Surrogate Cross Section Methodology for Advanced Nuclear Reactors

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Table 40
Results of the target accuracy study for the EFR reactor

Isotope	Cross-section	Energy range	Uncertainty Initial	Uncertainty Required
U-238	σ_{capt}	1.35 MeV–498 keV	5	3.7
		498–183 keV	5	3.2
		183–67.4 keV	5	2.6
		67.4–24.8 keV	5	2.2
		24.8–9.12 keV	5	2.1
		9.12–2.03 keV	3	2.5
		2.03 keV–454 eV	3	2.4
	σ_{fiss}	6.07–2.23 MeV	5	3.1
		2.23–1.35 MeV	5	3.6
	σ_{inel}	6.07–2.23 MeV	15	4
		2.23–1.35 MeV	10	4.3
		1.35 MeV–498 keV	10	5.3
	$\sigma_{n,2n}$	19.6–6.07 MeV	30	10.9
Pu-238	σ_{capt}	2.03 keV–454 eV	20	18.9
	σ_{fiss}	67.4–24.8 keV	30	16.6
		24.8–9.12 keV	30	17.8
		9.12–2.03 keV	30	19.9
		2.03 keV–454 eV	30	15.8
Pu-239	σ_{capt}	1.35 MeV–498 keV	15	12
		498–183 keV	15	7.1
		183–67.4 keV	15	5.3
		67.4–24.8 keV	10	5
		24.8–9.12 keV	10	4.4
		9.12–2.03 keV	5	4.1
		2.03 keV–454 eV	5	3.4
	σ_{fiss}	6.07–2.23 MeV	5	3.4
		2.23–1.35 MeV	5	3.4
		1.35 MeV–498 keV	5	1.9
		498–183 keV	5	1.8
		183–67.4 keV	5	1.7
		67.4–24.8 keV	5	2
		24.8–9.12 keV	5	2.3
		9.12–2.03 keV	5	2.7
		2.03 keV–454 eV	3	2.2
	$\sigma_{n,2n}$	19.6–6.07 MeV	50	32.4
Na-23	σ_{inel}	6.07–2.23 MeV	30	13.1
		1.35 MeV–498 keV	30	8.7

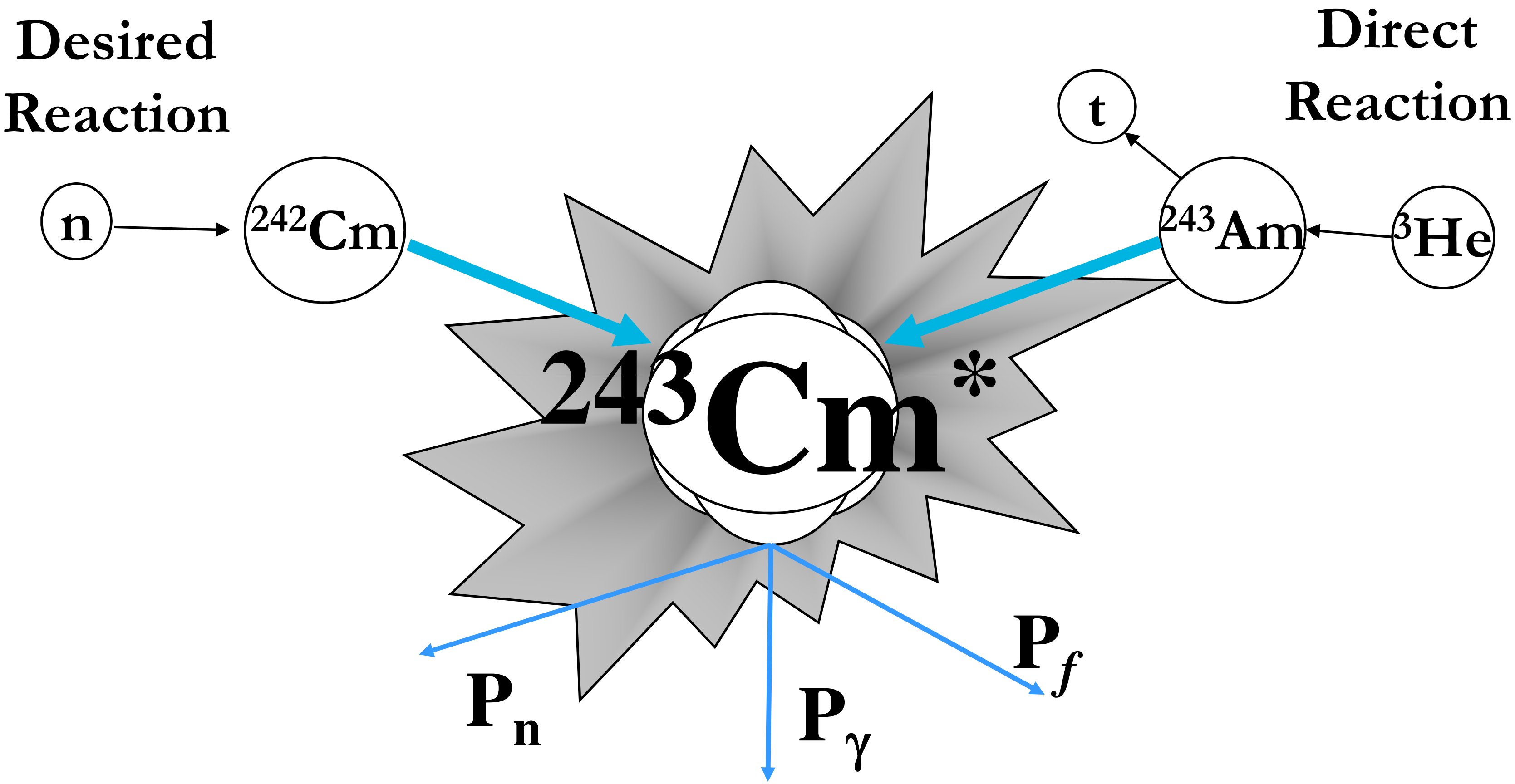
Isotope	Cross-section	Energy range	Uncertainty Initial	Uncertainty Required
Pu-240				
Pu-241				
		67.4–24.8 keV	10	4.1
		24.8–9.12 keV	10	4.3
		9.12–2.03 keV	10	4.8
		2.03 keV–454 eV	10	4.3
Am-241	σ_{capt}	183–67.4 keV	10	9.8
Am-242m	σ_{capt}	183–67.4 keV	40	32.7
	σ_{fiss}	183–67.4 keV	20	19.4
		67.4–24.8 keV	20	19.2
Cm-242	σ_{capt}	498–183 keV	40	18.6
		183–67.4 keV	40	12.9
		67.4–24.8 keV	40	10.4
		24.8–9.12 keV	40	10
		9.12–2.03 keV	40	11.4
		2.03 keV–454 eV	40	9.2
		454–22.6 eV	40	18
	σ_{fiss}	6.07–2.23 MeV	40	28.9
		2.23–1.35 MeV	40	29.1
		1.35 MeV–498 keV	40	18.4
		498–183 keV	40	29.3
O-16	σ_{capt}	6.07–2.23 MeV	20	11.7
	σ_{el}	498–183 keV	5	4.9

Isotope	Cross-section	Energy range	Uncertainty Initial	Uncertainty Required
	σ_{fiss}	6.07–2.23 MeV	40	19.6
		2.23–1.35 MeV	40	21.3
		1.35 MeV–498 keV	40	13.2
		498–183 keV	40	30.7
Cm-245	σ_{capt}	183–67.4 keV	40	30.4
		67.4–24.8 keV	40	30.9
		2.03 keV–454 eV	40	31.5
	σ_{fiss}	6.07–2.23 MeV	40	30.2
		2.23–1.35 MeV	40	29.7
		1.35 MeV–498 keV	40	17.4
		498–183 keV	40	14.3
		183–67.4 keV	40	12.5
		67.4–24.8 keV	40	13.5
		24.8–9.12 keV	40	14.6
		9.12–2.03 keV	40	16.6
		2.03 keV–454 eV	40	14.5
		454–22.6 eV	40	30.9
Fe-56	σ_{inel}	6.07–2.23 MeV	15	6.7
		2.23–1.35 MeV	10	7.2
		1.35 MeV–498 keV	20	9.1
Cr-52	$\sigma_{n,2n}$	19.6–6.07 MeV	100	22.3

Isotope	Cross-section	Energy range	Uncertainty Initial	Uncertainty Required
Cm-242	σ_{capt}	498–183 keV	40	18.6
		183–67.4 keV	40	12.9
		67.4–24.8 keV	40	10.4
		24.8–9.12 keV	40	10
		9.12–2.03 keV	40	11.4
		2.03 keV–454 eV	40	9.2
		454–22.6 eV	40	18
	σ_{fiss}	6.07–2.23 MeV	40	28.9
		2.23–1.35 MeV	40	29.1
		1.35 MeV–498 keV	40	18.4
		498–183 keV	40	29.3

G. Aliberti et al. / Annals of Nuclear Energy 33 (2006) 700–733

The Surrogate Method



Central assumption: Both reactions form a compound nucleus

External Surrogate Ratio Method

Consider two reactions:

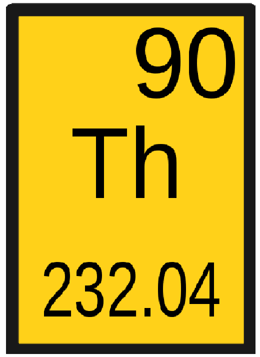
$$R = \frac{\sigma_{n,f}^{(1)}}{\sigma_{n,f}^{(2)}} = \frac{\sigma_n^{(1)}(E)\, P_{\beta f}^{(1)}(E)}{\sigma_n^{(2)}(E) P_{\beta f}^{(2)}(E)}$$

Experimentally Obtained:

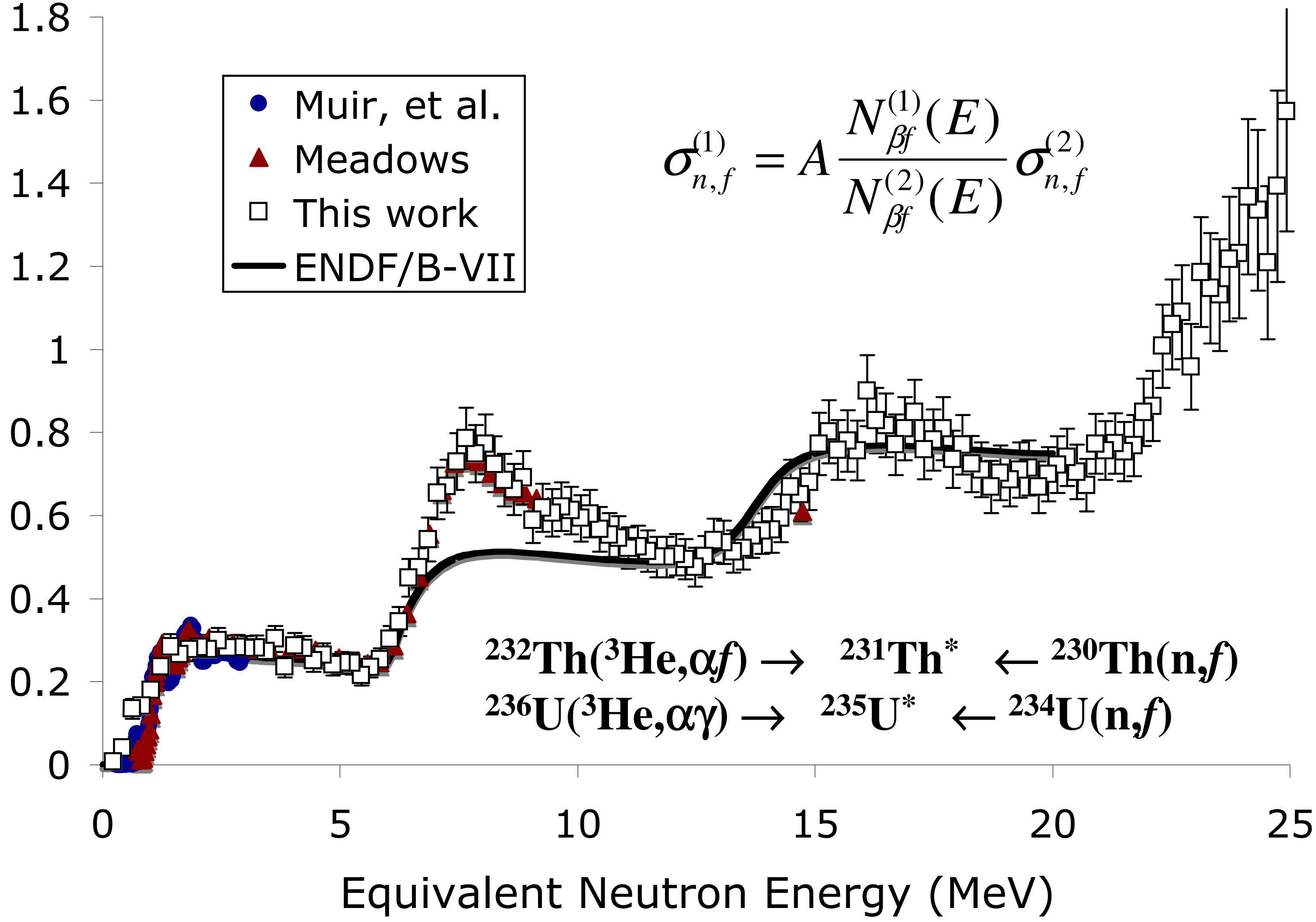
$$R = \frac{P_{\beta f}^{(1)}(E)}{P_{\beta f}^{(2)}(E)} = \frac{N_{\beta f}^{(1)}(E)}{N_{\beta}^{(1)}(E)} \frac{N_{\beta}^{(2)}(E)}{N_{\beta f}^{(2)}(E)} A_{norm}$$

$$\sigma_{n,f}^{(1)} = A_{norm} \frac{N_{\beta f}^{(1)}(E)}{N_{\beta f}^{(2)}(E)} \sigma_{n,f}^{(2)}$$

Thorium-Based Nuclear Reactors

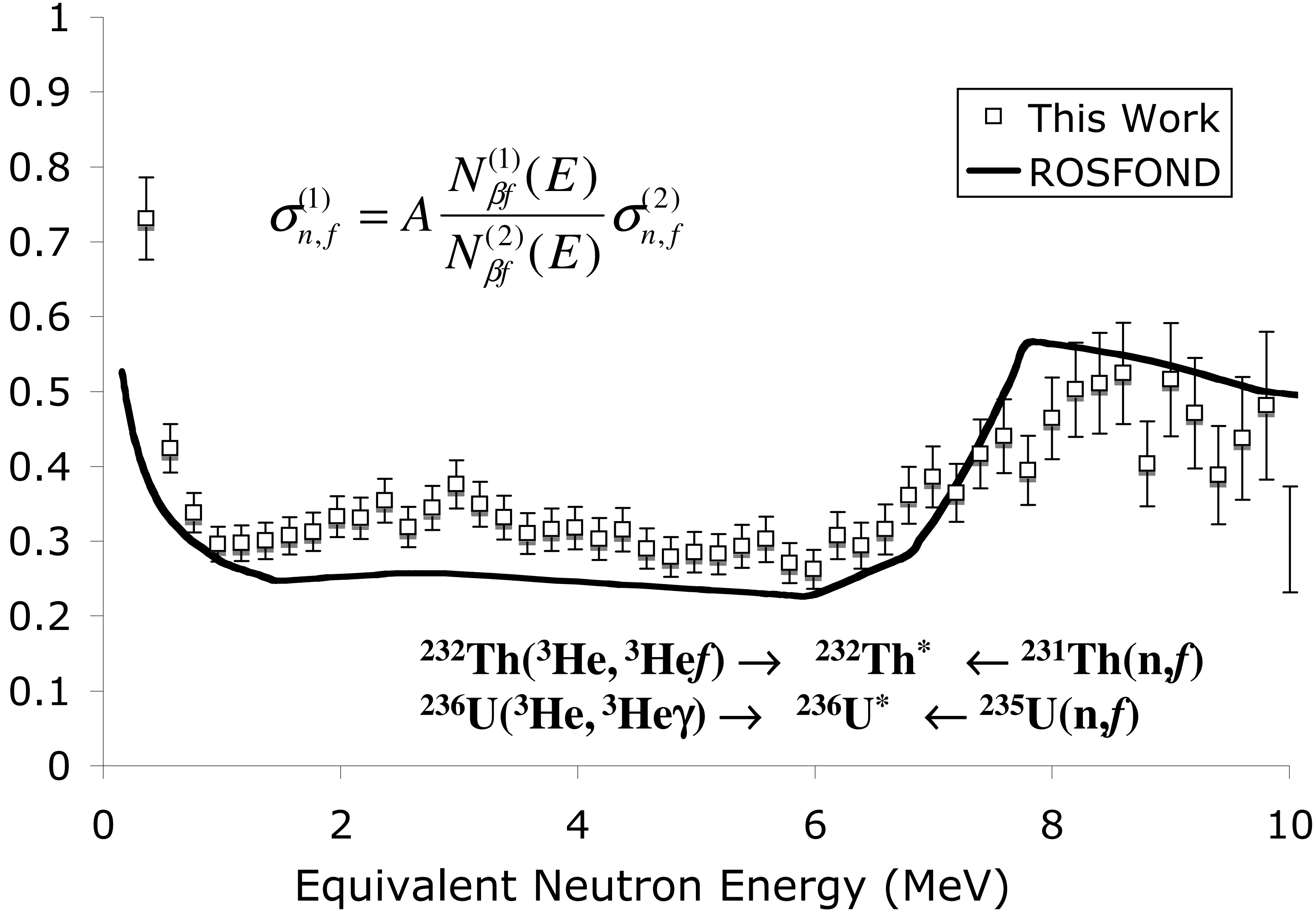


Applications in Nuclear Security and Advanced Nuclear Reactor Design



B.L. Goldblum, *et al.* Phys. Rev. C **80**, 044610 (2009).

Applications in Nuclear Security and Advanced Nuclear Reactor Design



B.L. Goldblum, *et al.* Phys. Rev. C **80**, 044610 (2009).

(n,γ) Cross Sections Using the External Surrogate Ratio Method

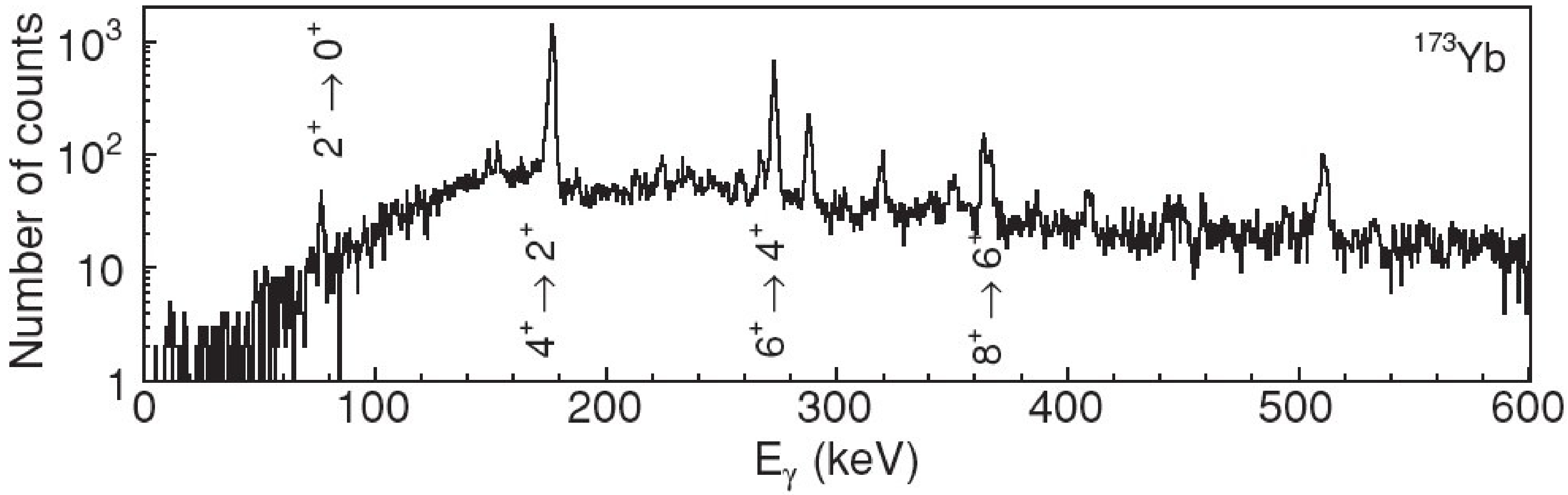
Discrete γ ray Tagging

Statistical γ ray Tagging

(n,γ) Cross Sections Using the External Surrogate Ratio Method

Discrete γ ray Tagging

Statistical γ ray Tagging

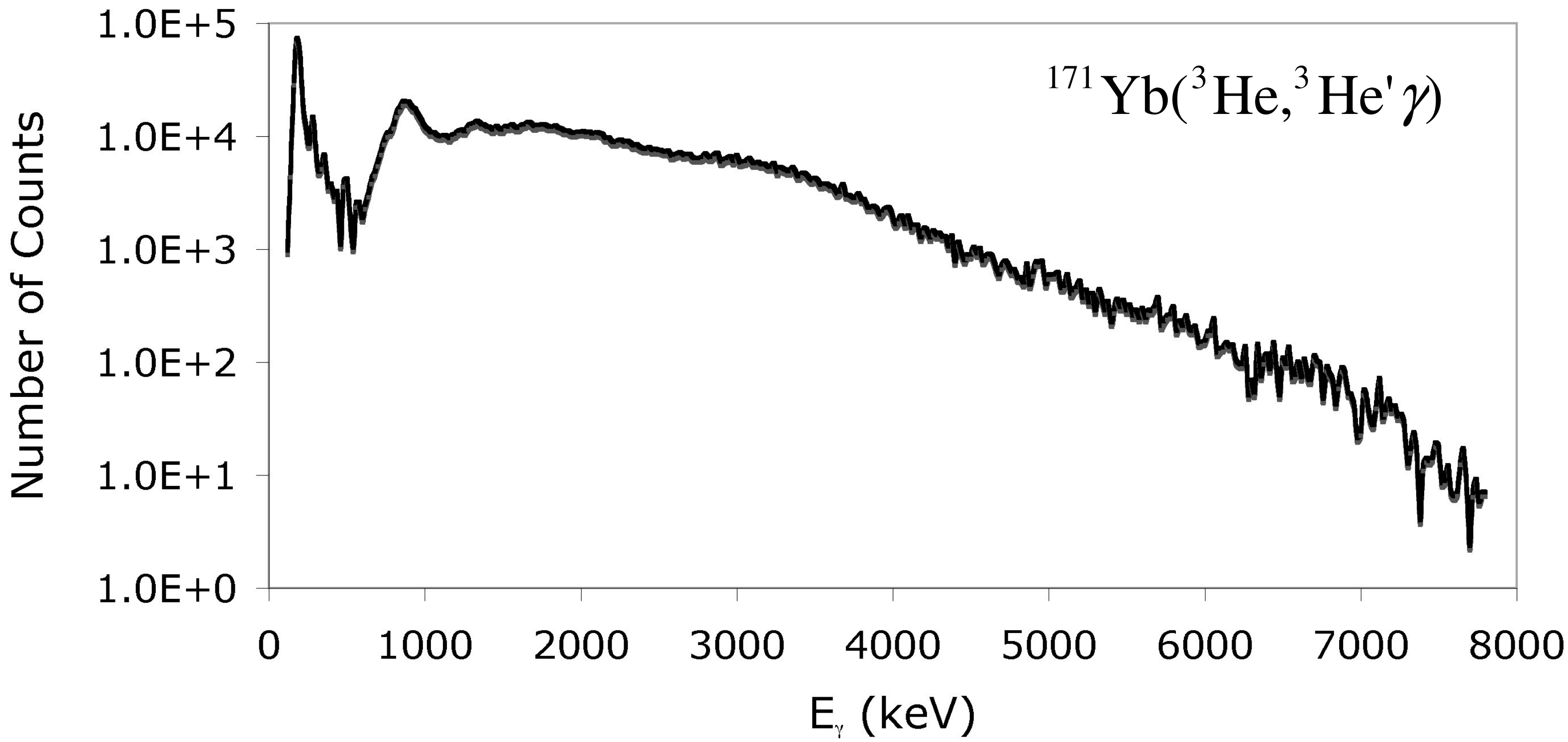


R. Hatarik, *et al.* Phys. Rev. C **81**, 011602(R) (2010).

(n,γ) Cross Sections Using the External Surrogate Ratio Method

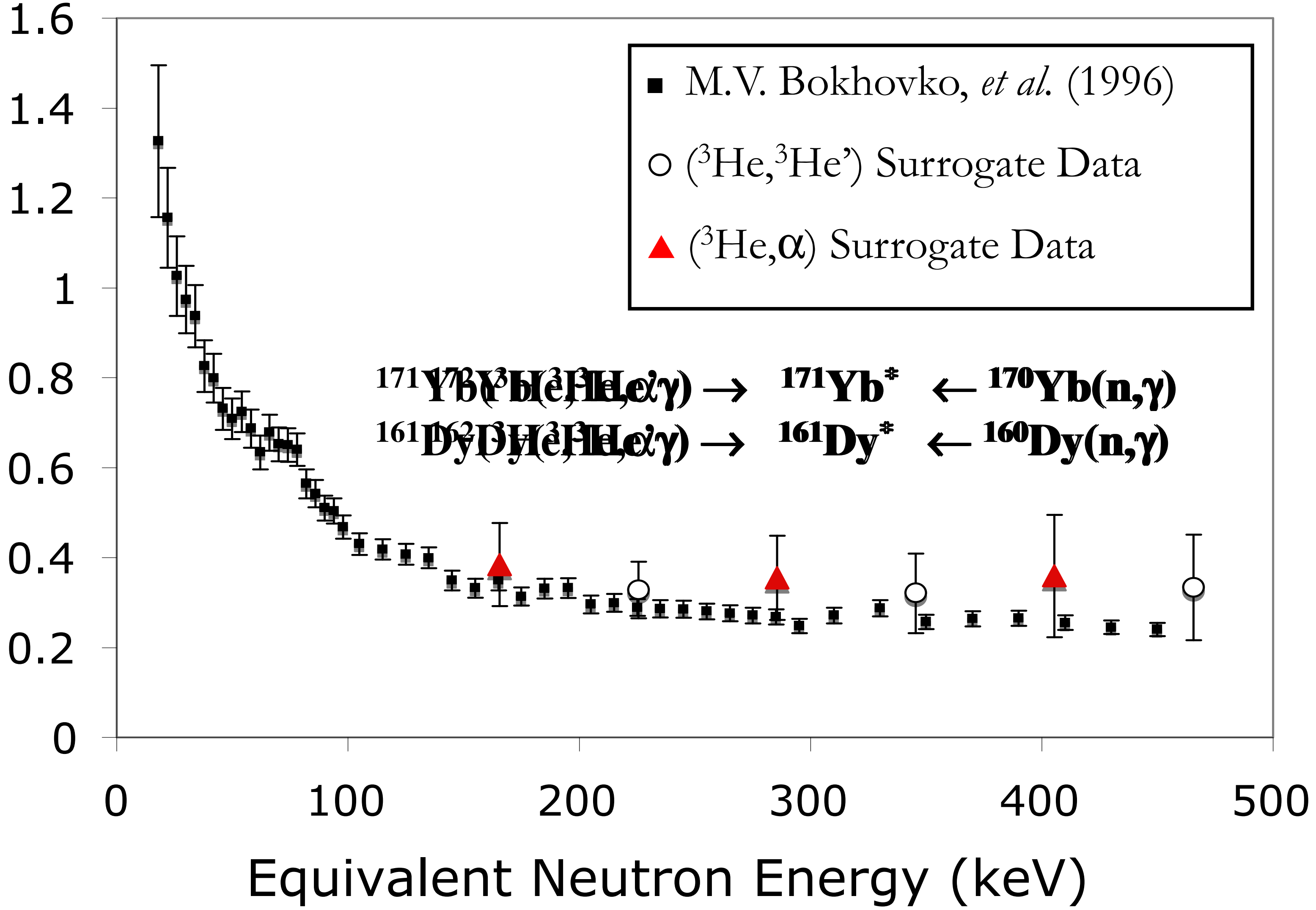
Discrete γ ray Tagging

Statistical γ ray Tagging



B.L. Goldblum, *et al.* Phys. Rev. C **78**, 064606 (2008).

^{170}Yb(n,γ) Cross Section using the Surrogate Ratio Method: Comparison of (^{3}He,^{3}He') and (^{3}He,α) Entrance Channels



B.L. Goldblum, *et al.* Phys. Rev. C **78**, 064606 (2008).

11

Surrogate Ratio Methodology for the Determination of (n,γ) Cross Sections

^{161}Dy — Z = 66, $\beta \approx 0.26$, $I^{\pi} = 5/2^{+}$	^{162}Dy — Z = 66, $\beta \approx 0.26$, $J^{\pi} = 0^{+}$

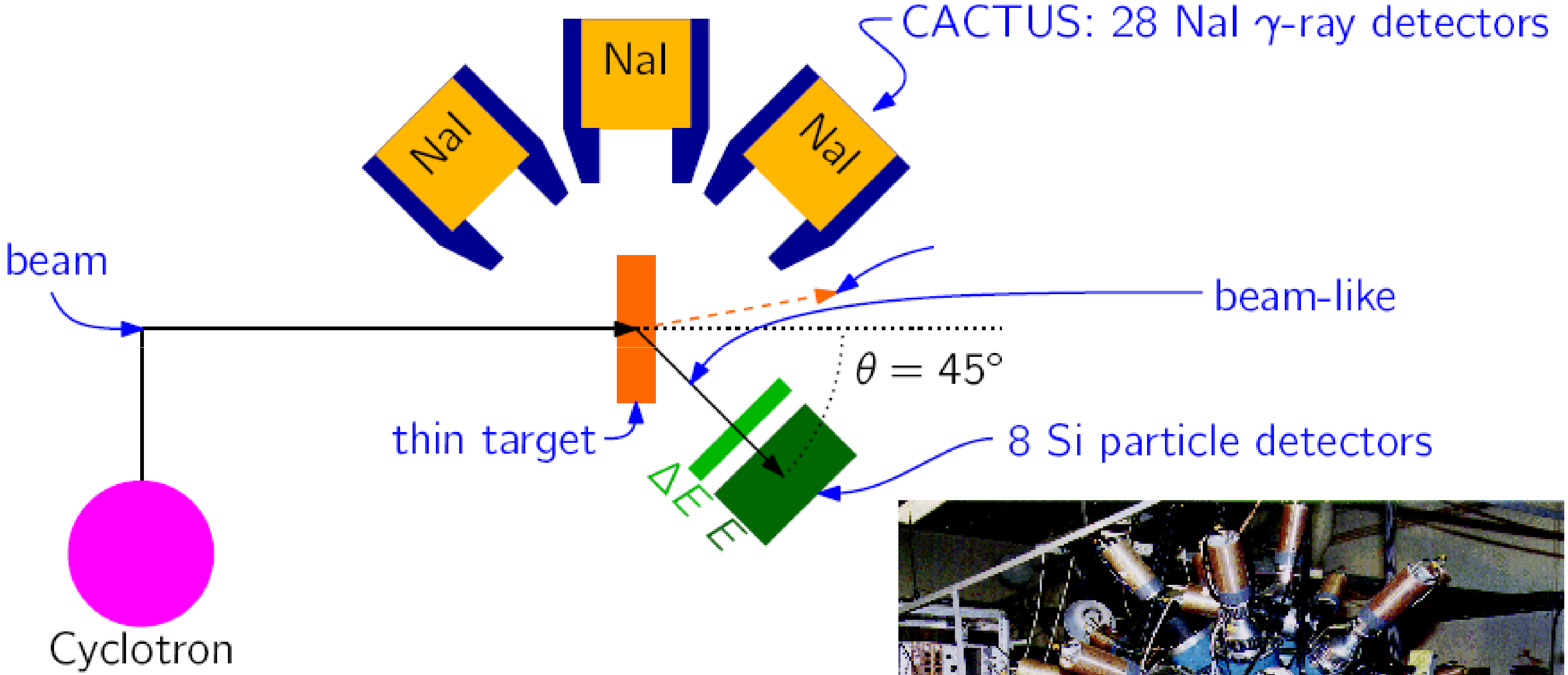
Inelastic scattering entrance channel:

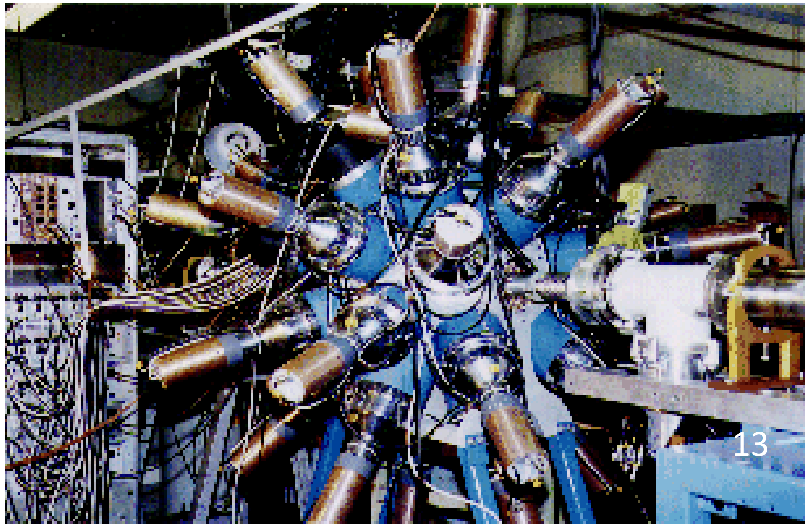
$$^{162}\mathrm{Dy}(^{3}\mathrm{He},^{3}\mathrm{He}'\gamma) \rightarrow \; ^{162}\mathrm{Dy}^{*} \leftarrow \; ^{161}\mathrm{Dy}(n,\gamma)$$
$$^{161}\mathrm{Dy}(^{3}\mathrm{He},^{3}\mathrm{He}'\gamma) \rightarrow \; ^{161}\mathrm{Dy}^{*} \leftarrow \; ^{160}\mathrm{Dy}(n,\gamma)$$

Pickup reaction entrance channel:

$$^{163}\mathrm{Dy}(^{3}\mathrm{He},\alpha\gamma) \rightarrow \; ^{162}\mathrm{Dy}^{*} \leftarrow \; ^{161}\mathrm{Dy}(n,\gamma)$$
$$^{162}\mathrm{Dy}(^{3}\mathrm{He},\alpha\gamma) \rightarrow \; ^{161}\mathrm{Dy}^{*} \leftarrow \; ^{160}\mathrm{Dy}(n,\gamma)$$

Experimental Apparatus

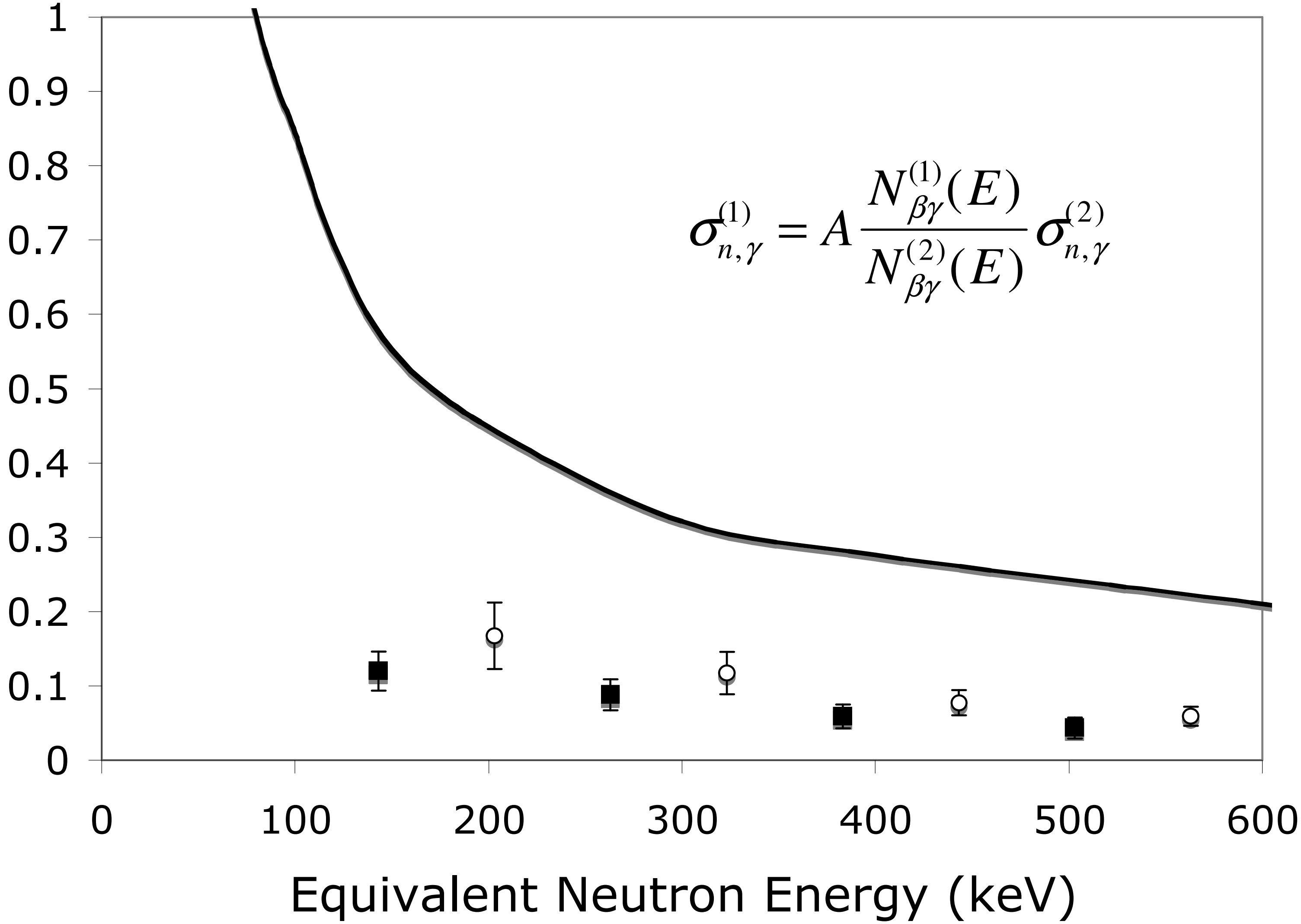




M. Guttormsen, et al., Phys. Rev. C **68**, 064306 (2003).

U. Agvaanluvsan, et al., Phys. Rev. C **70**, 054611 (2004).

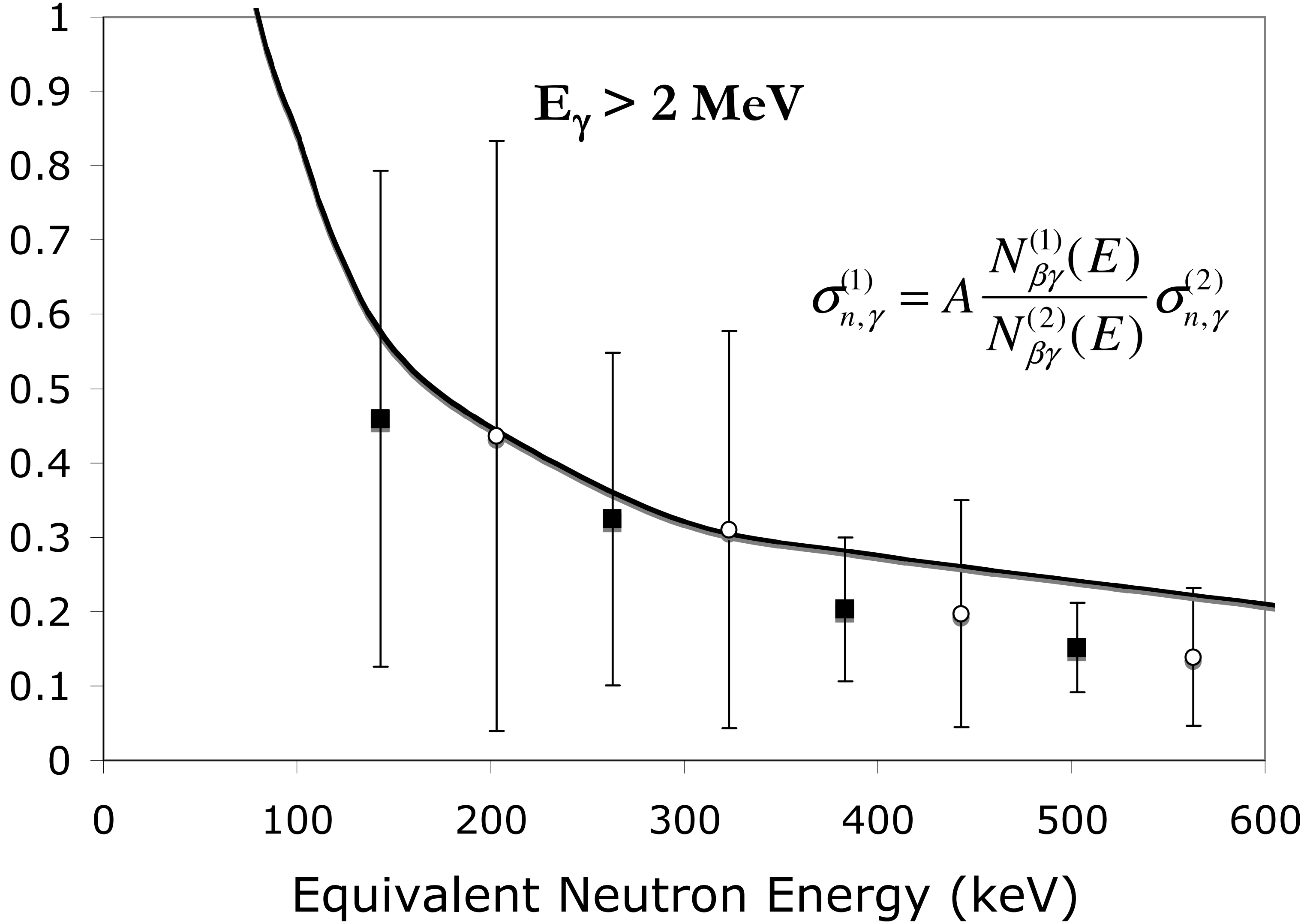
^{161}Dy(n,γ) Cross Section using the Surrogate Ratio Method



$$\sigma_{n,\gamma}^{(1)} = A \frac{N_{\beta\gamma}^{(1)}(E)}{N_{\beta\gamma}^{(2)}(E)} \sigma_{n,\gamma}^{(2)}$$

B.L. Goldblum, *et al.* Phys. Rev. C **81**, 054606 (2010).

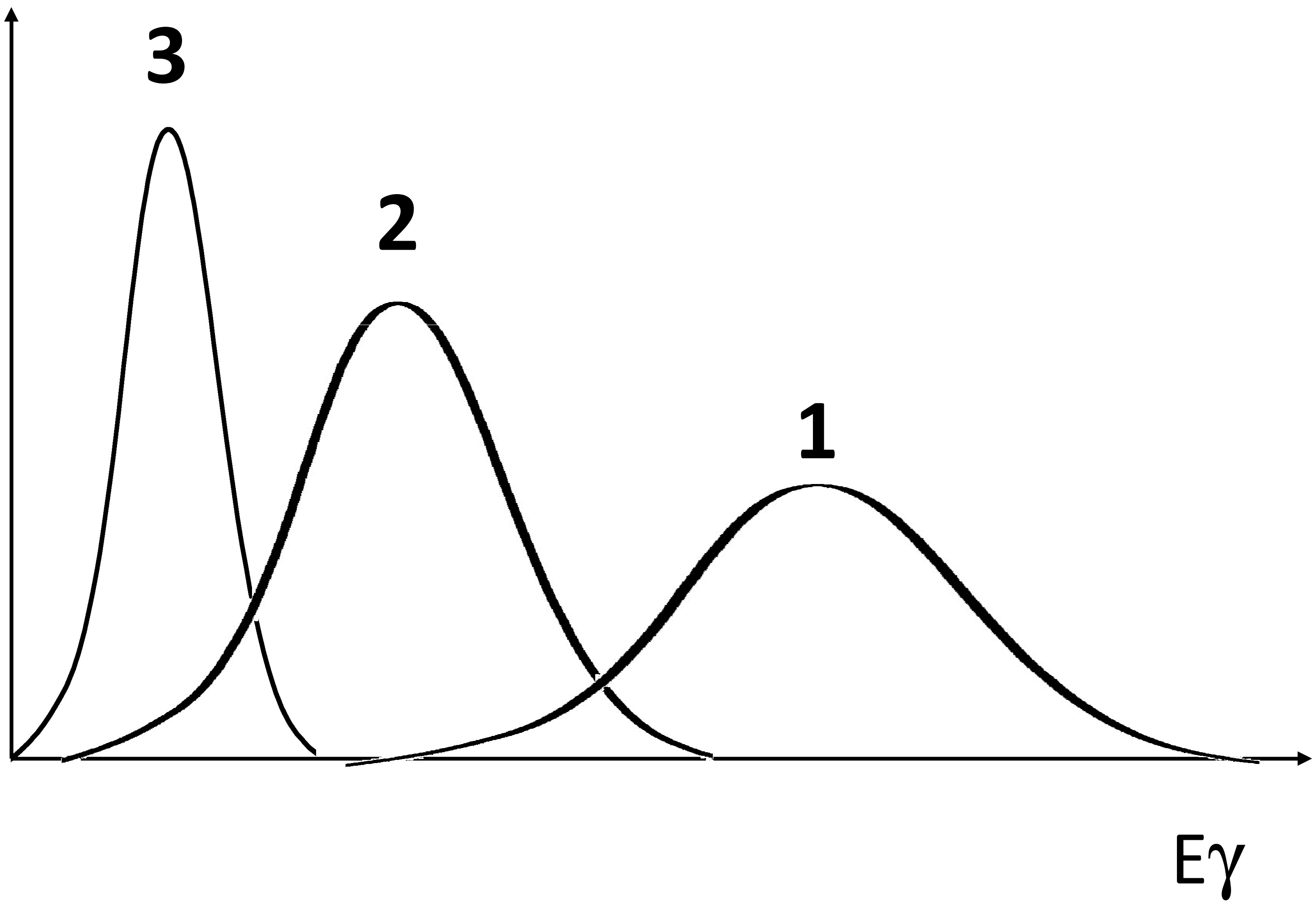
^{161}Dy(n,γ) Cross Section using SRM



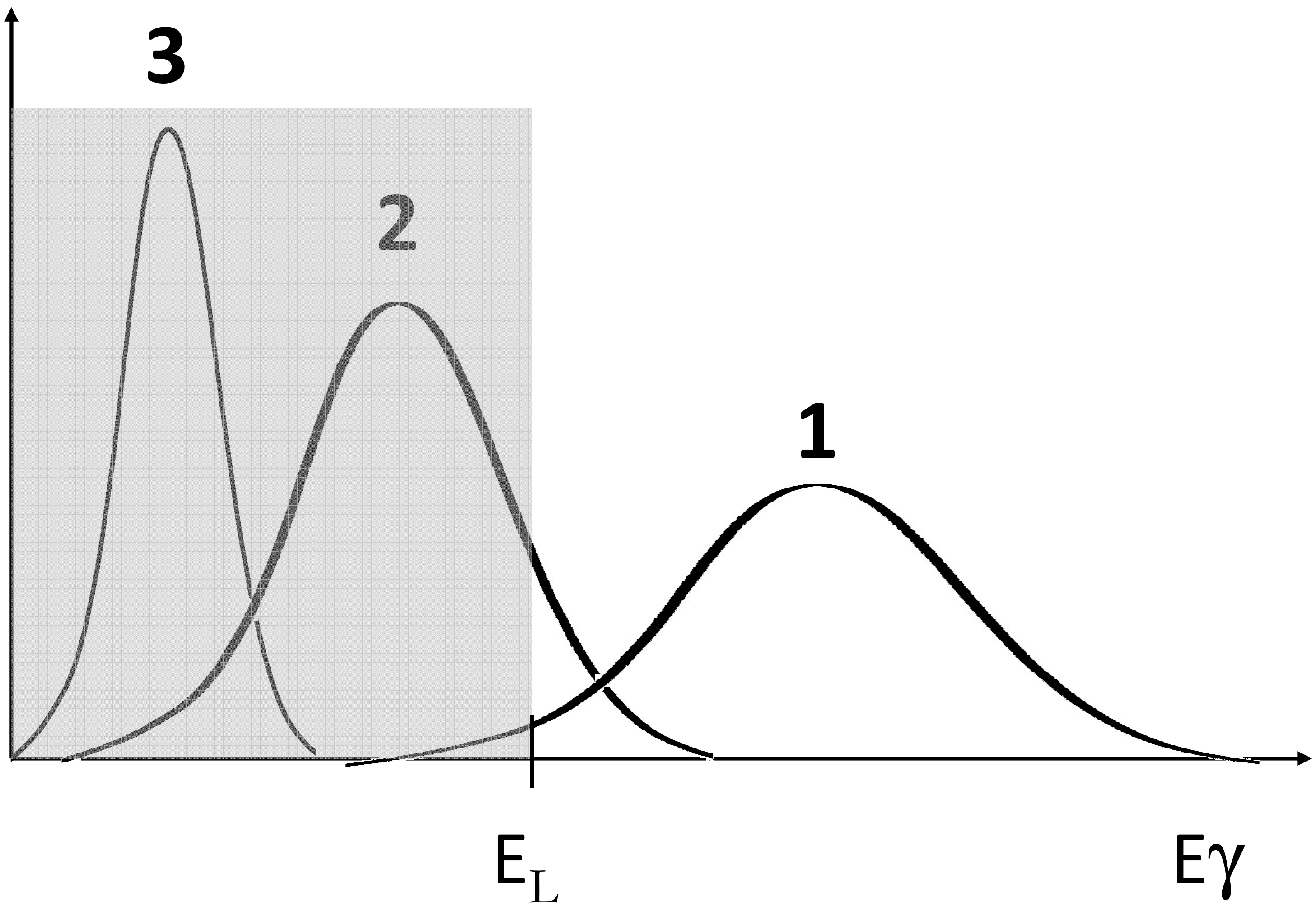
$$\sigma_{n,\gamma}^{(1)} = A\frac{N_{\beta\gamma}^{(1)}(E)}{N_{\beta\gamma}^{(2)}(E)}\sigma_{n,\gamma}^{(2)}$$

B.L. Goldblum, *et al.* Phys. Rev. C **81**, 054606 (2010).

Gamma De-excitation from Positive Equivalent Neutron Energy

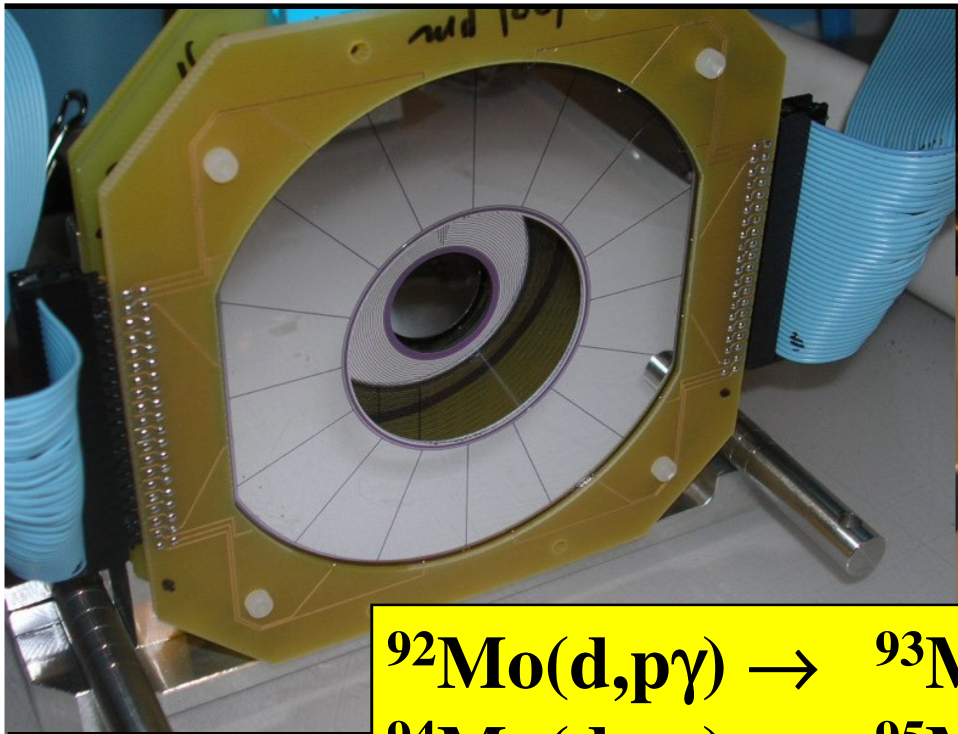


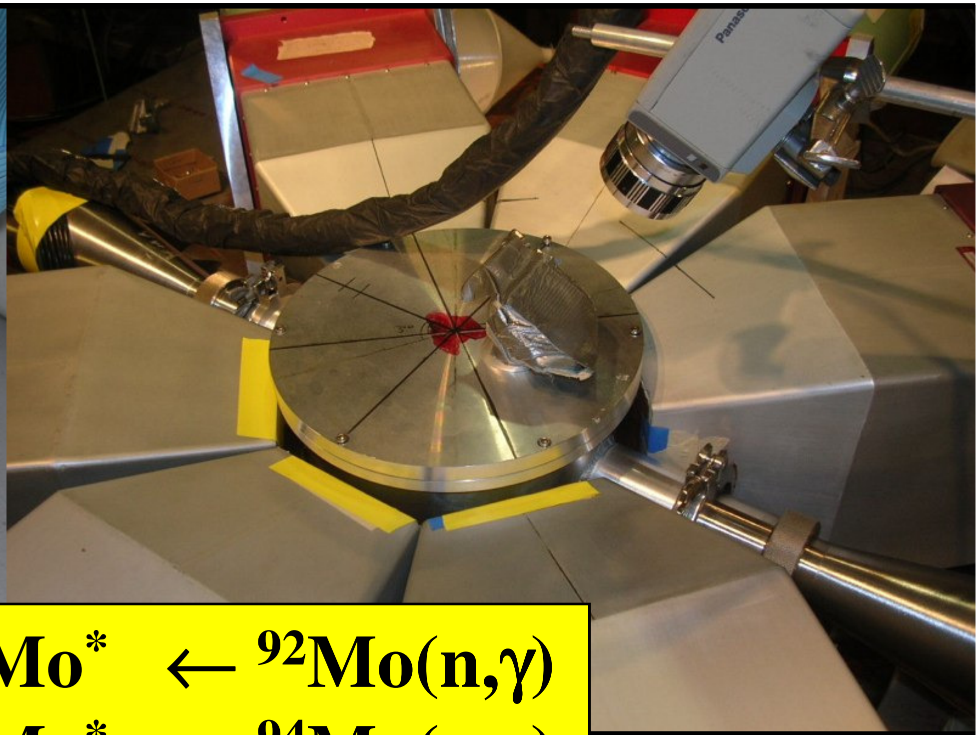
Application of γ-ray energy threshold



Surrogate Ratio Measurements on Spherical or Quasi-Spherical Nuclei?

$$A(E) = \frac{N_{\beta}^{(2)}(E)}{N_{\beta}^{(1)}(E)} = \frac{\rho^{(2)} \int_{0}^{\Delta t^{(2)}} I^{(2)} l^{(2)} dt}{\rho^{(1)} \int_{0}^{\Delta t^{(1)}} I^{(1)} l^{(1)} dt} \frac{\sigma_{\beta}^{(2)}(E)}{\sigma_{\beta}^{(1)}(E)}$$





^{92}Mo(d,pγ) → ^{93}Mo* ← ^{92}Mo(n,γ)

^{94}Mo(d,pγ) → ^{95}Mo* ← ^{94}Mo(n,γ)

External Surrogate Ratio Method

Consider two reactions:

$$R = \frac{\sigma_{n,f}^{(1)}}{\sigma_{n,f}^{(2)}} = \frac{\sigma_n^{(1)}(E)\, P_{\beta f}^{(1)}(E)}{\sigma_n^{(2)}(E) P_{\beta f}^{(2)}(E)}$$

Obtained via Experiment and Theoretical Modeling:

$$\sigma_{n,f}^{(1)} = A \frac{\sigma_n^{(1)}(E)}{\sigma_n^{(2)}(E)} \frac{N_{\beta f}^{(1)}(E)}{N_{\beta f}^{(2)}(E)} \sigma_{n,f}^{(2)}$$

$$A(E) = \frac{N_\beta^{(2)}(E)}{N_\beta^{(1)}(E)} = \frac{\rho^{(2)} \int_0^{\Delta t^{(2)}} I^{(2)} l^{(2)} dt}{\rho^{(1)} \int_0^{\Delta t^{(1)}} I^{(1)} l^{(1)} dt} \frac{\sigma_\beta^{(2)}(E)}{\sigma_\beta^{(1)}(E)}$$

Conclusions

- (n,f) benchmarking successful **for two similar compound nuclei** using the SRM
- Using **statistical γ-ray tagging,** no significant discrepancies in the external SRM (n,γ) cross sections **for two similar, deformed compound nuclei**
- Application of a **gamma-ray energy threshold may** emphasize statistical gamma-ray transitions

Collaborators

U. Agvaanluvsan, L.A. Bernstein, D.L. Bleuel, J.T. Burke, L. Ahle, J. Escher, F.S. Dietrich, S.L. Lesher, K. Moody, N.D. Scielzo, I. Thompson, M. Wiedeking, W. Younes

L. Phair, M.S. Basunia, P. Fallon, R.M. Clark, M. Cromaz, M.A. Delaplanque-Stephens, J.D. Gibelin, I.Y. Lee, A.O. Macchiavelli, M.A. McMahan, E. Rodriguez-Vieitez, S. Sinha, F.S. Stephens,

K. Alfonso, C. Angell, K. Evans, E.B. Norman, S.G. Prussin, R. Stroberg, E. Swanberg, R. Vial

M. Guttormsen, H.T. Nyhus

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