Surrogate reactions for (n,f) and (n,g) cross sections

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J.T. Burke
STARLiTeR Collaboration

Lawrence Livermore National Laboratory

LLNL-PRES-XXXXXX

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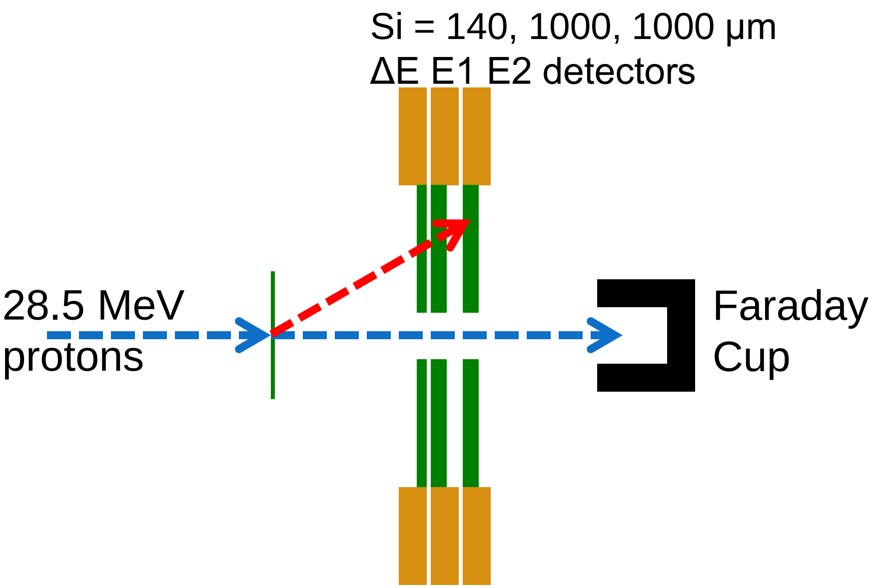
Overview

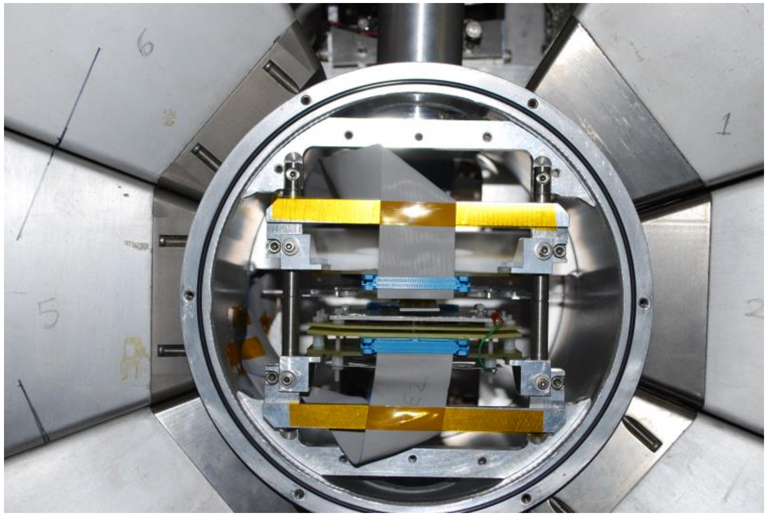
- Brief discussion of experimental setup – STARLiTeR
- Surrogate ratio measurements of (n,f) cross sections
  - Am24X
  - Pu23X
- Absolute surrogate measurement of 87Y(n,g)
- Summary

StarLiTeR at Texas A&M

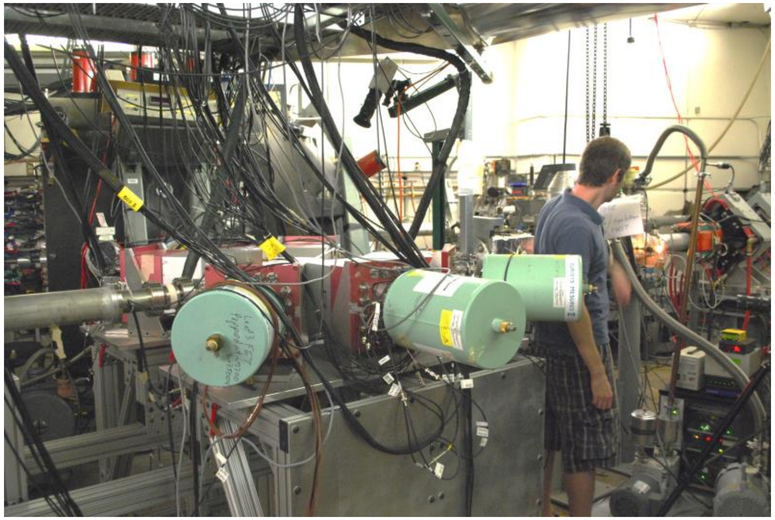


We record the total energy, angle and determine the particle type

Top view of the STARLiTeR array. Beam enters from top and exits bottom. HPGe surrounds chamber Si telescope in center.



STARLiTeR array closed up around the chamber. Cyclotron beam comes in from the right and exits on the left.

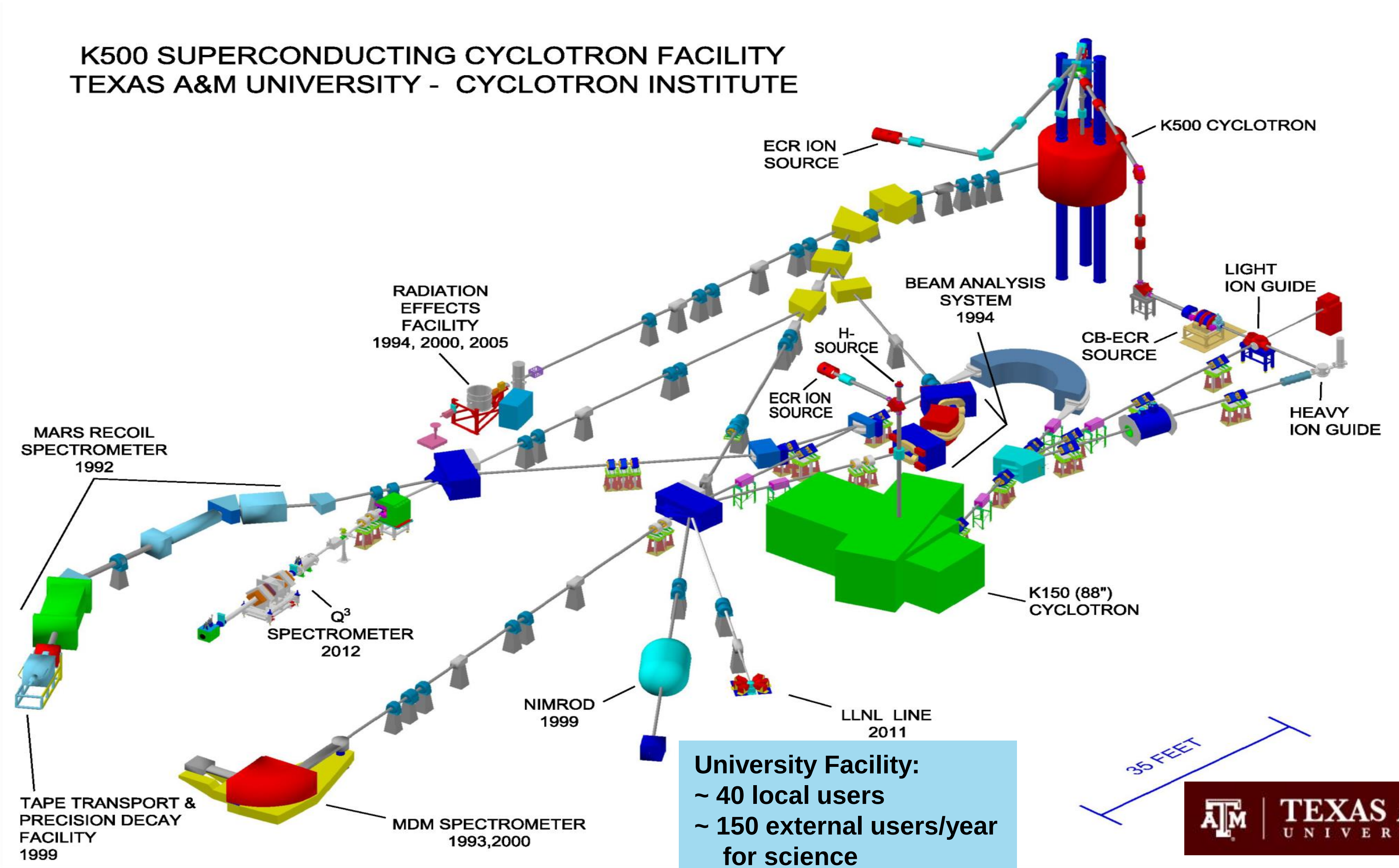


We have run 10 experiments totaling 11 weeks of beam time since April 2012.

Six more experiments planned through summer 2014.

Typical values:
- Si energy resolution 75 keV one sigma
- Gamma energy resolution 1.7 keV one sigma
- Angle range 30 to 60 degrees

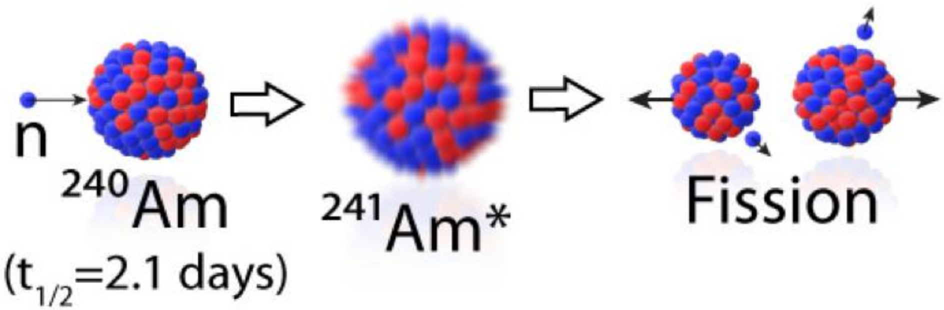
Texas A&M Cyclotron Institute, College Station, Texas
Two machines: K150 and K500 Cyclotrons stable beams available and radioactive beams under development



University Facility:
~ 40 local users
~ 150 external users/year for science

The desired reaction: $^{240}Am(n,f)$

This reaction has never been measured. ^{240}Am has a half-life of 2.1 days, which makes it unreasonable to use as a target.

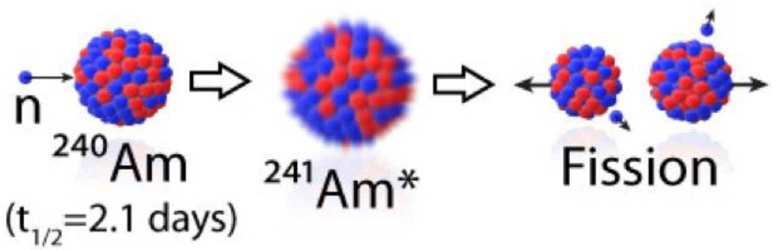


^{239}Am	^{240}Am	^{241}Am	^{242}Am	^{243}Am	^{244}Am
12 hours	2.1 days	433 years	16 hours	7370 years	10 hours

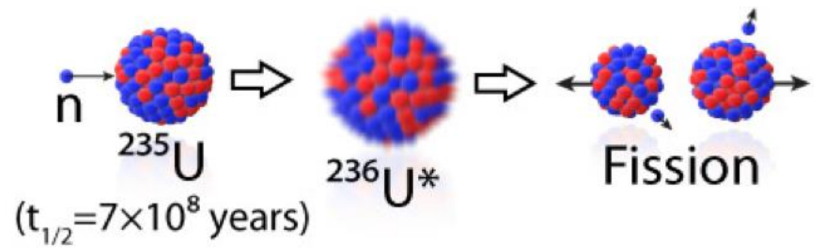
The surrogate ratio technique can be used, by populating the same compound nucleus using a longer-lived target.

The Surrogate Reaction

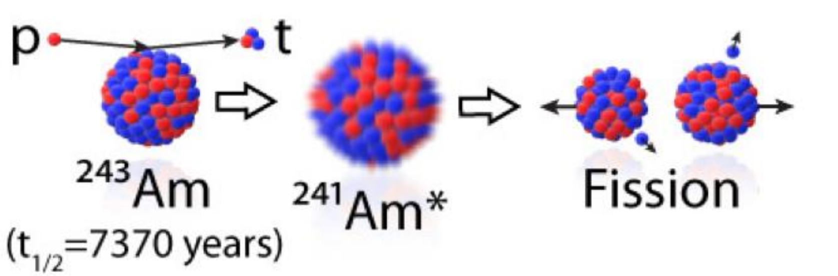
Desired Reaction: ^{240}Am(n,f)



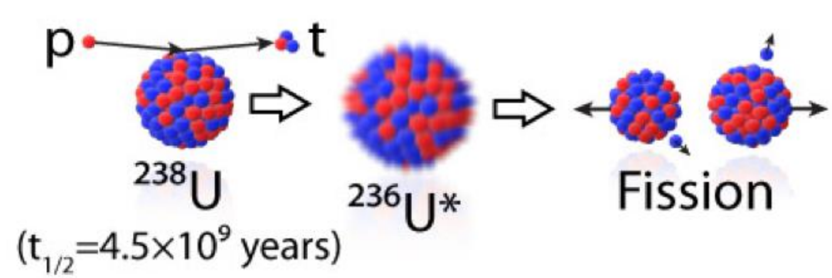
Reference Reaction: ^{235}U(n,f)



Surrogate Reaction: ^{243}Am(p,tf)



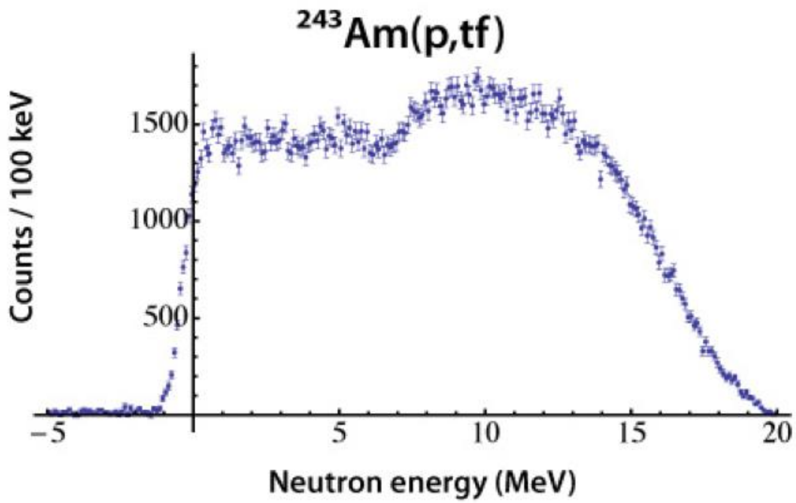
Ratio Reaction: ^{238}U(p,tf)

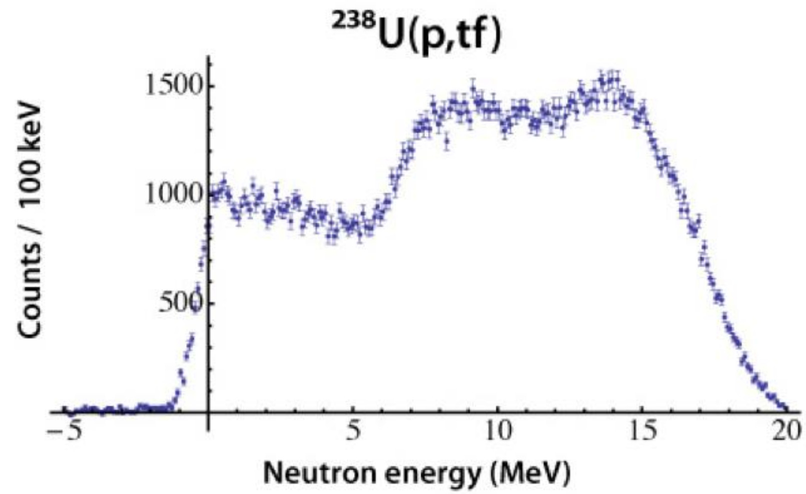


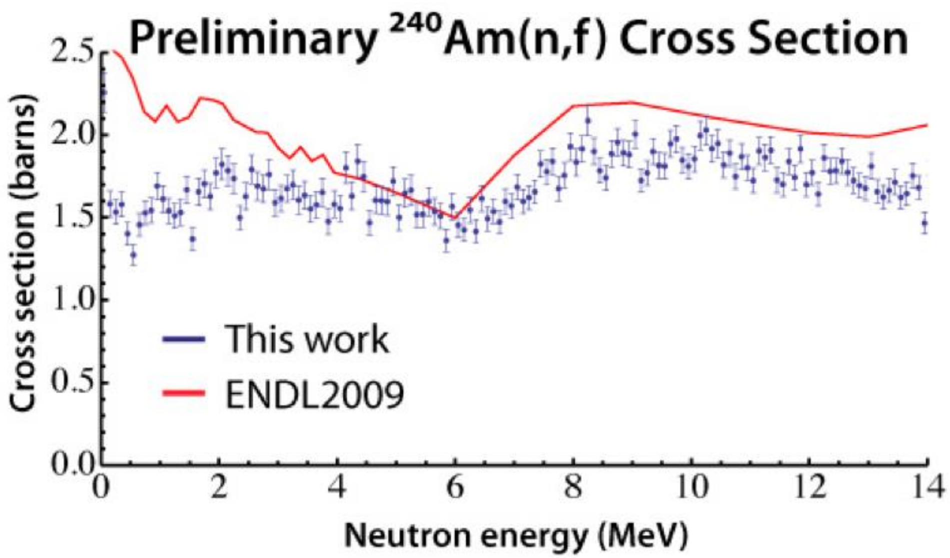
$$\sigma(^{240}\mathrm{Am}(n,f),E) = \frac{N(^{243}\mathrm{Am}(p,tf),E)}{N(^{238}\mathrm{U}(p,tf),E)} \times \frac{\sigma_{CN}(^{240}\mathrm{Am}(n,tot)^{241}\mathrm{Am}^{*},E)}{\sigma_{CN}(^{235}\mathrm{U}(n,tot)^{236}\mathrm{U}^{*},E)} \times \sigma(^{235}\mathrm{U}(n,f),E)$$

Courtesy Robert Casperson

Particle spectra and ^{240}Am(n,f)



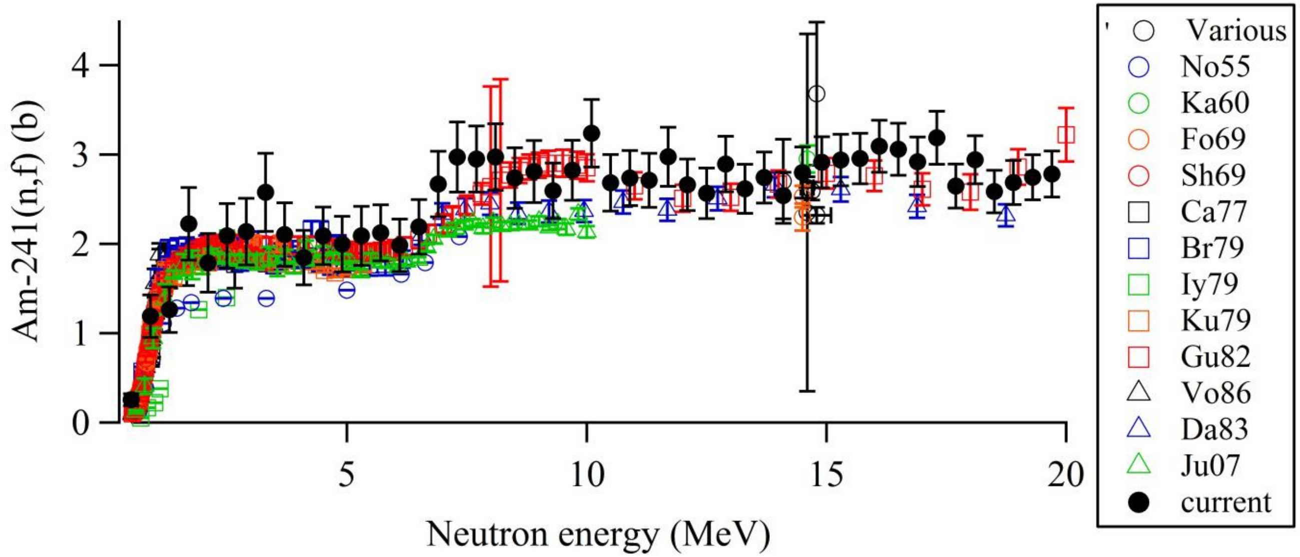


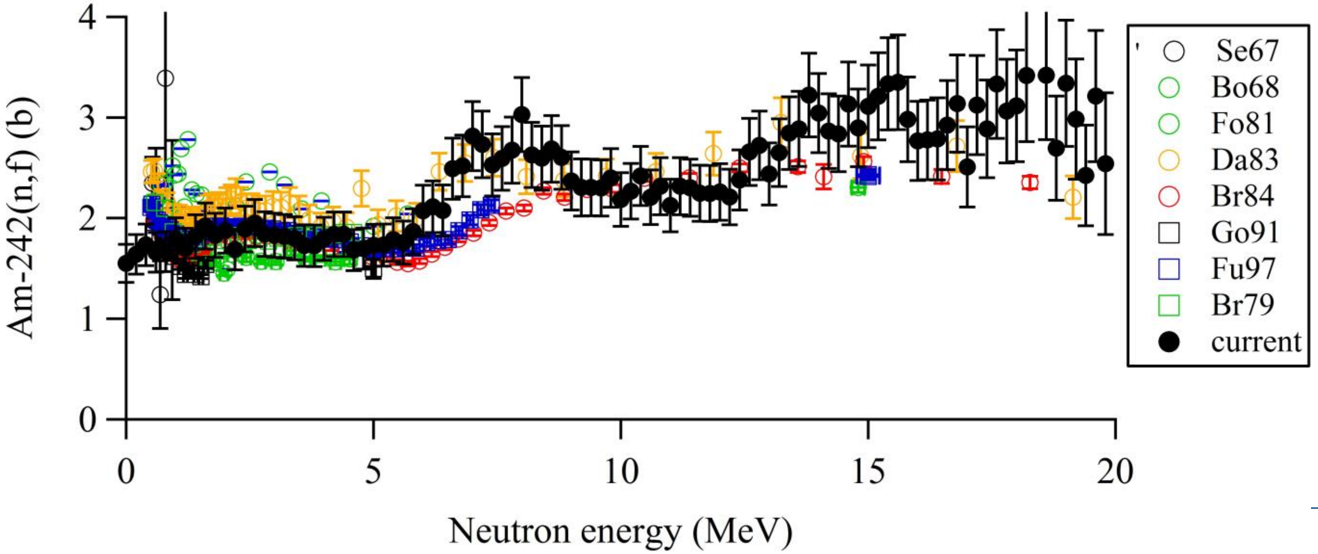


Courtesy Robert Casperson

^{242}Am(n,f) and ^{241}Am(n,f) cross section measurements using the surrogate ratio ^{243}Am(^{3}He,^{3}He') and ^{243}Am(^{3}He,^{4}He) direct reactions and ^{236}U(^{3}He,^{3,4}He)

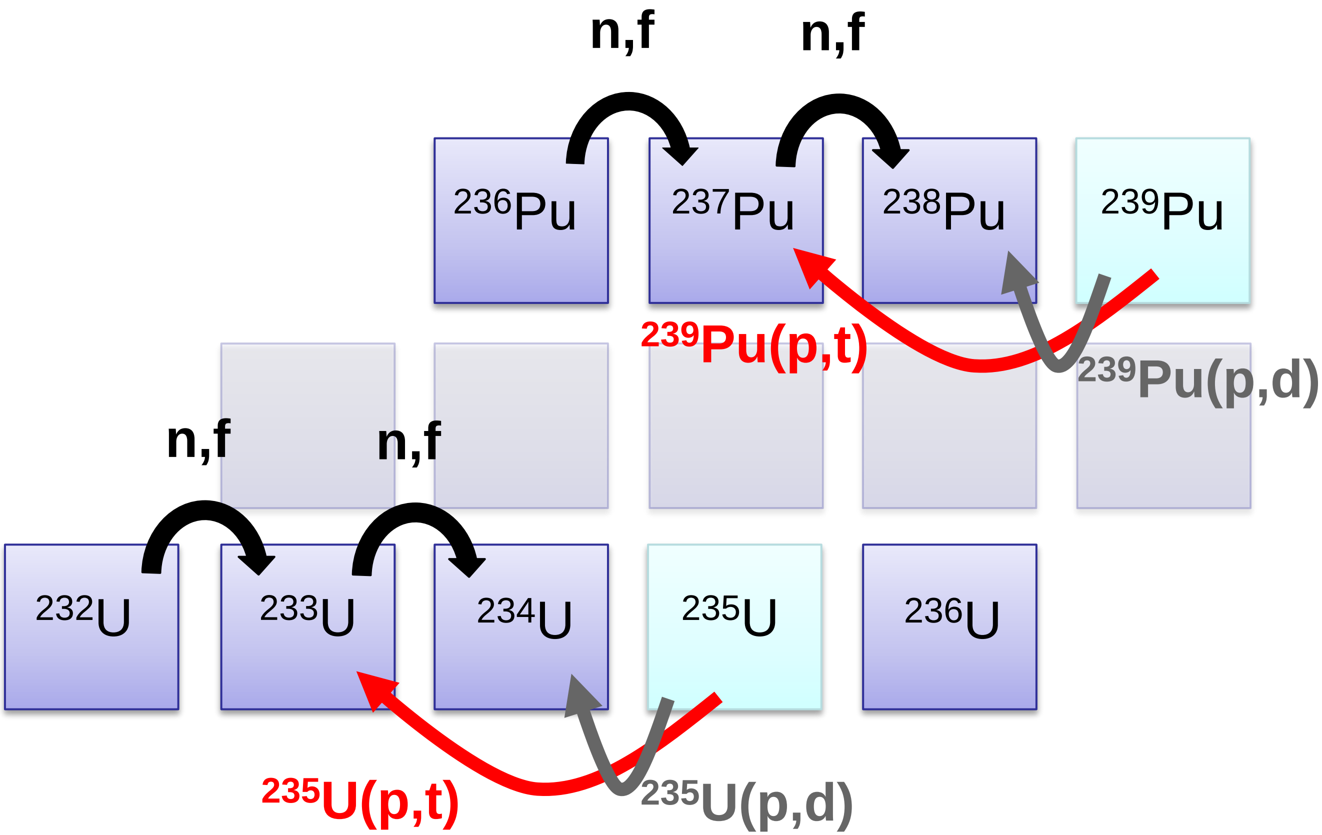
Courtesy Jo Ressler





^{23x}Pu cross section measurements using the Surrogate Ratio

Courtesy Richard Hughes



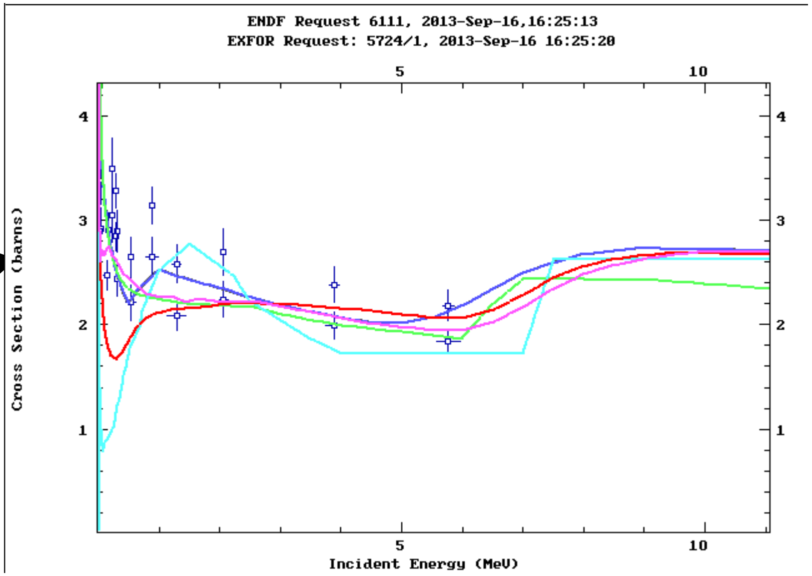
$$\sigma(^{236}Pu(n,f),E) = \frac{N(^{239}Pu((p,tf),E))}{N(^{235}U((p,tf),E))} \cdot \sigma(^{232}U(n,f),E)$$

Investigating ^{236}Pu (n,f) cross sections

Courtesy Richard Hughes

- Half lives rapidly fall off for isotopes lighter than ^{239}Pu:

Isotope	$T_{1/2}$
^{239}Pu	24110 yrs
^{238}Pu	87.7 yrs
^{237}Pu	45.64 days
^{236}Pu	2.86 yrs



Investigating ^{237}Pu (n,f) cross sections

Courtesy Richard Hughes

- Half lives rapidly fall off for isotopes lighter than ^{239}Pu:

Isotope	$T_{1/2}$
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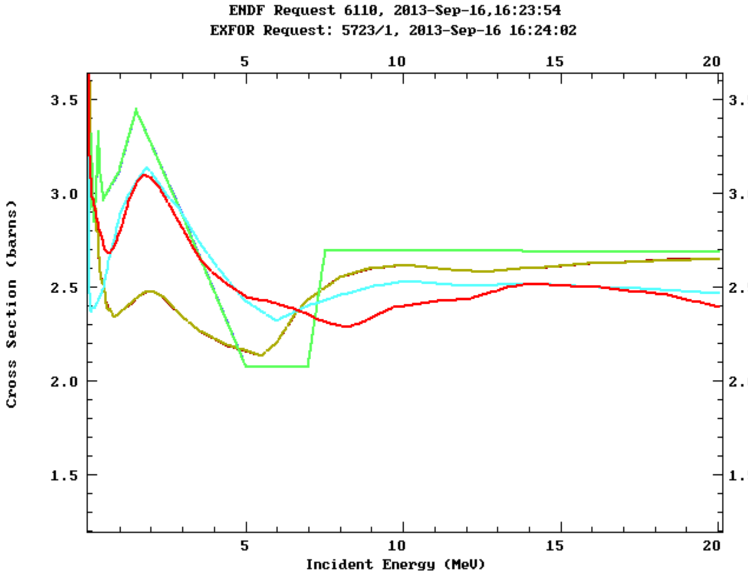

Investigating ^{238}Pu(n,f) cross sections

Courtesy Richard Hughes

- Half lives rapidly fall off for isotopes lighter than ^{239}Pu:

Isotope	$T_{1/2}$
^{239}Pu	24110 yrs
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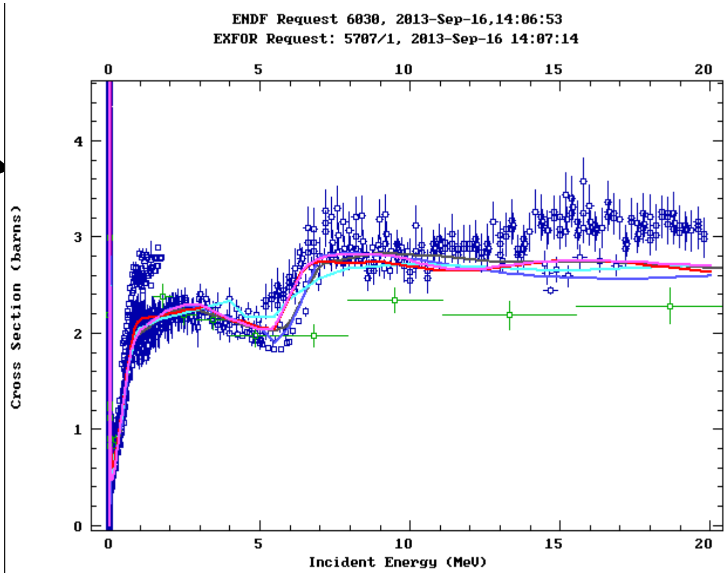
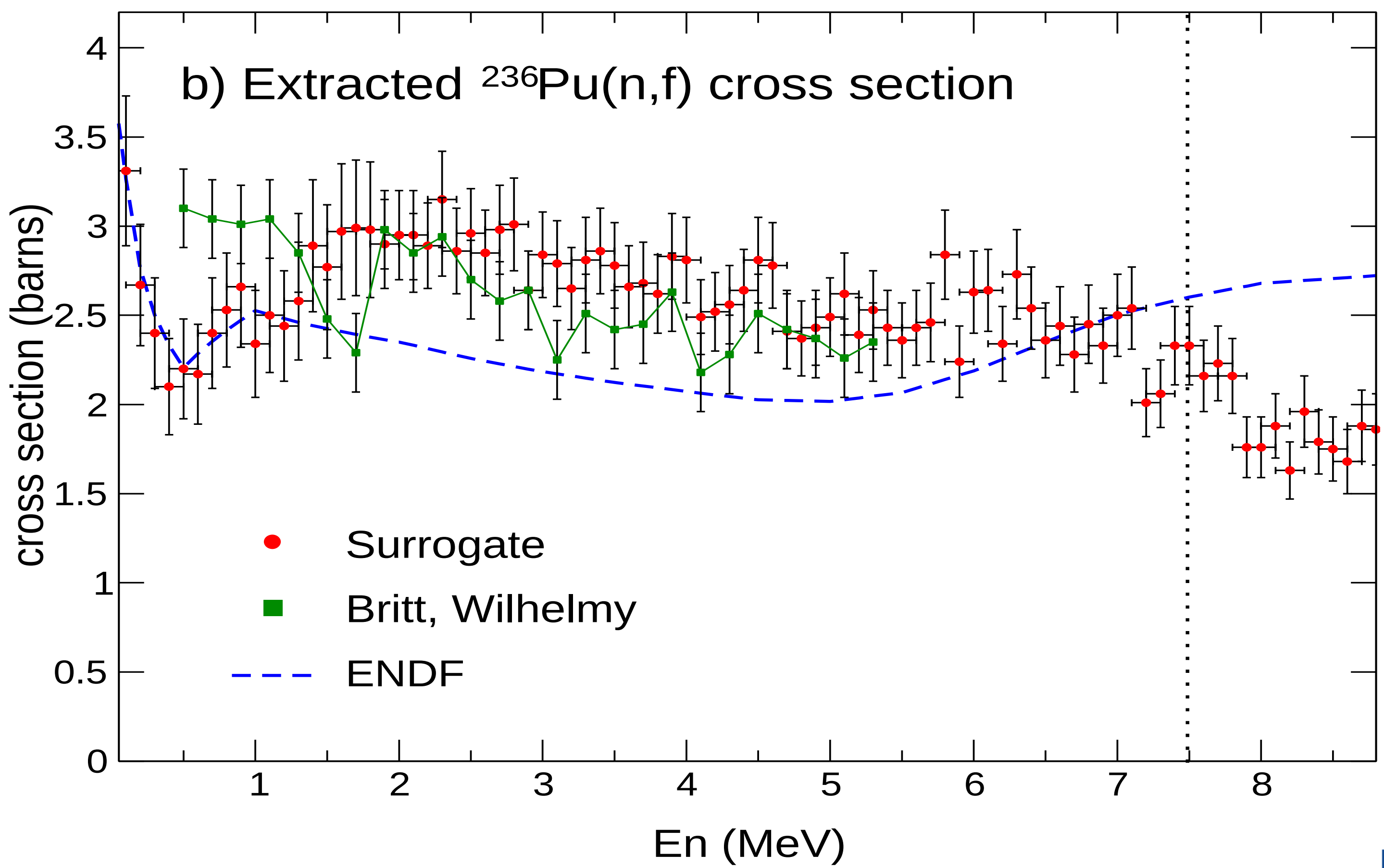
^{236}Pu	2.86 yrs



^{236}Pu(n,f) cross section from ^{239}Pu(p,t)^{237}Pu*/^{235}U(p,t)^{233}U* surrogate ratio

Courtesy Richard Hughes

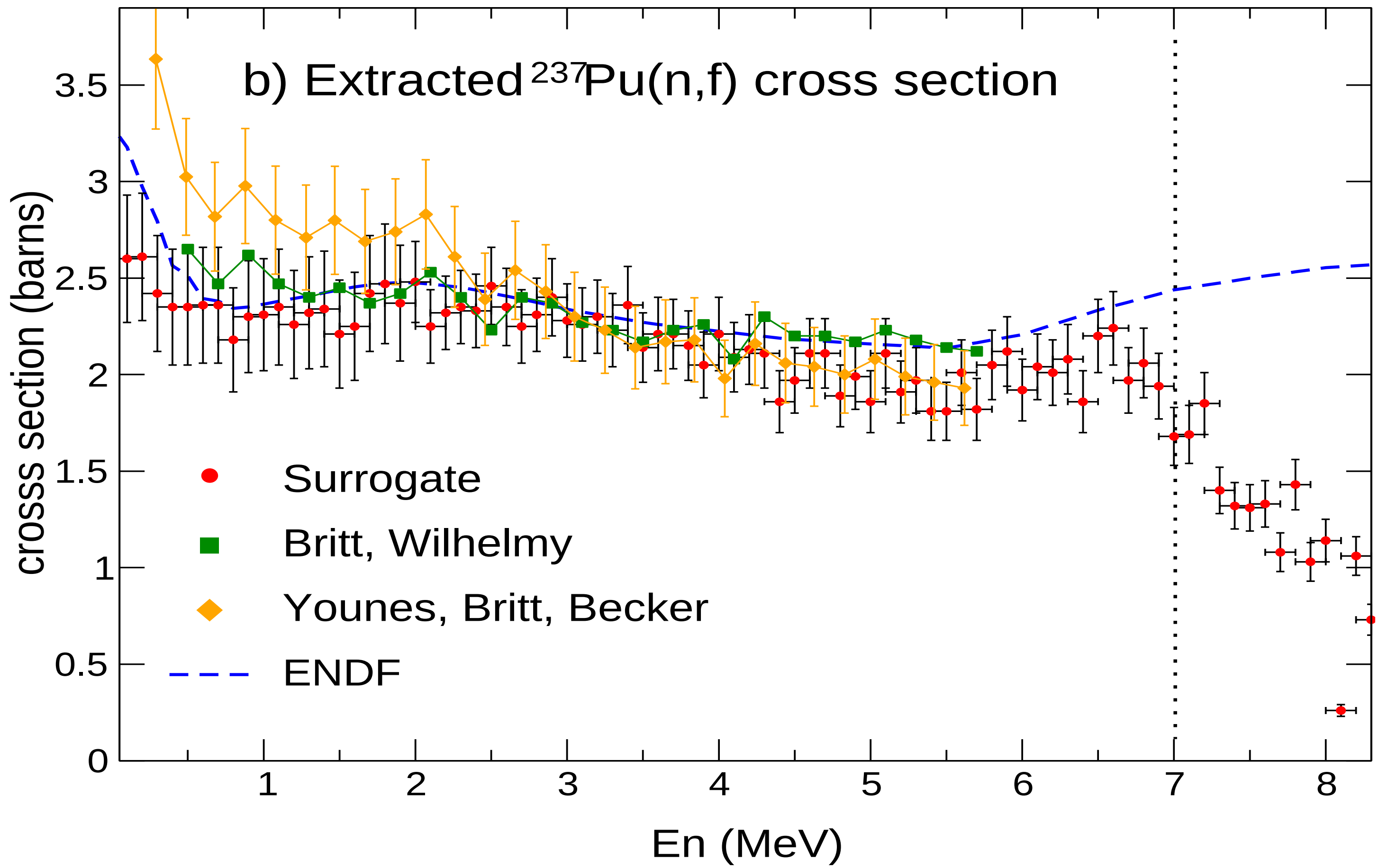
$$\sigma(^{236}Pu(n,f),E) = \frac{N(^{239}Pu((p,tf),E))}{N(^{235}U((p,tf),E))} \times \sigma(^{232}U(n,f),E)$$



^{237}Pu(n,f) cross section from ^{239}Pu(p,d)^{238}Pu*/^{235}U(p,d)^{234}U* surrogate ratio

Courtesy Richard Hughes

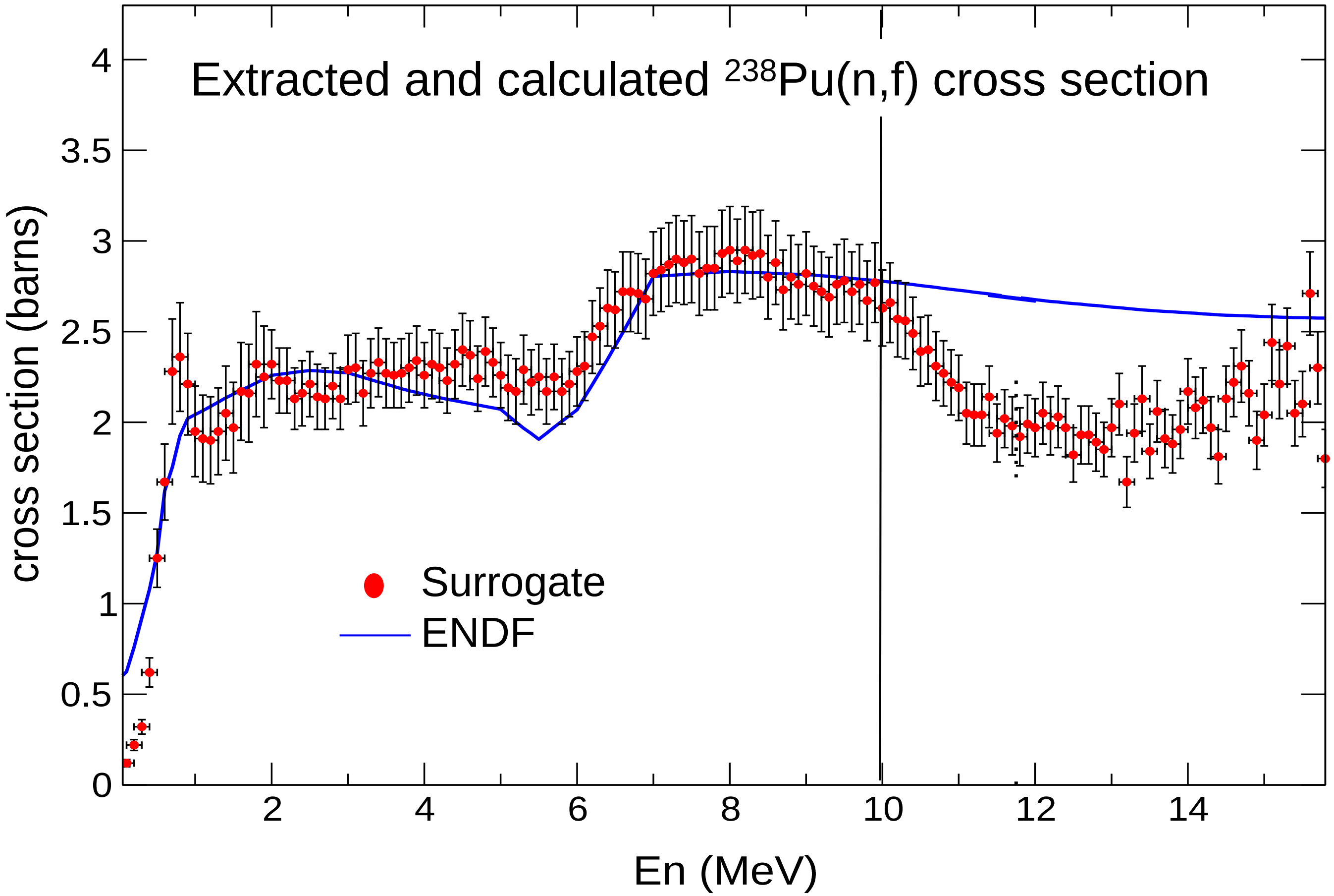
$$\sigma(^{237}Pu(n,f),E) = \frac{N(^{239}Pu((p,df),E))}{N(^{235}U((p,df),E))} \times \sigma(^{233}U(n,f),E)$$



^{238}Pu(n,f) cross section from ^{239}Pu(p,p')^{239}Pu*/^{235}U(p,p')^{235}U* surrogate ratio

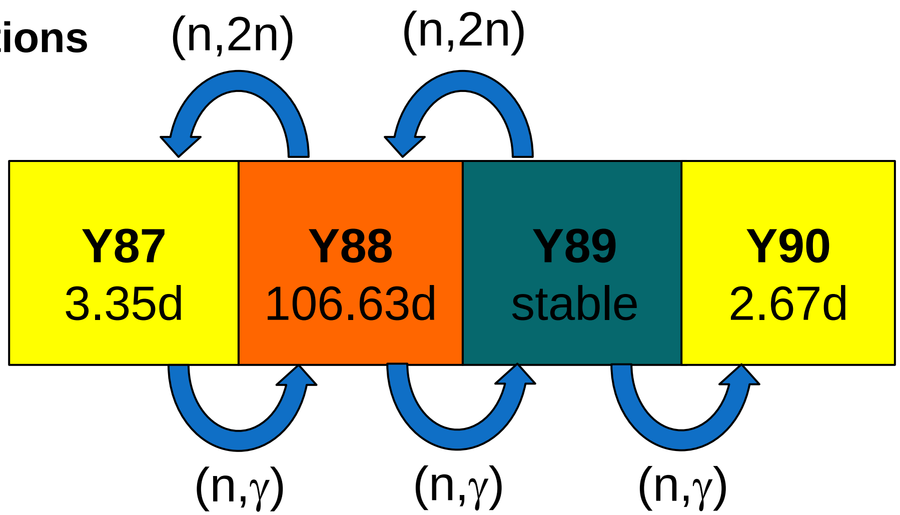
Courtesy Richard Hughes

$$\sigma(^{238}Pu(n,f),E) = \frac{N(^{239}Pu((p,p'f),E))}{N(^{235}U((p,p'f),E))} \times \sigma(^{234}U(n,f),E)$$



Where's the experimental challenge in determining $^{87}Y(n,\gamma)$?

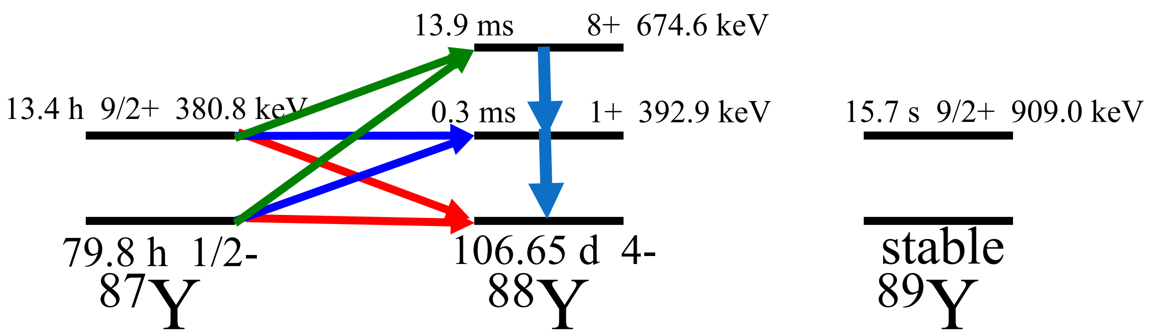
Yttrium nuclear reactions



Y89 is the only stable Yttrium isotope.
Nearly impossible to make and irradiate a Y87 target to get an energy dependent cross section.
Ex: 100 micrograms of Y87 equals 1.7×10^{12} becquerels or 44.8 Curies
Ex: 100 micrograms of Y88 equals 5.2×10^{10} becquerels or 1.5 Curies

Yttrium isotopes also contain multiple isomeric states…

Yttrium isotopes and isomer levels



We ran for 13 days (39 shifts) starting June 24, 2012. The experiment involved ~20 students, post-docs, and researchers from >5 institutions.
We collected 3 TeraBytes of data on multiple targets focusing on Y89 (also Zr9x).

- Si energy resolution 75 keV one sigma
- Gamma energy resolution 1.7 keV one sigma
- Particle angular range 30 to 60 degrees
- Y89 mono-isotopic 760 micrograms/cm^2
- Zr9x ~1000 micrograms/cm^2

Strategies for constraining HF inputs

I. **Calculate γSF & LD**:

- Theory challenging, not all nuclei covered, but progress is being made
- Experiments needed to verify theory & improve

II. **Constraints from neighbors**:

- Measure (n,γ) cross sections in other nuclei & do regional fits
- Extrapolations required

III. **Constraints from surrogate observables**:

- Measure quantities in **actual nuclei of interest**
- Theory needed to relate measurement to desired cross section

The surrogate method

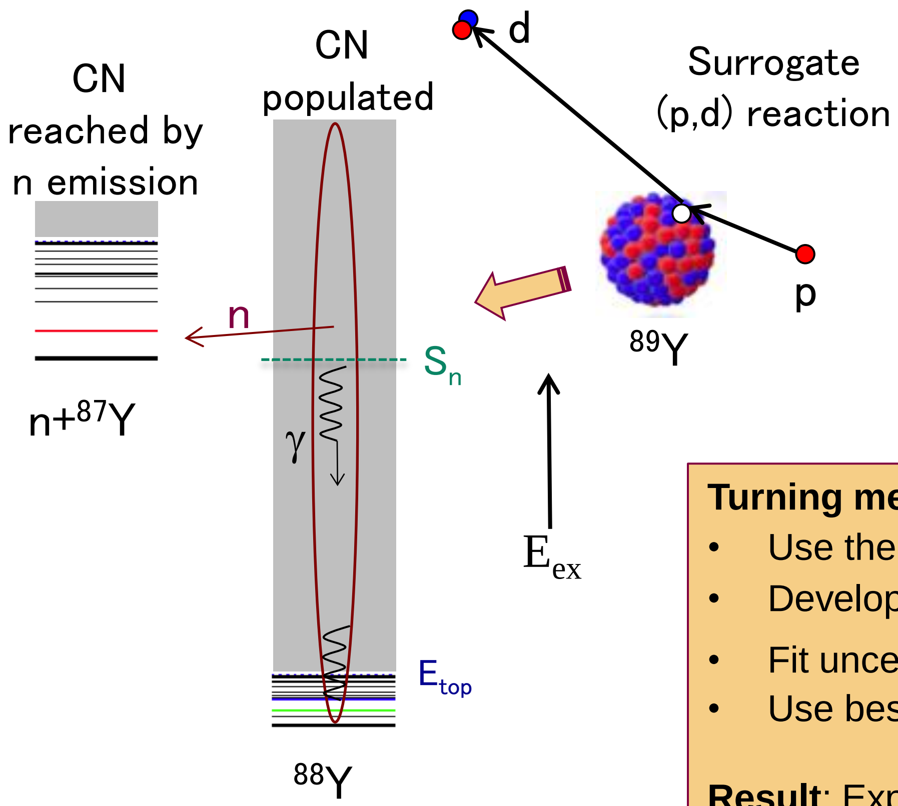
Experiment

Produce CN ^{88}Y via alternative reaction **p + ^{89}Y -> d + ^{88}Y** involving stable ^{89}Y

Measure outgoing surrogate particle **d** in coincidence with observables indicative of relevant decay channel ➔ $P_{\delta\gamma}(E)$

Here: γ rays measured in coincidence with deuterons:

$$P_{\delta\gamma}(E) = \frac{N_{\delta\text{-}\gamma}(E_{exc})}{N_{\delta}(E_{exc})}$$



Formalism

A Surrogate experiment gives

$$P_{\delta\gamma}(E) = \sum_{J,\pi} F_{\delta}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

Hauser-Feshbach description of “desired” CN reaction

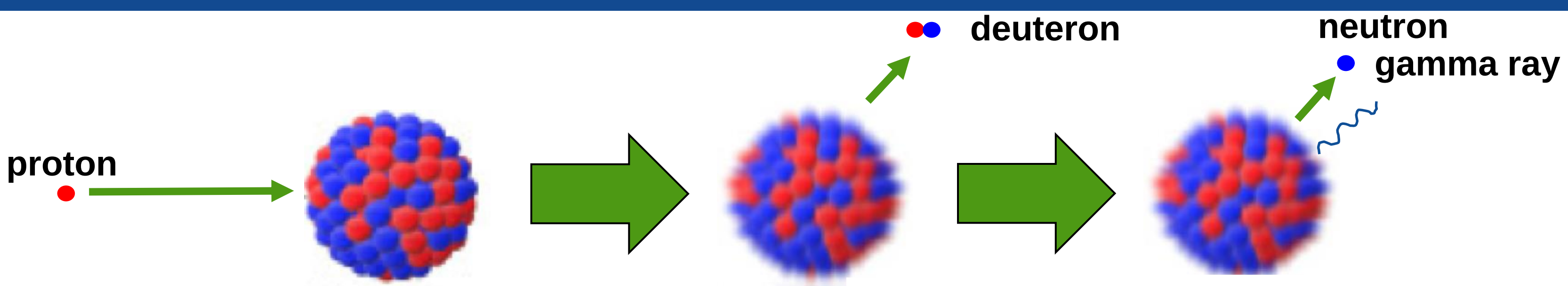
$$\sigma_{\alpha\gamma} = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

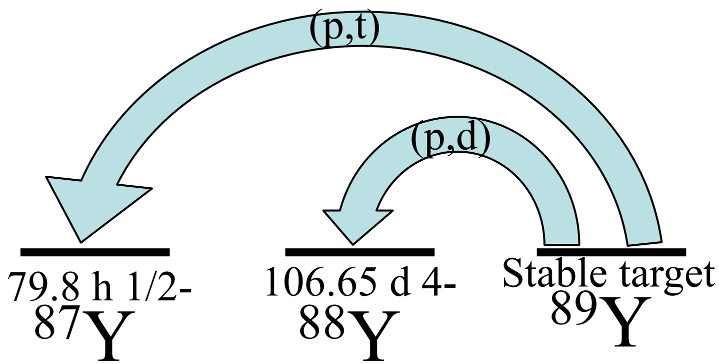
Turning measurement into cross section

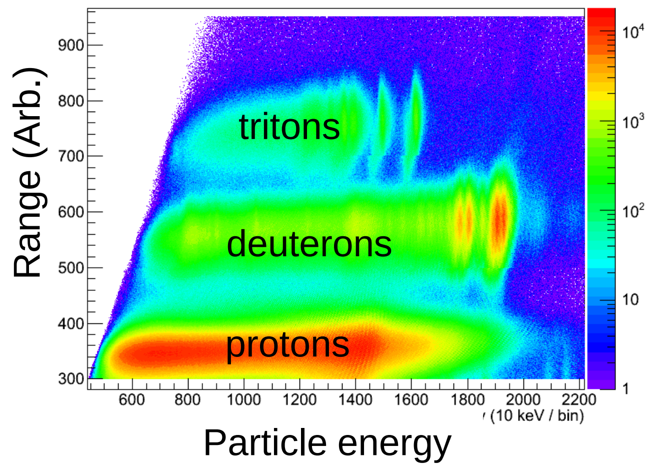
- Use theory to describe Surrogate reaction, predict F_{δ}^{CN}
- Develop rough decay model G^{CN}_{γ}
- Fit uncertain parameters in G^{CN}_{γ} to reproduce $P_{\delta\gamma}$
- Use best-fit parameters to calculate desired $\sigma_{\alpha\gamma}$

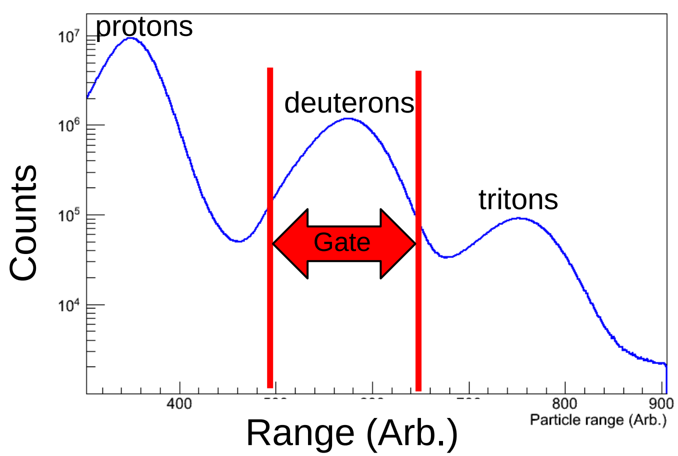
Result: Experimentally constrained cross section.

Yttrium surrogate nuclear reactions
Reactions populate Y89, Y88, Y87 nuclei





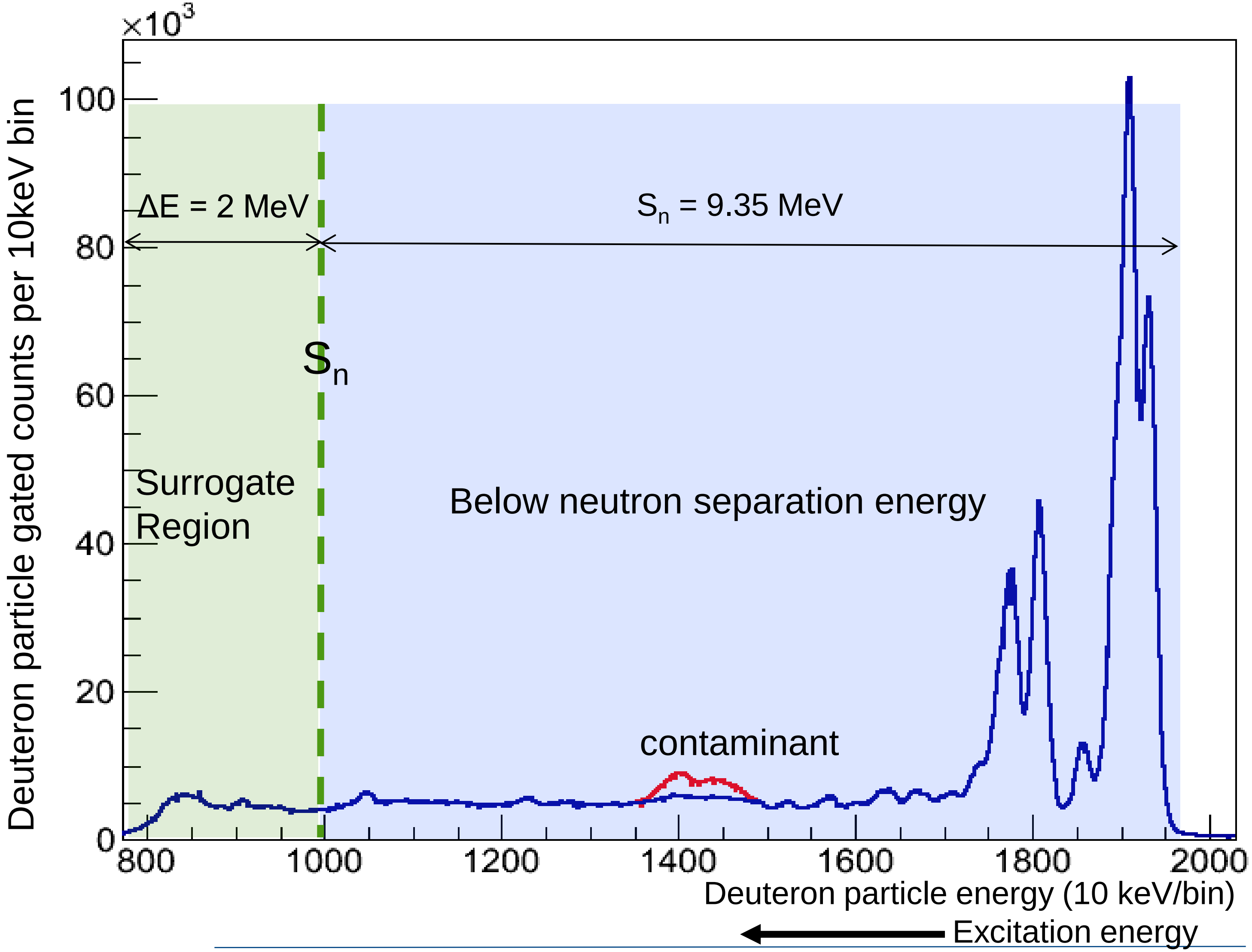




Data summary:
>500 million Y89(p,p') reactions
96 million Y89(p,d)Y88* reactions
7.8 million Y89(p,t)Y87* reactions

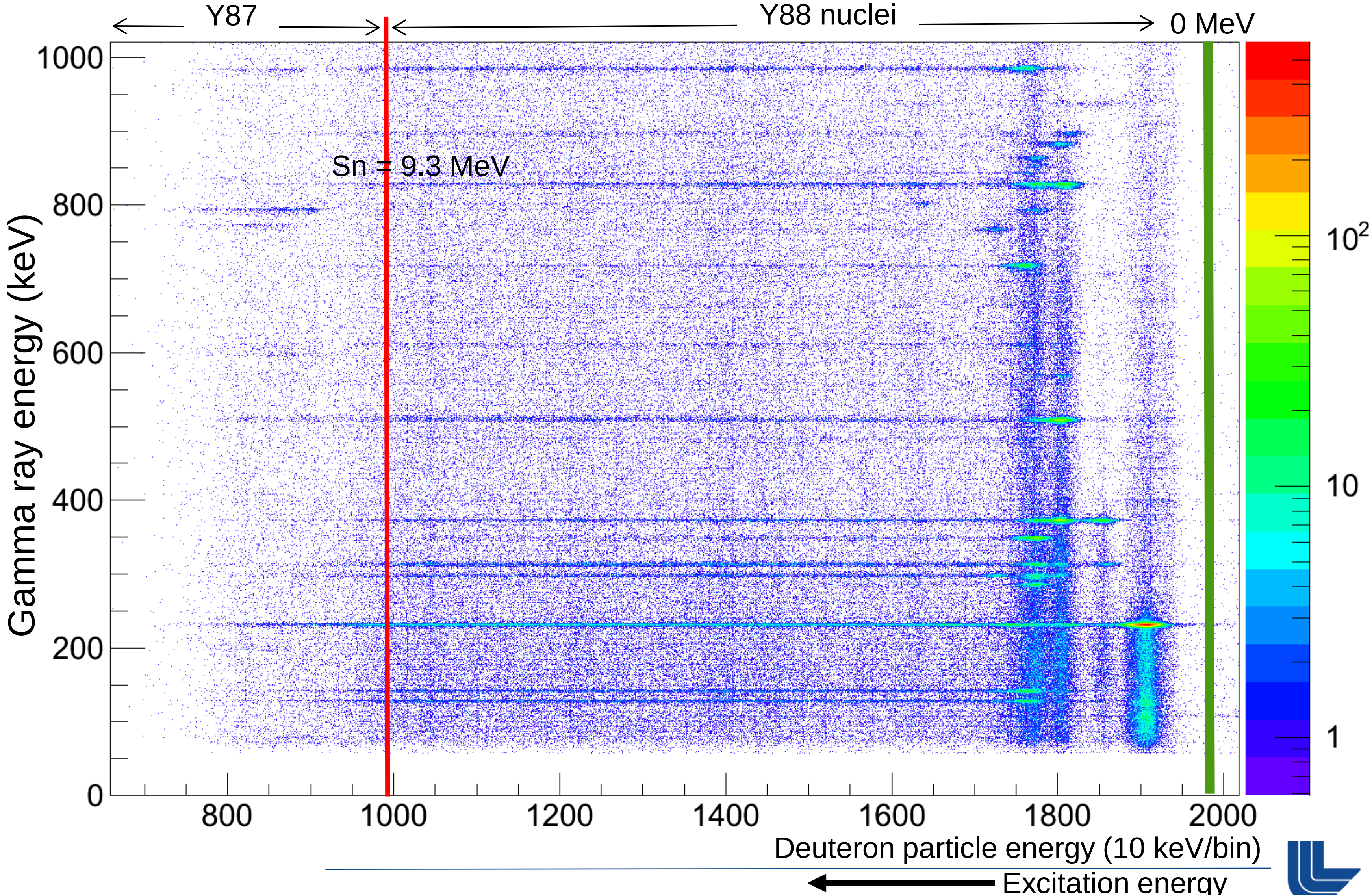
Particle singles data used to determine $^{89}Y(n,\gamma)$ using the $^{89}Y(p,d)^{88}Y^*$ reaction

$$P_{\delta\gamma}(E) = \frac{N_{\delta\text{-}\gamma}(E_{exc})}{N_{\delta}(E_{exc})}$$



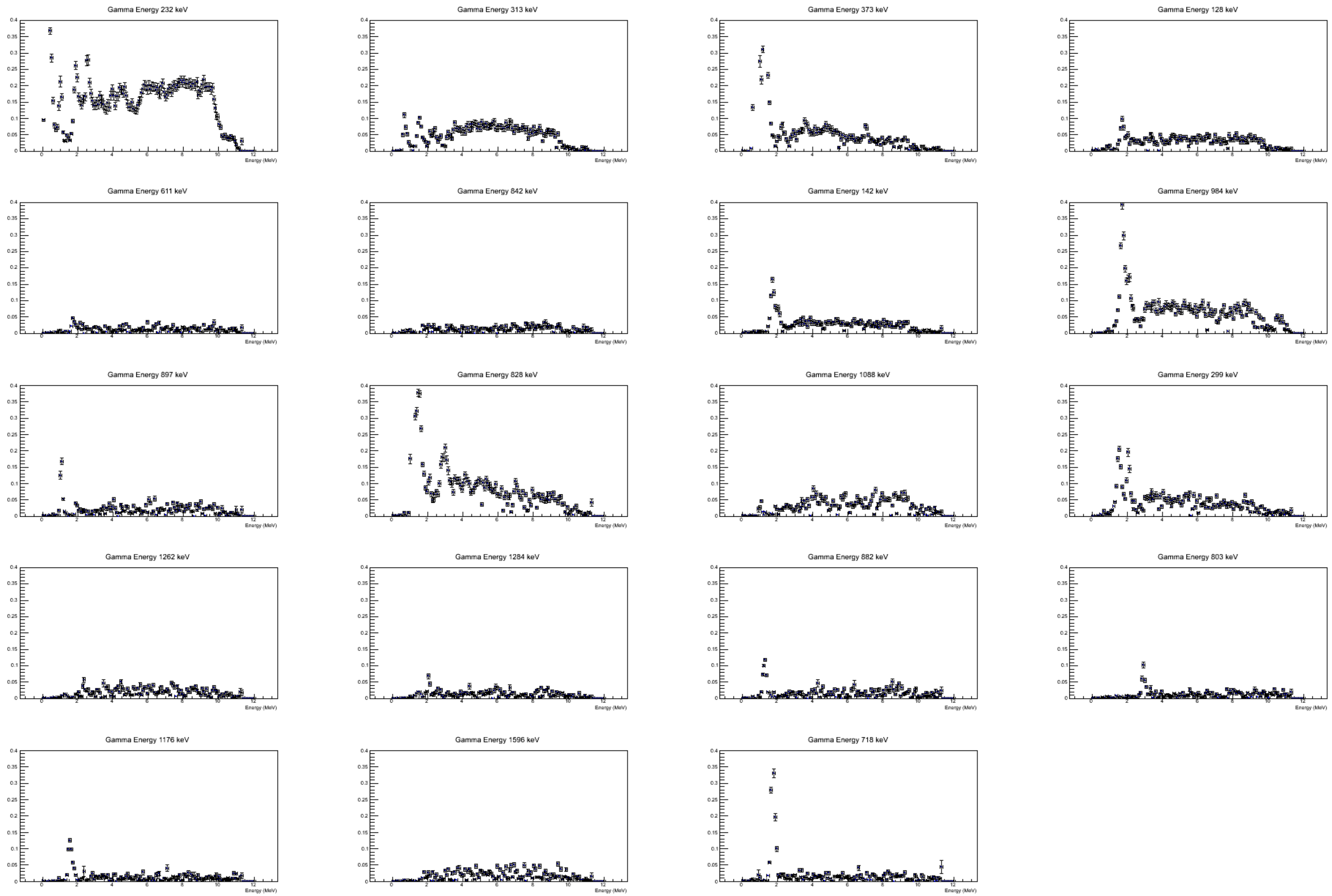
$^{89}Y(p,d)^{88}Y$ Gamma production versus excitation energy

$$P_{\delta\gamma}(E) = \frac{N_{\delta\text{-}\gamma}(E_{exc})}{N_{\delta}(E_{exc})}$$



$^{89}Y(p,d)\,^{88}Y$ gamma decay probabilities
Many contributions used to determine the final parameters

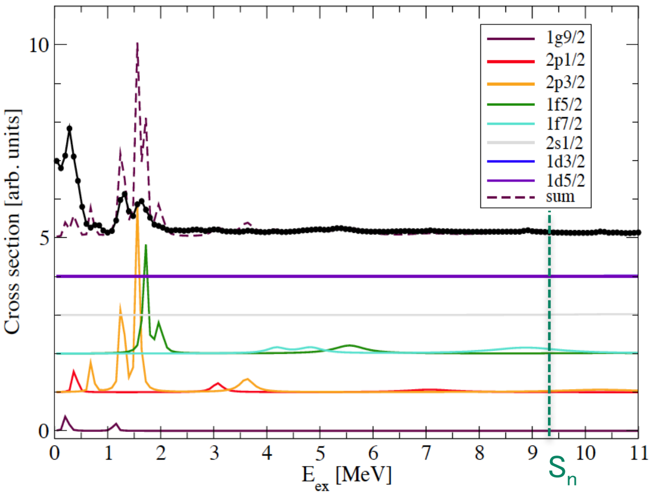
$$P_{\delta\gamma}(E) = \frac{N_{\delta-\gamma}(E_{exc})}{N_{\delta}(E_{exc})}$$



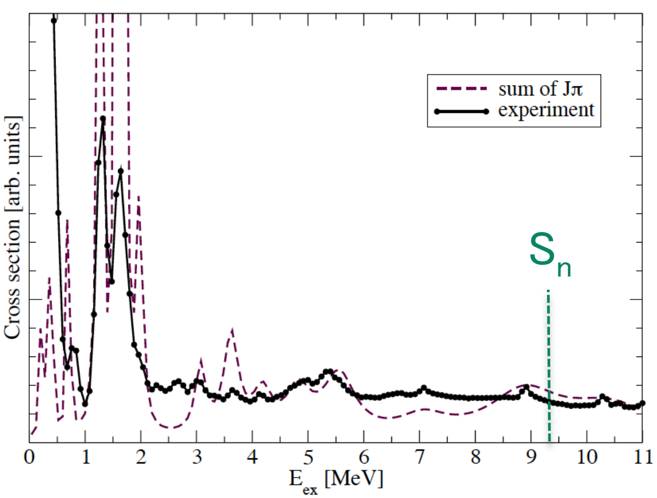
From measurement to cross section: Theory step I

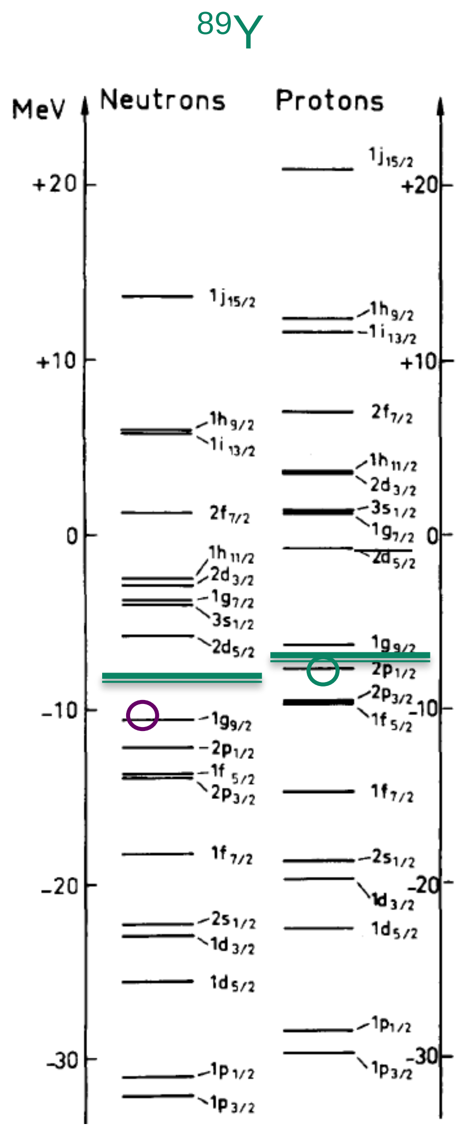
$P_\chi(E) = \Sigma_{J,\pi} F_\delta^{CN}(E,J,\pi) \cdot G^{CN}_\chi(E,J,\pi)$

- Theoretical description of $^{89}Y(p,d)^{88}Y^*$

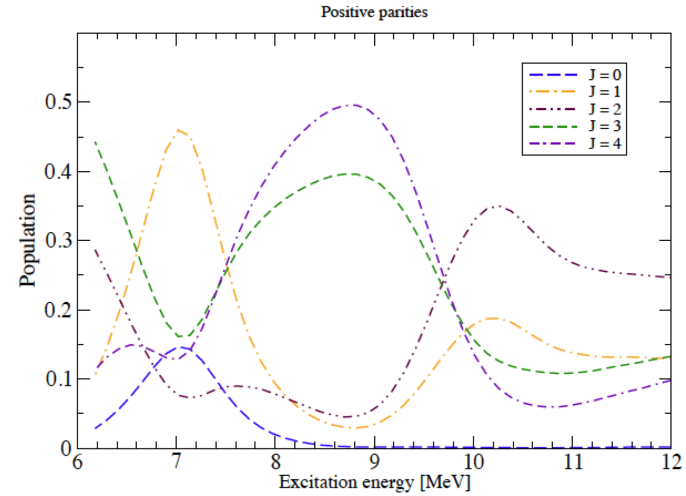


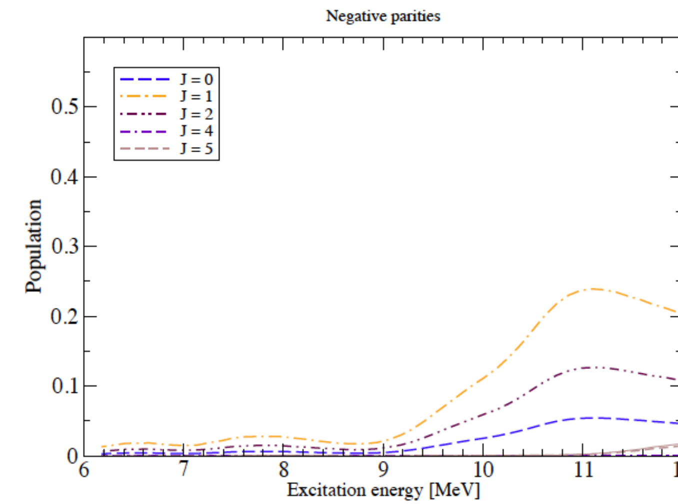
- Closer comparison with experiment:





- Extract spins, determine J^π distribution of ^{88}Y as function of E.





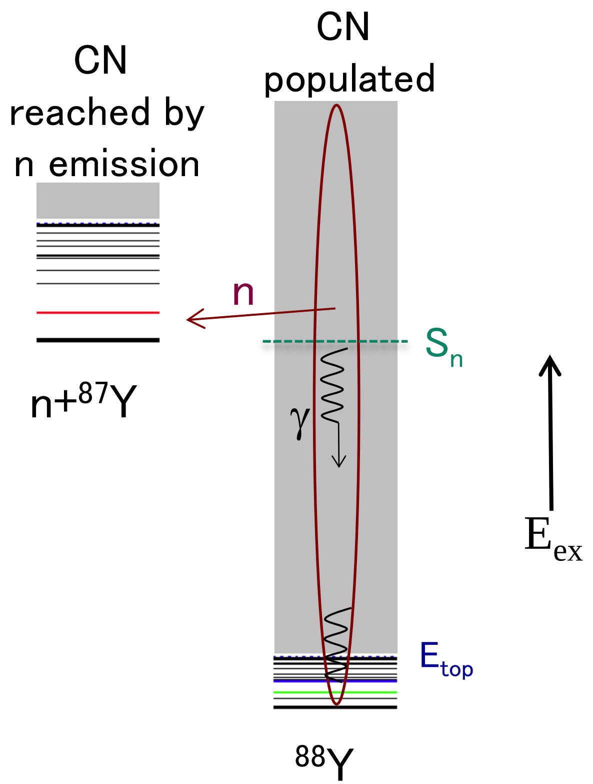
(do for proton holes $2p_{1/2}$, $2p_{3/2}$, $1g_{9/2}$)

○ neutron hole made in reaction

From measurement to cross section: Theory step II

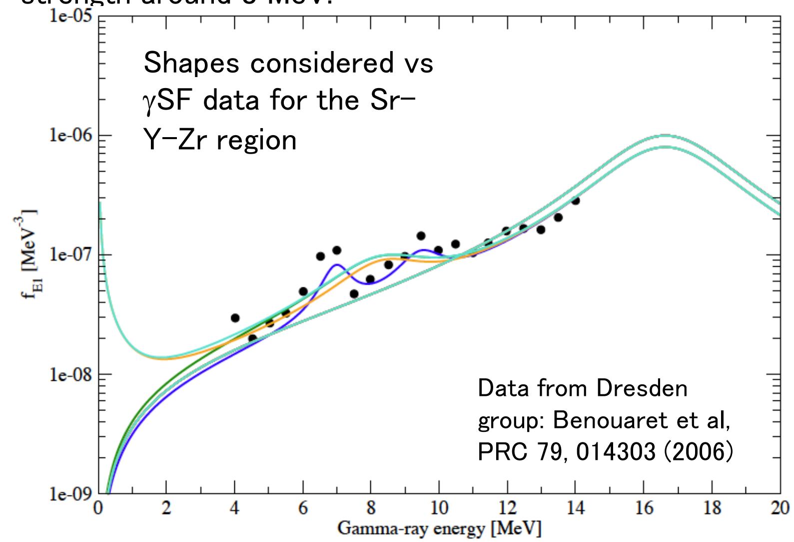
Develop rough decay model for $^{88}Y^{*}$:

- Literature values for energies + spins of low–lying states states
- Literature values for branchings between low states states
- LDs of Gilbert–Cameron form w/variable parameters parameters
- asurements &



Example γSF:

Considering 5 shapes, w and w/o upturn and/or extra strength around 8 MeV.



Decay model gives $G^{CN}_{\chi}(E,J,\pi)$ for range of LD and γSF parameters.

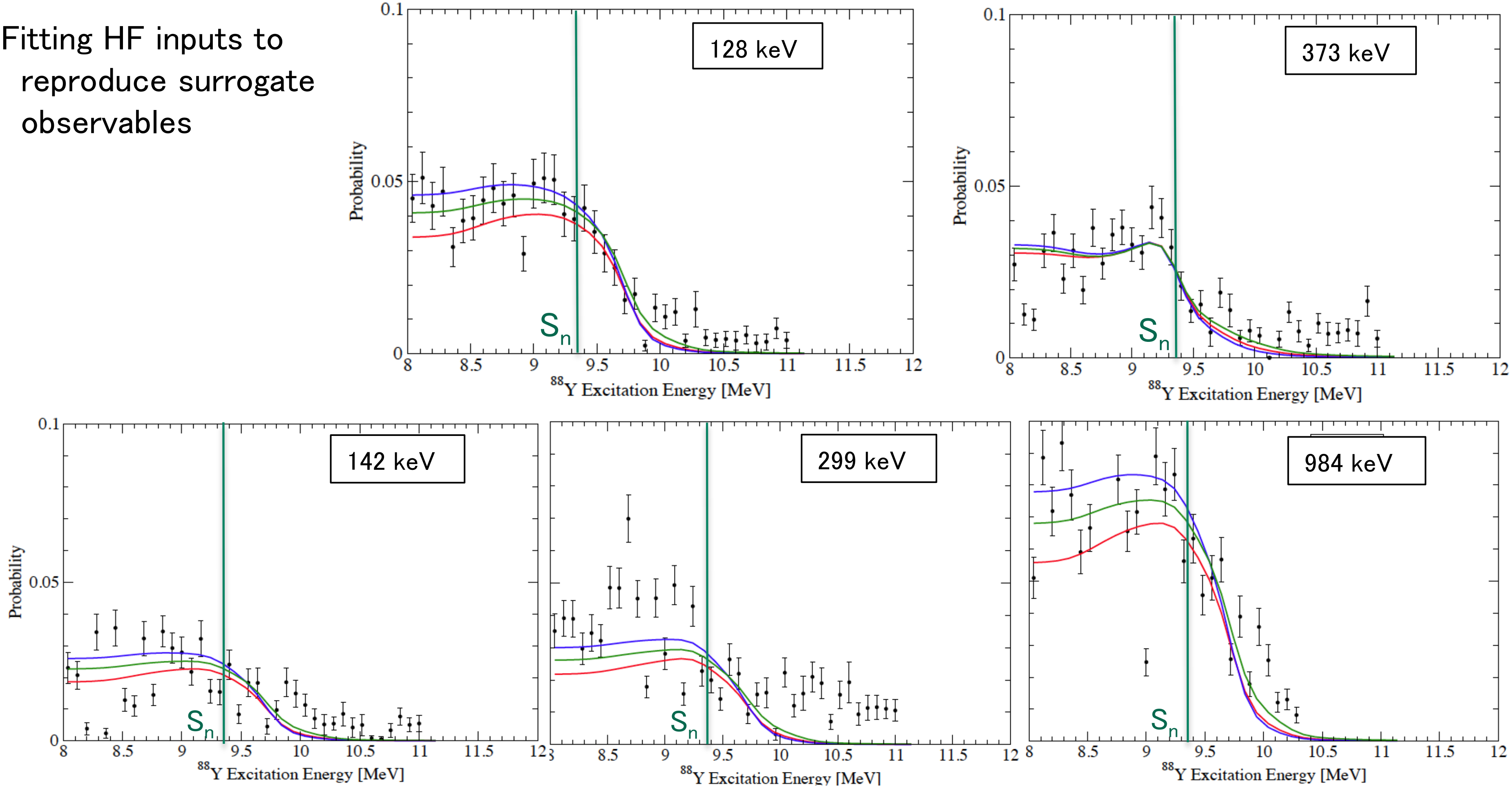
$$P_{\chi}(E) = \Sigma_{J,\pi} F_{\delta}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$$

Getting ready for fitting:

- Study of sensitivity to HF inputs was used to isolate relevant parameters for fit.
- Checks of γ decay against surrogate data used to identify incorrect branchings, etc.

From measurement to cross section: Theory step III

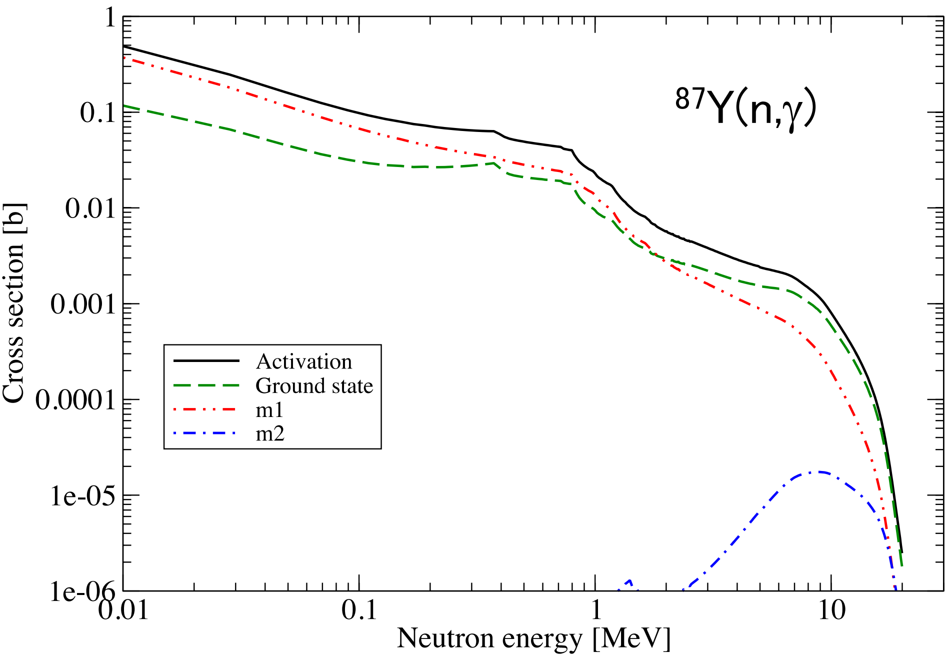
Fitting HF inputs to reproduce surrogate observables

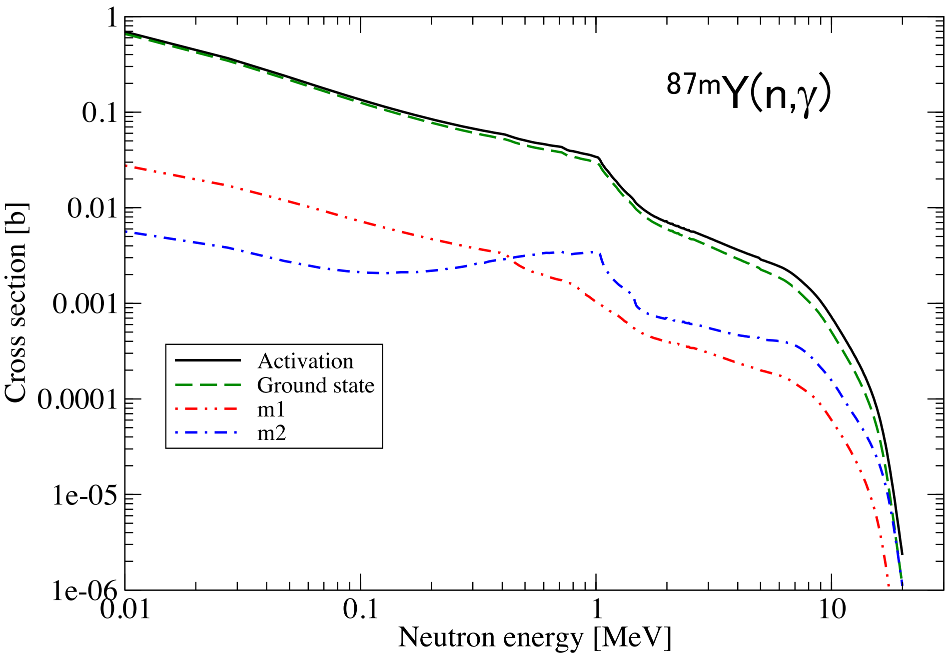


Fit yields ‘best’ set of parameters & uncertainty estimate.

$$P_\chi(E) = \Sigma_{J,\pi} F_\delta^{CN}(E,J,\pi)\cdot G^{CN}_\chi(E,J,\pi)$$

From measurement to cross section: Theory step IV

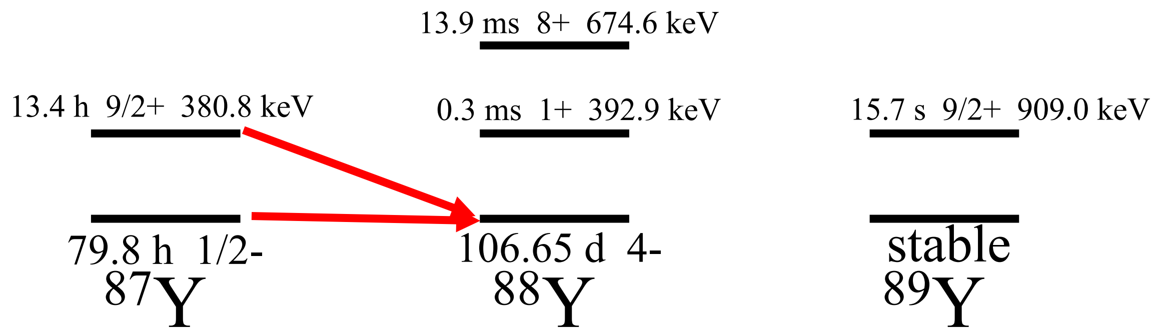




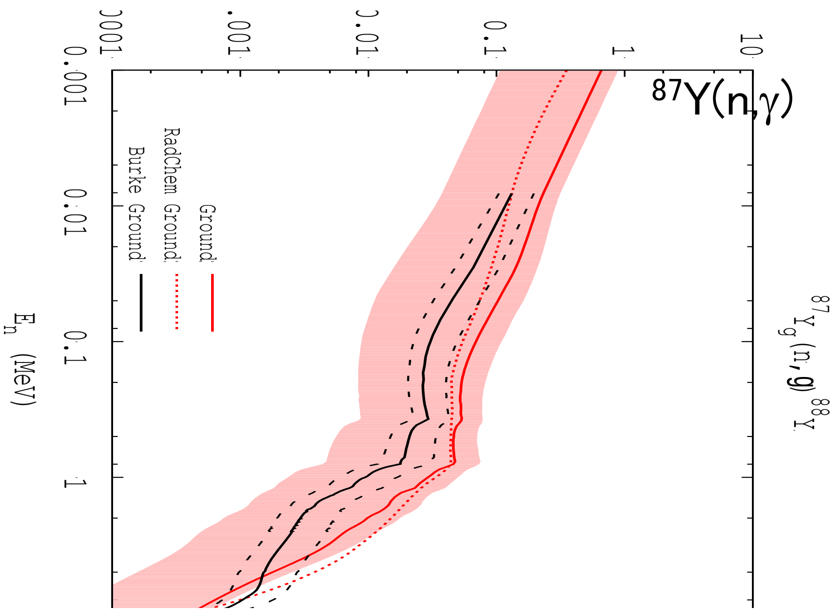
Using 'best' set of parameters to calculate $^{87}Y(n,\gamma)$ and $^{87m}Y(n,\gamma)$, including cross sections for gs and isomers in ^{88}Y

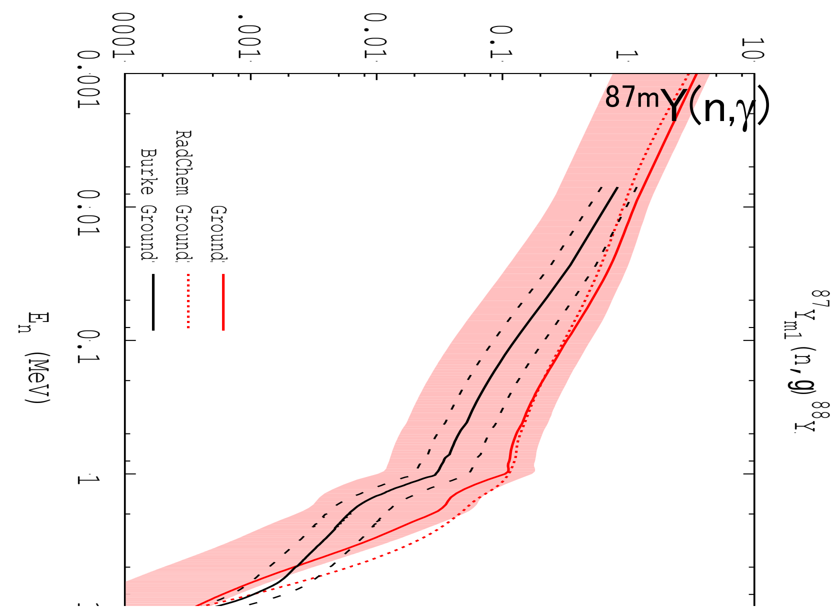
$$\sigma_{\alpha\chi} = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E,J,\pi) \cdot G^{CN}_{\chi}(E,J,\pi)$$

Results – to GS



^{87}Y(n,γ) to ^{88}Y ground state (4$^-$ at 0 keV)



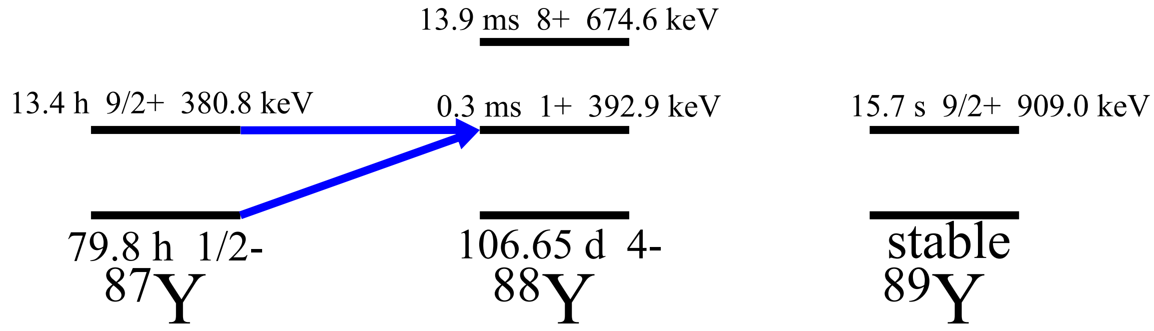


Plots courtesy of R.D. Hoffman

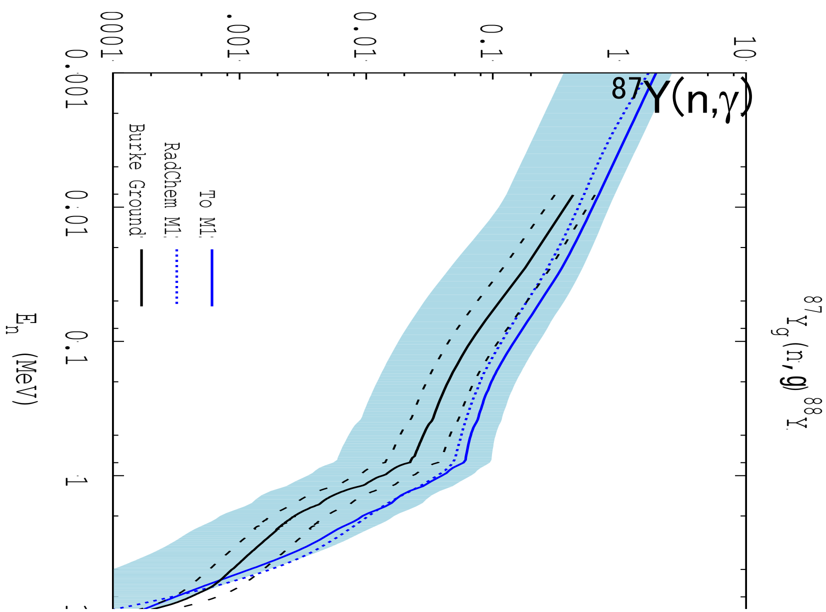
Target ^{87}Y in gs (1/2$^-$ at 0 keV)

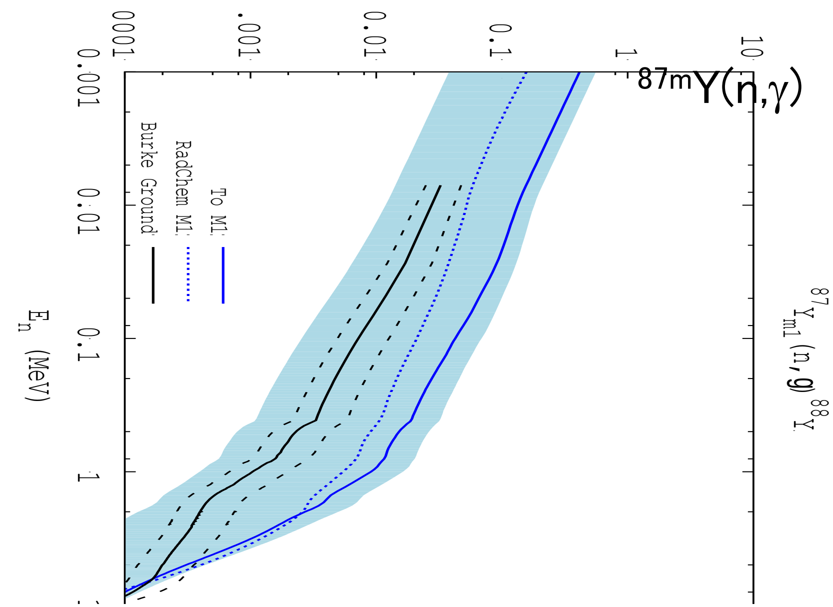
Target ^{87}Y in M1 (9/2$^+$ at 381 keV)

Results – to M1



^{87}Y(n,γ) to ^{88}Y M1 isomer (1^{+} at 393 keV)



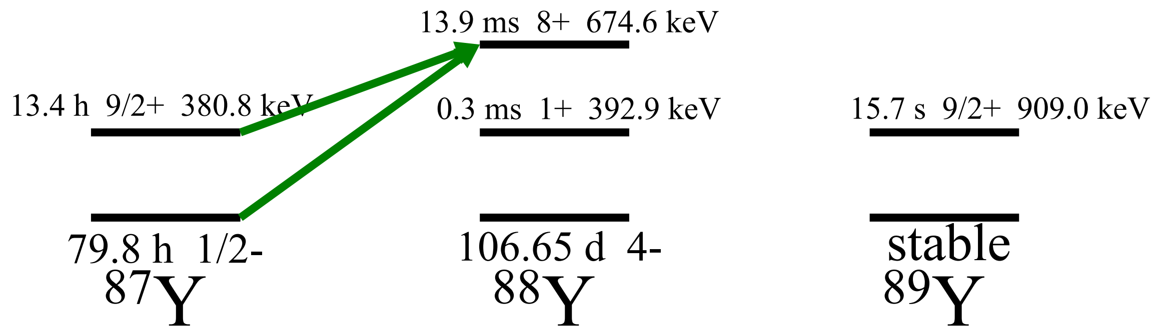


Plots courtesy of R.D. Hoffman

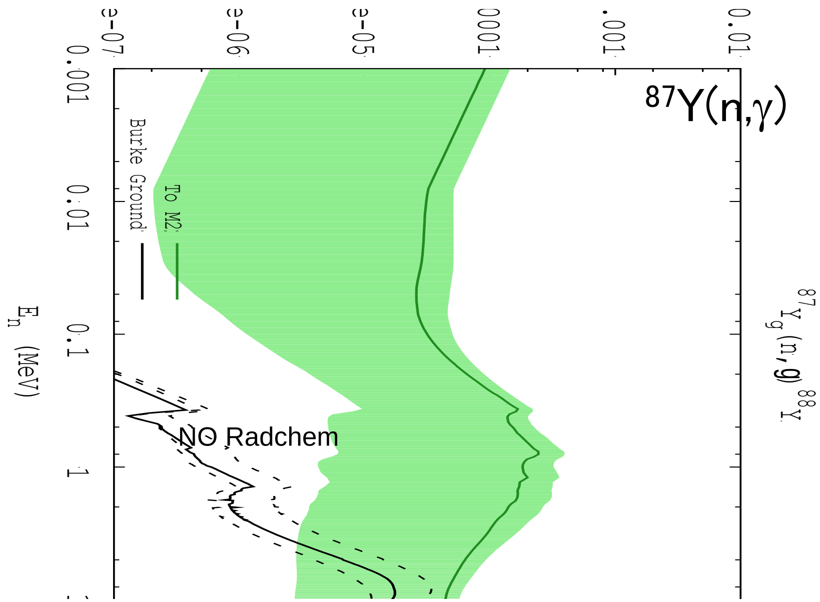
Target ^{87}Y in gs (1/2^{-} at 0 keV)

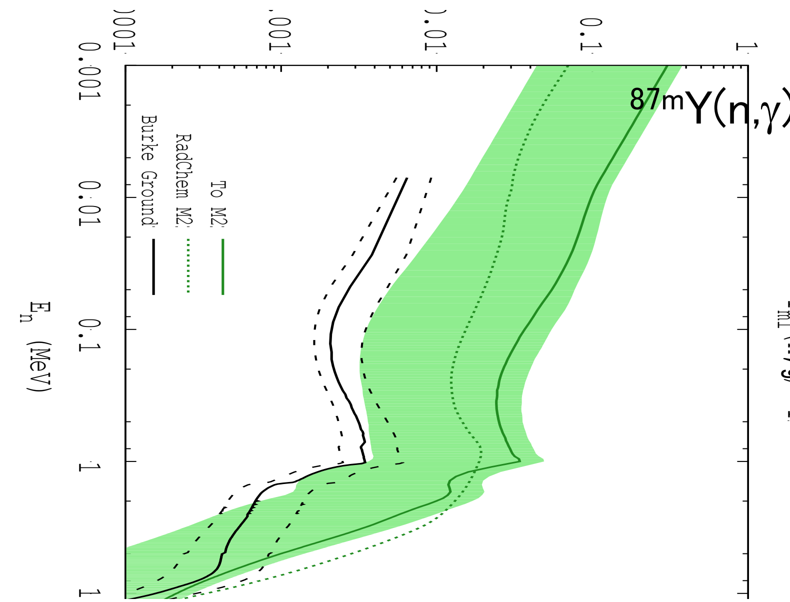
Target ^{87}Y in M1 (9/2^{+} at 381 keV)

Results – to M2



^{87}Y(n,γ) to ^{88}Y M2 isomer (8^{+} at 675 keV)





Plots courtesy of R.D. Hoffman

Target ^{87}Y in gs (1/2^{-} at 0 keV)

Target ^{87}Y in M1 (9/2^{+} at 381 keV)

Concerns we are addressing

I. **Improve nuclear structure in ^{88}Y and ^{87}Y**:
- Unknown or incorrect spins & parities in literature
- Poorly known or incorrect γ branching ratios in literature
- Improvements through more detailed study of present data, coupled with theory: e.g. compare angular distributions of singles to fix spins; study $\gamma\gamma$ coincidences to fix branching ratios

II. **Improve calculations for ^{89}Y(p,d)**:
- Use results of improvements above to revisit predicted J^{π} distributions

III. **Improved experimental analysis**:
- Revisit experimental coincidence probabilities to reduce data scatter

IV. **Improved fitting of theory to experimental results**:
- Use improved experimental coincidence probabilities in fits
- Carry out more detailed parameter variation in fit
- Carry out more detailed uncertainty analysis

V. **High-E region**:
- Include direct-semidirect cross section contributions

VI. **Benchmark**:
- Use approach to determine known ^{90}Zr(n,γ) cross section: underway
- ^{91}Zr(p,d), ^{92}Zr(p,d), ^{94}Zr(p,d), ^{96}Zr (p,d) were also measured

Summary

1) We have measured the following cross sections using the surrogate ratio method in the past couple of years.

- $^{236}Pu(n,f)$
- $^{237}Pu(n,f)$
- $^{238}Pu(n,f)$
- $^{240}Am(n,f)$
- $^{241}Am(n,f)$
- $^{242}Am(n,f)$

2) We have a path forward and preliminary results for measuring (n,g) reactions for ground states and isomeric states for spherical nuclei

$^{87}Y(n,g)$ GS -> GS
$^{87}Y(n,g)$ GS -> M1
$^{87}Y(n,g)$ GS -> M2

$^{87}Y(n,g)$ M1 -> GS
$^{87}Y(n,g)$ M1 -> M1
$^{87}Y(n,g)$ M1 -> M2

3) **The burden of proof is on us.** We are benchmarking the surrogate (n,g) using ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{94}Zr, ^{96}Zr (p,d) data from the same experiment. $^{90}Zr(n,g)$ is the key benchmark from the surrogate reaction $^{92}Zr(p,d)$.

Collaborators
(undergraduate students, graduate students, post-docs)

J.T. Burke, N.D. Scielzo, J.E. Escher, J.J. Ressler, I.J. Thompson, R.J. Casperson, F.S. Dietrich, R. Henderson, J. Gostic, R.D. Hoffman- *Lawrence Livermore National Laboratory*

R.E. Tribble, M. McCleskey, A. Saastamoinen, E. Simmons, A. Spiridon, A. Starke, B. Abromeit, G. Pizzone, L. Heilborn, M. DeVanzo, M. Maguire, N. Foley, R. Gonzalez, T. Salzilla, W. McGrew *Texas A&M University*

A. Voinov, S. Grimes, A. Schiller – *Ohio State University*

V. Meot, O. Roig, E. Bauge, A. Blanc - *Bruyeres le Chatel, France*

B. Jurado, M. Aiche, G. Boutoux – *CENBG, Bordeaux, France*

J. Benstead – AWE, England

L.W. Phair, M.S. Basunia, A. Hurst, P.Fallon, I.Y. Lee, A.O. Macchiavelli - *Lawrence Berkeley National Laboratory*

C.W. Beausang and R.A. Hughes , E. Good, K. Gell, T. Tarlow- *University of Richmond*

V. Werner, N. Cooper – *Yale University*

J. Tostevin, T. Ross, P. Humby - *University of Surrey, England*

J.A. Cizewski, N. Koller, A. Ratkiewicz, B. Manning, S. Burcher, S. Rice - *Rutgers University*

E.B. Norman, J. Munson, A. Czeszumska, P. Chodash, E. Swanberg - *U.C. Berkeley*

R. Austin - *St. Mary's University, Canada*

S. Chiba, K. Nishio, H. Koura, I. Nishinaka – *JAEA, Japan*

Kairuken Garden in Mito

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Yttrium surrogate nuclear reactions