日本学術振興会
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^{87}Y(n,γ) and ^{89}Zr(n,γ) from surrogate reaction approach

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STARLiTeR Collaboration

15th Capture Gamma-ray Spectroscopy
Dresden, Germany, Aug.25, 2014

Outline

- **Surrogate reaction approach**
  - Motivation – why do we need the surrogate approach ?-
  - Basic idea of the approach
  - Successes in (n,f) cross section measurements and **challenges to (n, γ) cross section measurements**

- **Experimental details**
  - STARLiTeR @ Texas A&M cyclotron

  (Si Telescope Array for Reaction studies and Livermore, Texas, and Richmond)

- **Measurements of (n, γ) reactions**
  - ^{87}Y (n, γ) and ^{89}Zr (n, γ)
  - Preliminary cross sections and future strategy

Motivation

- When reaction cross sections ((n,f), (n,γ), etc) cannot be measured directly or predicted reliably, we need to access them by an indirect method → **Surrogate reaction approach**

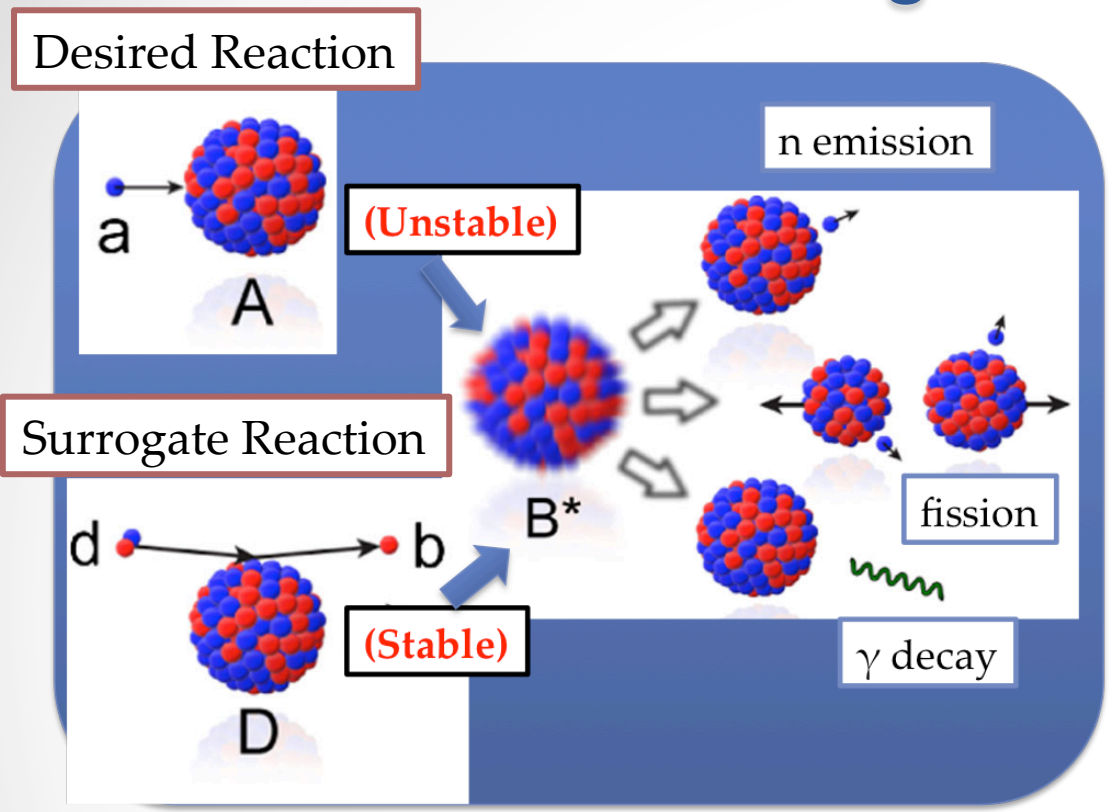
  Reaction cross sections of unstable isotopes are very important in fields of

  - Nuclear Astrophysics → (n,γ) for s-process study, e.g. ^{95}Zr(n,γ)
  - Nuclear Engineering → (n,f), etc., e.g. ^{238}Pu(n,f), ^{241}Am(n,f)
  - National Security→ (n,f) , (n,γ), etc., e.g. ^{87}Y(n,γ)

- **Basic Idea:** Create the same compound nucleus as the one created by a desired reaction (e.g. (n,γ)) by alternative ways (e.g. (p,d) or (d,p))

- Observe branching ratios of decay of interests (fission, γ emission) from the created compound nucleus → **Experimentally constraining the cross section of the desired reaction**

The Surrogate Reaction



Cross section in desired reaction

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

- *Assume formation and decay of CN are independent of each other in first order.*
- *$\sigma_\alpha^{CN}(E,J,\pi)$ is precisely accessible by theory for case of neutron reaction*

→ $G^{CN}_\chi(E,J,\pi)$ is goal by Surrogate

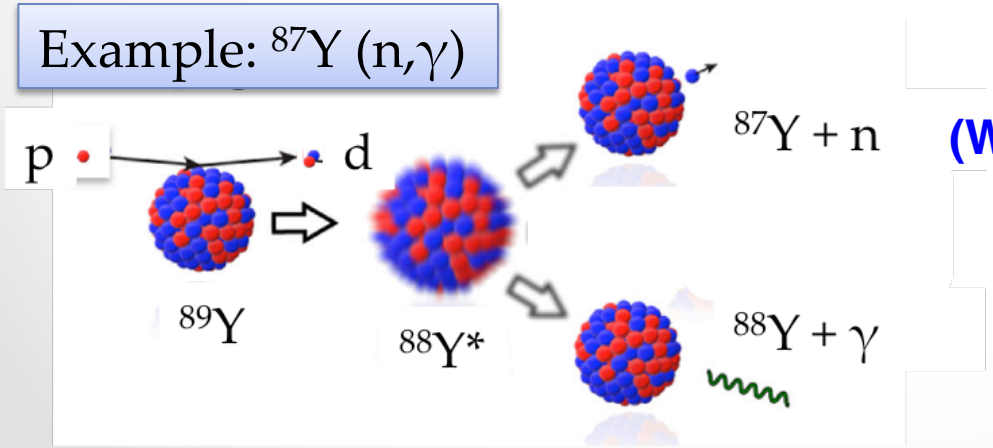
Accessible by surrogate experiment

$$P_{\delta\chi}(E) = \frac{N_{\delta\text{-}\chi}(E)}{N_\delta(E)} = \frac{N_{d\text{-}\gamma}(E)}{N_d(E)}$$

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

(Weisskopf-Ewing Limit)→$P_{\delta\gamma}(E)=G^{CN}_\gamma(E)$

Example: ^{87}Y (n,γ)

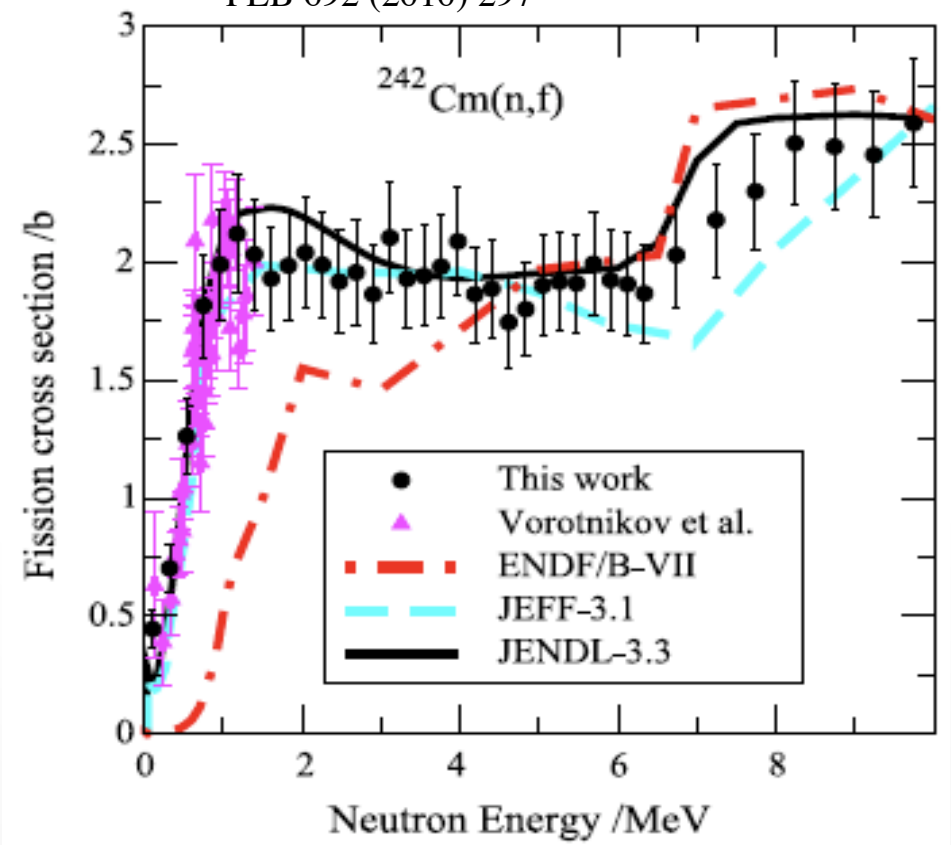


α, δ: incident, χ: exit channel
σ_α^{CN}: CN formation cross section
G^{CN}_χ: branching ratio of CN
F_δ^{CN}: spin-parity distribution of CN
E,J,π: energy, spin, parity of CN

(n,f) cross sections from surrogate with WE approximation

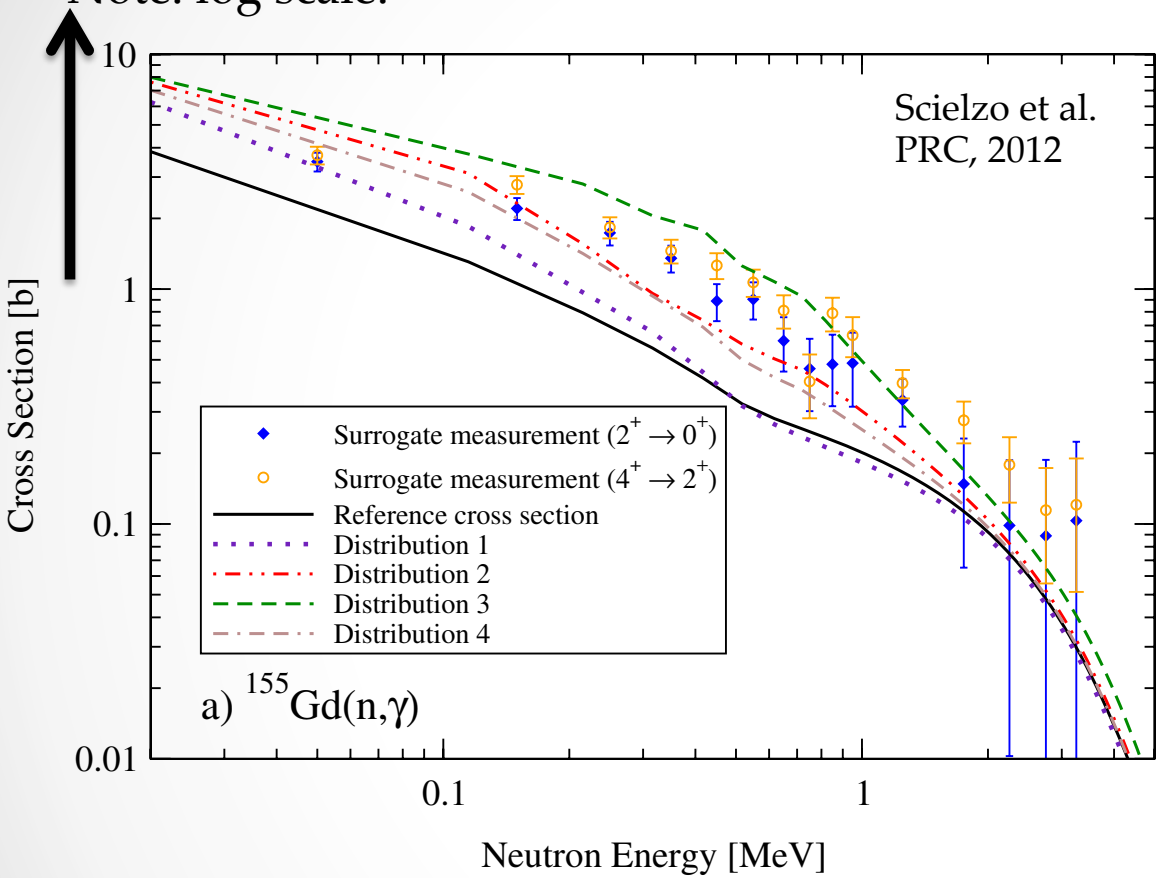
Surrogate method has successfully produced a number of (n,f) cross sections in recent years.
Typically employed the **Weisskopf-Ewing approximation**.

Kessedjian *et al*., CENBG
PLB 692 (2010) 297



(n,γ) from surrogate reaction with WE approximation

Note: log scale!



WE approximation doesn't work well for (n,γ)

Probably due to **J,π dependence** of $G^{CN}_{\gamma}(E,J,\pi)$

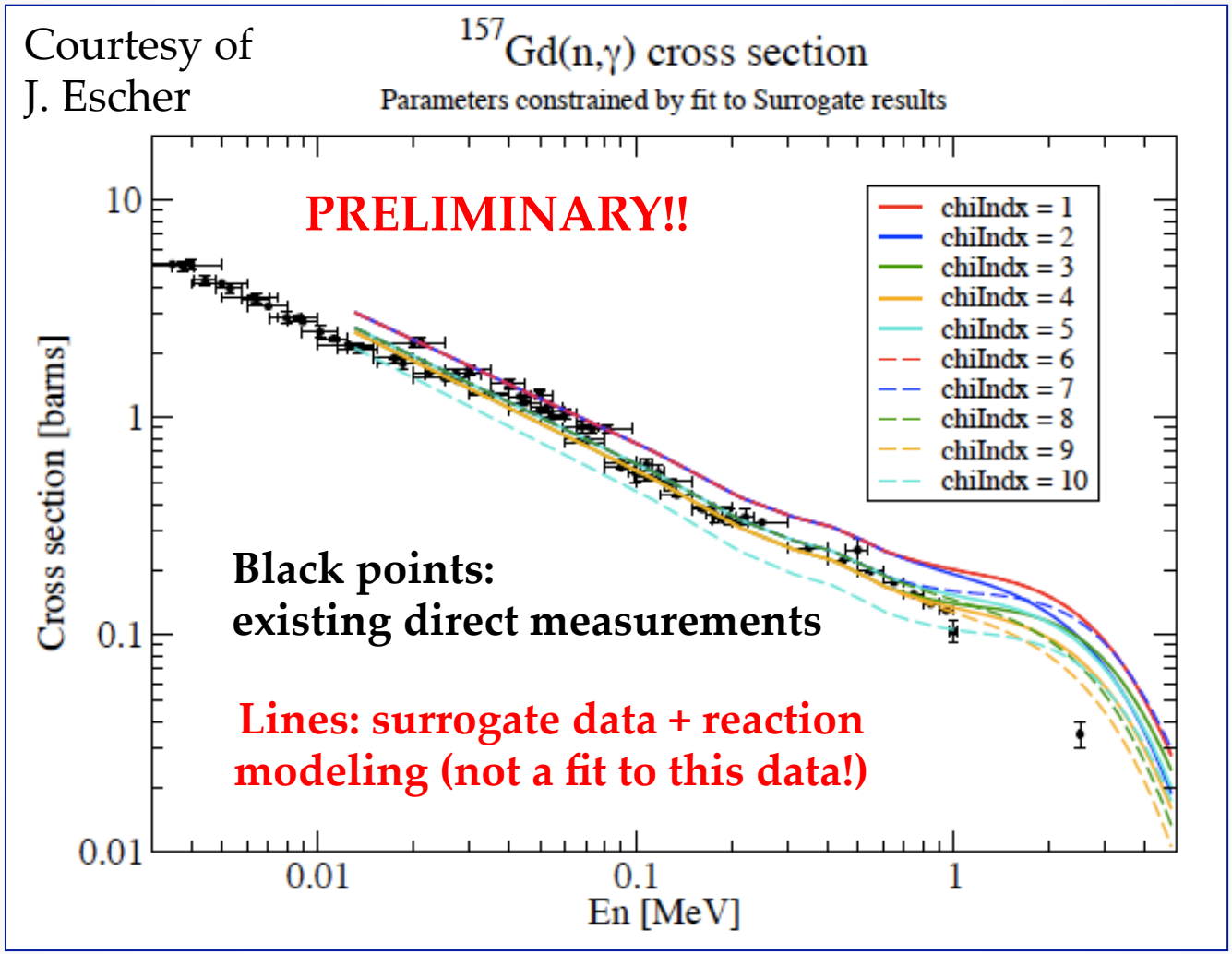
$$P_{\delta\gamma}(E) = \frac{N_{\delta\text{-}\gamma}(E_{exc})}{N_{\delta}(E_{exc})} \neq G^{CN}_{\gamma}(E,J,\pi)$$

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

(F_{δ}^{CN}: J,π distribution of the CN)

We have to obtain $G^{CN}_{\gamma}(E,J,\pi)$ from the experimentally accessible $P_{\delta\gamma}(E)$. (for ex., by Jπ correction)

(n,γ) from surrogate reaction (J^{π} corrected)



If we correct for J,π distribution, get better agreement with direct measurements

Next step: Improve precision of the technique and determine unknown $^{87}Y(n,\gamma)$ and $^{89}Zr(n,\gamma)$ cross sections

Strategy to obtain $^{87}Y(n,\gamma)$ by Surrogate method

a) Measurement

Produce CN ^{88}Y via alternative reaction **p + ^{89}Y → d + ^{88}Y.**

Measure outgoing particle **d** in coincidence with **γ**

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

b) Formalism

A Surrogate experiment gives

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

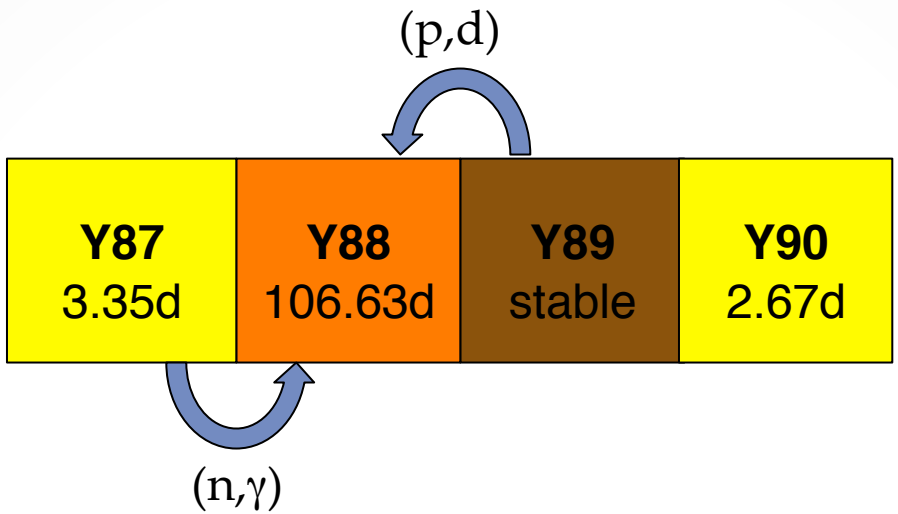
Hauser-Feshbach description of "desired" CN reaction

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

c) Turning measurement into cross section

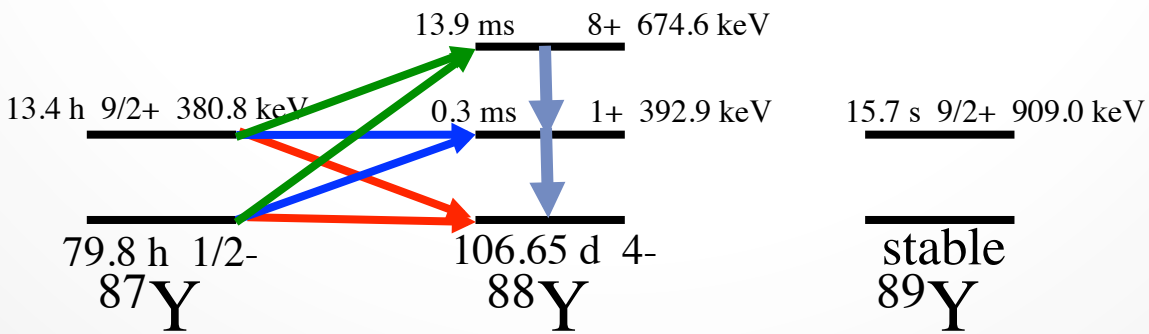
1) Use theory to describe Surrogate, predict F_d^{CN}
2) Develop rough decay model G^{CN}_{γ}
3) Fit uncertain parameters in G^{CN}_{γ} to reproduce $P_{d\gamma}$
4) Use best-fit parameters to calculate desired $\sigma_{n\gamma}$

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



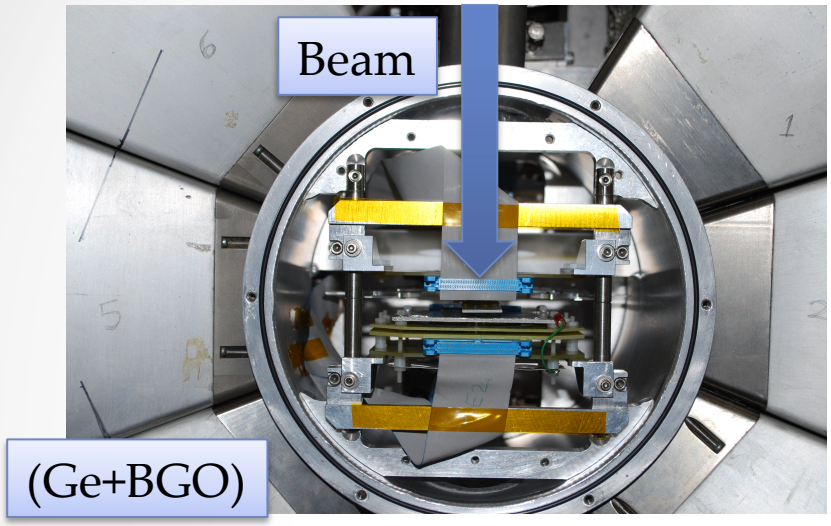
Y89 is the only stable Yttrium isotope.
Nearly impossible to make and irradiate a Y87 target to get an energy dependent cross section.

Yttrium isotopes also contain multiple isomeric state

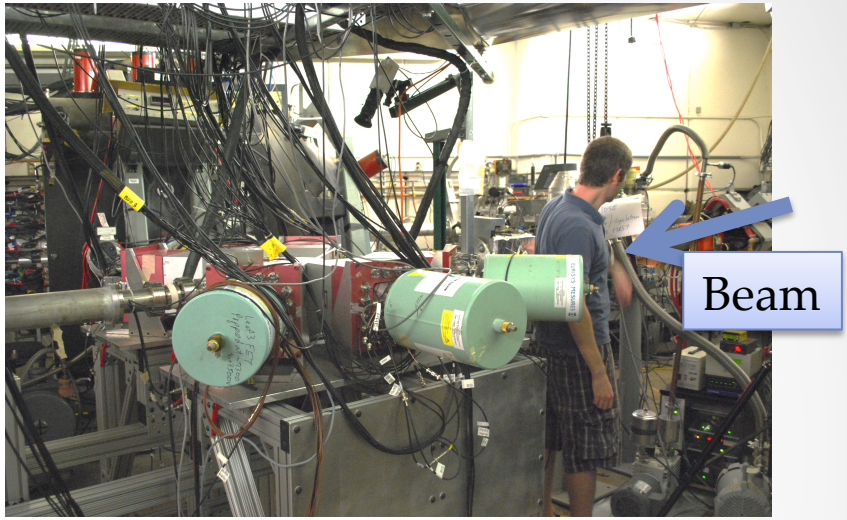


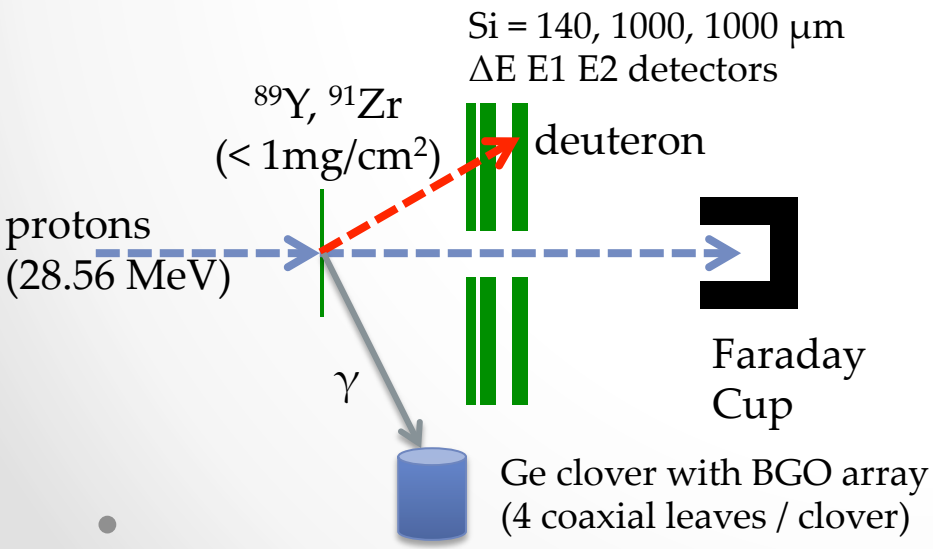
StarLiTeR at Texas A&M

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.



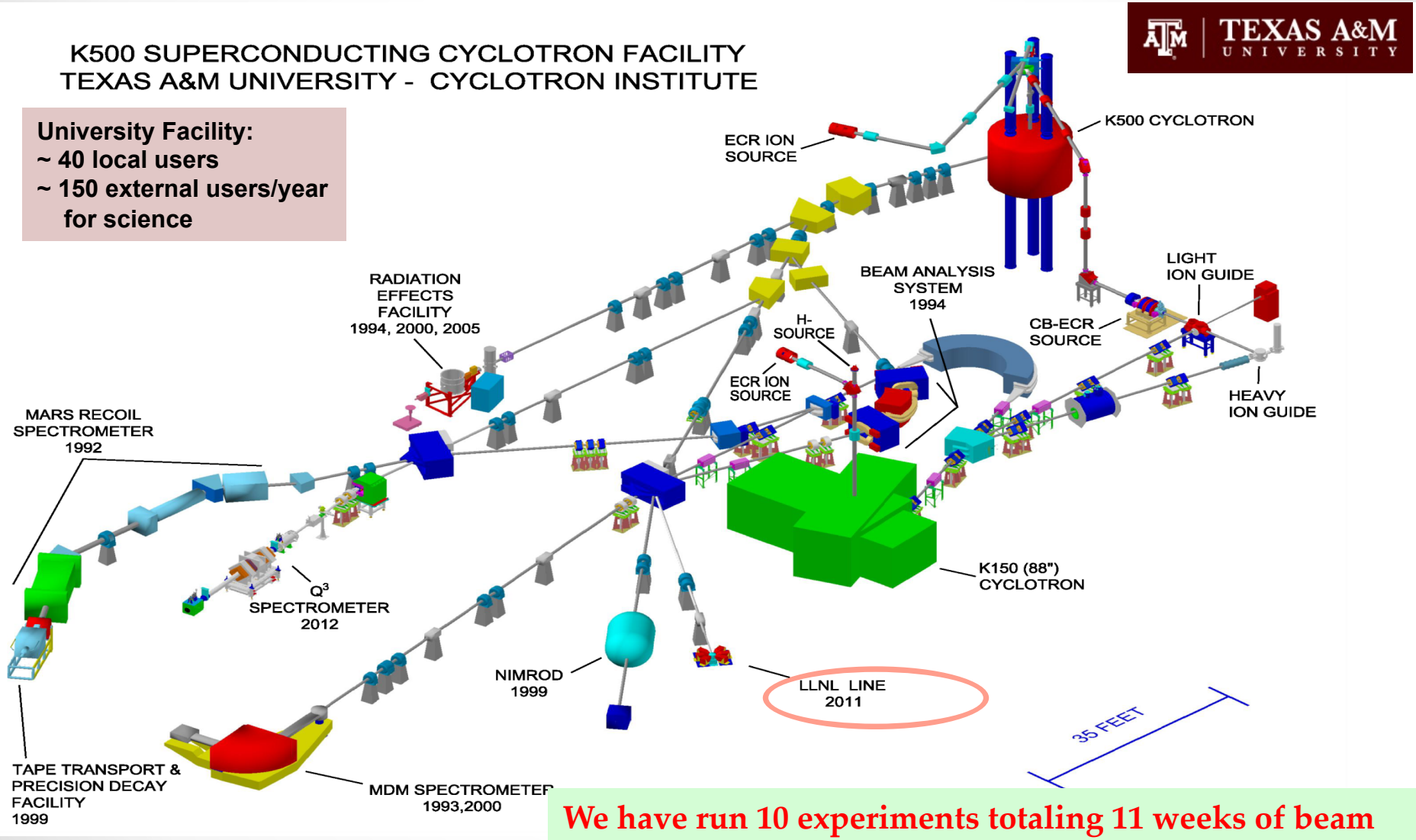


We record the dE, E, θ of the charged particles and also record the coincident γ-ray energies

Typical values:
- Si energy resolution 80 keV FWHM
- Gamma energy resolution 1.7 keV FWHM
- Charged Particle Angle range 30 to 60 degrees (pixelated by 24 rings & 8 sectors)

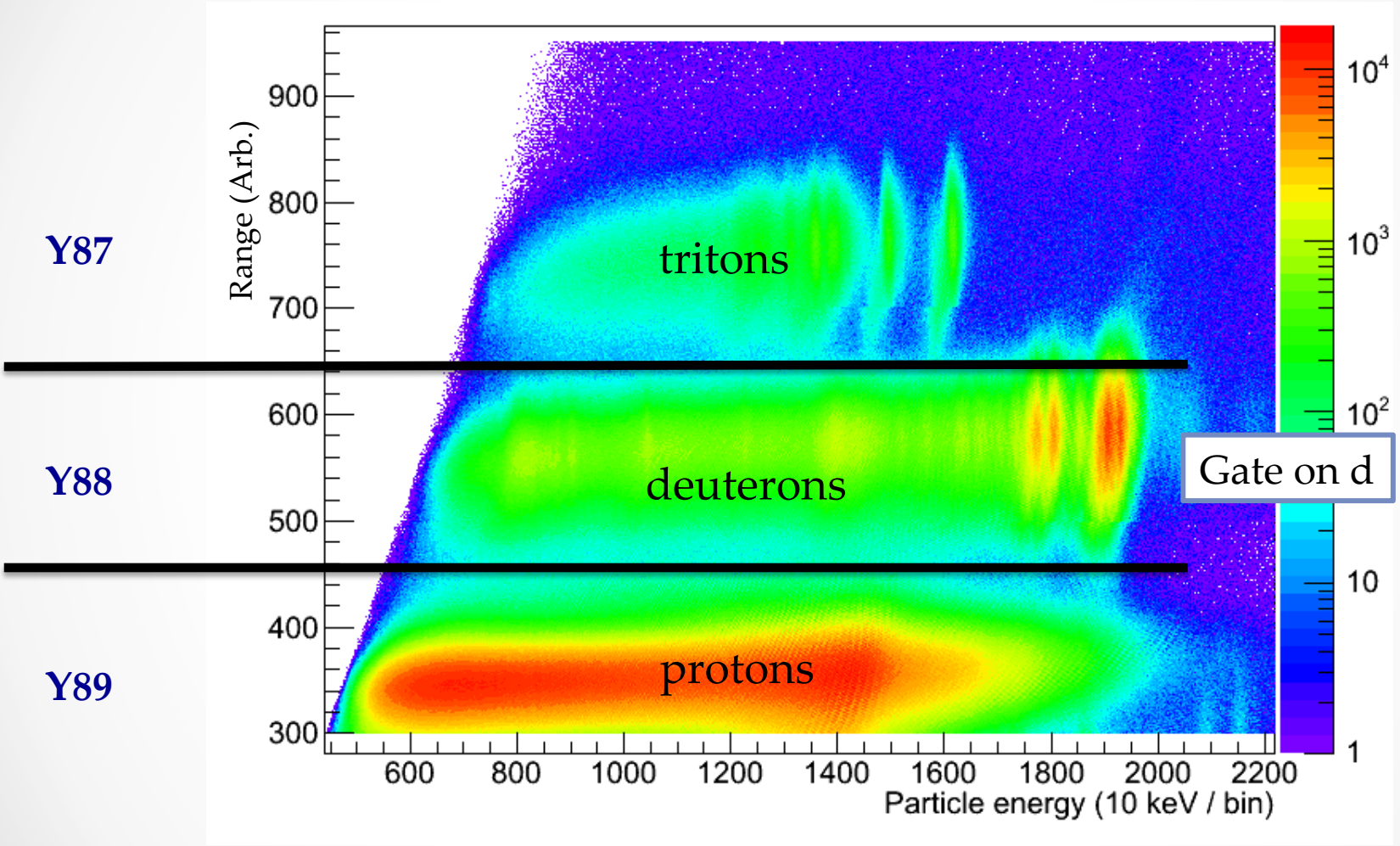
Texas A&M Cyclotron Institute, College Station, Texas

Two machines: K150 and K500 Cyclotrons stable beams available and radioactive beams under development



We have run 10 experiments totaling 11 weeks of beam time since April 2012.
(including p + $^{92, 94, 96}$Zr experiments, not discussed today)

PID plot from p + ^{89}Y

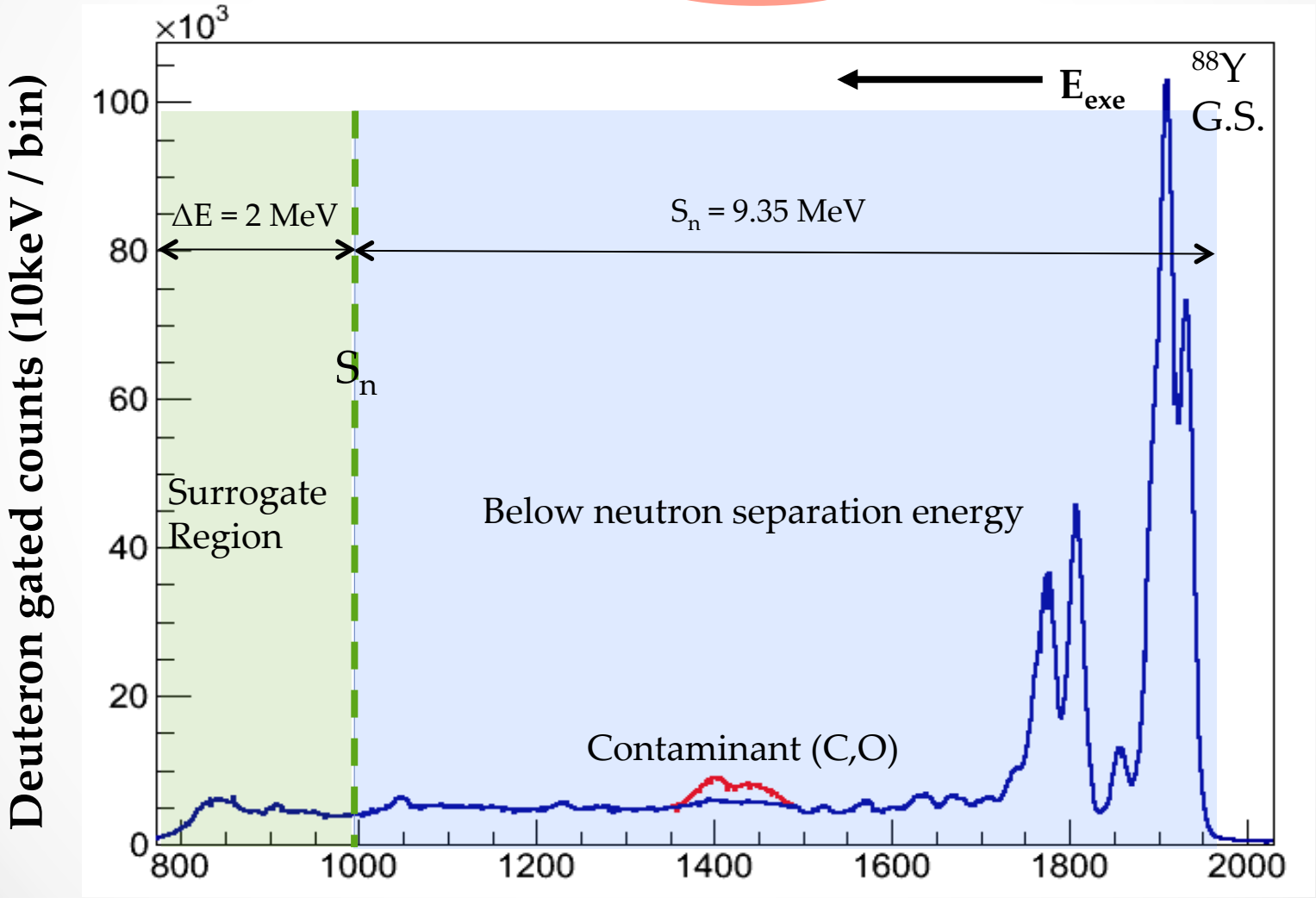


Data summary: >500 million Y89(p,p') reactions

96 million Y89(p,d)Y88* reactions, 7.8 million Y89(p,t)Y87* reactions

Deuteron singles spectrum used to determine the number of created ^{88}Y

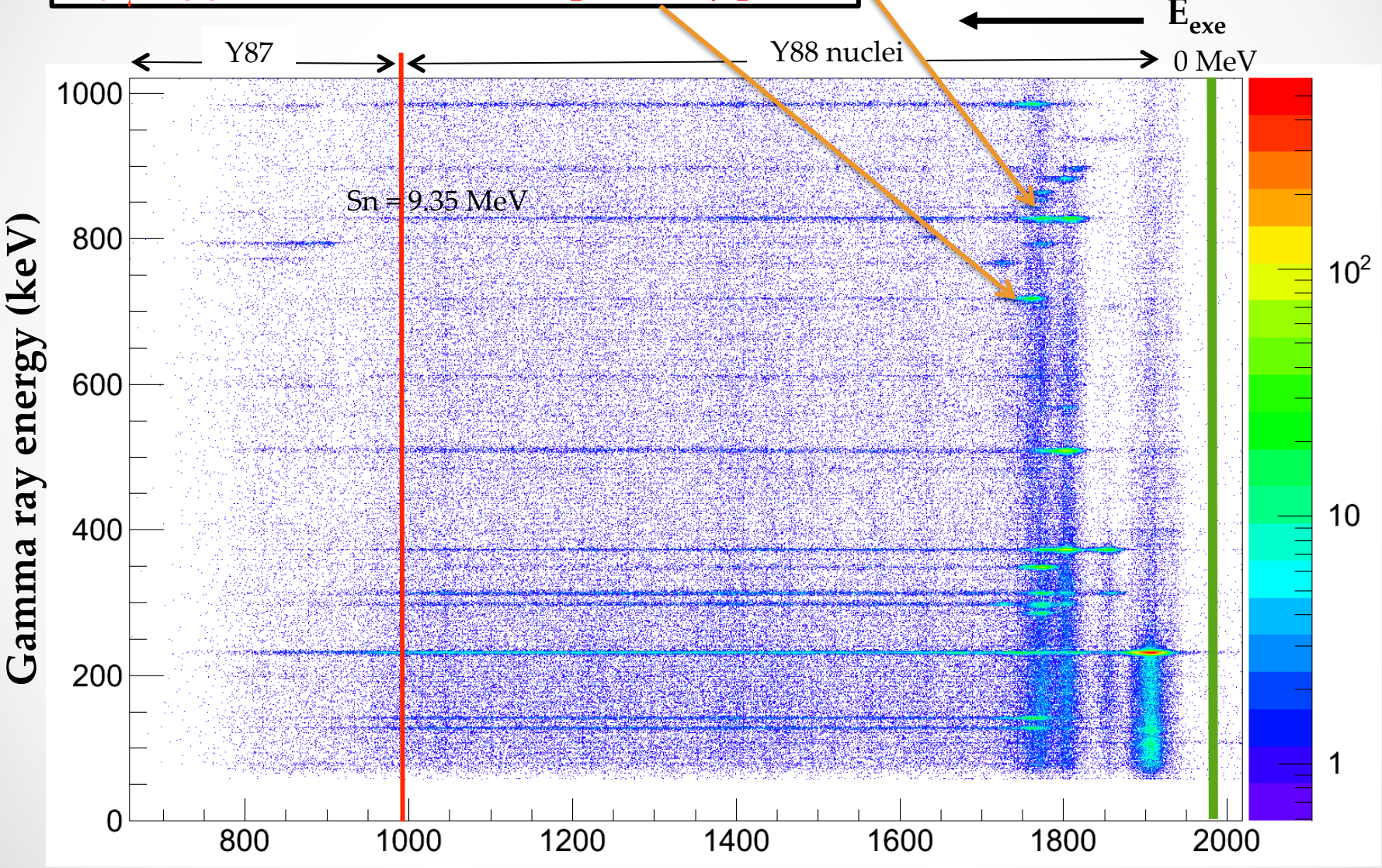
$$P_{d\gamma}(E) = \frac{N_{d\text{-}\gamma}(E_{exc})}{N_d(E_{exc})}$$



d-γ coincidence from $^{89}Y(p,d)^{88}Y$

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

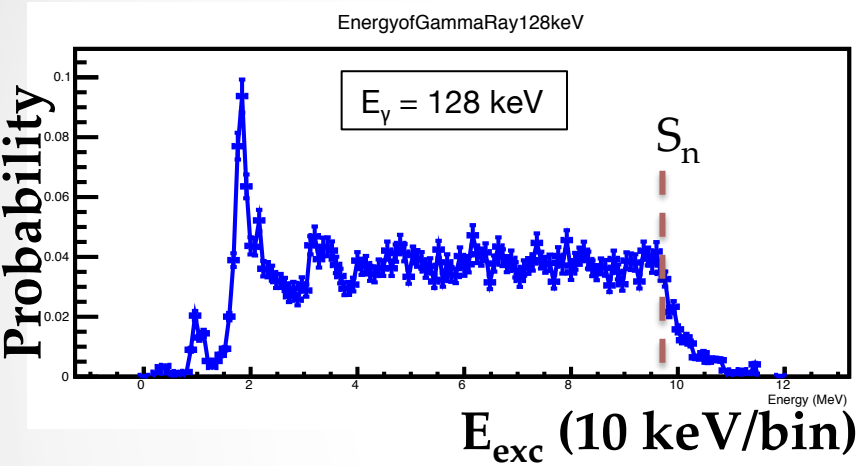
$N_{d\text{-}\gamma}(E_{exe})$ are obtained for respective γ-peaks

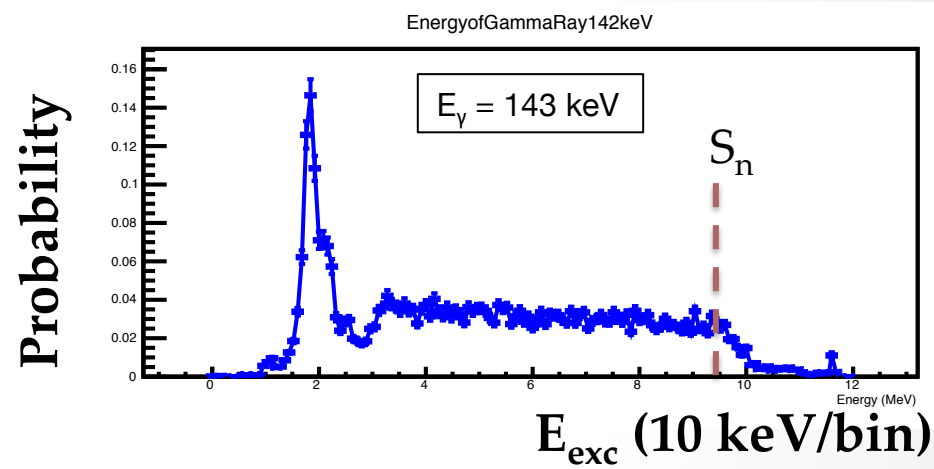


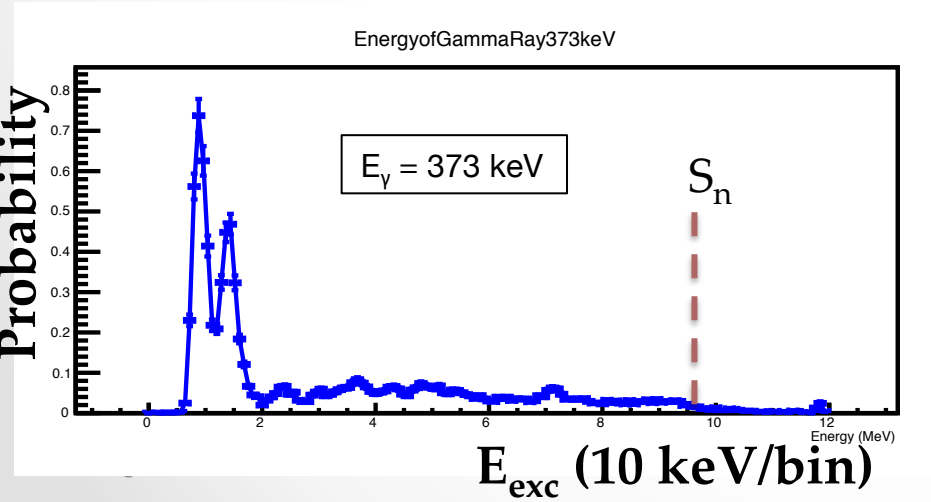
$^{89}Y(p,d)\ ^{88}Y$ γ decay probabilities (for 4 γ peaks are shown, but total 19 peaks were analyzed) used to determine the final parameters in G^{CN}_{γ}

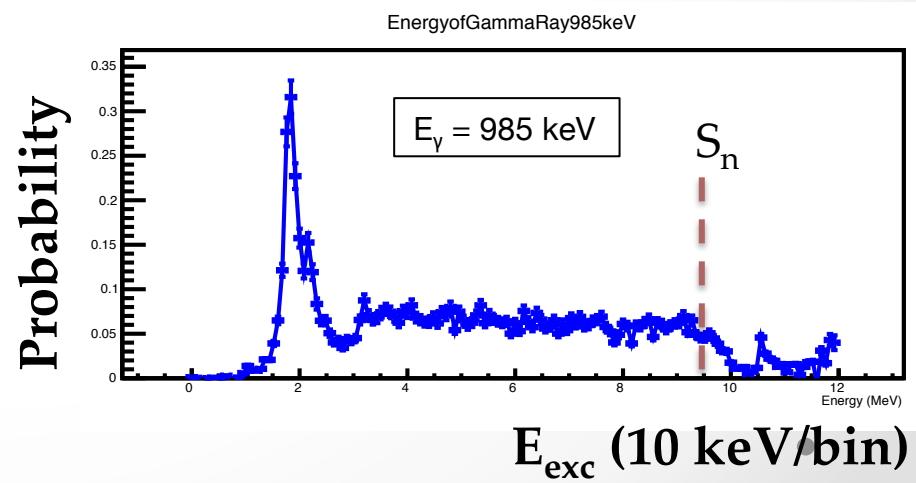
$$P_{d\gamma}(E) = \frac{N_{d\text{-}\gamma}(E_{exc})}{N_d(E_{exc})}$$

Courtesy of J. T. Burke





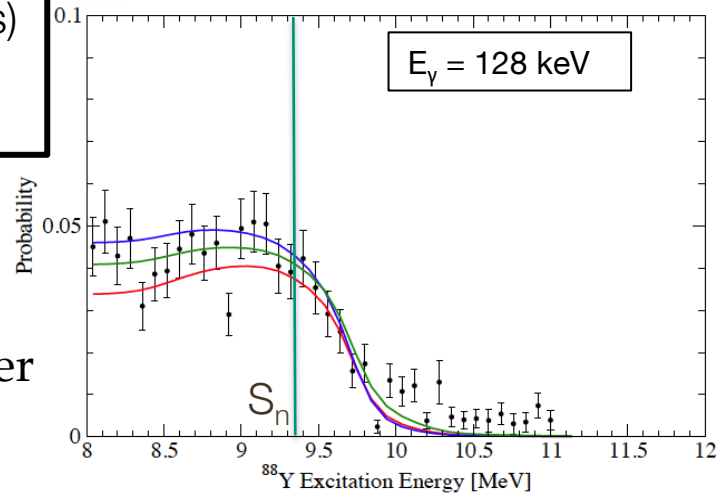


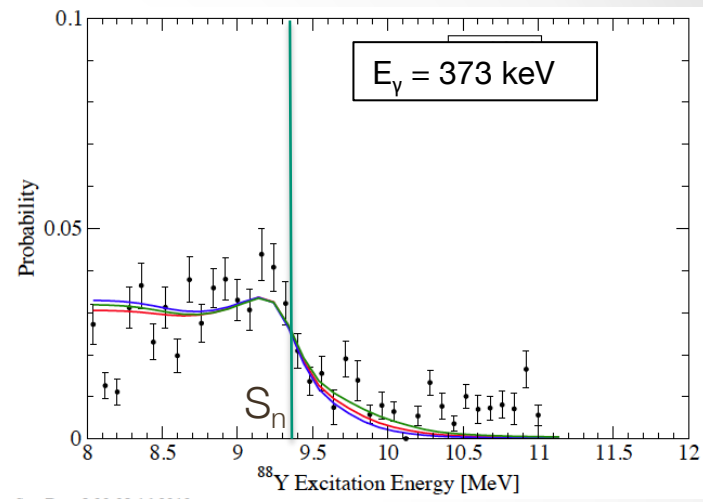


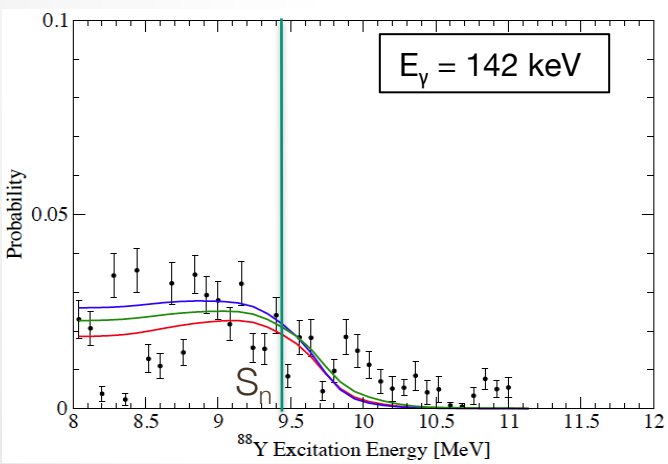
From measurement to cross section (PRELIMINARY!)

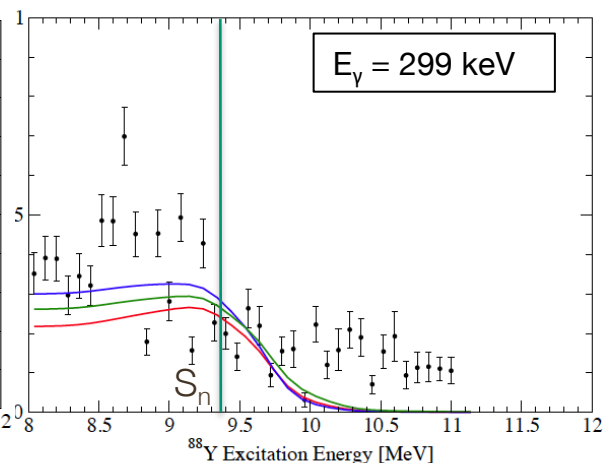
Fitting HF inputs (3 lines) to reproduce surrogate observables

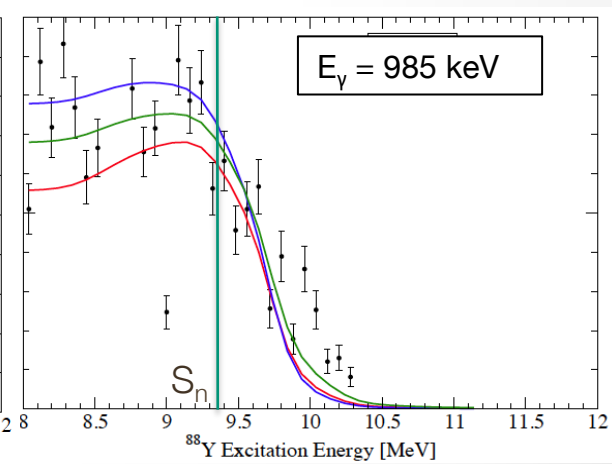
Courtesy of J. Escher & J.T. Burke









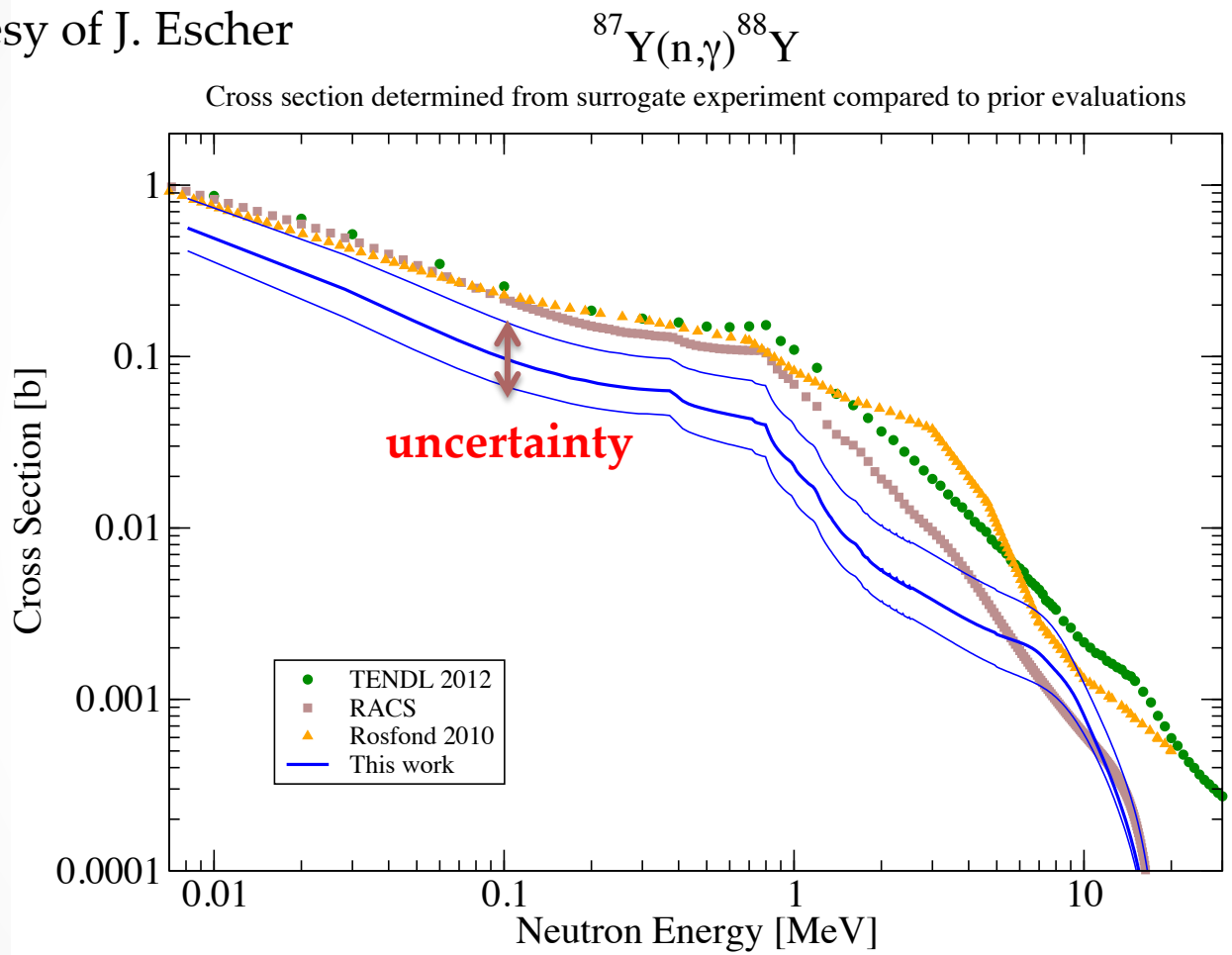


Fit yields 'best' set of parameters & uncertainty estimate.

$$P_{d\gamma}(E)=\Sigma_{J,\pi}\, F_d^{CN}(E,J,\pi)\cdot G^{CN}_{\gamma}(E,J,\pi)$$

^{87}Y (n,γ) cross sections (PRELIMINARY!!)

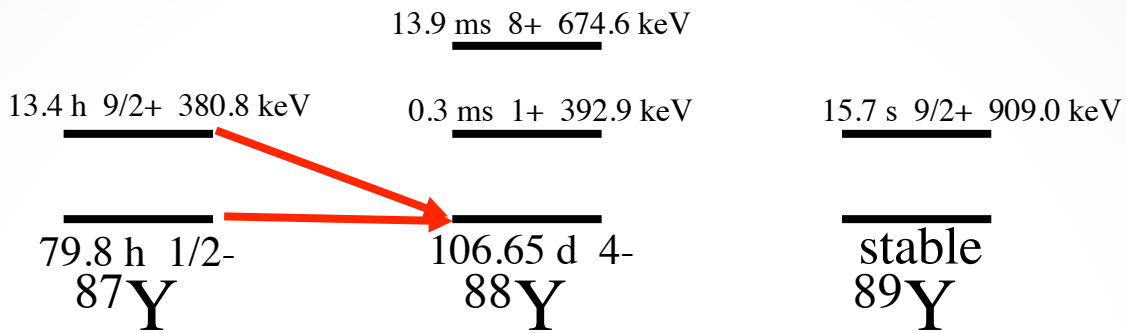
Courtesy of J. Escher



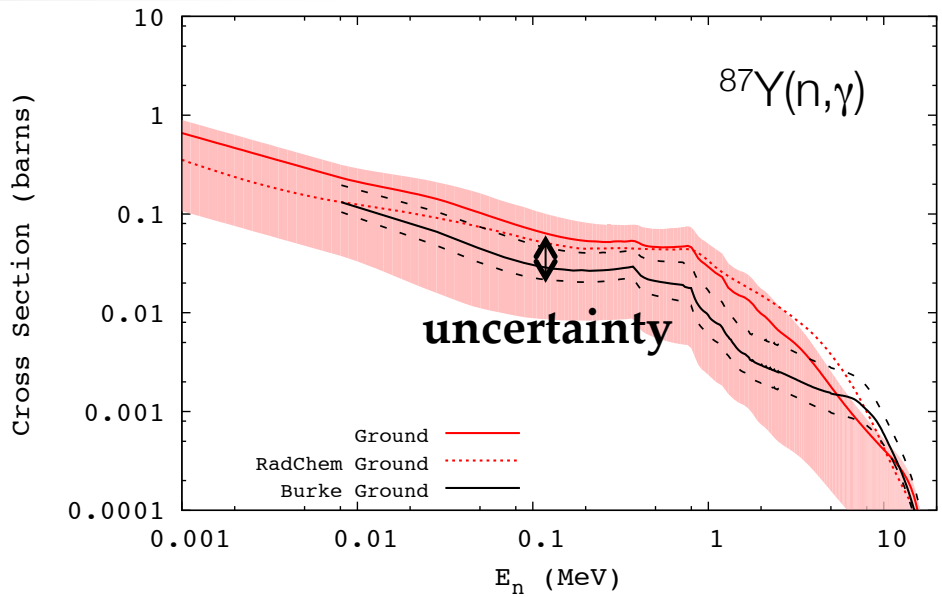
Using 'best' set of parameters to calculate ^{87}Y(n,γ) and ^{87m}Y(n,γ), including cross sections for gs and isomers in ^{88}Y

$$\sigma_{n\gamma} = \Sigma_{J,\pi}\, \sigma_n^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

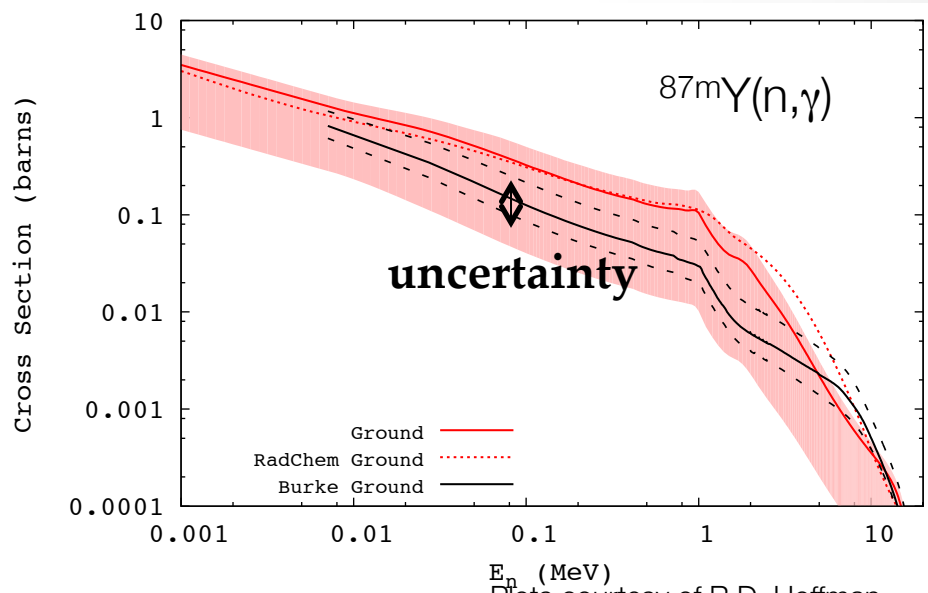
^{87}Y (n,γ) and ^{87m}Y (n,γ) – to GS (PRELIMINARY!)



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



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



Plots courtesy of R.D. Hoffman

^{87}Y(n,γ) and ^{87m}Y(n,γ) to ^{88}Y in M1 and M2 have been also obtained (Waiting for validation of our surrogate method)

Strategy & Major Concerns

I. Benchmark + Further step: (S. Ota & J.T. Burke)

- Use the same approach to compare with known $^{90}Zr(n,\gamma)$ cross section (by $^{92}Zr(p,d)$)
- Measure unknown $^{89}Zr(n,\gamma)$ cross section (by $^{91}Zr(p,d)$. τ_{89Zr}: 3 days)

II. Improve nuclear structure in ^{88}Y, ^{87}Y: (R.O. Hughes, J. T. Burke)

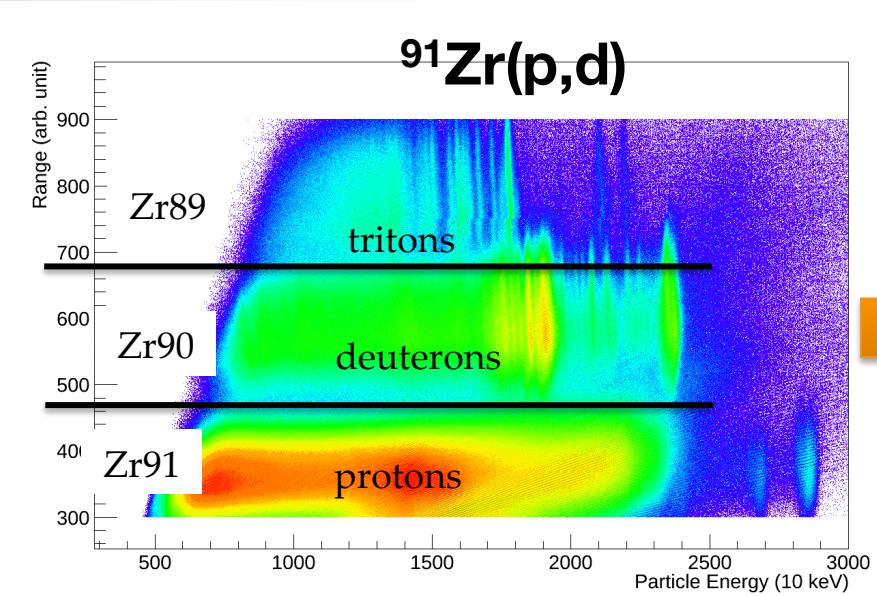
- Unknown or incorrect J^{π} and γ branching ratios in literature
- Improvements through more detailed study of present data, coupled with theory: e.g. use angular distributions of singles to fix spins; study γ–γ coincidences to fix branching ratios

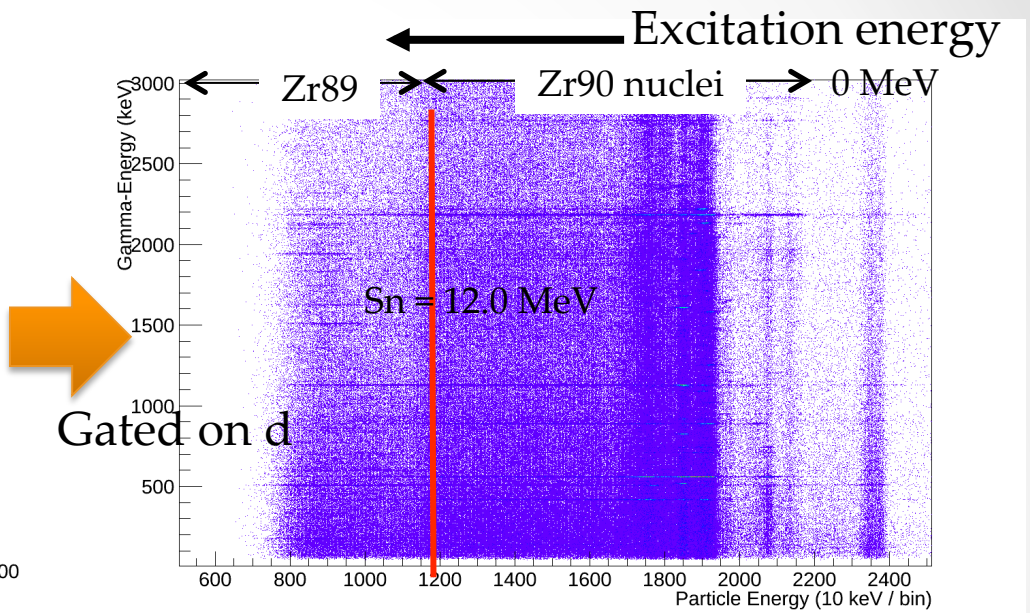
III. Improve calculations for $^{89}Y(p,d)$: (J.E. Escher)

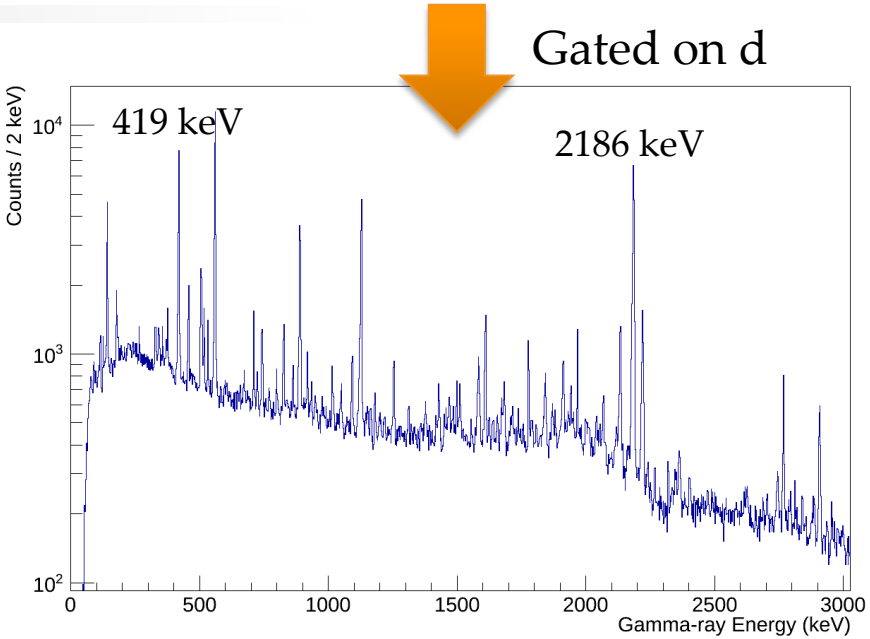
- Use results of improvements above to revisit predicted F_d^{CN} & G^{CN}_{γ}

There are still some unmentioned concerns as well

Preliminary Results from ^{89}Zr(n,γ) (1)







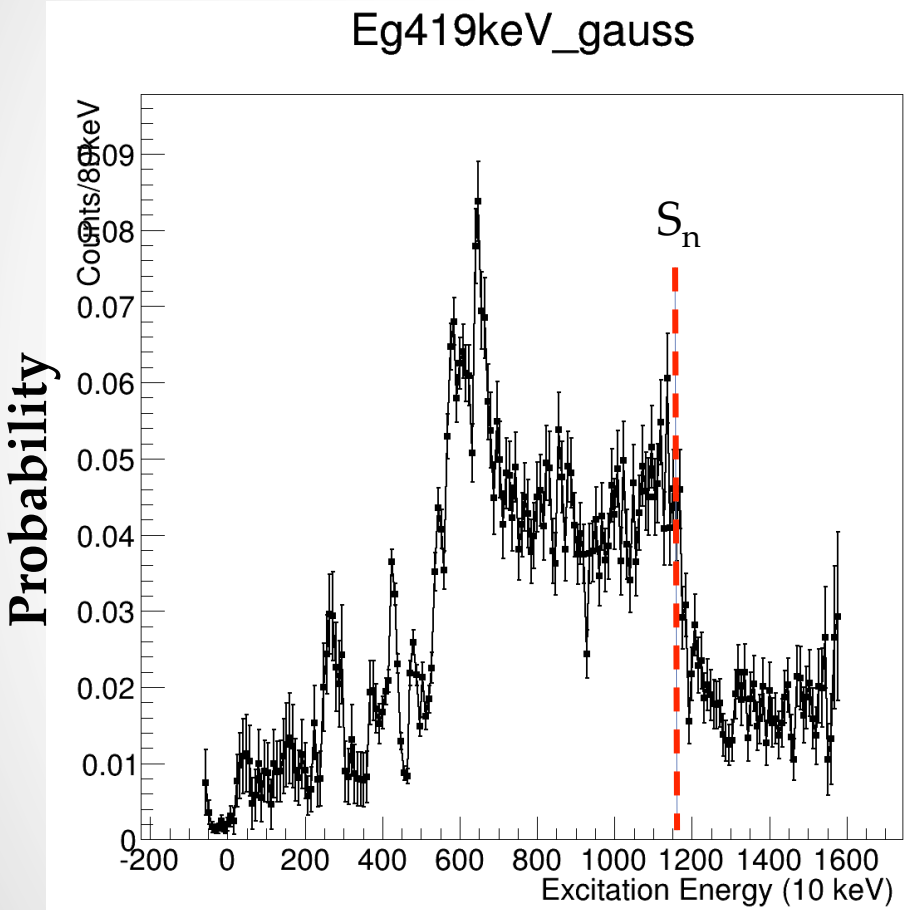
$P_{d\gamma}(E)$ for ~ 30 γ peaks are being obtained. (E_γ = 140 – 3309 keV)

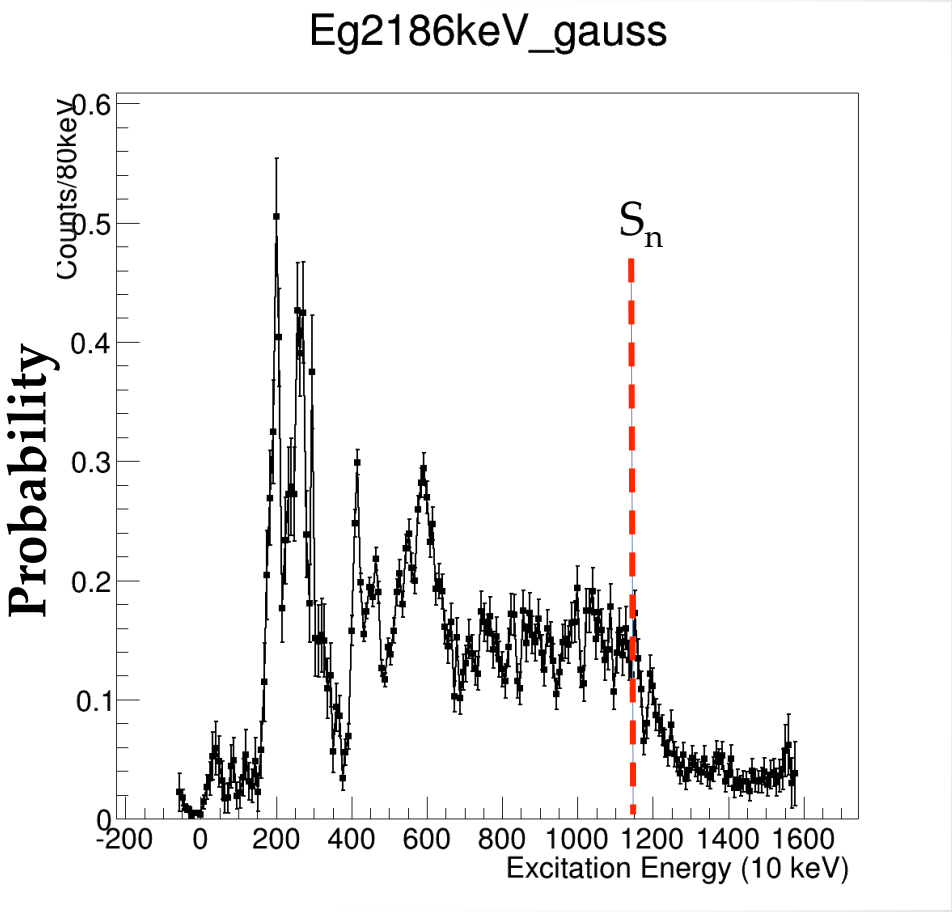
$$P_{d\gamma}(E) = \frac{N_{d\text{-}\gamma}(E_{exc})}{N_d(E_{exc})}$$

→ **These results will be used to obtain ^{89}Zr(n,γ) cross sections**

Preliminary Results from $^{89}Zr(n,\gamma)$ (2)

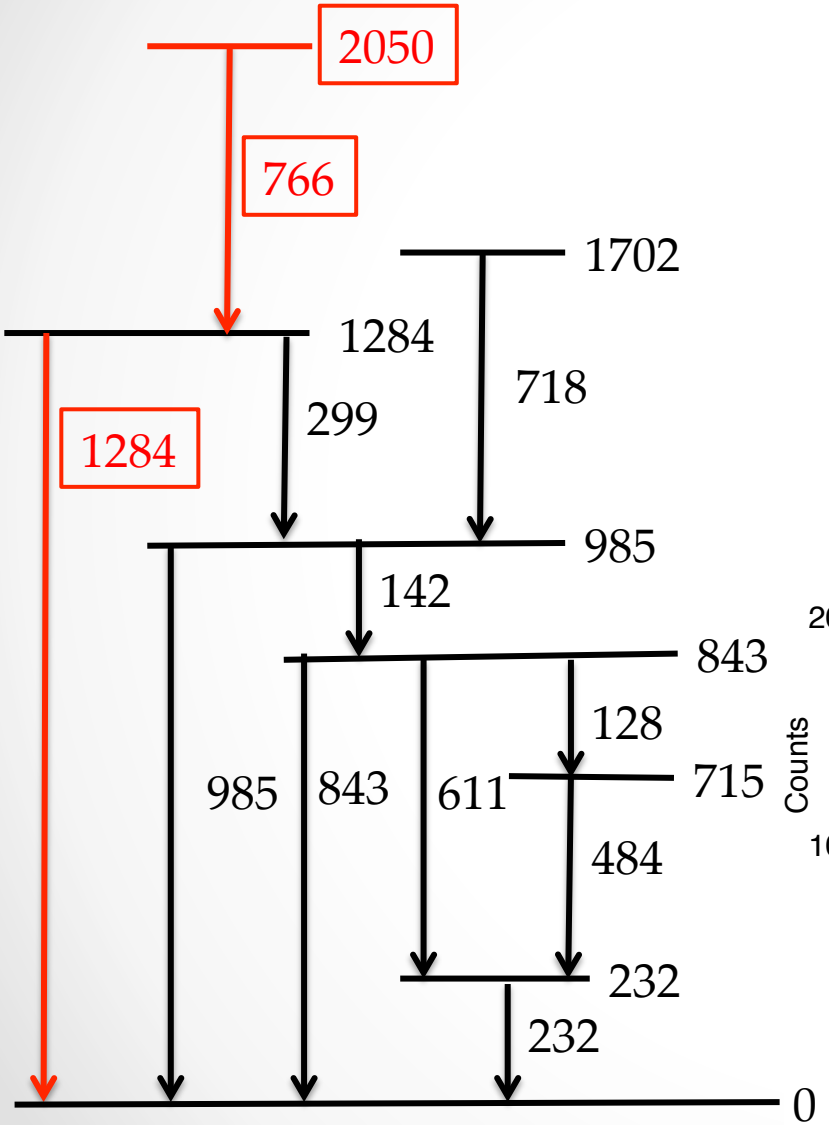
Both probabilities drop at $E = S_n$ as seen in ^{87}Y (n,γ)





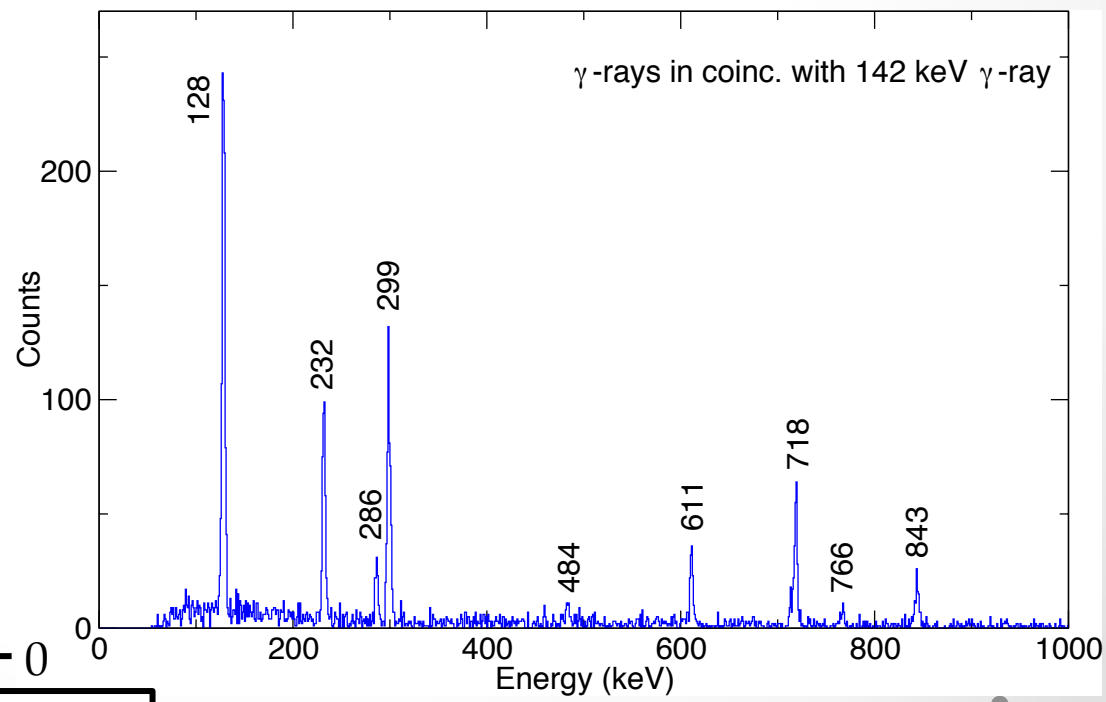
$^{90}Zr(n,\gamma)$ data analysis is in the same progress and waiting for theorist's analysis to obtain G^{CN}_{γ}

d-γ-γ data (^{88}Y structure by ^{89}Y(p,d))



By transfer reactions.
For improvement of Unknown or incorrect
- J^{π}
- γ branching

(Courtesy of R. O. Hughes)



unit: keV. γs in coincidence with 142 keV

Summary

1) **The surrogate reaction approach to experimentally constrain reaction cross sections** of some unstable isotopes has been studied. In astrophysics and nuclear science, these cross sections are very important.

2) WE approximation does not work for (n, γ) reactions, however, we have a path forward **and preliminary results for ^{87}Y(n, γ) have been obtained**.

3) **To validate 2), benchmarking using ^{90}Zr, ^{92}Zr, ^{94}Zr(p,d) data is underway**. ^{90}Zr(n, γ) (=^{92}Zr(p,d)) is the key benchmark.

4) Unknown (and important) ^{89,95}Zr(n, γ) are being studied as well, and we are also studying nuclear structure of ^{88}Y to improve our theory part.

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, R.O. Hughes , S. Ota, 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*

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