Lawrence Livermore National Laboratory

USNDP – CSWEG update of LLNL experimental activities
Brookhaven National Laboratory
Long Island, New York
November 4, 2009

Jason T. Burke

for LLNL and STARS/LIBERACE Collaboration

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

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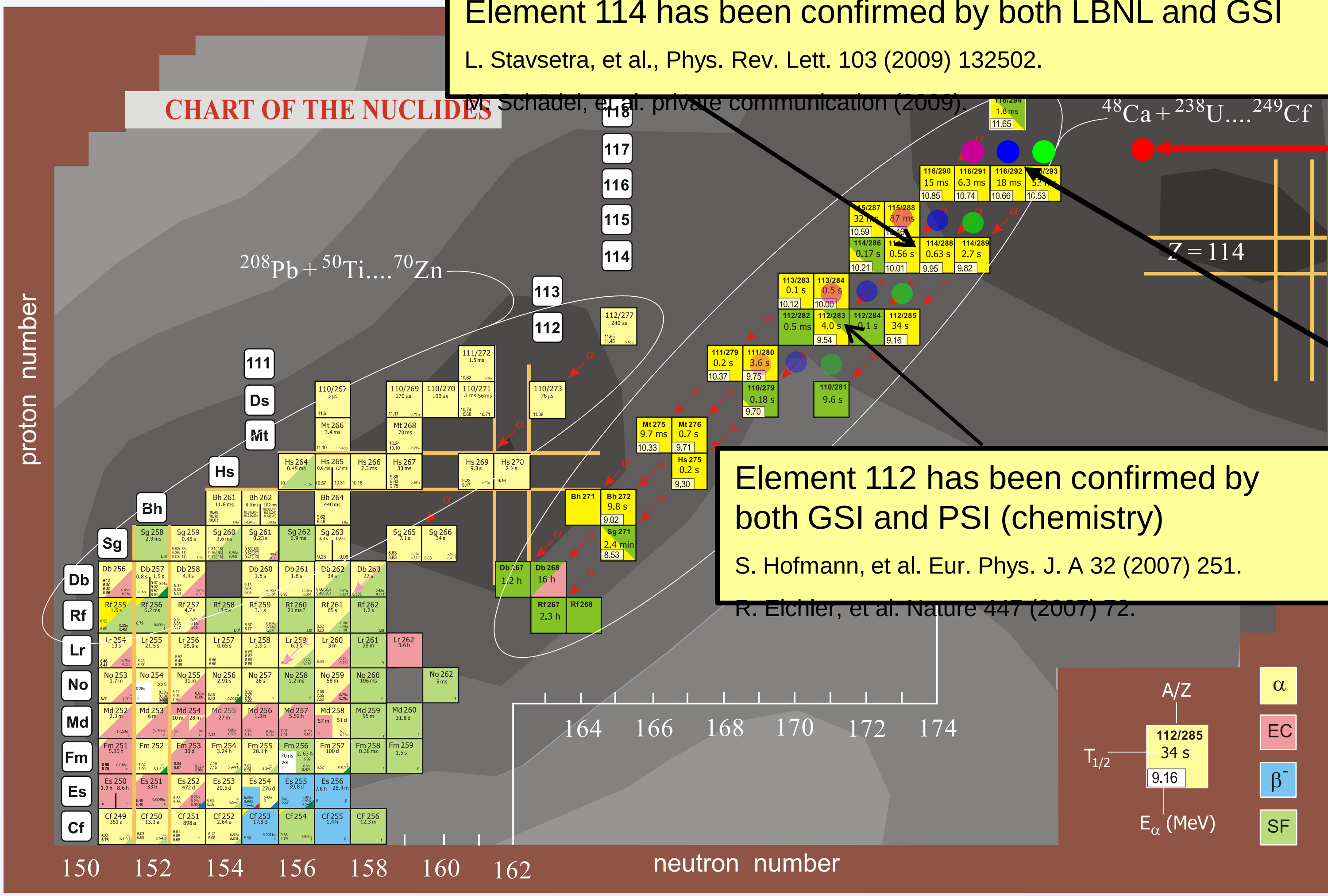
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

The $^{48}Ca + ^{249}Bk$ reaction is running at JINR now to attempt to produce element 117 - Courtesy Mark Stoyer

Element 114 has been confirmed by both LBNL and GSI

L. Stavsetra, et al., Phys. Rev. Lett. 103 (2009) 132502.

M. Schädel, et al. private communication (2009).



Compound nucleus

3n evap. channel

4n evap. channel

5n evap. channel

Element 112 has been confirmed by both GSI and PSI (chemistry)

S. Hofmann, et al. Eur. Phys. J. A 32 (2007) 251.

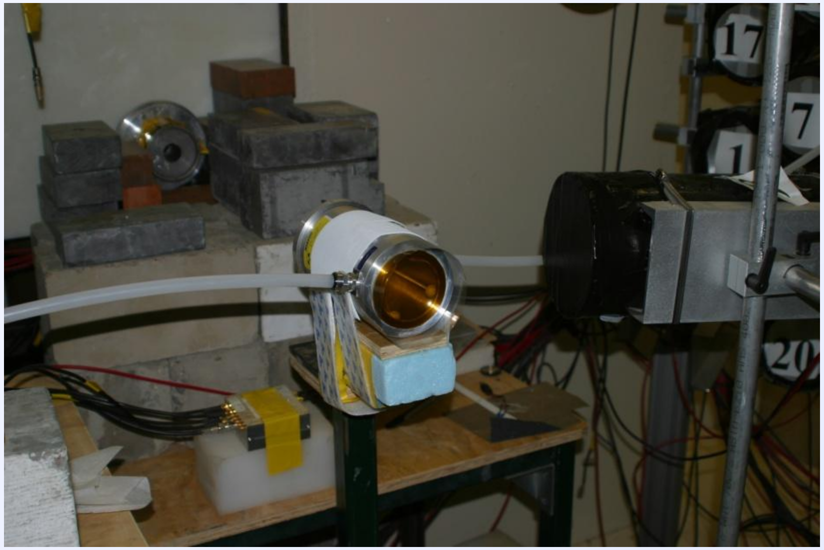
R. Eichler, et al. Nature 447 (2007) 72.

In the 5n-channel, alpha decay would produce previously studied nuclides

A Dubna/LLNL/GSI collaboration is forming to attempt confirmation of elements 115 & 116 at GSI

LLNL Fission chamber at LANL – Ching-Yen Wu

1. Experiment to measure the fission neutron spectrum using the newly developed fission chamber in conjunction with FIGARO, has been fielded at LANL/LANSCE from August 6 to 15, 2009 and extended for at least a week.
2. Fission chamber performed extremely well with the initial indication of huge success.



LLNL fission chamber at FIGARO

Surrogate reactions using the ratio technique

"Surrogate" reactions

^{237}U(n,f)

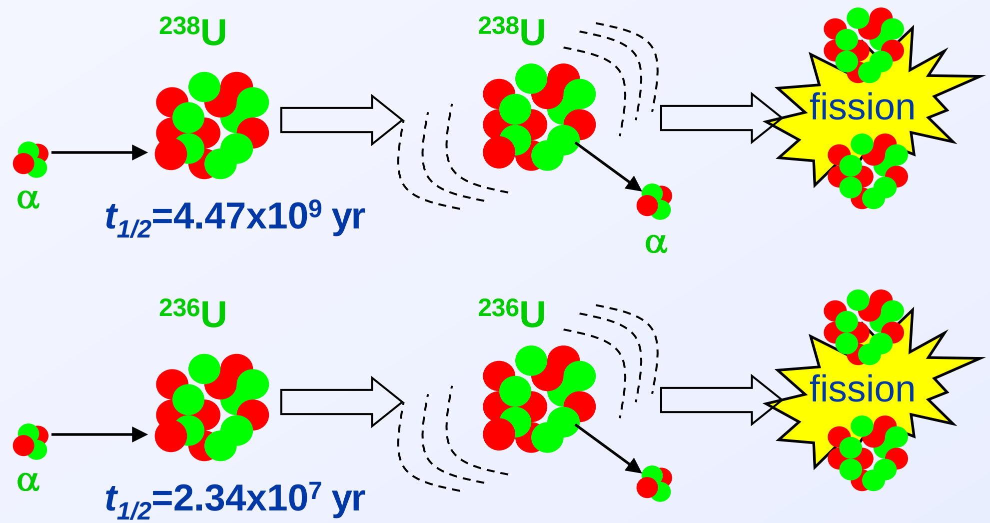
$t_{1/2}$=6.75 days

unkown

^{235}U(n,f)

$t_{1/2}$=7.04x10^{8} yr

known



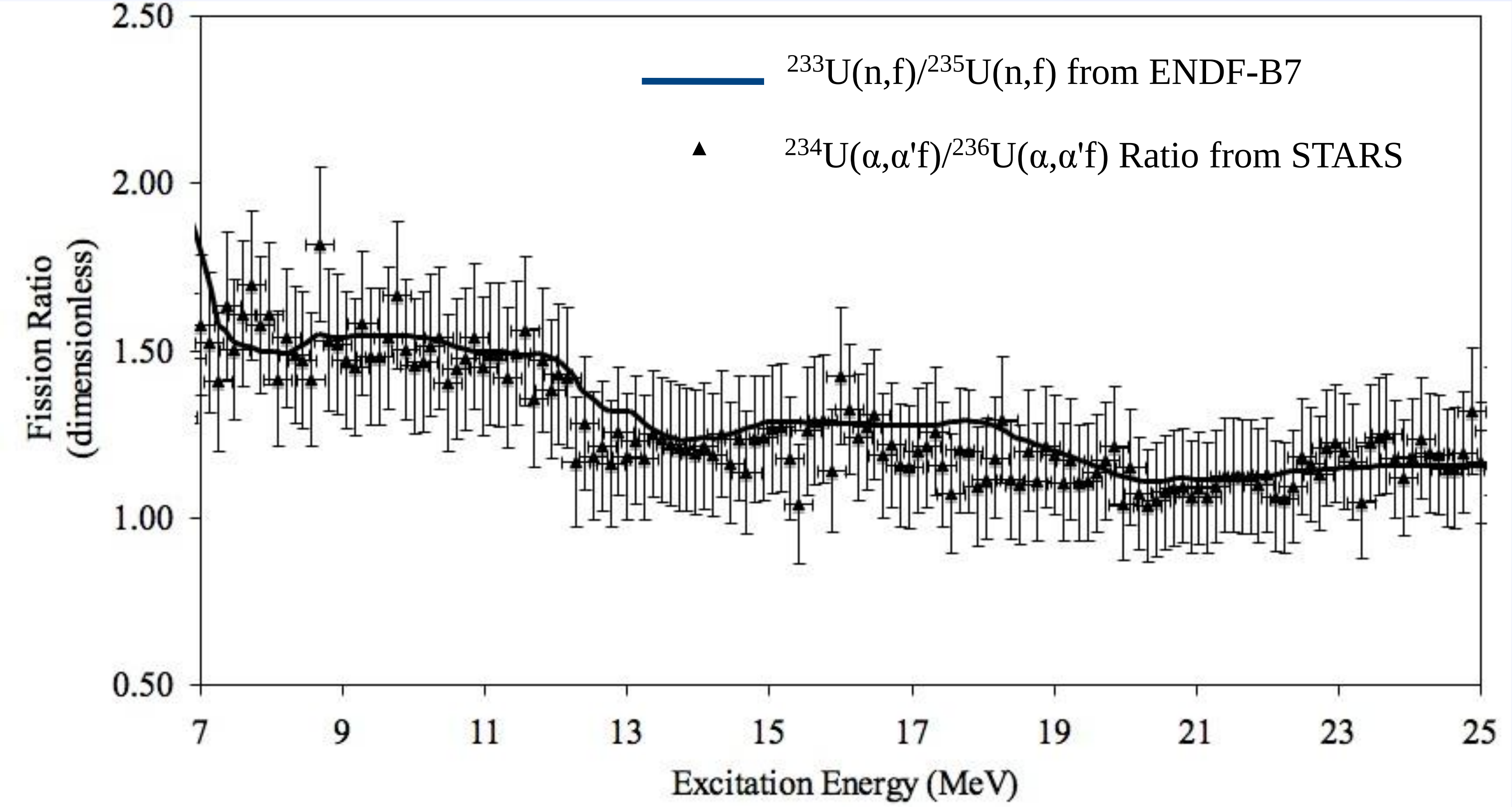
$$P_f = \frac{N_f(^{238}U)}{\varepsilon_{p-f} N_\alpha(^{238}U)}$$

$$P_f = \frac{N_f(^{236}U)}{\varepsilon_{p-f} N_\alpha(^{236}U)}$$

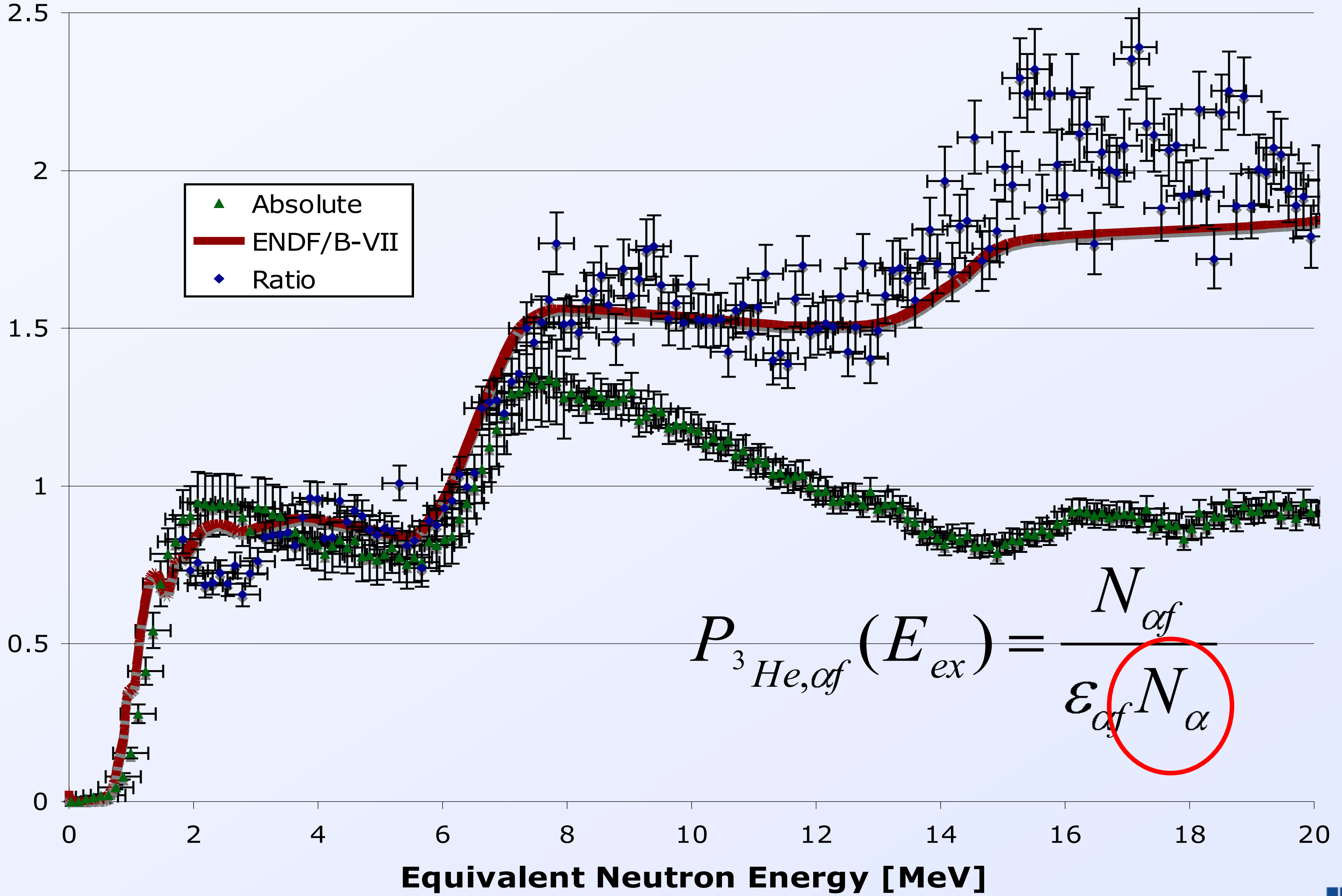
Largest source of systematic error

$$\frac{P_f(^{238}U(\alpha,\alpha' f))}{P_f(^{236}U(\alpha,\alpha' f))} = \frac{\cancel{\varepsilon_f} N_{\alpha-f}(^{238}U) / \cancel{N_\alpha(^{238}U)}}{\cancel{\varepsilon_f} N_{\alpha-f}(^{236}U) / \cancel{N_\alpha(^{236}U)}} = \frac{\sigma^{^{237}U}_{(n,f)}}{\sigma^{^{235}U}_{(n,f)}}$$

Ratio of ^{233}U(n,f)/^{235}U(n,f) compared to ^{234}U(α,α'f)/^{236}U(α,α'f) Courtesy Shelly Lesher (LLNL)



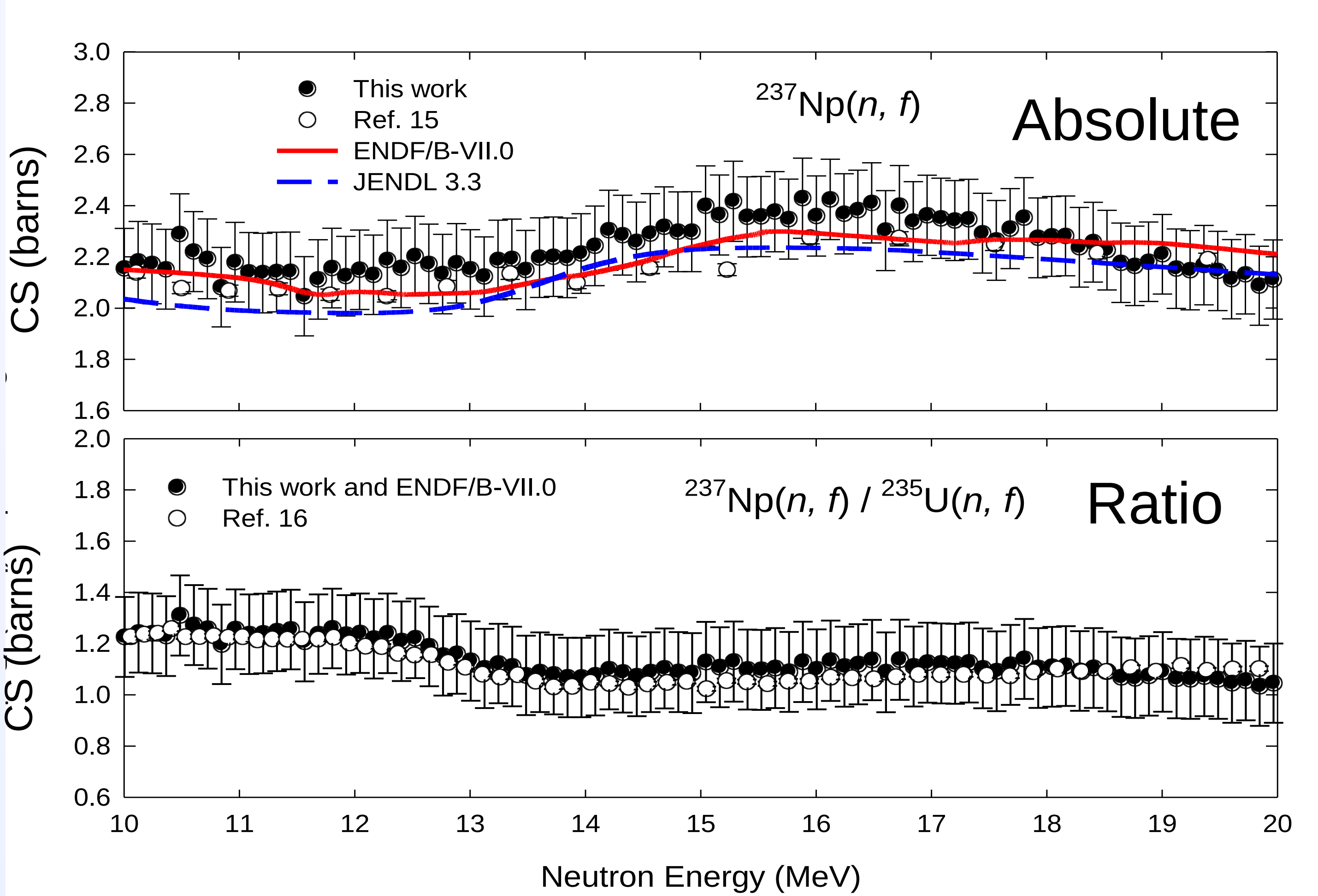
^{236}U(n,f) Cross Section from ratio of ^{238}U(^{3}He,α'f)/^{235}U(^{3}He,α'f) x σ[^{233}U(n,f)] Courtesy B.F. Lyles U.C.B.



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

^{237}Np(n,f) cross section from ^{238}U(^{3}He,tf) surrogate reaction

Courtesy S. Basunia (LBNL)

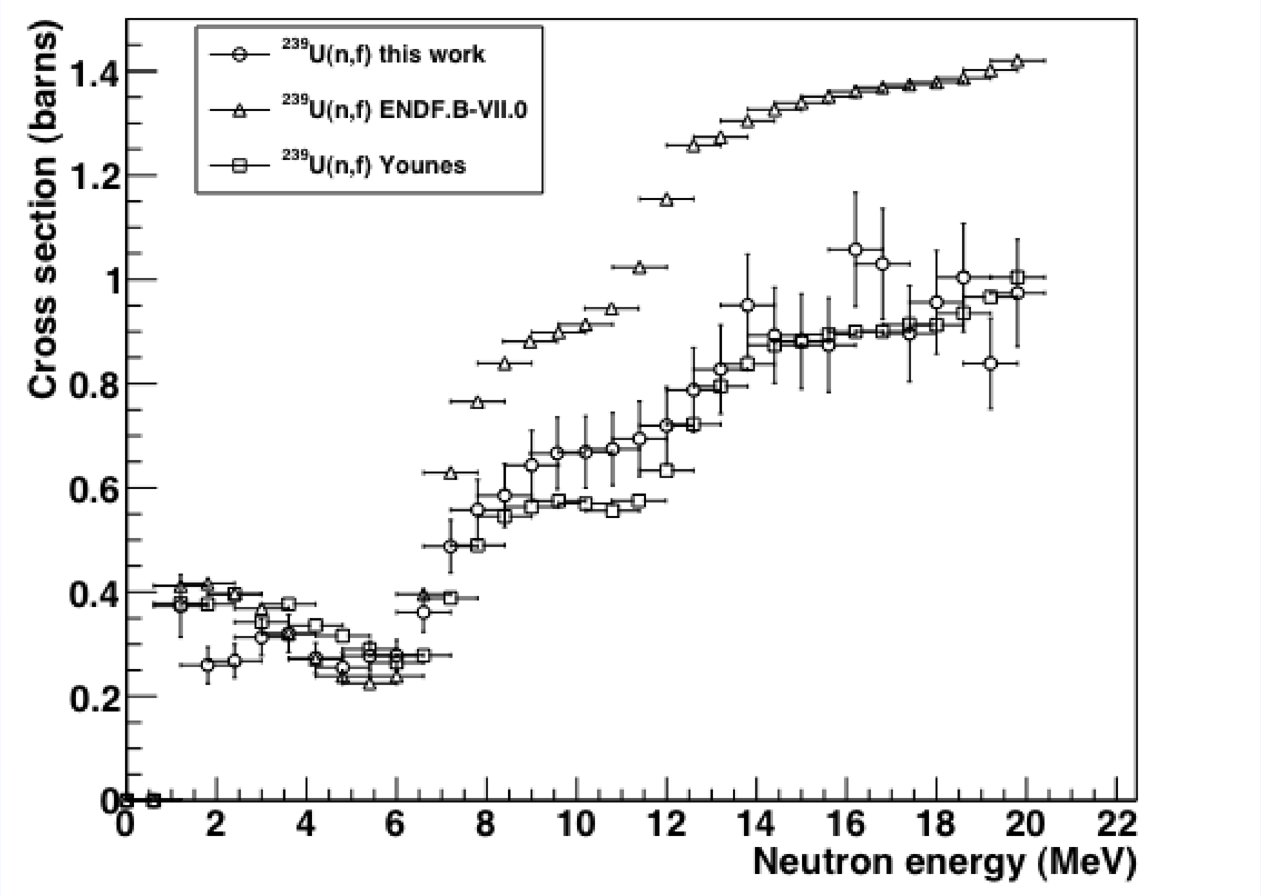


Ref. 15. O. Shcherbakov *et al.*, J. Nucl. Sci. and Tech., Supp. 2, 230, 2002

Ref. 16. F. Tovesson and T. S. Hill, Phys. Rev. C 75, 034610, 2007.

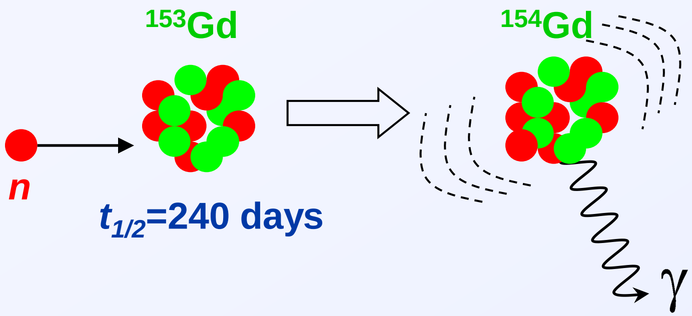
^{239}U(n,f) ($\tau_{1/2}$=24minutes) determined from ^{238}U(^{18}O,^{16}O)^{240}U
J.T. Burke to be submitted to PRC fall 2009

$$\sigma\left({}^{239}U(n,f)\right) = \frac{N_{p-f}({}^{238}U({}^{18}O,{}^{16}Of))}{N_{p-f}({}^{234}U({}^{18}O,{}^{16}Of))} \times \sigma\left({}^{235}U(n,f)\right)$$

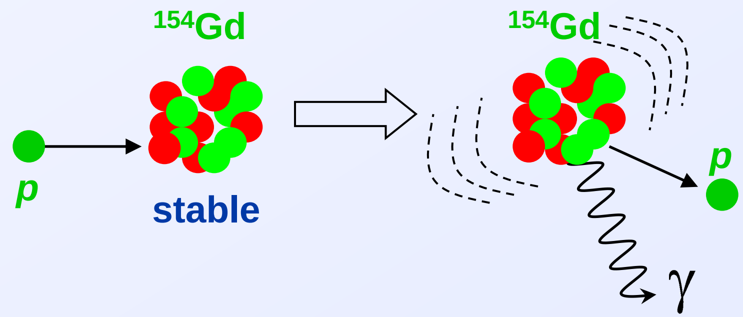


Surrogate nuclear reaction method using inelastic scattering

"Desired" reaction



"Surrogate" reaction



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

Hauser-Feshbach theory describes the "desired" reaction as a product of entrance channels (σ_{α}^{CN} *– can be calculated reliably*) and exit channel branching ratios (**G_{χ}^{CN}** – *can't be calculated reliably*)

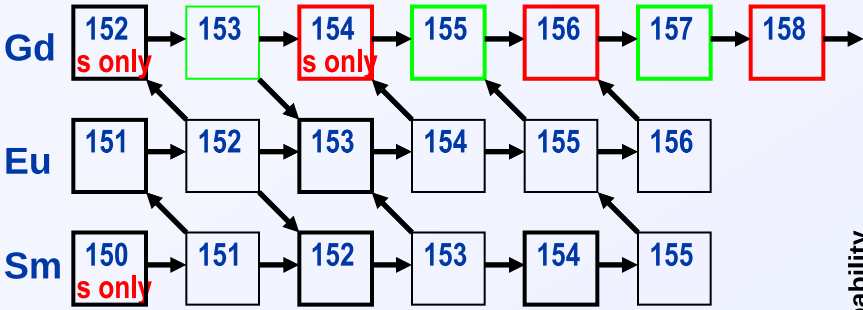
$$P_{\chi}(E) = \sum_{J,\pi} F_{\alpha}^{CN}(E,J,\pi)\, G_{\chi}^{CN}(E,J,\pi) = \frac{N_{(p,p\gamma)}(E)}{N_{(p,p)}(E)}$$

Alternative ("surrogate") reaction can be used to form the same compound-nucleus of interest and determine **G_{χ}^{CN}**

We measure this ratio

s-process branch-point nucleus ^{153}Gd
Courtesy Nick Scielzo (Lawrence Fellow/LLNL)

s-process network in Sm-Eu-Gd region



Targets used …

… for (n, γ) on these isotopes

^{152,154}Gd cannot be produced by the *r*-process and therefore these isotopes can be used to understand the *s*-process

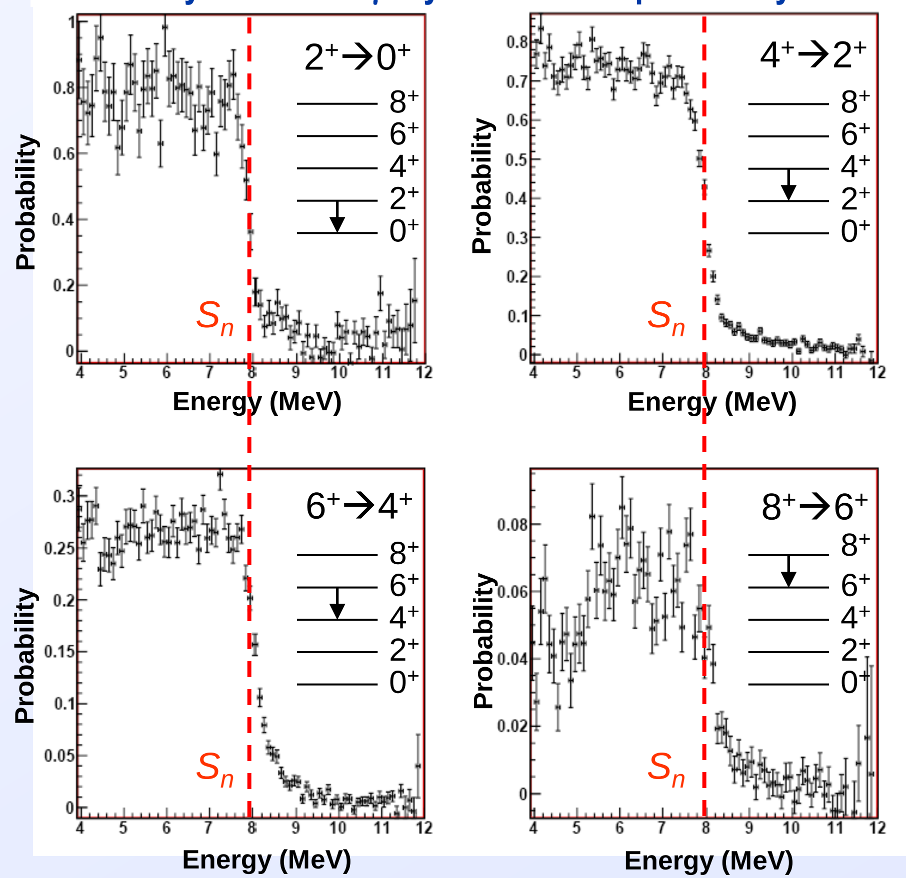
(n,γ) cross sections for branch-point nuclei (n capture and β-decay rates are comparable) such as ^{153}Gd are needed

^{153}Gd is radioactive ($t_{1/2}$=240 days) → direct measurements very difficult

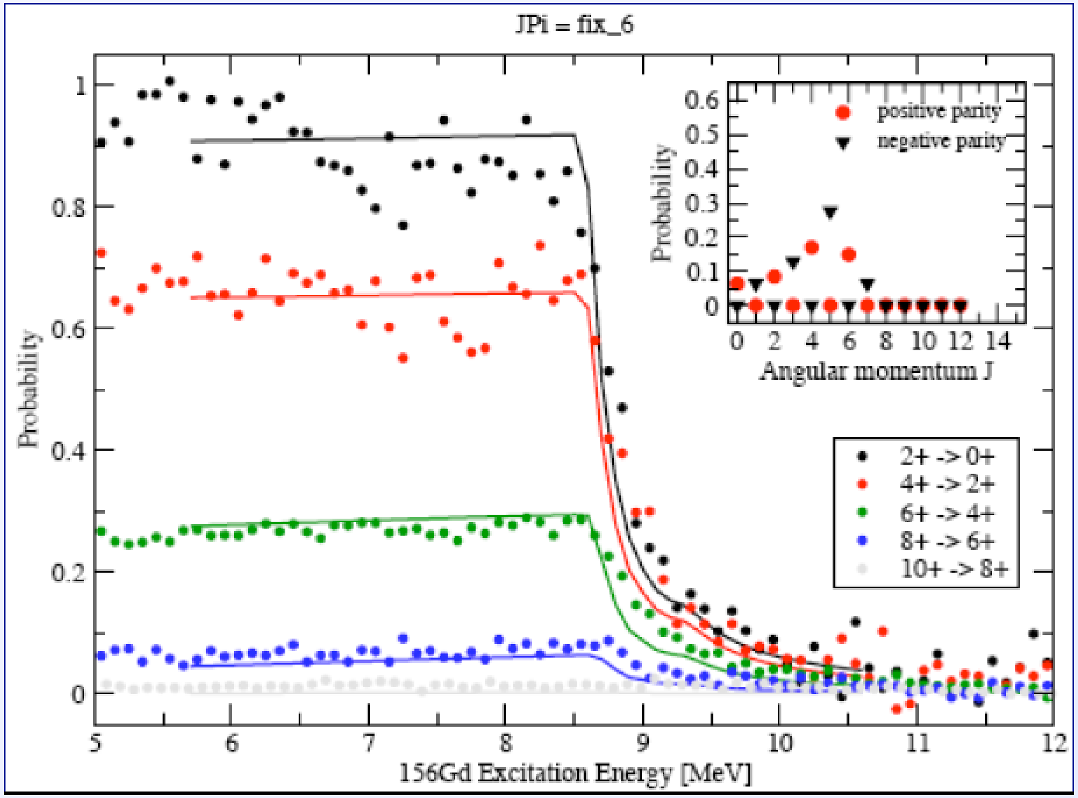
Well-suited for surrogate techniques because many stable Gd isotopes can be used for measurement and benchmarks.

Compound nucleus created through inelastic (p,p') scattering

Preliminary results for γ-ray exit channel probability in ^{158}Gd



Determining the compound nucleus spin-parity Nick Scielzo and Jutta Escher



The measured γ-ray yields compared to calculated yields for different spin distributions (error bars not shown).

Extract most likely J^π distribution from a comparison of data and calculations…

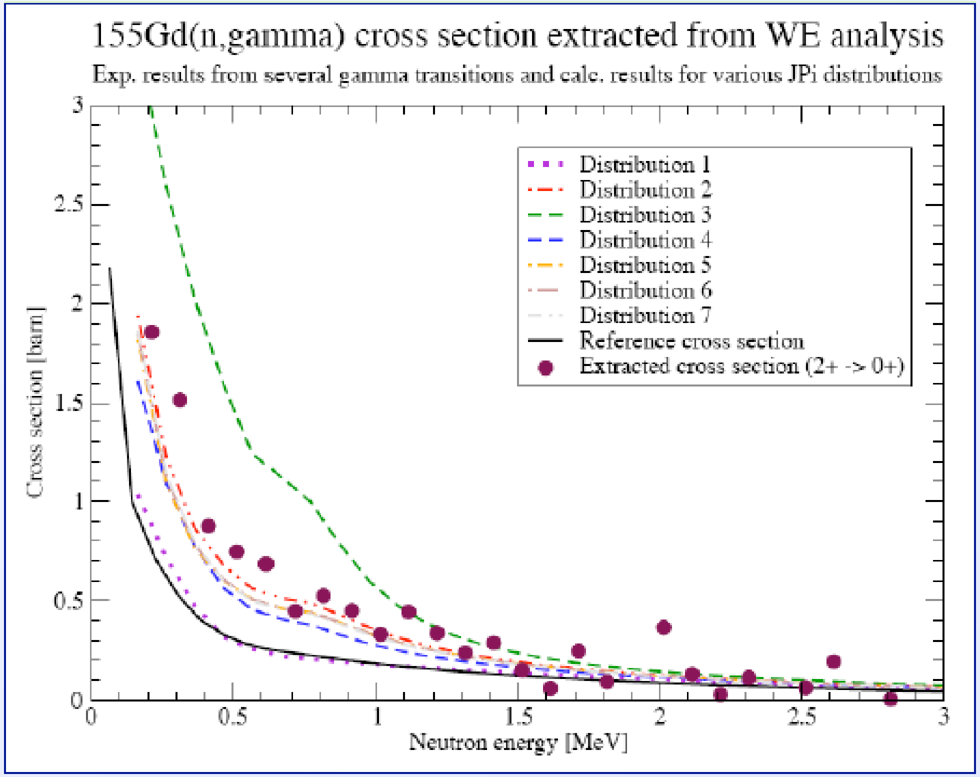
$^{155}Gd(n,\gamma)$ cross section from a Weisskopf-Ewing analysis

Cross section (purple dots) obtained by using Weisskopf-Ewing approximation

$$\sigma_{\alpha\chi}(E) = \sigma_{\chi}^{CN}(E) \cdot G_{\chi}^{CN}(E)$$

compared to cross sections obtained using simulated surrogate analysis with different compound nucleus spin-parity distributions

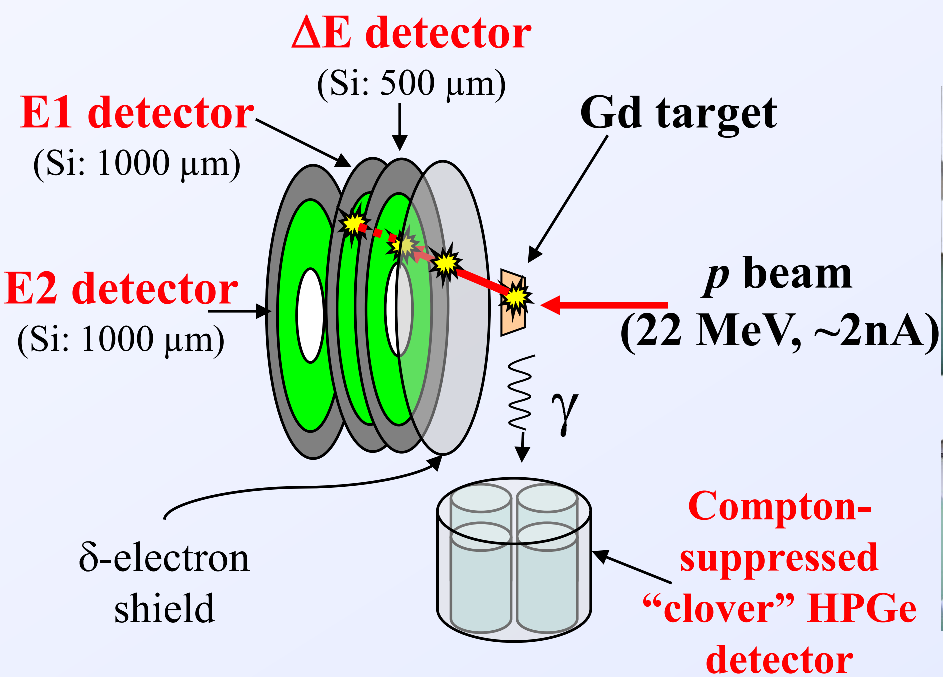
Distributions 2-6 are closest to reproducing γ-ray cascade and are also closest to extracted cross section results



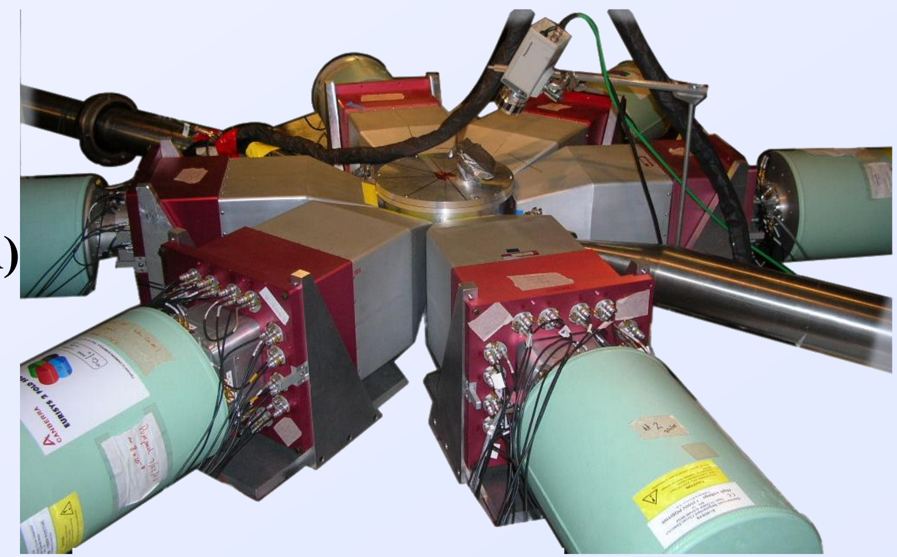
Experimental Set-up with STARS-LiBerACE

Enriched, self-supporting, metal ^{154,156,158}Gd targets bombarded with 22-MeV protons from the 88-Inch Cyclotron at LBNL to create the same compound nuclei as ^{153,155,157}Gd(n,γ) reactions

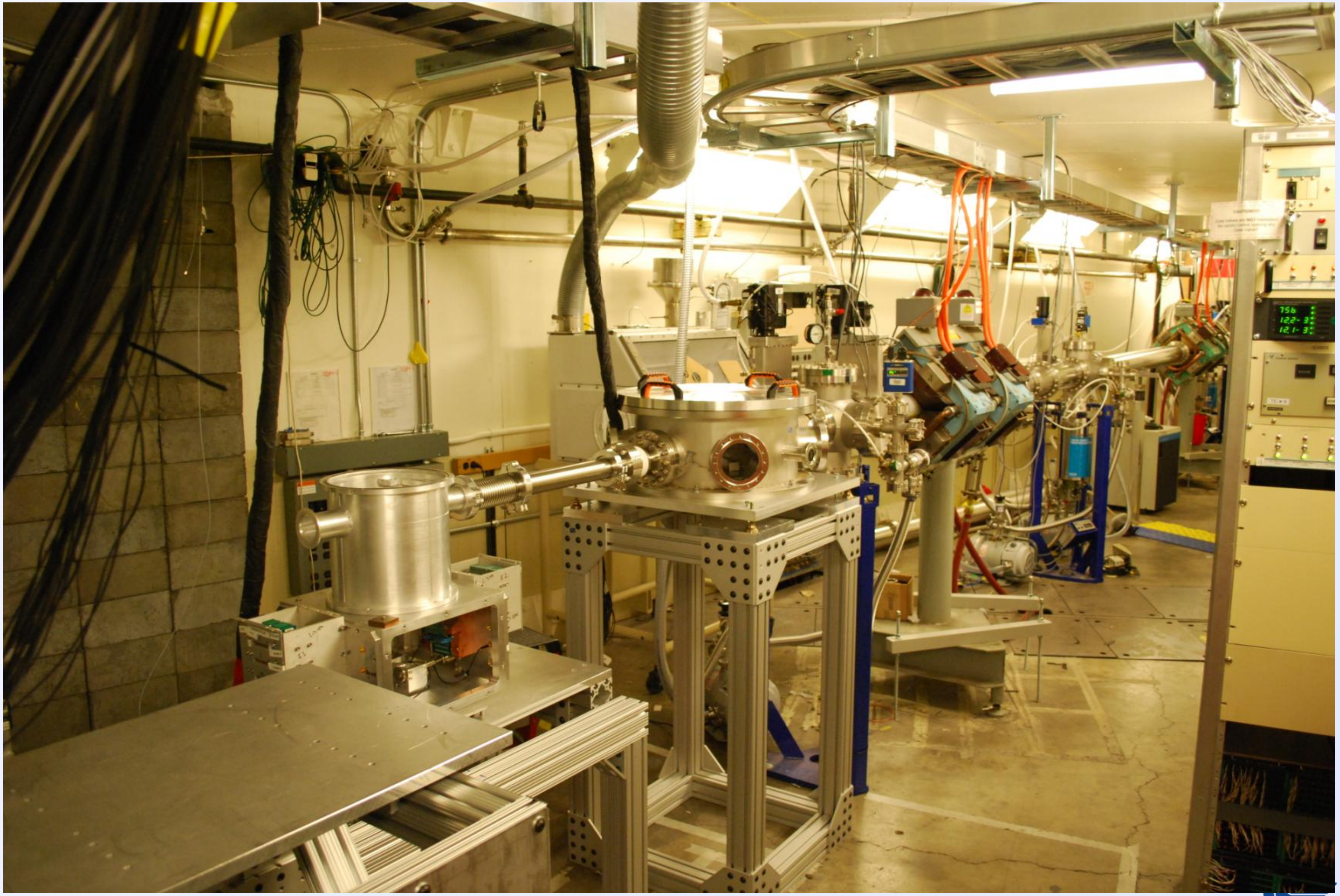
Detect scattered *p* in segmented silicon detector array



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



New experimental hall – Cave 2 @ 88 Inch Cyclotron
$150k investment in equipment by LLNL

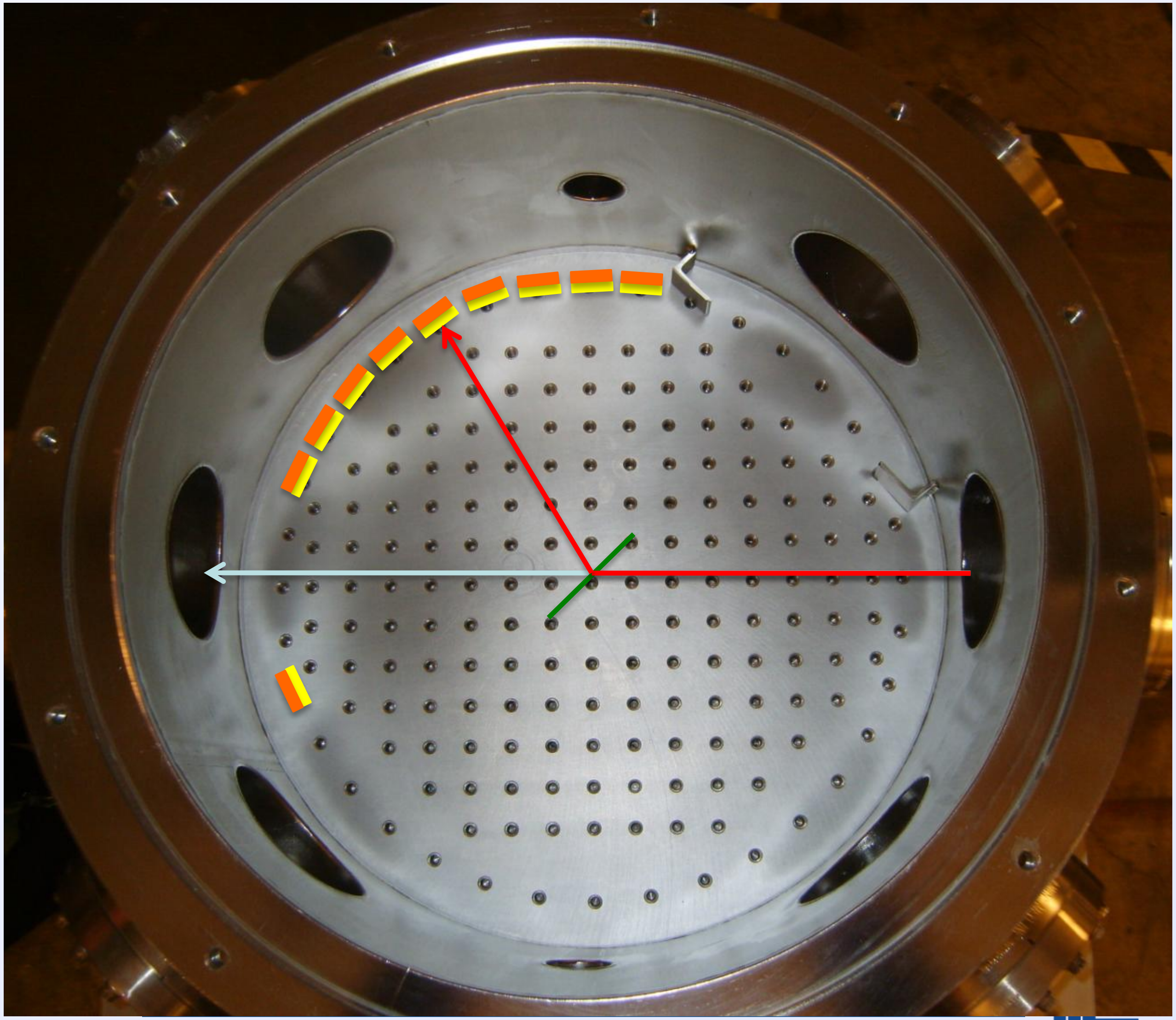


Hydra
New scattering chamber for precision studies.

- 17 inch diameter
- 9 inch deep
- dome roof for out of plane studies of fission

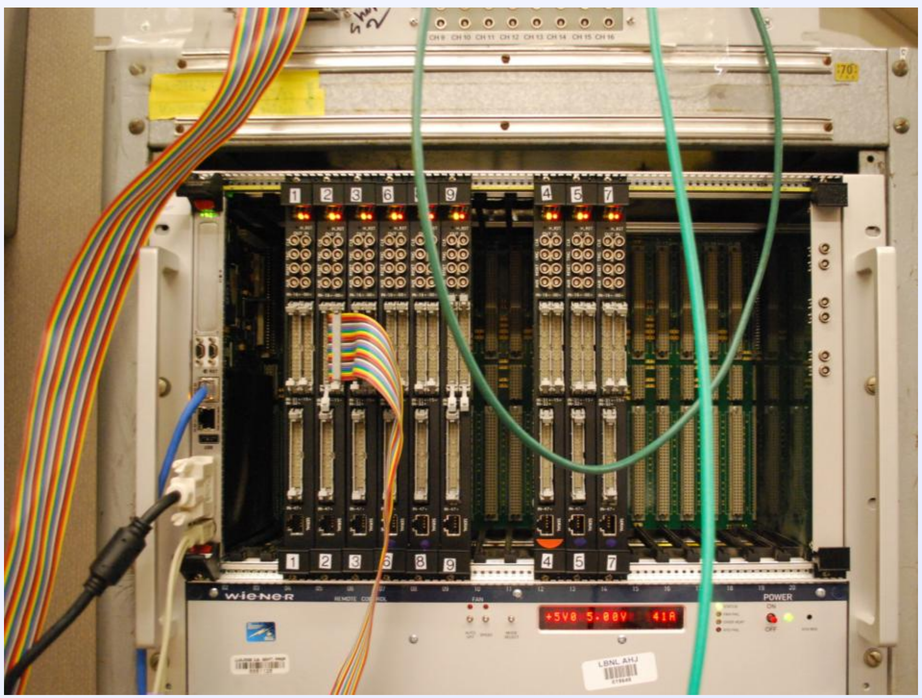
Delta E – E telescope

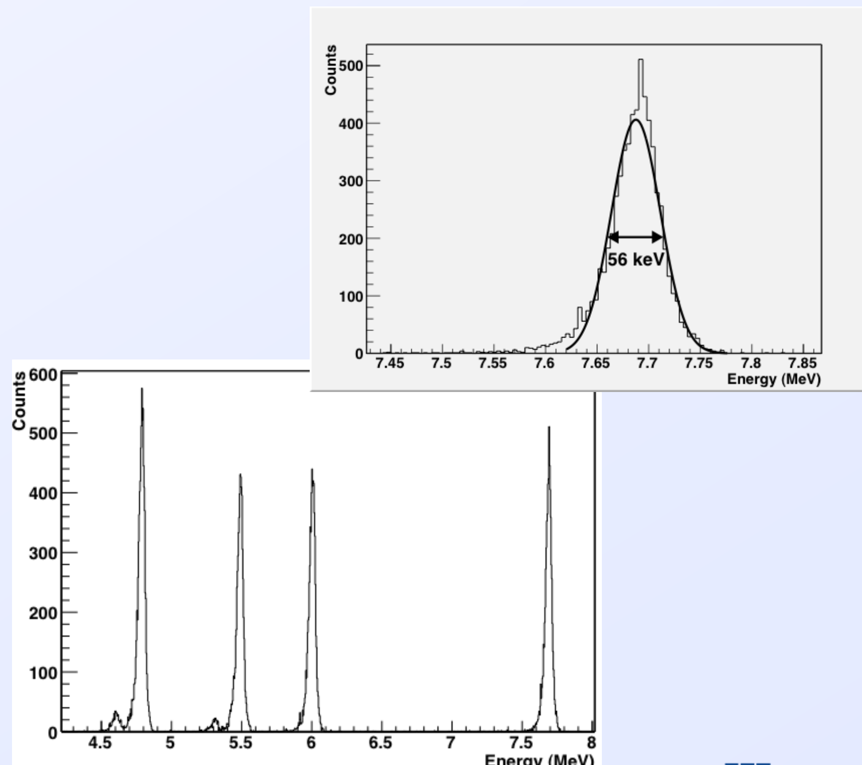
- Up to 12 or so ΔEE pairs
- 200 μm thick ΔE
- 5000 μm thick E
- 2 degree uncertainty due to acceptance



Digital Electronics Upgrade – VF48 VME
$150k investment from LBNL/U.Richmond/LLNL

- Silicon digital electronics:
  - 528 channels of energy and time with waveform sampling of each channel. 10 bit ADCs which have 12 bit equivalent number of bits resolution (4096 chns).
- Germanium digital electronics:
  - 6 GRETINA 10 channel modules which have 14 enob resolution.





New detectors courtesy NA-22
$60k investment in new detectors LLNL

Delta E – E telescope

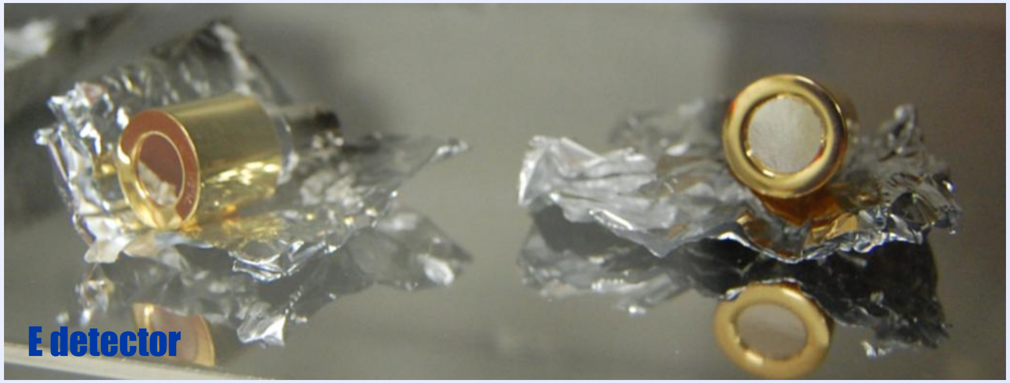
Stops a 33 MeV proton

- Up to 12 or so ΔEE pairs

- 200 μm thick ΔE

-5000 μm thick E

-2 degree uncertainty due to acceptance



Upcoming work on CS for FY10

-Continue to develop surrogate method reaction theory Ian Thompson, Jutta Escher, Jason Burke & Nick Scielzo

-Measure (n,gamma) and/or (n,2n) cross sections in Y/Zr region - LLNL

-Measure ^{238}Pu(n,f) cross section over energy range of 0 to 20 MeV – LLNL/NA-22

-Measure ^{23x}Np(n,f) cross section – UCB/Donuts

-Collaborate with French labs BRC/CENBG to measure ^{17x}Lu(n,gamma) cross sections using surrogate technique

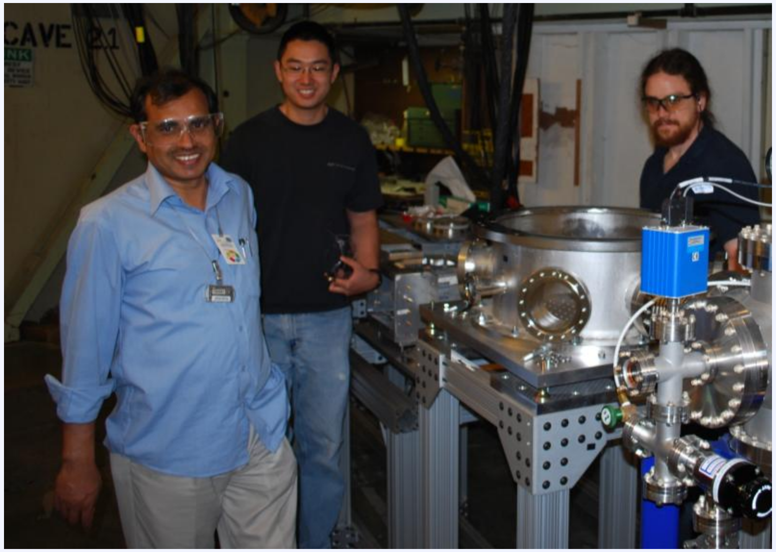
-Start collaboration with JAERI I. Nishinaka – interested in surrogate method

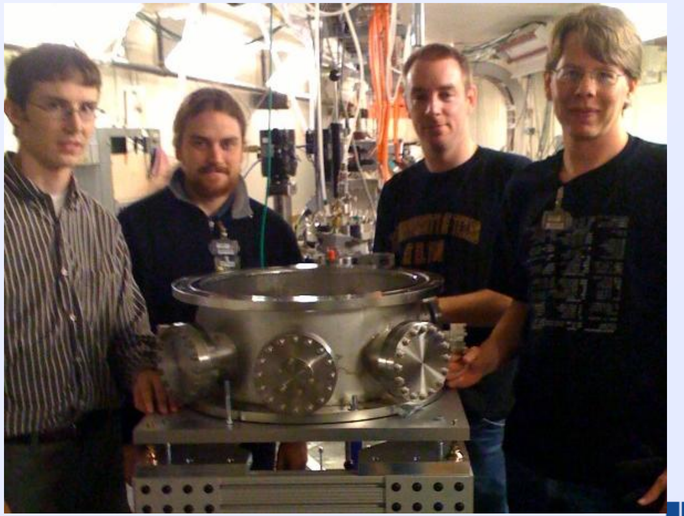
-New People coming to join the Collaboration:

- -D. Meyer – Prof., Rhodes College/SSAA
- -Tim Ross – GS, University of Surrey
- -J. Ressler – Staff, LLNL
- -TBD - Post-Doc, University of Richmond/SSAA
- -Robert Casperson – Post-Doc, LLNL

Ultimate goal of the Surrogate Program is to be able to measure cross sections in inverse kinematics experiments at FRIB

Really a team effort among institutions





Collaborators (students in red post-docs underlined)

J. Burke, N. Scielzo, I. Thompson, J. Escher, L.A. Bernstein, D. Bleuel, M. Wiedeking,

K. Moody, M. Stoyer R. Henderson

Lawrence Livermore National Laboratory

L.W. Phair, S. Basunia, P.Fallon, R.M. Clark, I.Y. Lee, A.O. Macchiavelli, M.A. McMahan

Lawrence Berkeley National Laboratory

C.W. Beausang and J.M. Allmond

University of Richmond

T. Ross

University of Surrey

J.J.Ressler and J.A.Caggiano

Pacific Northwest National Laboratory

J.A. Cizewski, P.D. O'Malley and T. Swan

Rutgers University

E.B. Norman, R. Hatarik, B.F. Lyles, R. Yee and C. Angell

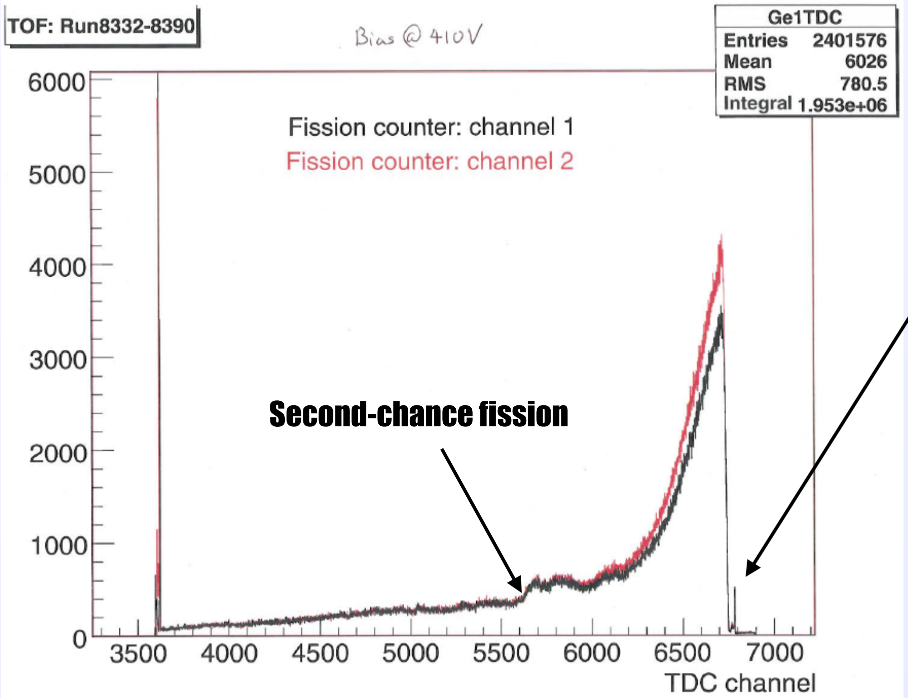
University of California Berkeley

D. A. Meyer

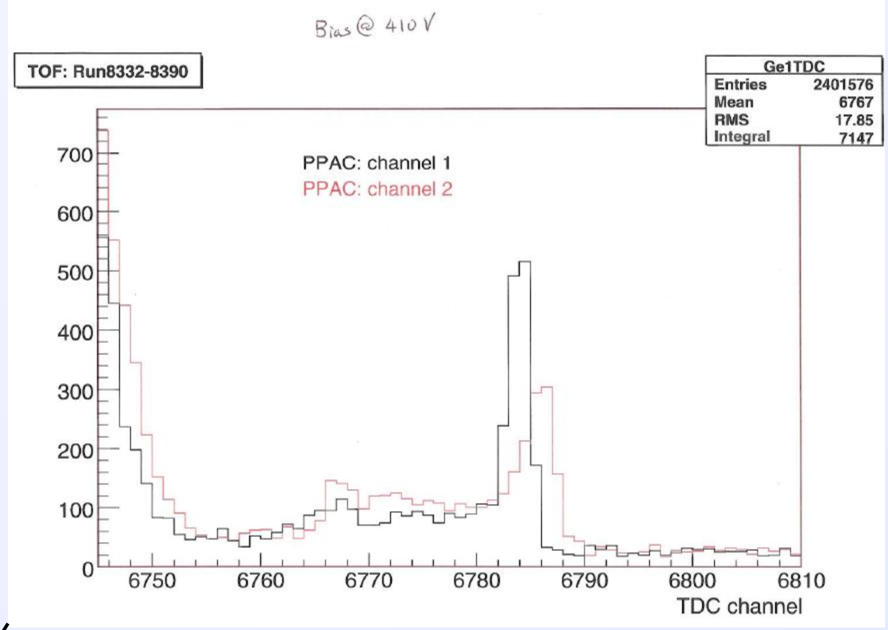
Rhodes College

Fission chamber performance – Ching-Yen Wu

Time-of-flight spectra



Second-chance fission

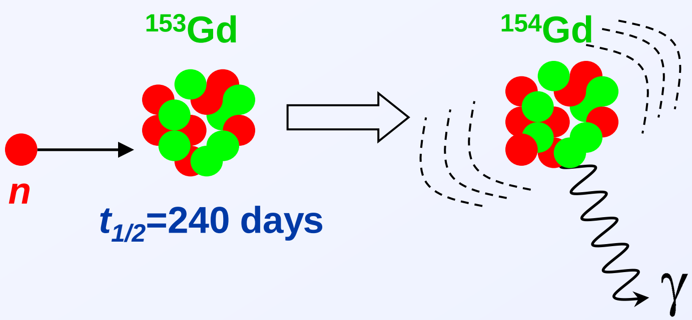


Photofission peak with a time-resolution ~ 1 ns

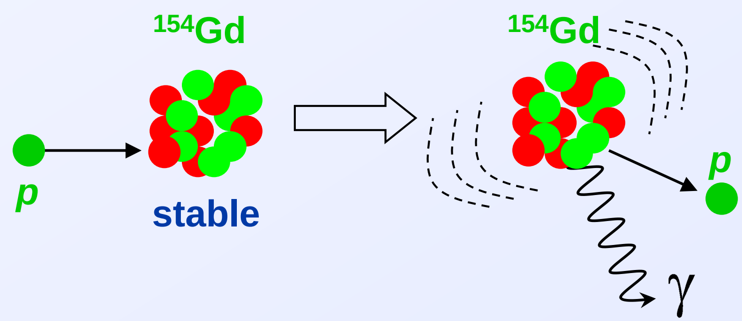
Weisskopf-Ewing Approximation

Weisskopf-Ewing Approximation: branching ratios $\boldsymbol{G_\chi^{CN}}$ are independent of spin and parity when many decay channels are open

"Desired" reaction



"Surrogate" reaction



$$\sigma_{\alpha\chi}(E) = \sigma_\chi^{CN}(E) \cdot G_\chi^{CN}(E)$$

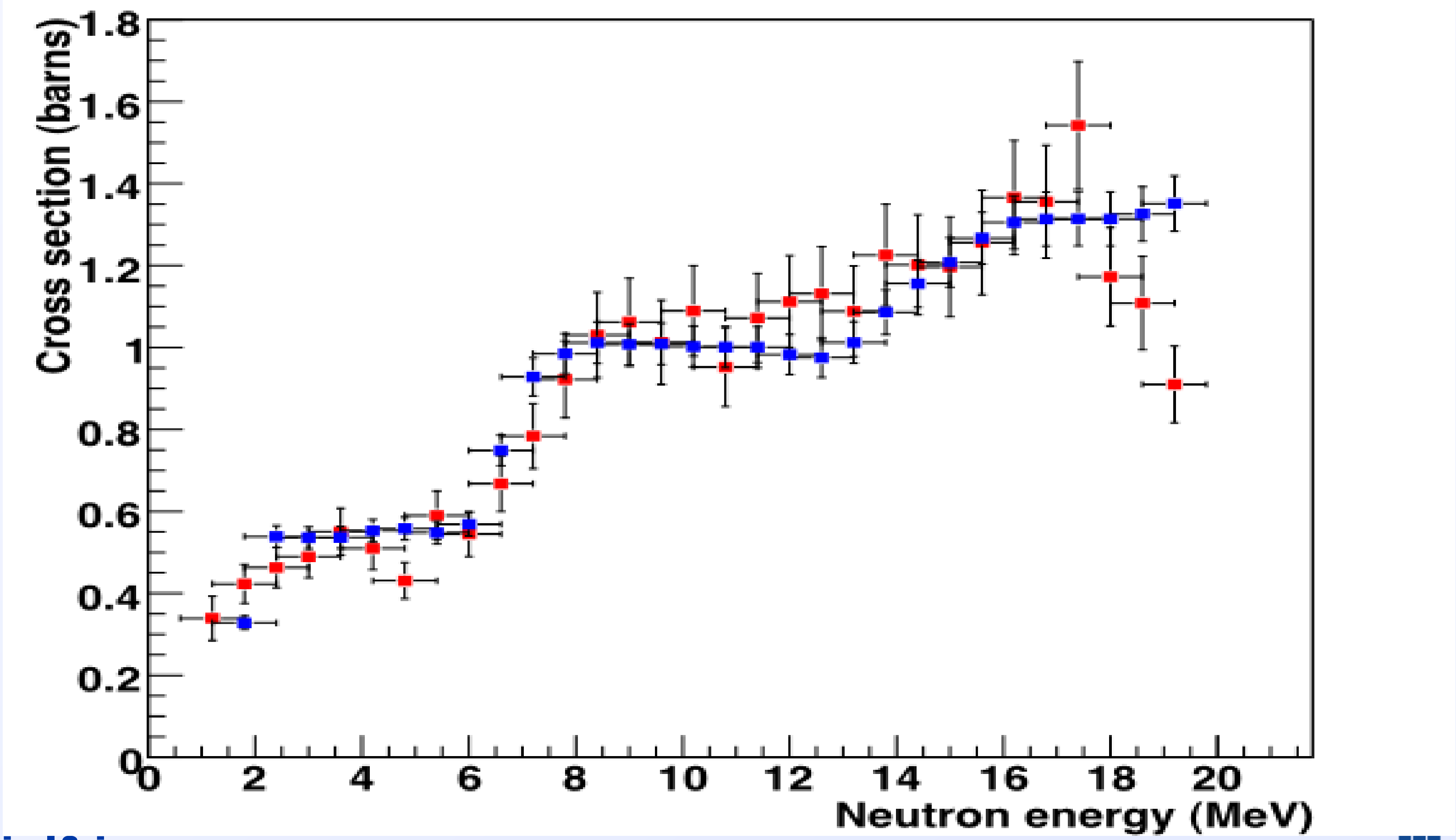
Hauser-Feshbach theory describes the "desired" reaction as a product of entrance channels (σ_α^{CN} – *can be calculated reliably*) and exit channel branching ratios ($\boldsymbol{G_\chi^{CN}}$ – *can't be calculated reliably*)

$$P_\chi(E) = G_\chi^{CN}(E) = \frac{N_{(p,p\gamma)}(E)}{N_{(p,p)}(E)}$$

Alternative ("surrogate") reaction can be used to form the same compound-nucleus of interest and determine $\boldsymbol{G_\chi^{CN}}$

$^{238}U(n,f)$ determined from $^{238}U(^{18}O,^{17}O)^{239}U$/ $^{234}U(^{18}O,^{17}O)^{235}U$
J.T. Burke (LLNL)

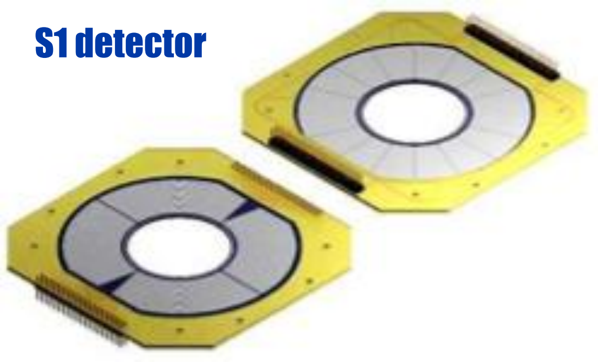
$$\sigma\left(^{238}U(n,f)\right)=\frac{N_{p-f}(^{238}U(^{18}O,^{17}Of))}{N_{p-f}(^{234}U(^{18}O,^{17}Of))}\times\sigma\left(^{234}U(n,f)\right)$$

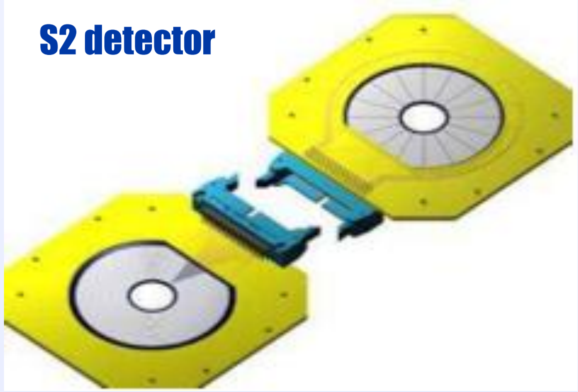


Electronics Upgrade: Implementation started Burke and Phair

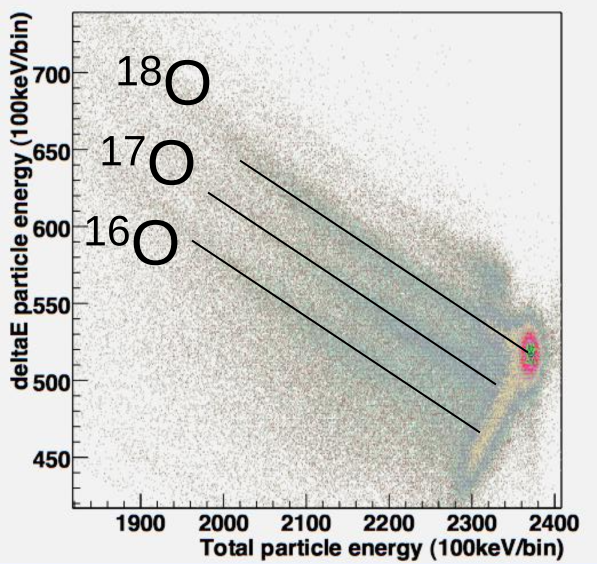
- Silicon detectors:
  - 140 µm, 500 µm, 1000 µm thick silicon S2
    - 48 rings 0.5 mm wide and 16 sectors (64 channels needed)
  - 500 µm, 1000 µm thick silicon S1
    - 48 rings 0.5 mm wide and 16 sectors (64 channels needed)
  - 300 µm, 1000 µm thick silicon W2
    - 4x16=64 rings 1.5 mm wide and 16 sectors (80 channels needed)

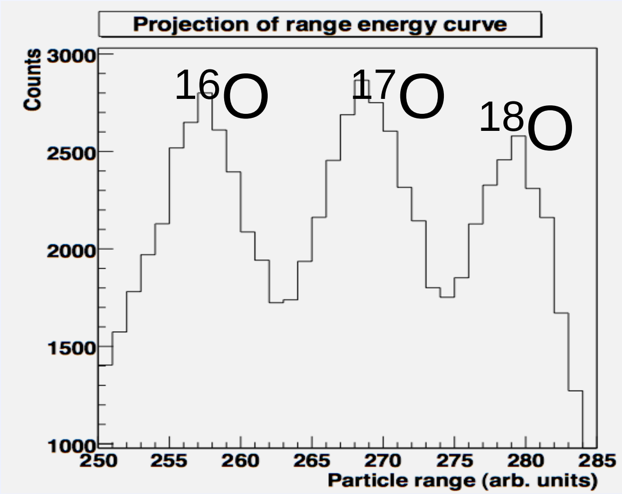
Typical experiment: STARS annular telescope (128 to 144 channels)
STRIPES square telescope (2X(32+32)=128 channels)
Total silicon channels = 256 to 272 channels of energy and time



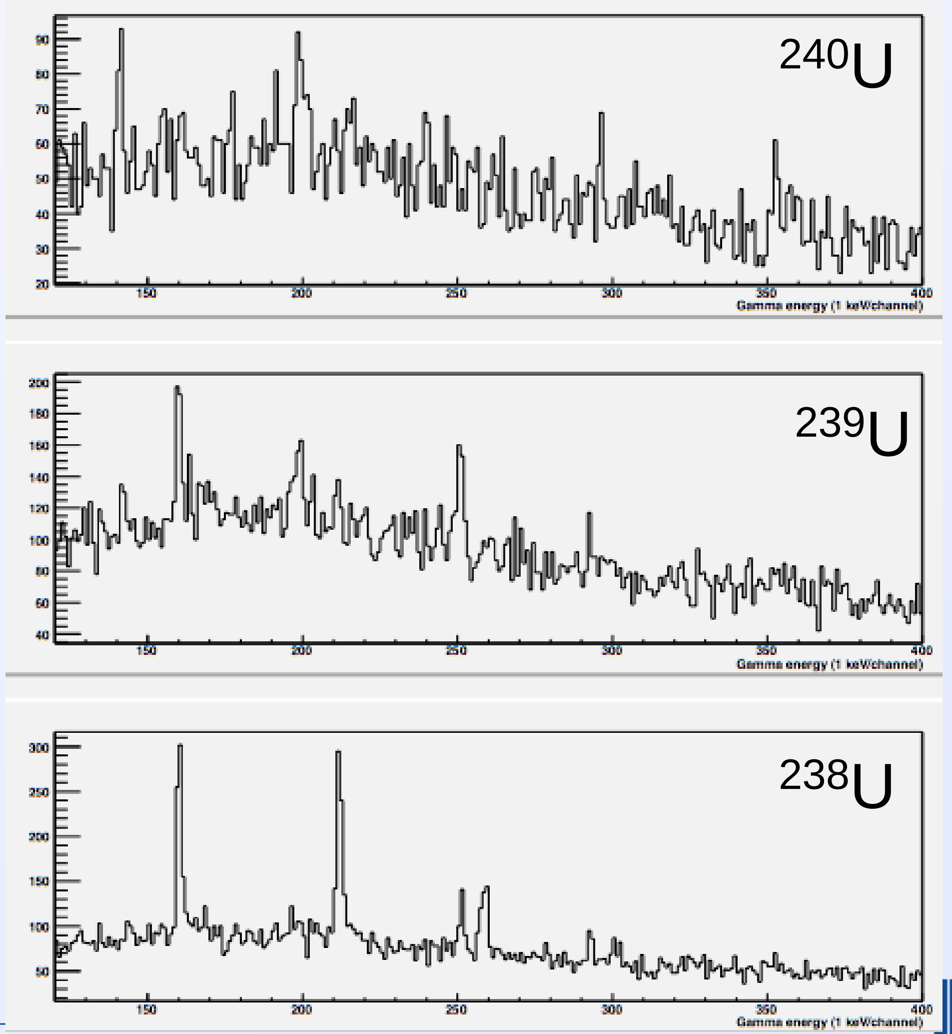


$^{239}U(n,f)(n,\gamma)$, and (n,2n) ($\tau_{1/2}$=24minutes) determined from the $^{238}U(^{18}O,^{16}O)^{240}U$ (preliminary data analysis)

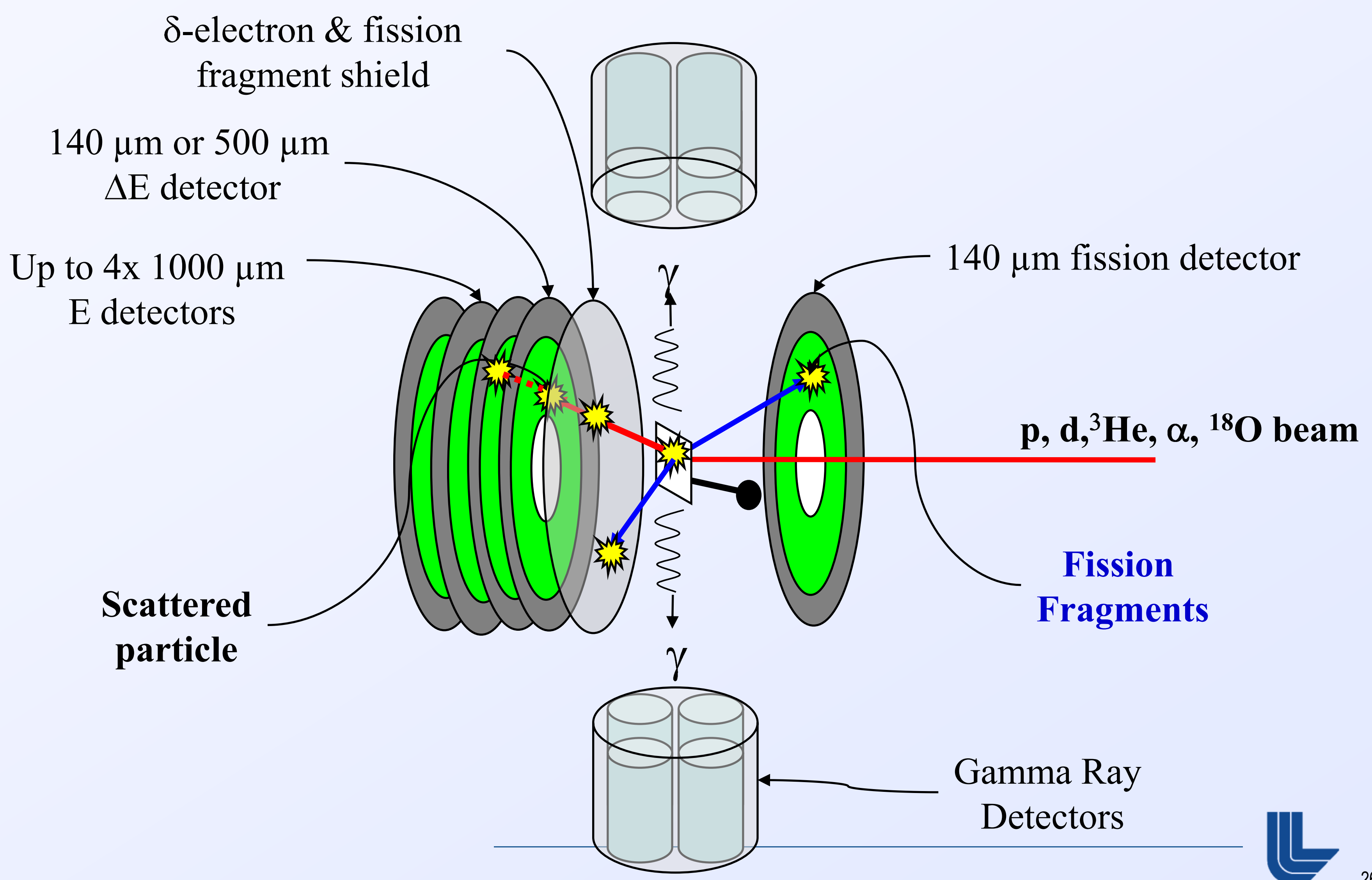




Gamma ray spectrum gated on ^{16}O



Silicon Telescope Array for Reaction Studies (STARS)
Livermore Berkeley Array for Collaborative Experiments (LIBERACE)



Surrogate Nuclear Reactions Approach

The Surrogate Nuclear Reactions approach is an indirect method for determining cross sections of compound-nuclear reactions

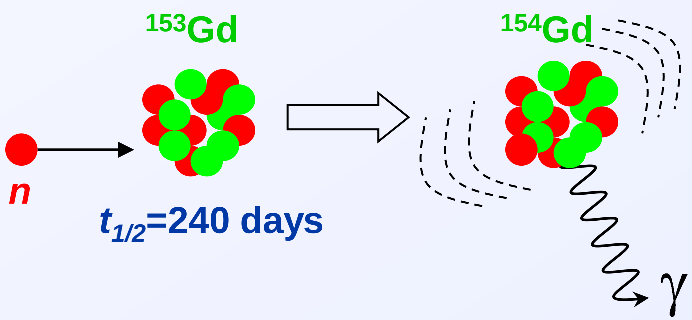
Used when direct measurements are not possible because of beam and/or target limitations.

For *s*-process branch nuclei, this approach circumvents limitations imposed by low flux of neutron beams and small mass of radioactive targets – create compound nucleus through reaction of light-ion beam on a stable isotope of same element

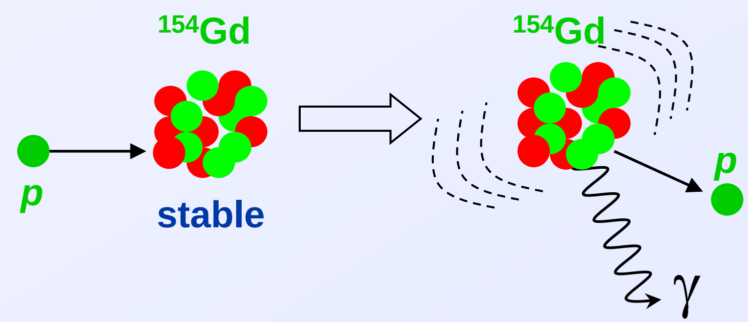
Surrogate nuclear reaction method using (p,p')

The surrogate nuclear reactions approach is an indirect method for determining cross sections of compound-nuclear reactions that can be used when direct measurements are not possible because of beam and/or target limitations.

"Desired" reaction



"Surrogate" reaction



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

Hauser-Feshbach theory describes the "desired" reaction as a product of entrance channels (σ_α^{CN} – *can be calculated reliably*) and exit channel branching ratios (***G_χ^{CN}*** – *can't be calculated reliably*)

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

Alternative ("surrogate") reaction can be used to form the same compound-nucleus of interest and determine ***G_χ^{CN}***

We measure this ratio

Measuring γ-ray decay probabilities

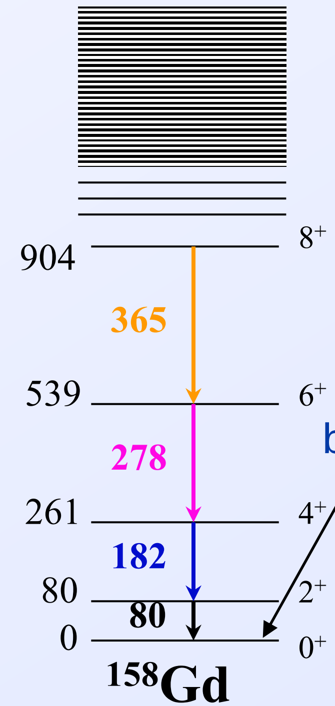
γ-ray decay probability can be measured:

$$P_{(p,p\gamma)}(E_{ex}) = \frac{\varepsilon_p (1+\alpha_{IC})}{\varepsilon_p \varepsilon_\gamma f} \times \frac{N^{obs}_{(p,p\gamma)}(E_{ex})}{N^{obs}_{(p,p)}(E_{ex})}$$

with E_{ex} determined from scattered proton energy:

$$E_{ex} = E_{beam} - (E_p^{obs} + E_{deadlayer} + E_{recoil})$$

Ground state band collects majority of γ-ray strength

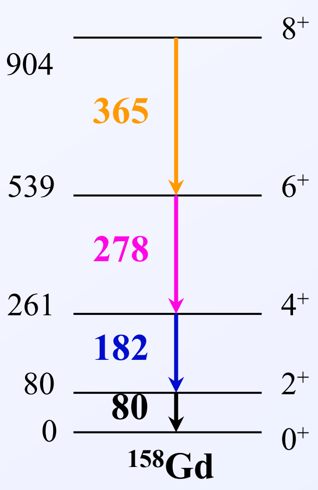


but a fraction of decays (1 – f) bypass transition

(Energies in keV)

γ-ray Detection

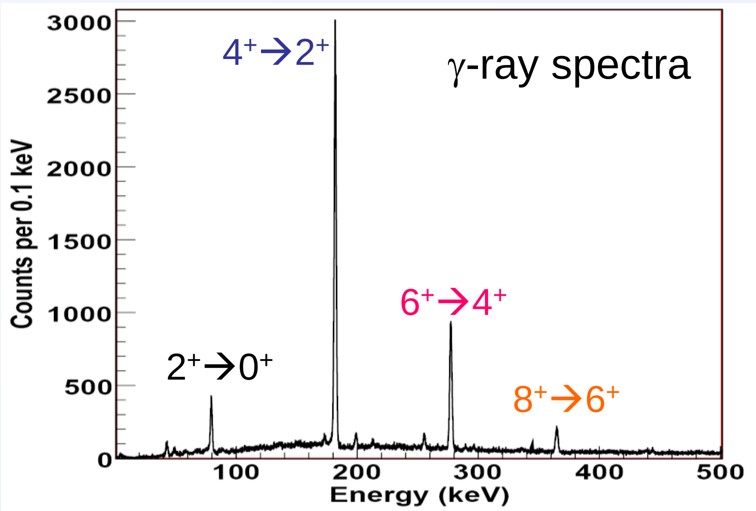
As nucleus de-excites, many γ-ray cascades pass through the lowest excited states



(Energies in keV)

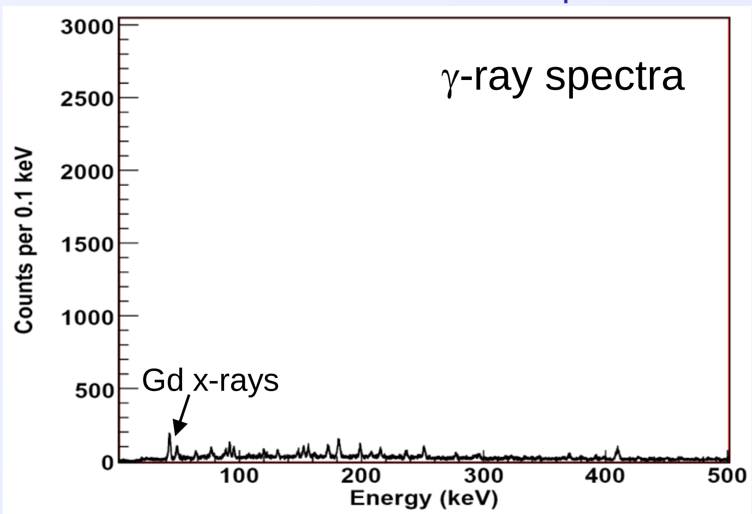
Excitation Energy < S_n

Nucleus de-excites through γ emission



Excitation Energy > S_n

Neutron emission more probable



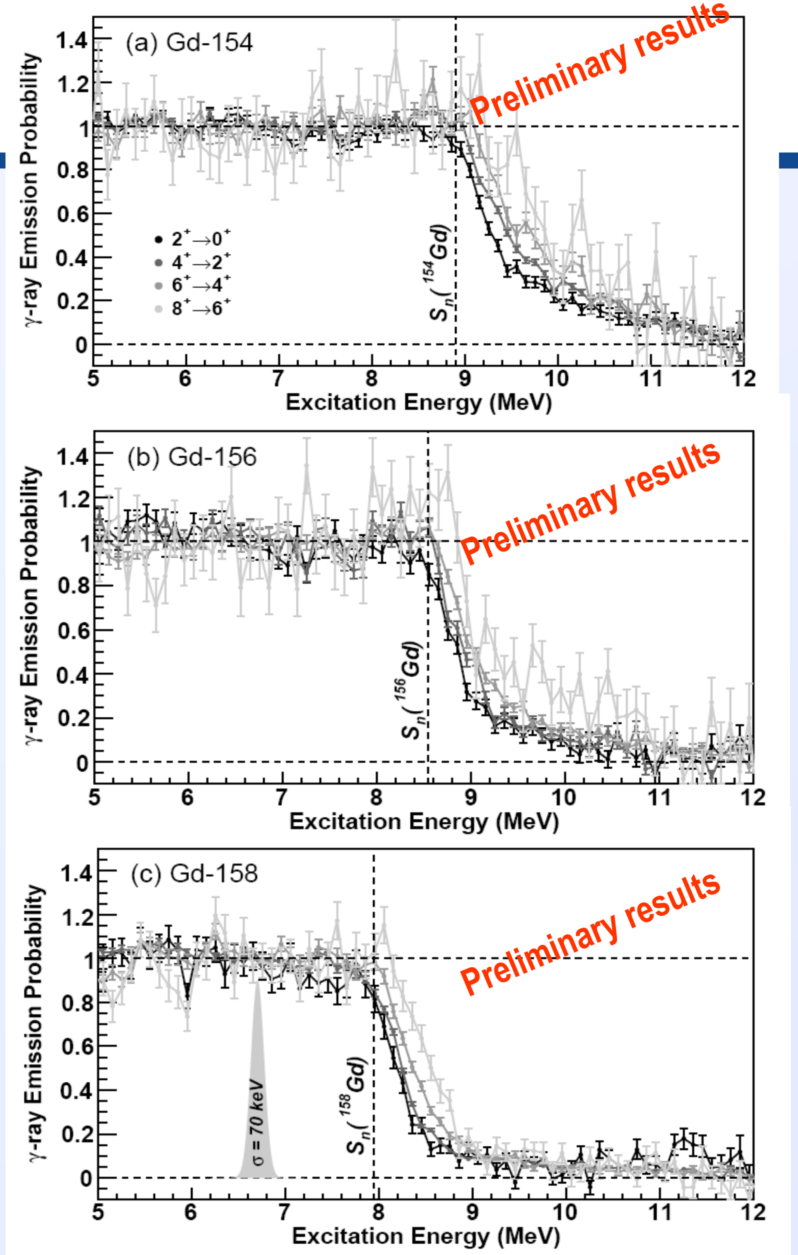
All $8^+ \rightarrow 6^+$, $6^+ \rightarrow 4^+$, $4^+ \rightarrow 2^+$, and $2^+ \rightarrow 0^+$ transition γ-rays observed with good statistics.

Exit Channel Probabilities

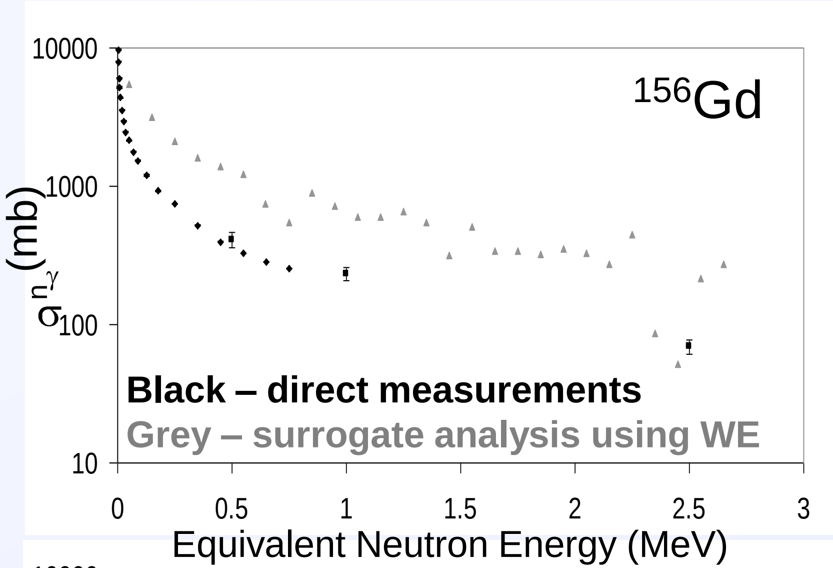
$$P_{(p,p\gamma)}(E_{ex}) = \frac{(1+\alpha_{IC})}{\varepsilon_\gamma f} \times \frac{N^{obs}_{(p,p\gamma)}(E_{ex})}{N^{obs}_{(p,p)}(E_{ex})}$$

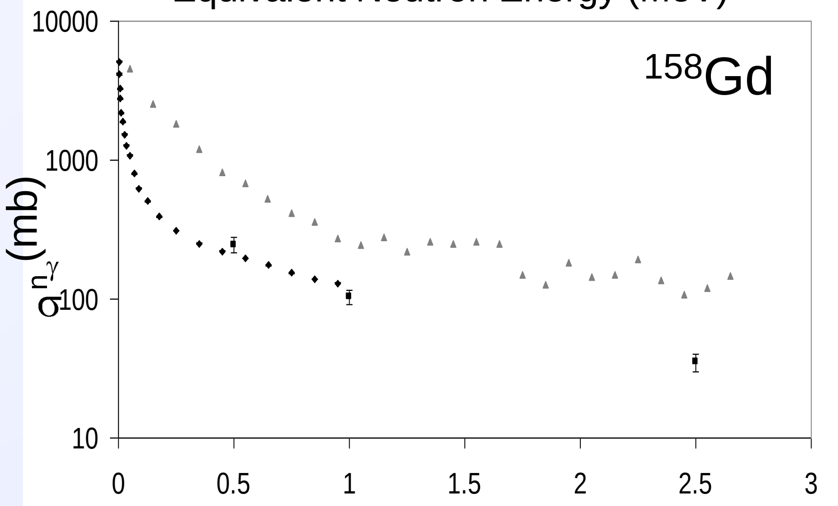
With $P_{(p,p\gamma)}$ at hand, next step is to combine these experimental results with reaction modeling to determine (n,γ) cross sections…

…and compare to known ^{155}Gd and ^{157}Gd cross sections to determine reliability



Weisskopf-Ewing Approximation





Absolute cross sections obtained using Weisskopf-Ewing approximation (assuming spin-parity of compound nucleus doesn't matter) and absorption cross sections. No surprise this simple strategy doesn't work.

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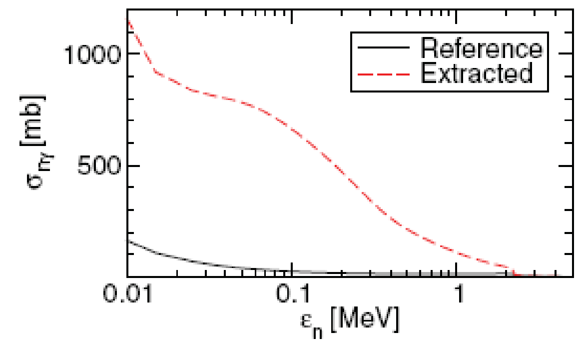
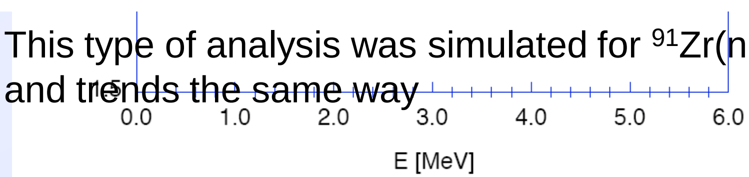


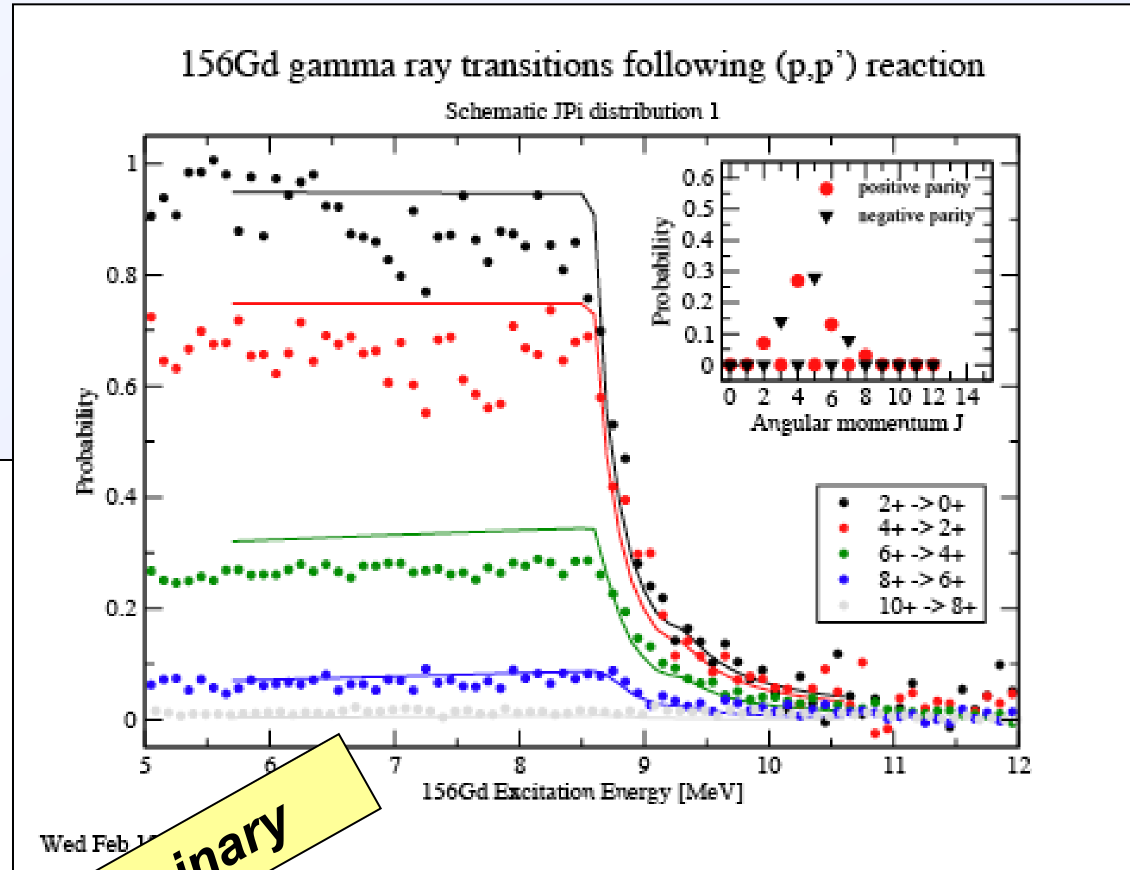
FIG. 7. (Color online) Extraction of (n, γ) cross section from a surrogate experiment simulation using the Weisskopf-Ewing approximation; see WE simulation of Table III and discussion in text.

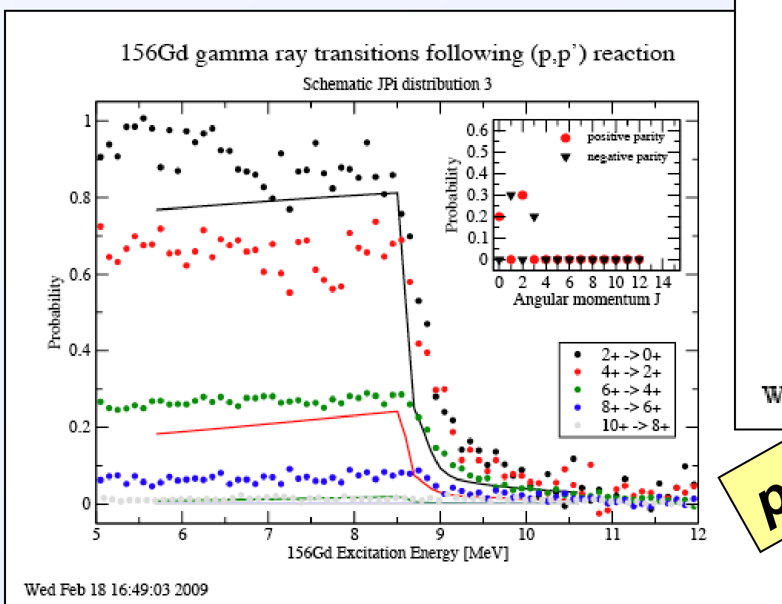
This type of analysis was simulated for $^{91}Zr(n,\gamma)^{92}Zr$ and trends the same way



Determining the compound nucleus spin-parity

Measured relative γ-ray yields compared to calculated yields for various spin distributions (error bars not shown).





Conclusions and outlook

- Developing new technique to measure (n,γ) cross sections for radioactive isotopes
- Surrogate nuclear reactions method combines measured exit channel probabilities with reaction modeling
- Exit channel probabilities for ^{153,155,157}Gd(n,γ) surrogate reactions have been measured
- Effort underway to determine J^{π} sensitivity and incorporate entrance channel to extract cross sections

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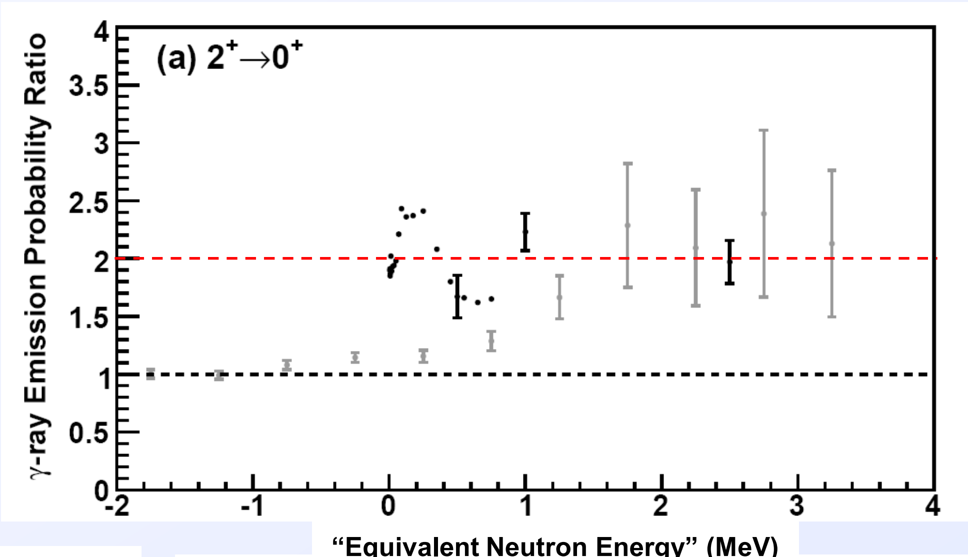
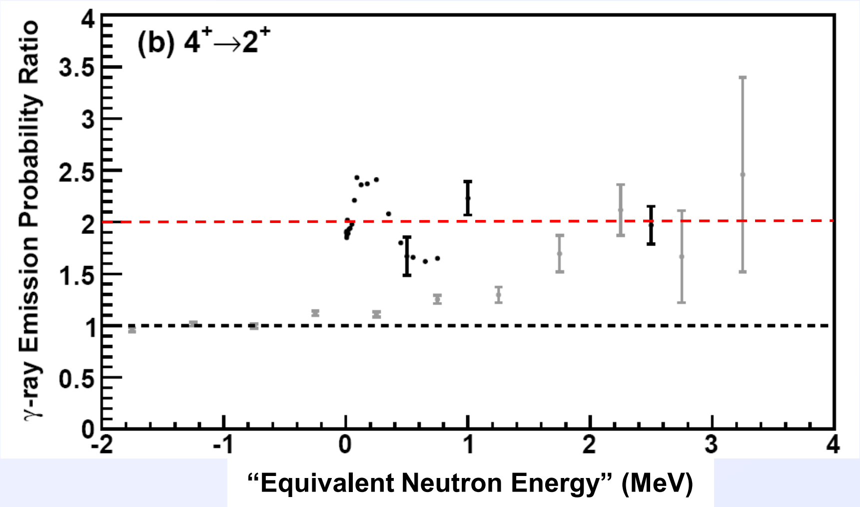
What about ratios?

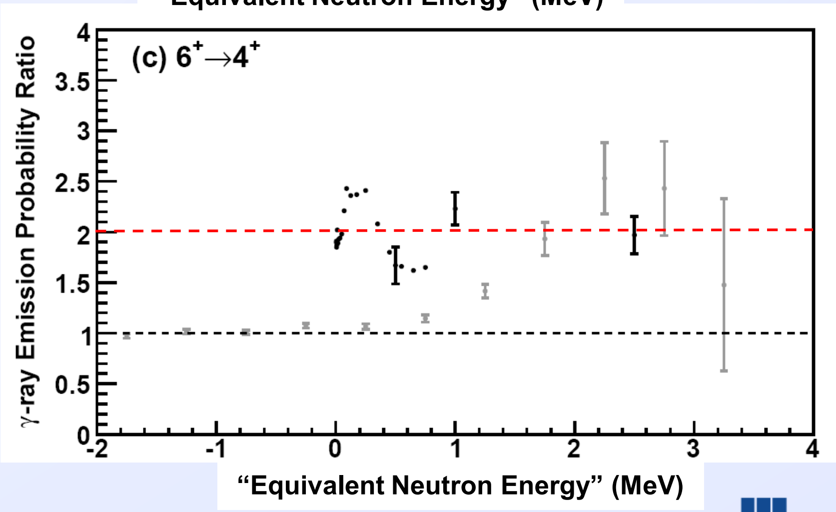
If we assume J^π issues cancel in ratio:

$$\frac{\sigma_{156}(E_n)}{\sigma_{158}(E_n)} \approx \frac{P_{156}(E_n)}{P_{158}(E_n)}$$

in "neutron energy", so the $P_{(p,p\gamma)}$ spectra are shifted by ΔS_n of 0.5 MeV





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