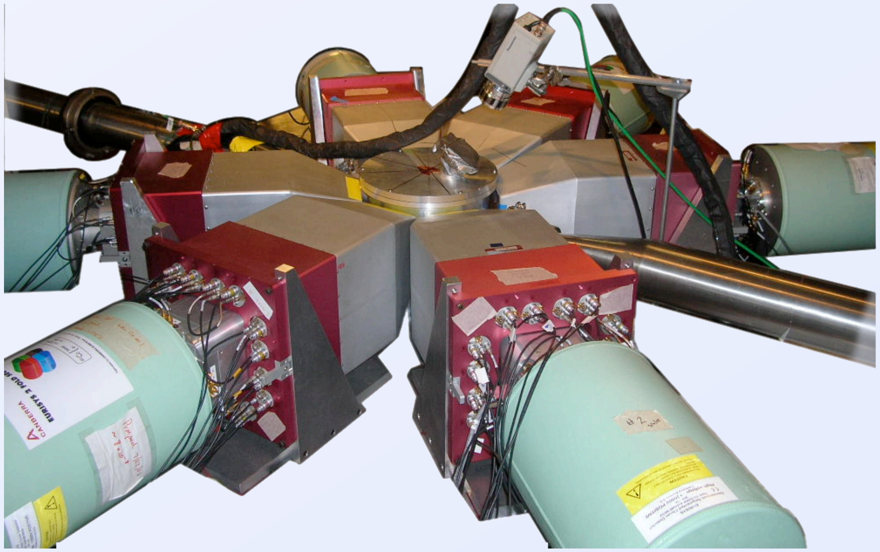
Experimental Set-up with STARS-LiBerACE

Excite Gd nuclei (S_n≈8-9 MeV) through inelastic (p, p') scattering

Detect scattered *p* in segmented silicon detector array



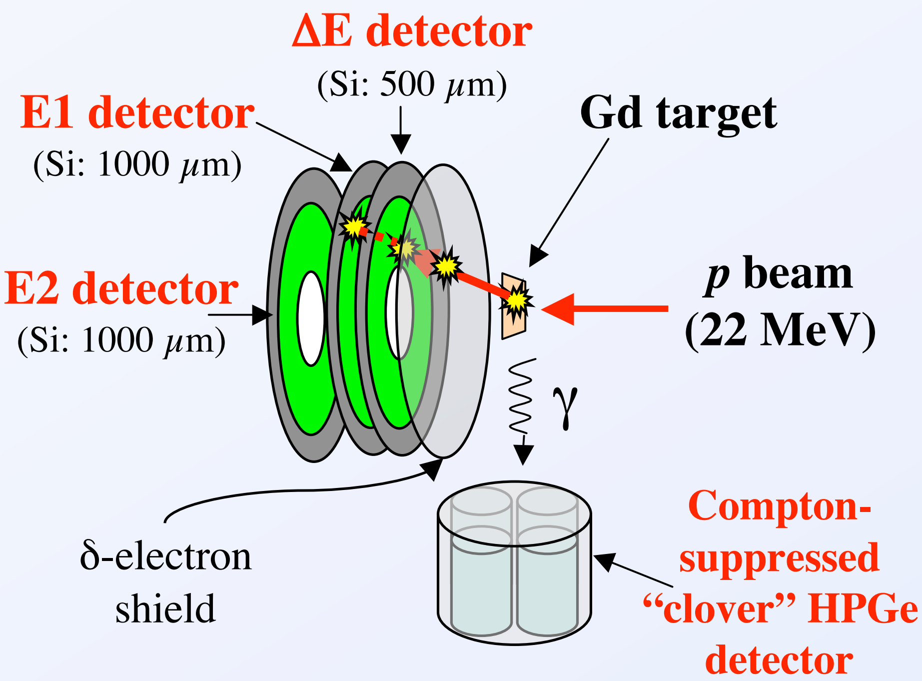
Coincident detection of characteristic γ-rays using an array of Compton-suppressed "clover" HPGe detectors



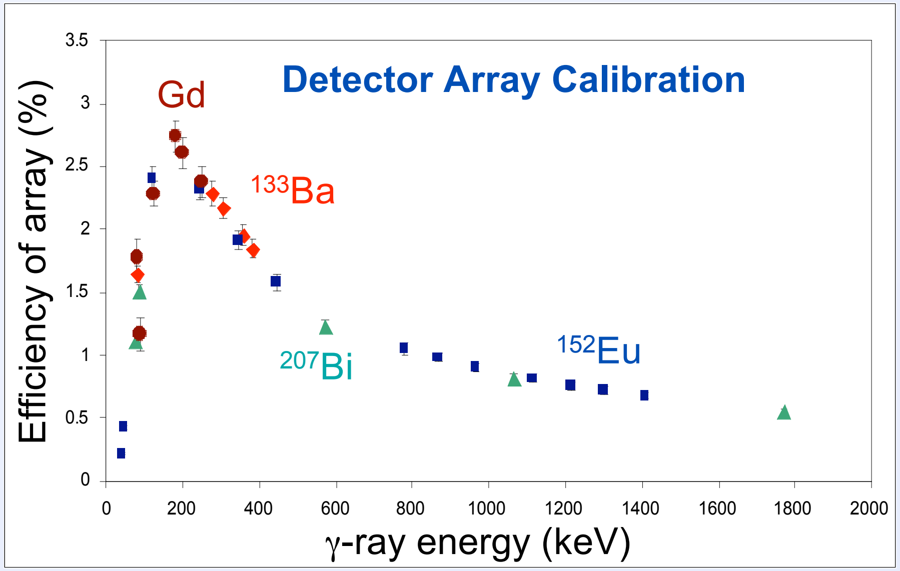
Experimental Set-up with STARS-LiBerACE

Excite Gd nuclei (S_n≈8-9 MeV) through inelastic (*p*, *p*') scattering

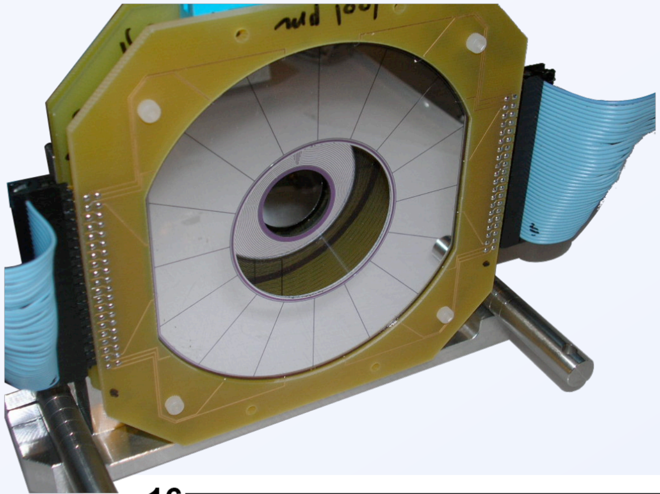
Detect scattered *p* in segmented silicon detector array



Coincident detection of characteristic γ-rays using an array of Compton-suppressed "clover" HPGe detectors

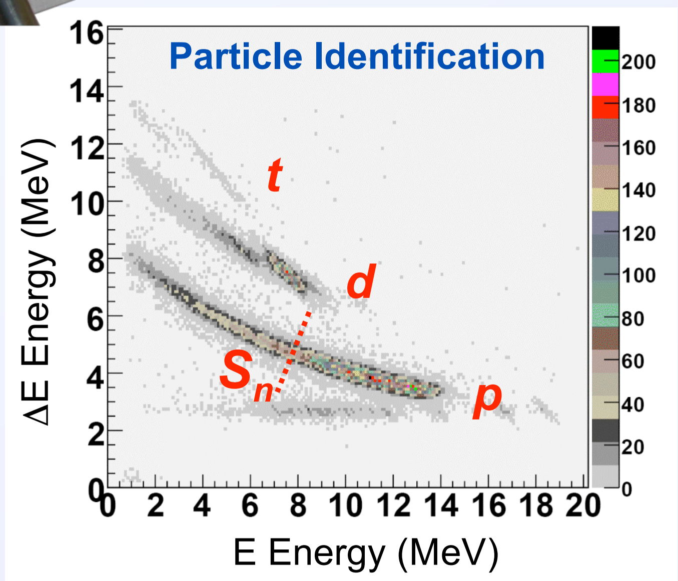


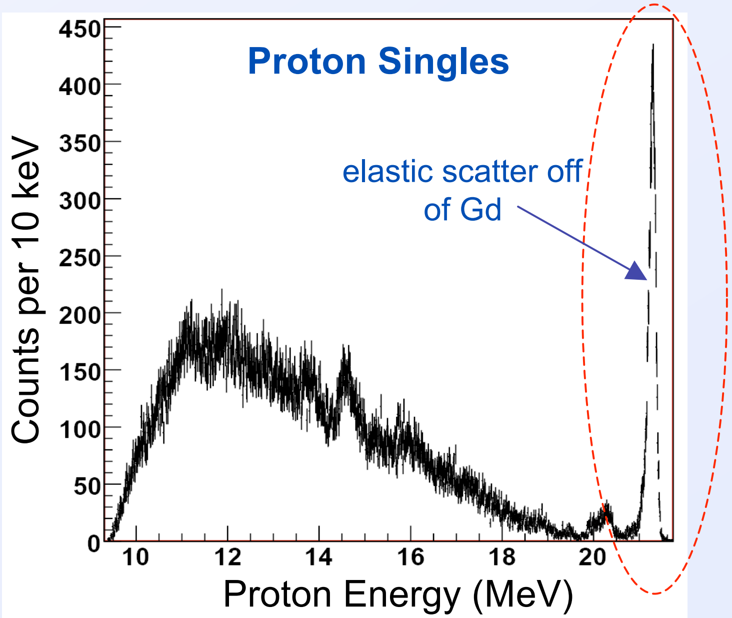
Particle Detection



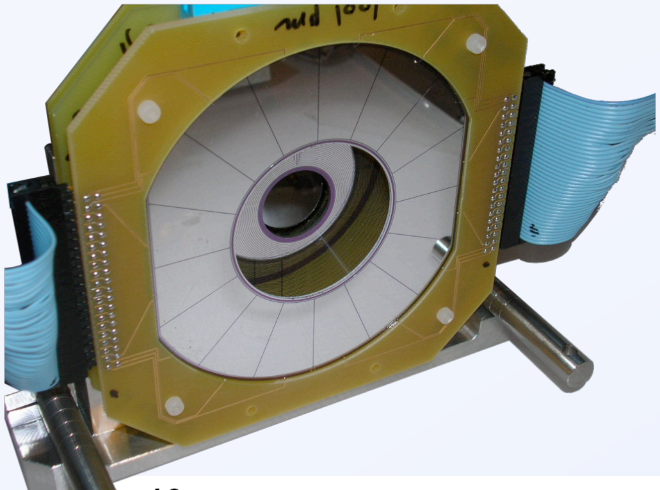
Highly-segmented, chilled silicon array for particle identification and precise energy determination

Detector response must be very well understood:
65 keV resolution for 22 MeV beam energy is <0.3%!



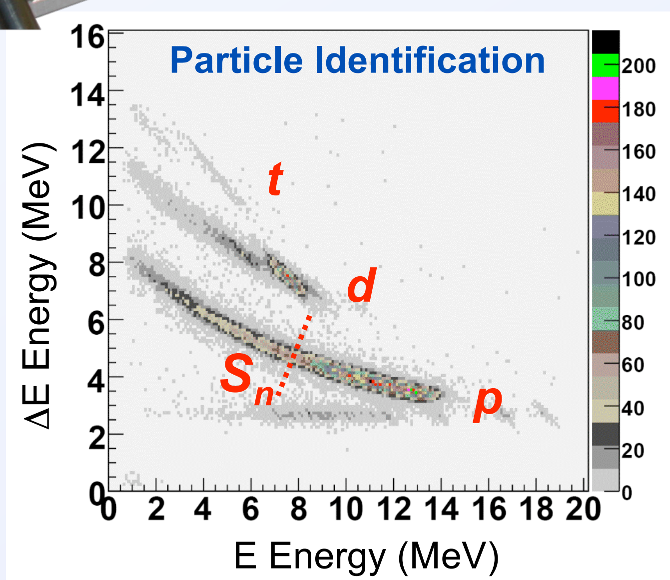


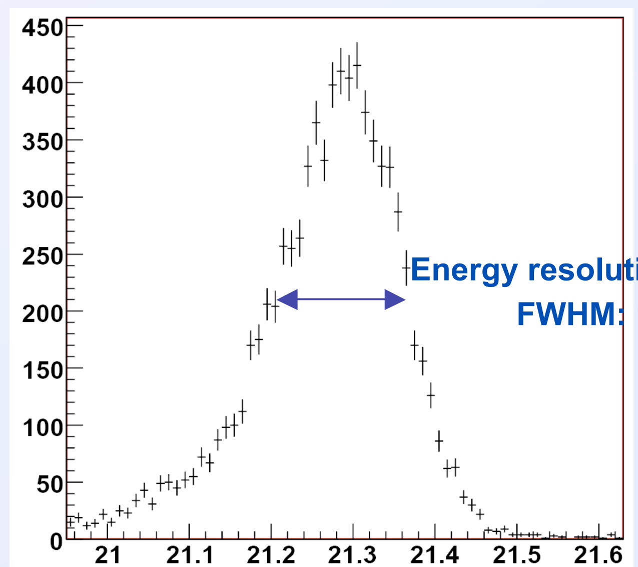
Particle Detection



Highly-segmented, chilled silicon array for particle identification and precise energy determination

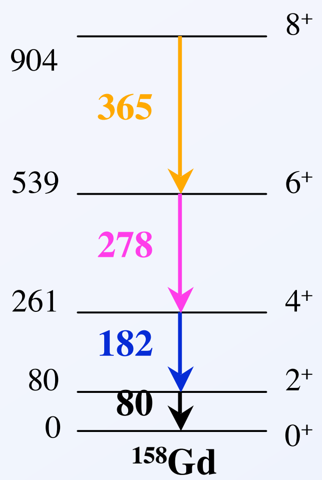
Detector response must be very well understood:
65 keV resolution for 22 MeV beam energy is <0.3%!





γ-ray Detection

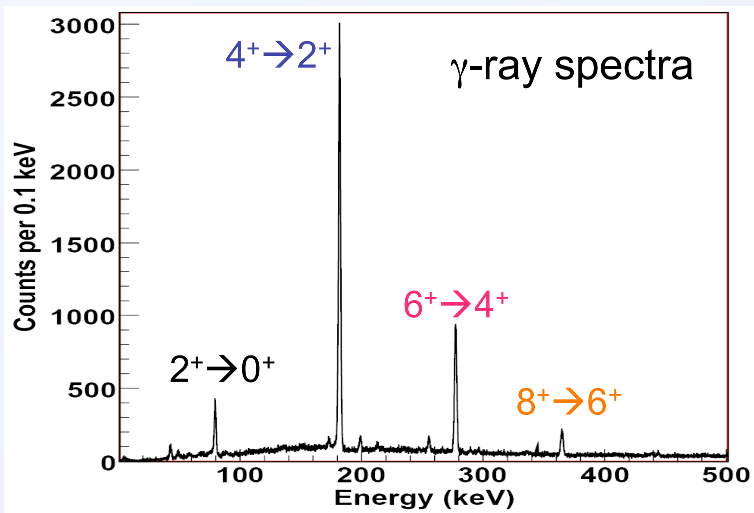
As nucleus de-excites, many γ-ray cascades pass through the lowest excited states



(Energies in keV)

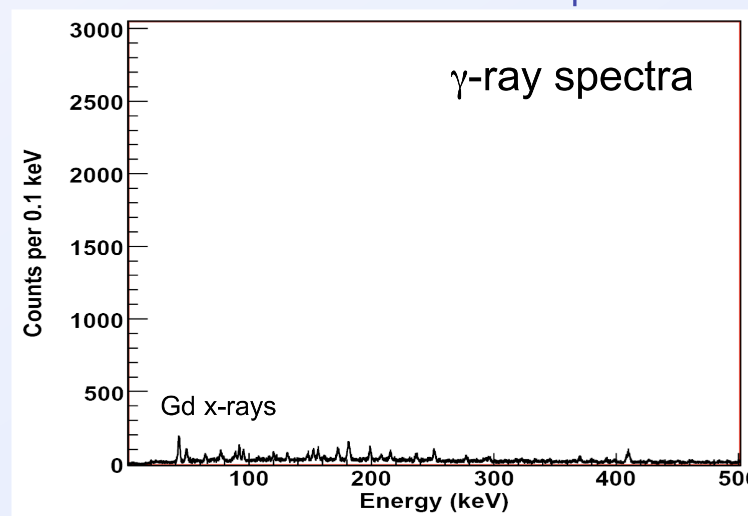
Excitation Energy < S_n

Nucleus de-excites through γ emission



Excitation Energy > S_n

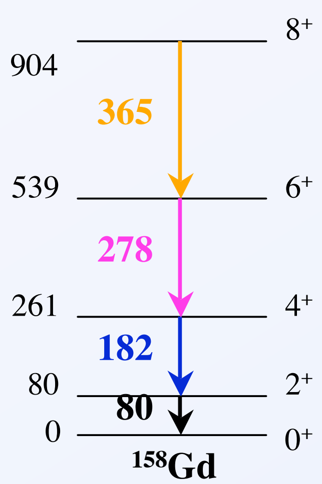
Neutron emission more probable



All $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ transition γ-rays observed with good statistics.

γ-ray Detection

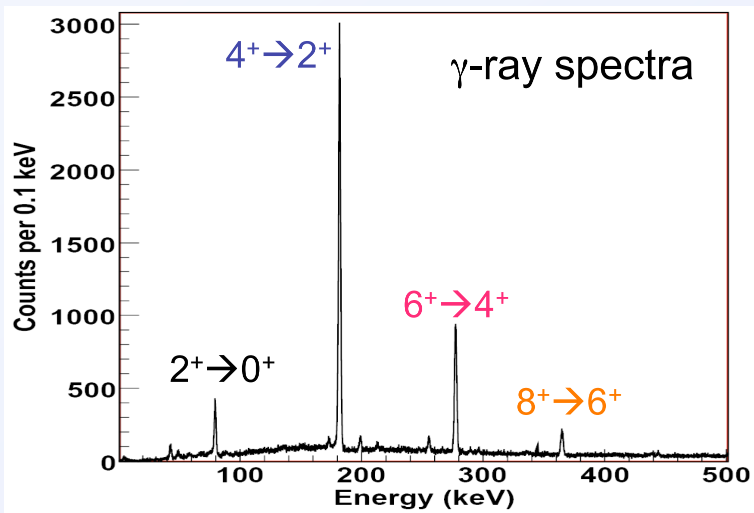
As nucleus de-excites, many γ-ray cascades pass through the lowest excited states



(Energies in keV)

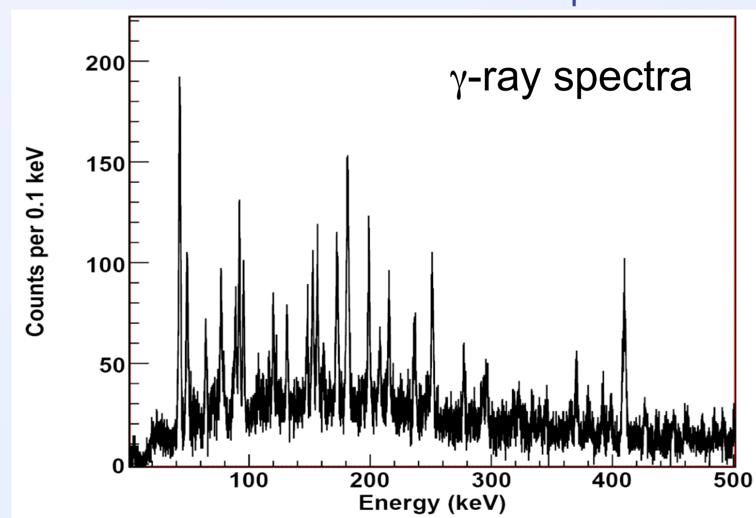
Excitation Energy < S_n

Nucleus de-excites through γ emission



Excitation Energy > S_n

Neutron emission more probable

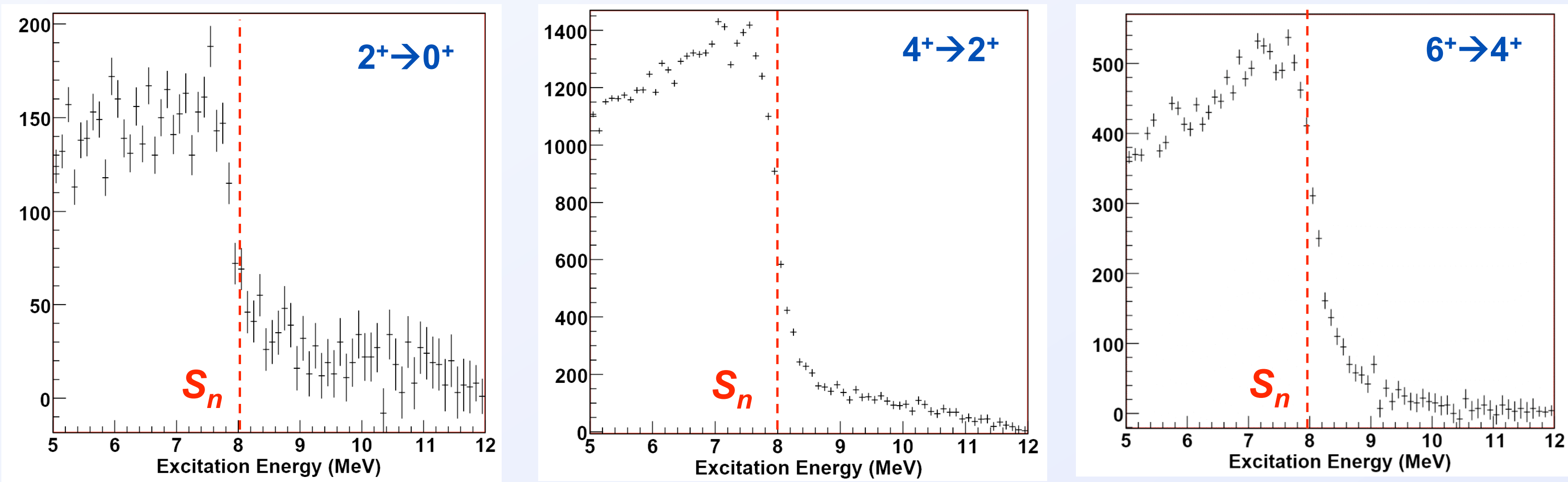


All $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ transition γ-rays observed with good statistics.

Towards an (n,γ) cross section

Data analysis for ^{158}Gd…

p-γ coincidences as a function of ^{158}Gd* excitation energy show drop as S_n is crossed



Need to study whether there are weak γ-ray lines at the transitions of interest

$J\Pi$ population mismatch must be modeled

We are interested in low energies so the Weisskopf-Ewing limit is not satisfied and angular-momentum considerations are important

$J\Pi$ populations between *n*-induced reaction and surrogate reaction can be very different so we need input from theorists to interpret results as (n,γ) cross-section and estimate sensitivity to $J\Pi$ population mismatch

Data can guide the prediction of the $J\Pi$ population and the extraction of an (n,γ) cross-section…

- Data extends into energy region where Weisskopf-Ewing limit is valid (>3 MeV) and can be used as an additional normalization for the calculations
- Relative intensities of discrete γ-ray transitions can constrain the calculated $J\Pi$ distribution
- Angular dependence of γ-ray emission may also give information on $J\Pi$ distributions
- Data taken with ^{156}Gd and ^{158}Gd targets provide benchmarks to test the theory and experiment

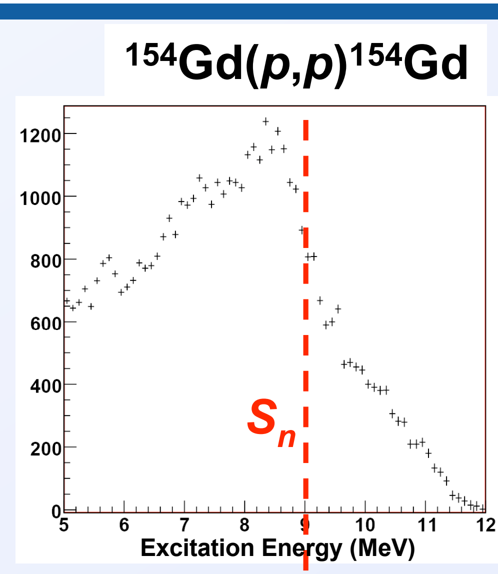
Corrections to data

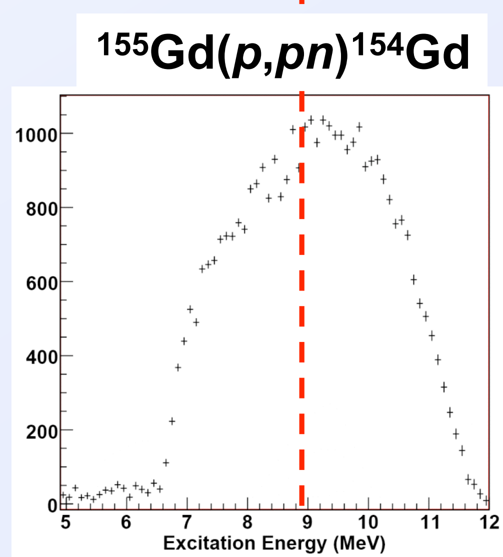
Need to account for contribution from (*p*, *pn*) reactions on Gd contaminants with one additional neutron.

Target

Composition	^{154}Gd	^{156}Gd	^{158}Gd
^{152}Gd	0.08%	0.00%	0.00%
^{154}Gd	**66.53%**	0.11%	0.00%
^{155}Gd	**17.50%**	1.96%	0.96%
^{156}Gd	7.32%	**93.79%**	1.70%
^{157}Gd	3.24%	**2.53%**	3.56%
^{158}Gd	3.45%	1.20%	**92.00%**
^{160}Gd	1.88%	0.41%	1.82%

Correction for the ^{154}Gd target is at the energy of interest…





Summary

- Surrogate reactions can provide new opportunities to determine cross-sections for reactions that are difficult or impossible to measure directly
- Analysis underway to determine (n, γ) cross-section for ^{153}Gd which is of interest to the astrophysics community
- Need theory to determine effect of $J\Pi$ distribution mismatch and to interpret results
- Technique will be benchmarked against precise direct measurements and reliability of surrogate approach tested at low energy

Experimental Collaborators

Lawrence Livermore National Laboratory

L.A. Bernstein, D.L. Bleuel (PD), J.T. Burke, S.R. Lesher (PD), E.B. Norman, N.D. Scielzo (Lawrence Fellow), S. Sheets (PD)

U.C. Berkeley and Lawrence Berkeley National Laboratory

M.S. Basunia, R.M. Clark, P. Fallon, J. Gibelin (PD), B. Lyles (GS), M.A. McMahan, L. Moretto, L.W. Phair, E. Rodriguez-Vieitez (GS), M. Wiedeking (PD)

University of Richmond

J.M. Allmond (PD), C. Beausang