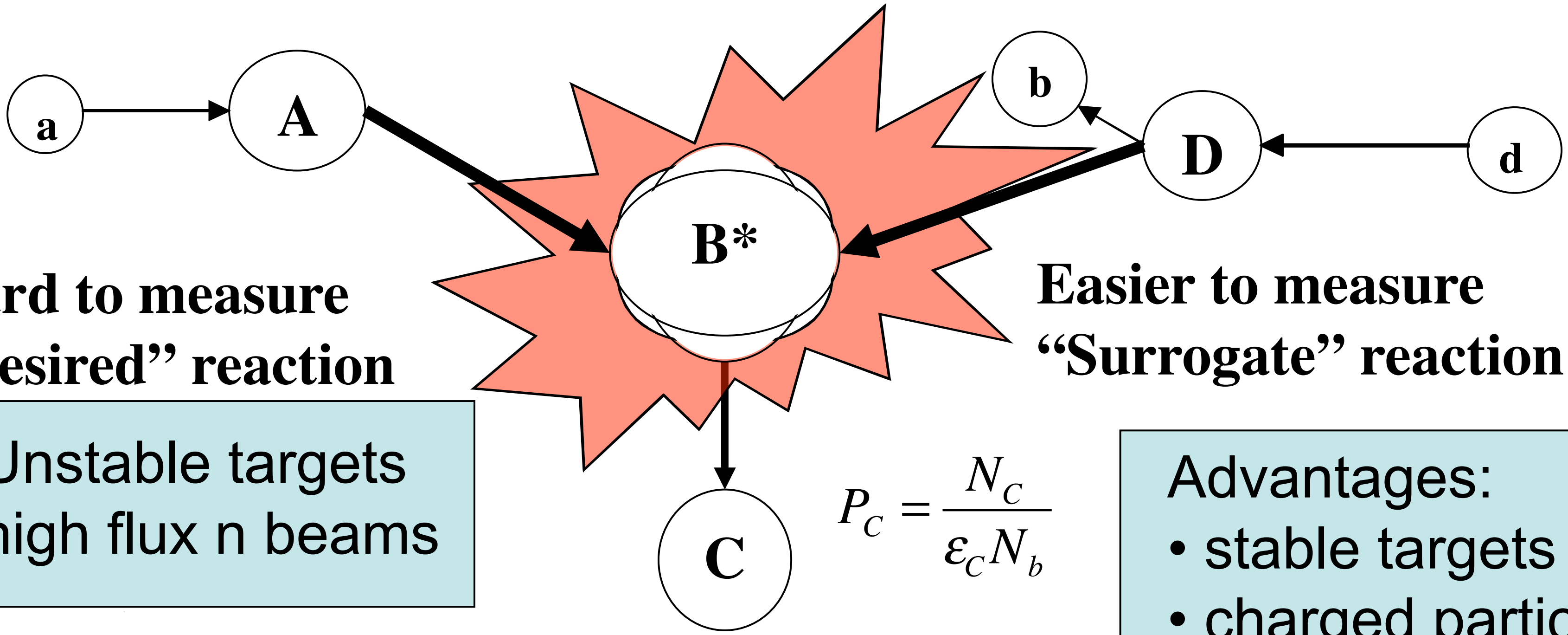
Surrogate reactions and their applications

Larry Phair

Lawrence Berkeley National Laboratory

The Surrogate Method



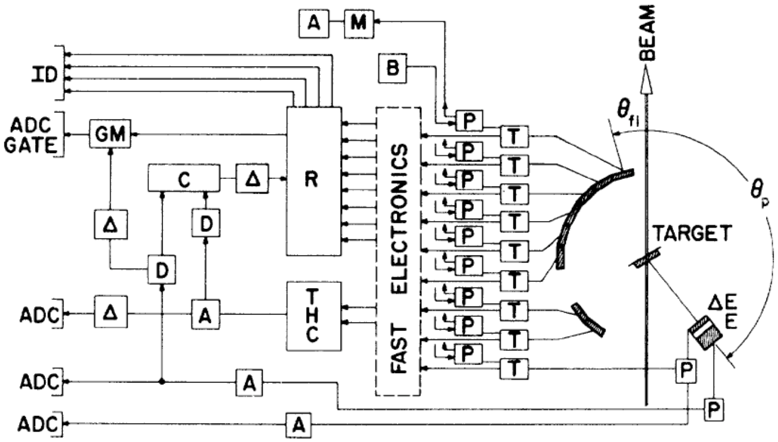
Hard to measure
“Desired” reaction

- Unstable targets
- high flux n beams

Easier to measure
“Surrogate” reaction

$$P_C = \frac{N_C}{\varepsilon_C N_b}$$

Advantages:
- stable targets
- charged particle beams



J.D. Cramer and H.C. Britt, Phys. Rev. C 2, 2350 (1970)

(t,pf) reactions on: ^{230}Th, ^{232}Th, ^{234}U, ^{236}U, ^{238}U, ^{238}Pu, ^{240}Pu, ^{242}Pu

Outline:

I. "New" surrogate methods: ratios

II. Measurement details

III. Examples: new cross sections, ^{237}U(n,f)

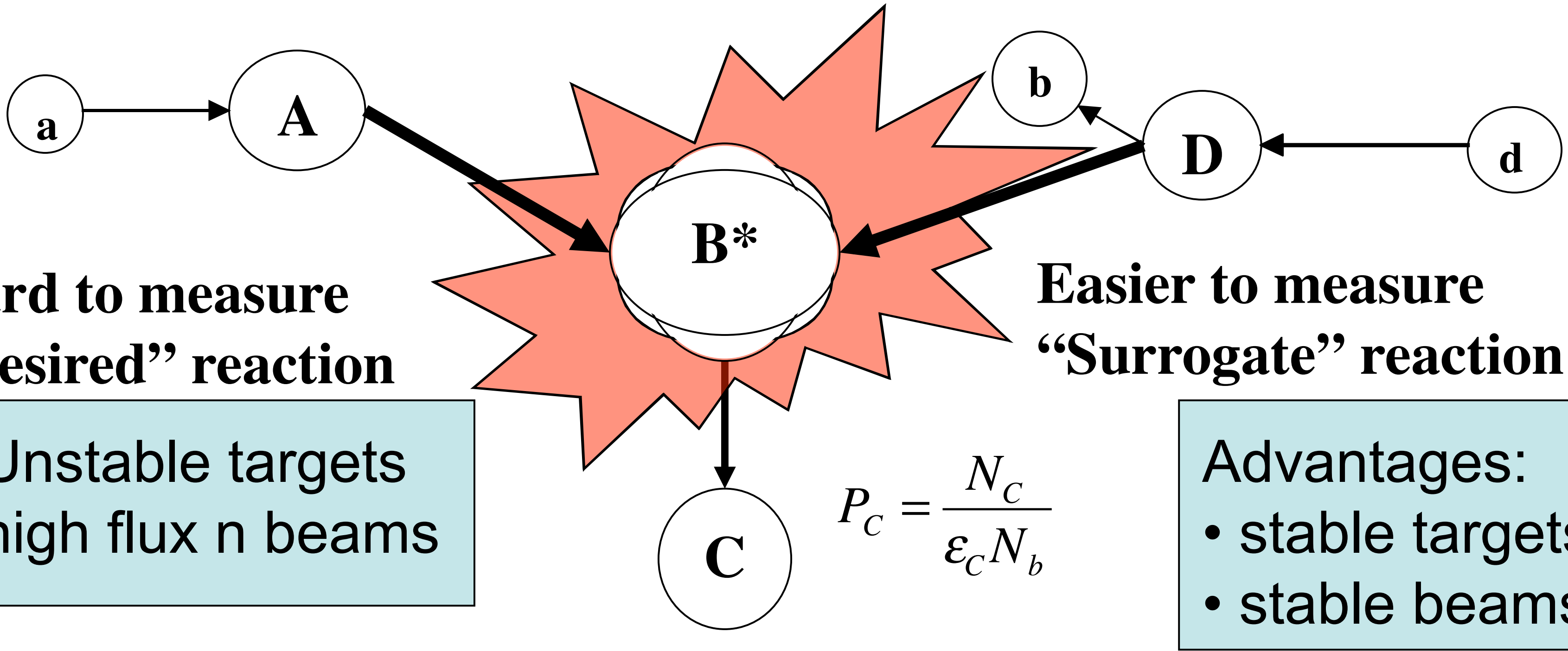
IV. Benchmarking
   - (a,a'f)
   - (d,pf)
   - (^{3}He,af)
   - (^{3}He,tf)

V. Theory (or lack thereof)

VI. Applications

- Surrogate reaction collaborators
  - L.A. Bernstein, D.L. Bleuel, J.T. Burke, L. Ahle, J. Church, J. Escher, F.S. Dietrich, S.L. Lesher, K. Moody, J. Punyon, N. Scielzo, M. Wiedeking
  - L. Phair, M.S. Basunia, P. Fallon, R.M. Clark, M. Cromaz, M.A. Delaplanque-Stephens, I.Y. Lee, A.O. Macchiavelli, M.A. McMahan, E. Rodriguez-Vieitez, S. Sinha, F.S. Stephens, J.D. Gibelin
  - B.F. Lyles, L.G. Moretto, E.B. Norman, P. Lake
  - Yale – H. Ai, C. Plettner,
  - C.W. Beausang, B. Crider, J.M. Allmond, B. Darakchieva, M. Evtimova
  - PNNL – J. Cagianno, J. Ressler
  - Rutgers – R. Hatarik, J. Cizewski,

The Surrogate Method



Hard to measure
"Desired" reaction

- Unstable targets
- high flux n beams

Easier to measure
"Surrogate" reaction

Advantages:

- stable targets
- stable beams

$$P_C = \frac{N_C}{\varepsilon_C N_b}$$

$$\sigma_{A(a,x)C} = \sum_{J,\pi} \sigma_{a+A}^{comp\,reac}(J,\pi,E_x) P_c(J,\pi,E_x)$$

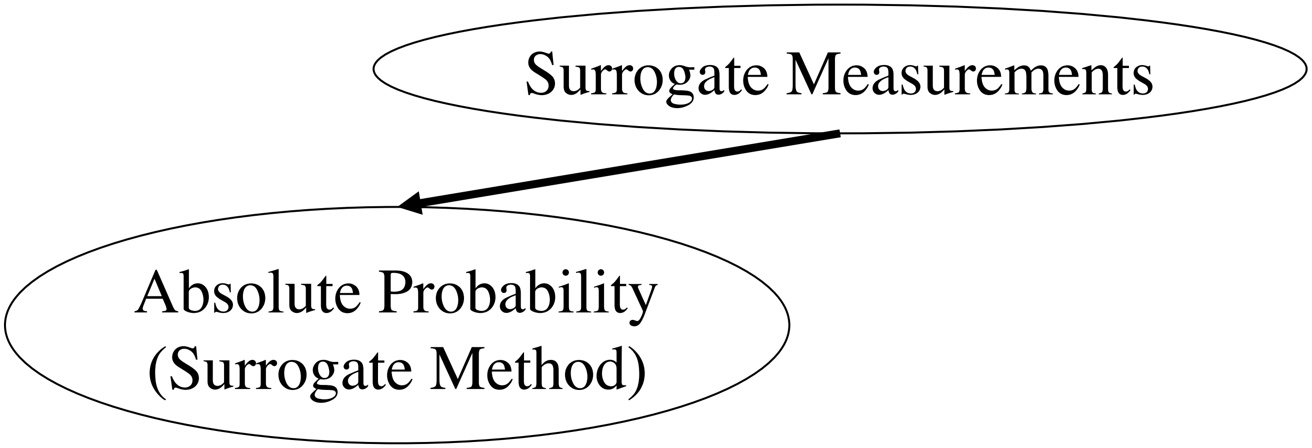
$$Weisskopf - Ewing : \sigma_{A(a,x)C} = \sigma_{a+A}^{comp\,reac} P_C$$

If $P_C \neq P_C(J,\pi)$

Central assumption: Both reactions form a compound nucleus

Surrogate Reaction “Flavors”

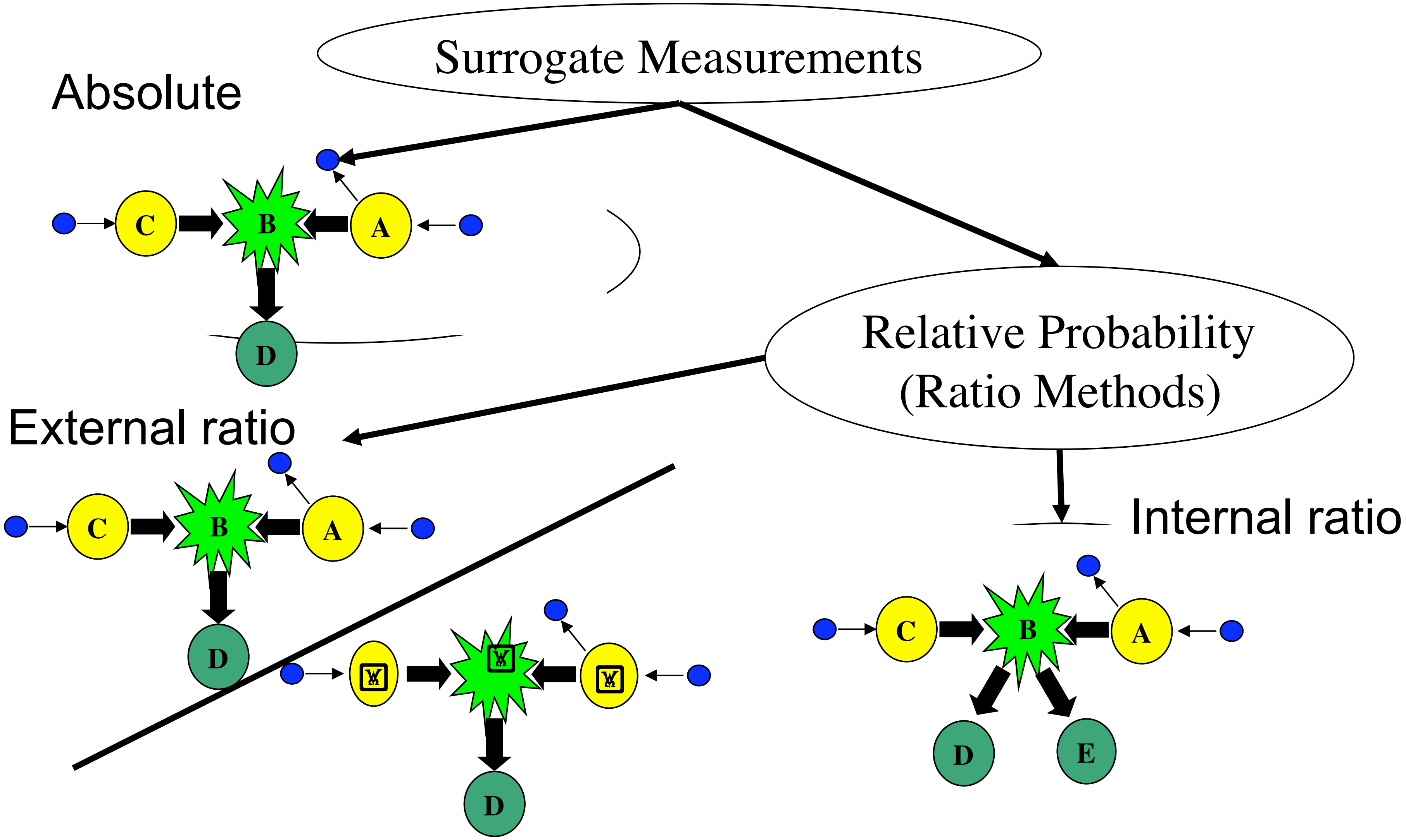
J.D. Cramer, H.C. Britt, Nucl. Sci. Eng. **41**, 177 (1970)
H.C. Britt, J.B. Wilhelmy, *ibid.* **72**, 222 (1979)



Surrogate Measurements

Absolute Probability
(Surrogate Method)

Surrogate Reaction “scorecard”



Surrogate Measurements

Absolute

Relative Probability
(Ratio Methods)

External ratio

Internal ratio

Example: ^{237}U(*n,f*) via surrogate external <u>ratio</u>

- Spirit of the method

$$\sigma_{n,f}(238) = \underbrace{\sigma_n^0(238)}_{\text{formation}}\underbrace{P_f(238)}_{\text{decay}}$$

From 3 cross sections that I know, infer 1 that I don't

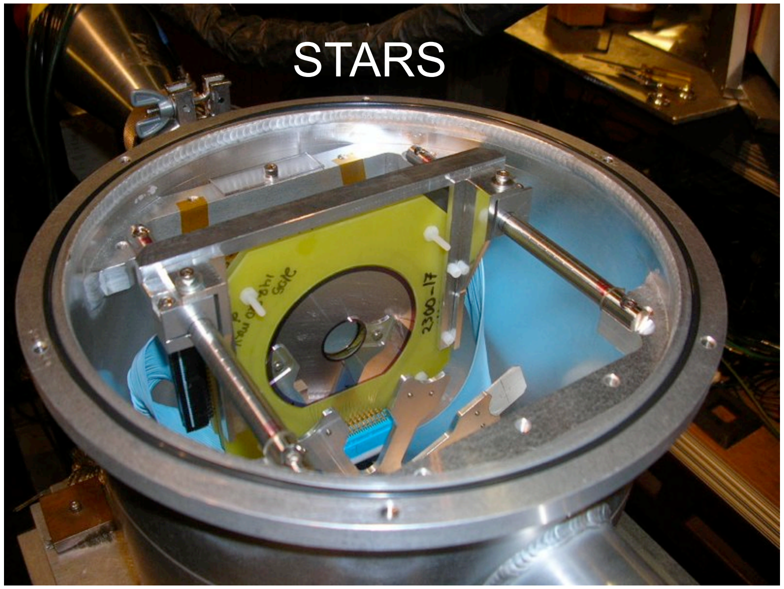
$$\boxed{\sigma_{n,f}(238) \approx \sigma_{n,f}(236)\frac{\sigma_{\alpha,\alpha' f}(238)}{\sigma_{\alpha,\alpha' f}(236)}}$$

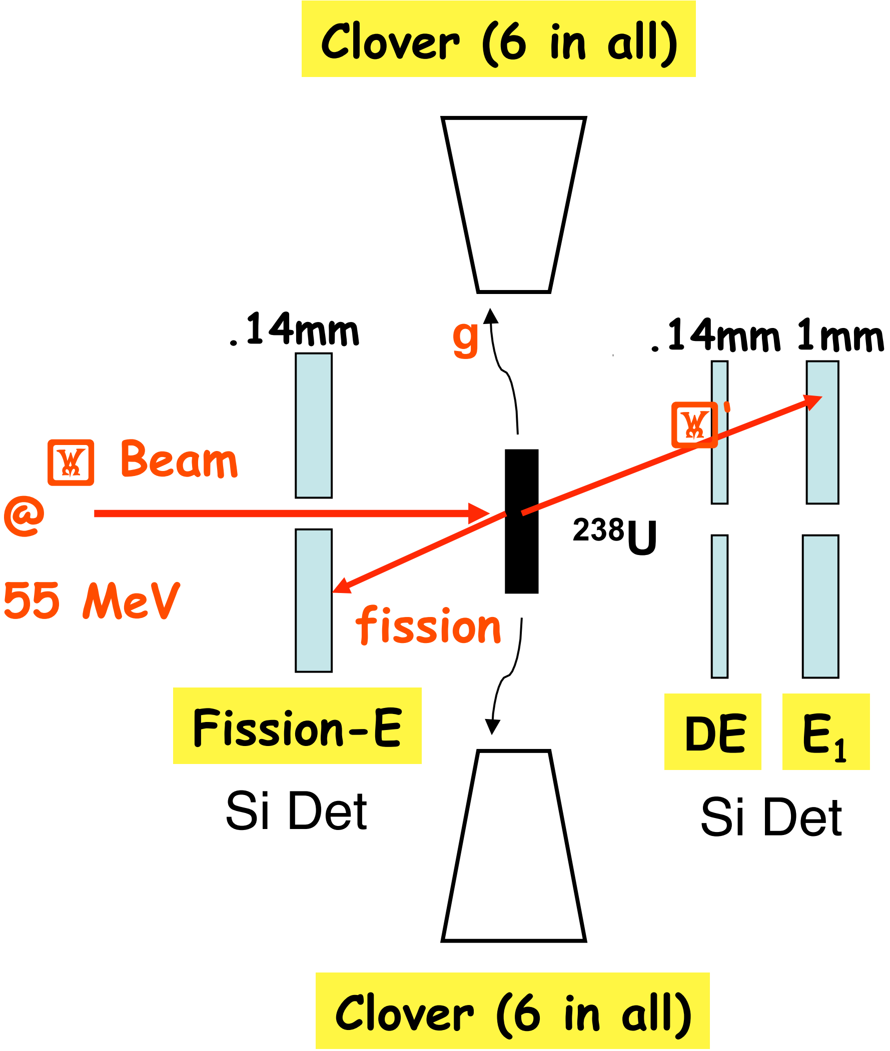
Relatively insensitive to efficiency

$$\approx \sigma_n^0(236)\cancel{P_f(236)}\frac{\cancel{\sigma^0_{\alpha,\alpha'}(238)}P_f(238)}{\cancel{\sigma^0_{\alpha,\alpha'}(236)}\cancel{P_f(236)}}$$

How to Measure: STARS-LIBERACE

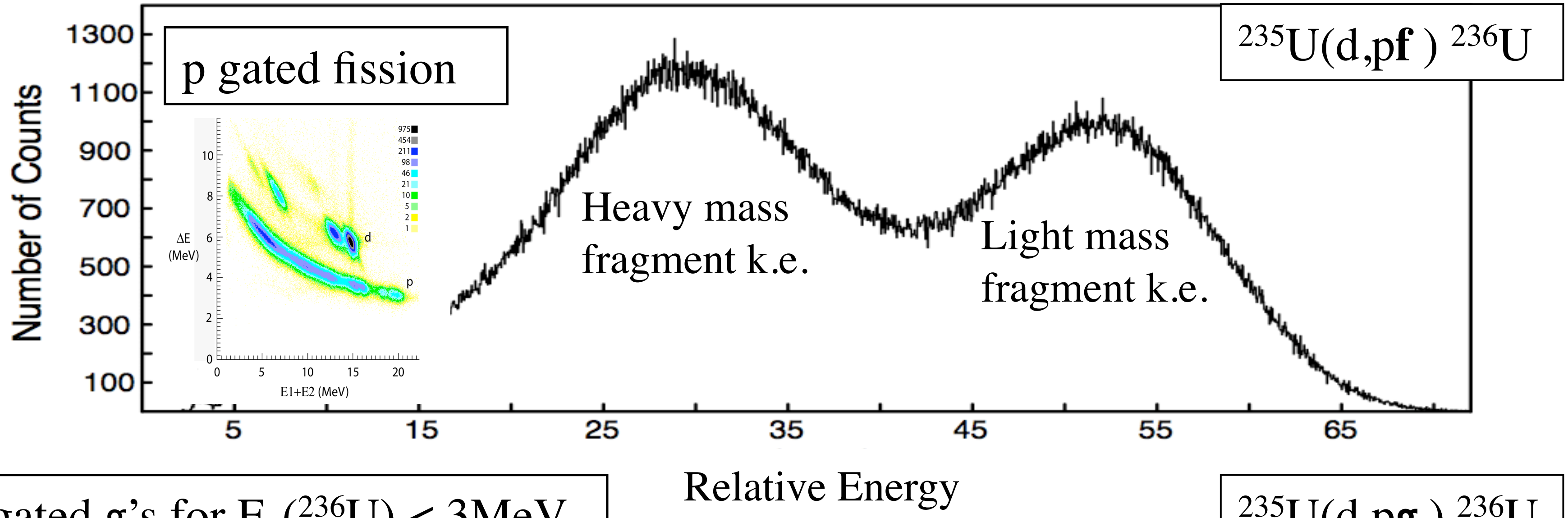
- Initiated in 12/04
- 128 Si channels, 24 Ge channels
- 5 years, 50+ experiments





292 mg/cm^2 target with no backing

Example of light particle, fission and g Spectra

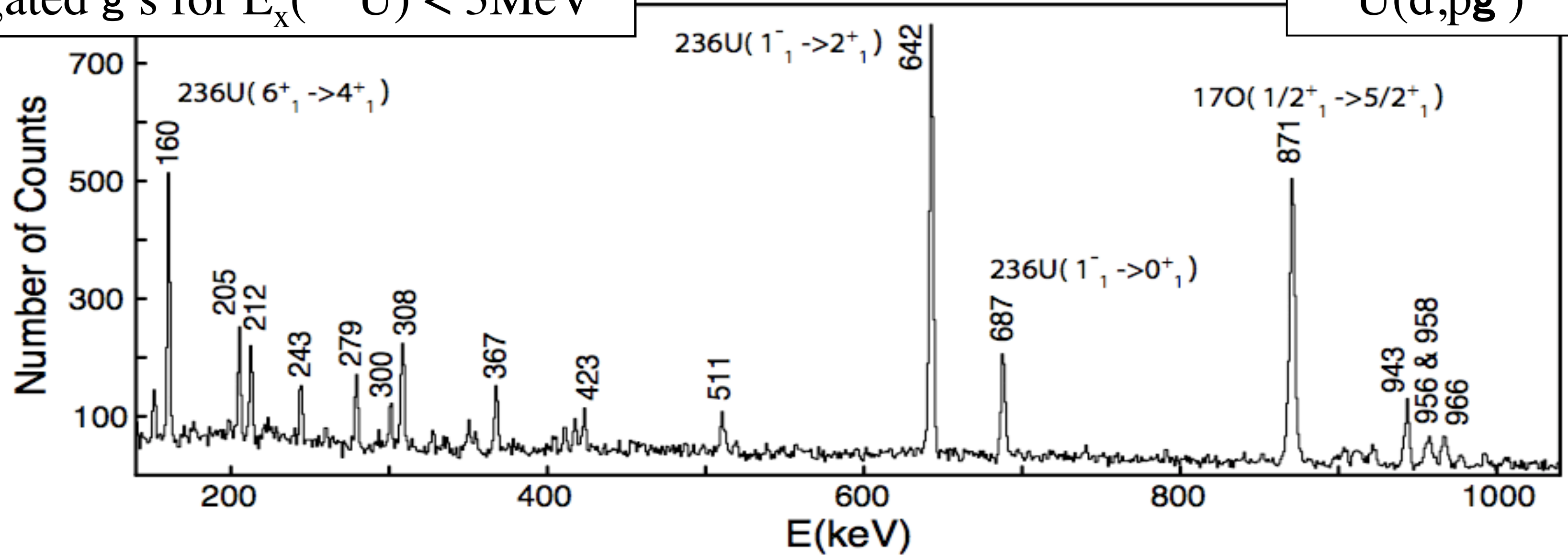


p gated fission

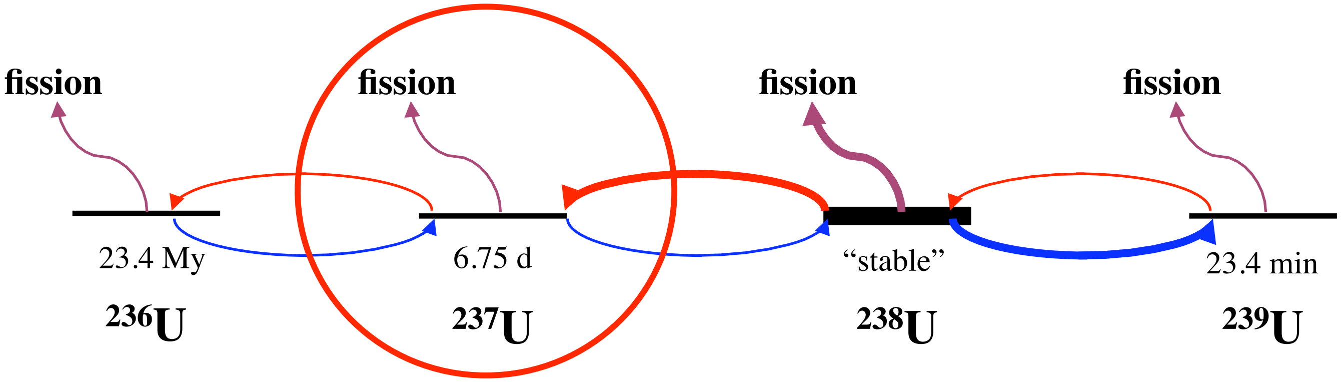
^{235}U(d,**pf**) ^{236}U

p gated g's for $E_x(^{236}U) < 3MeV$

^{235}U(d,**pg**) ^{236}U



The surrogate ratio method has been applied to the ^{237}U(n,x) cross sections



Uranium Reaction Network

- Understanding the destruction of ^{237}U is important for a number of applications
- Activity associated with a 10 mg target: 810 Curies!
- An earlier attempt to measure ^{237}U(*n*,*f*) used an “unconventional” neutron source (Bomb)

Example: ^{237}U(*n,f*) via surrogate external ratio

- Spirit of the method

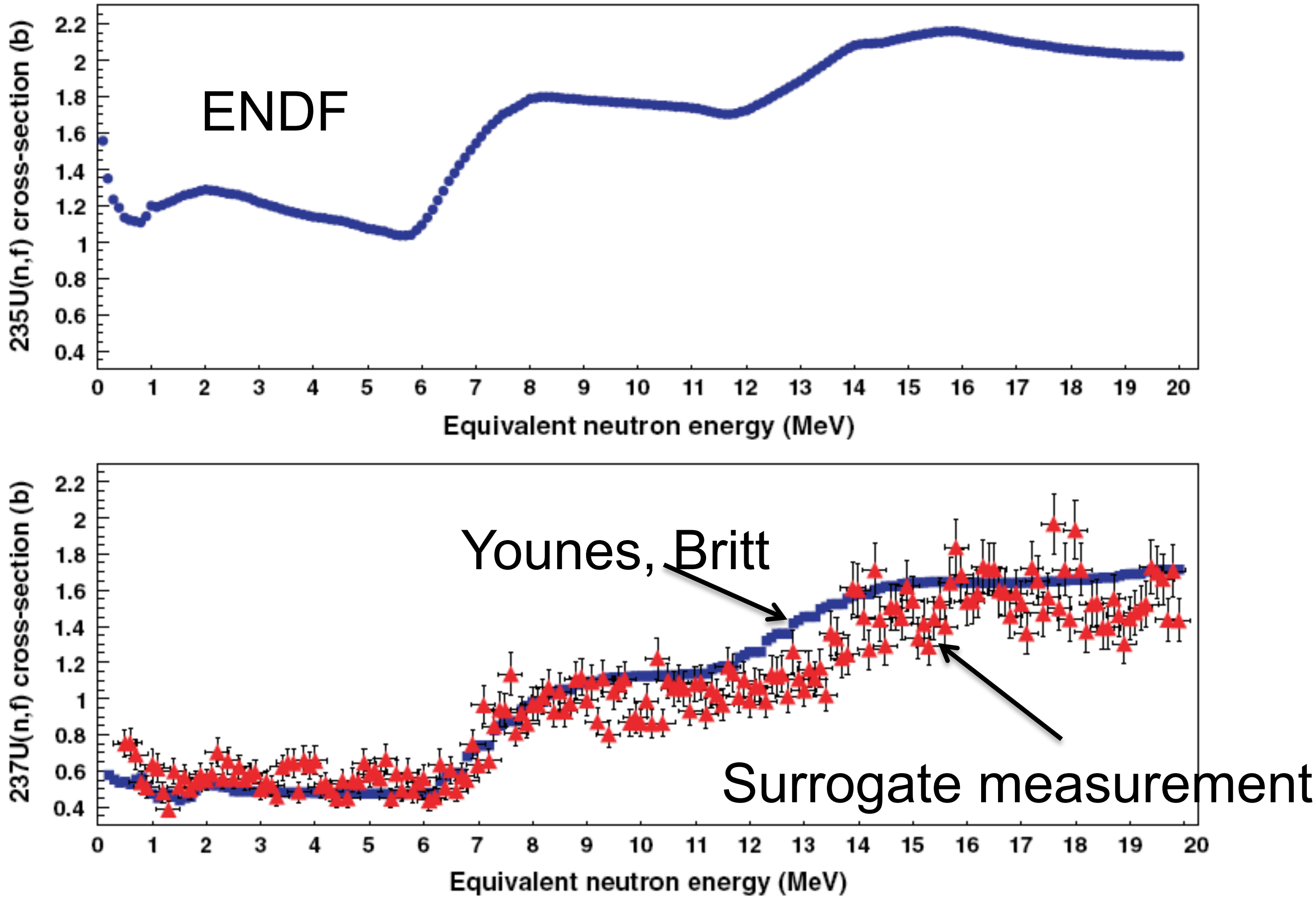
$$\sigma_{n,f}(238) = \underbrace{\sigma_n^0(238)}_{\text{formation}}\underbrace{P_f(238)}_{\text{decay}}$$

From 3 cross sections that I know, infer 1 that I don't

$$\boxed{\sigma_{n,f}(238) \approx \sigma_{n,f}(236)\frac{\sigma_{\alpha,\alpha' f}(238)}{\sigma_{\alpha,\alpha' f}(236)}}$$

Relatively insensitive to efficiency

$$\approx \sigma_n^0(236)\cancel{P_f(236)}\frac{\cancel{\sigma_{\alpha,\alpha'}^0(238)}P_f(238)}{\cancel{\sigma_{\alpha,\alpha'}^0(236)}\cancel{P_f(236)}}$$


ENDF

Younes, Britt

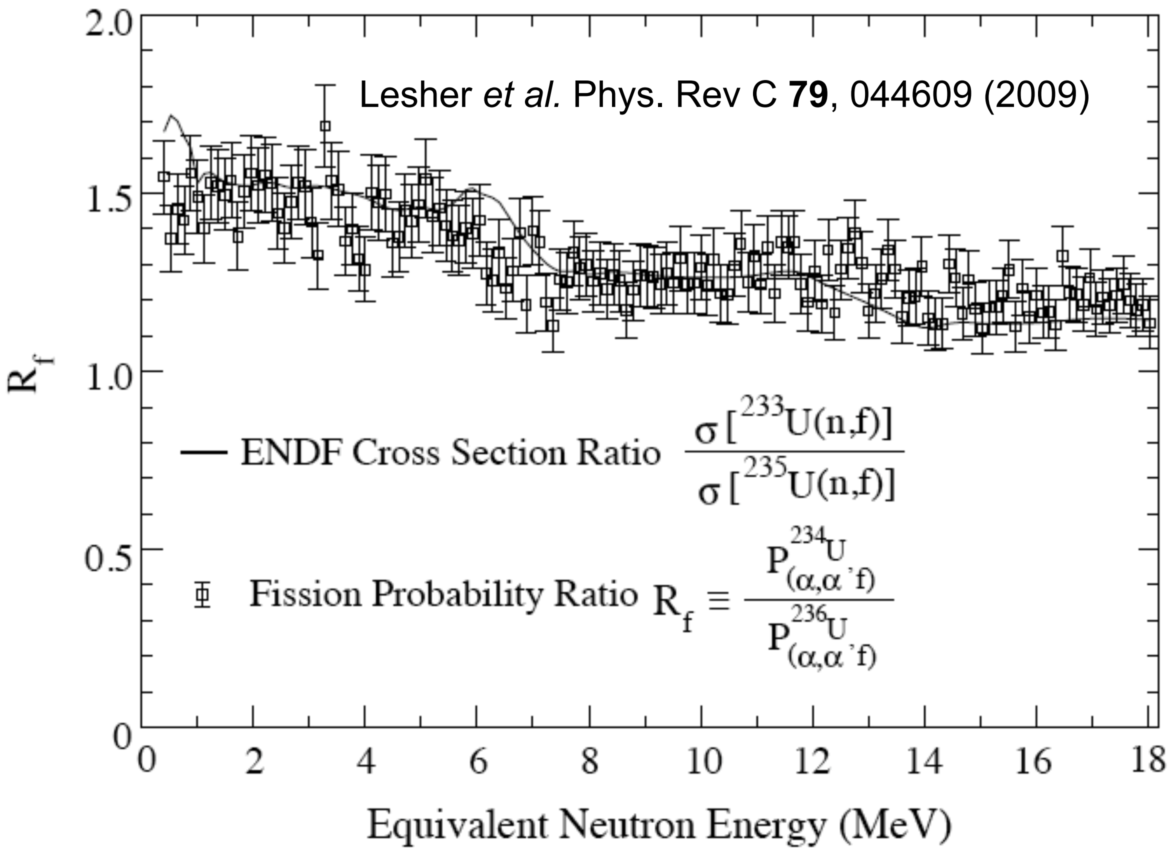
Surrogate measurement

Burke *et al*, Phys. Rev. C **73**, 054604 (2006)

Testing the surrogate method(s)

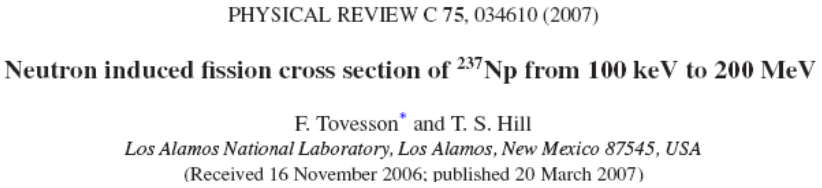
- ([illegible],[illegible]’*f*) for (*n,f*), external ratio
- (*d*,*pf*) for (*n*,*f*)
- (^{3}He,[illegible]*f*) for (*n,f*)
- (^{3}He,*tf*) for (*n,f*)
- …

Benchmarking the external ratio method - ^{234}U(α,α'f)/^{236}U(α,α'f) vs. ^{233}U(n,f)/^{235}U(n,f)


Lesher *et al.* Phys. Rev C **79**, 044609 (2009)

Ratios work even when we are not in the Weisskopf-Ewing limit

Recent LANL work allows us to compare our $^{238}\mathrm{U}(^{3}\mathrm{He},tf)^{238}\mathrm{Np}$ reaction to a direct $^{237}\mathrm{Np(n,f)}$ measurement


PHYSICAL REVIEW C 75, 034610 (2007)

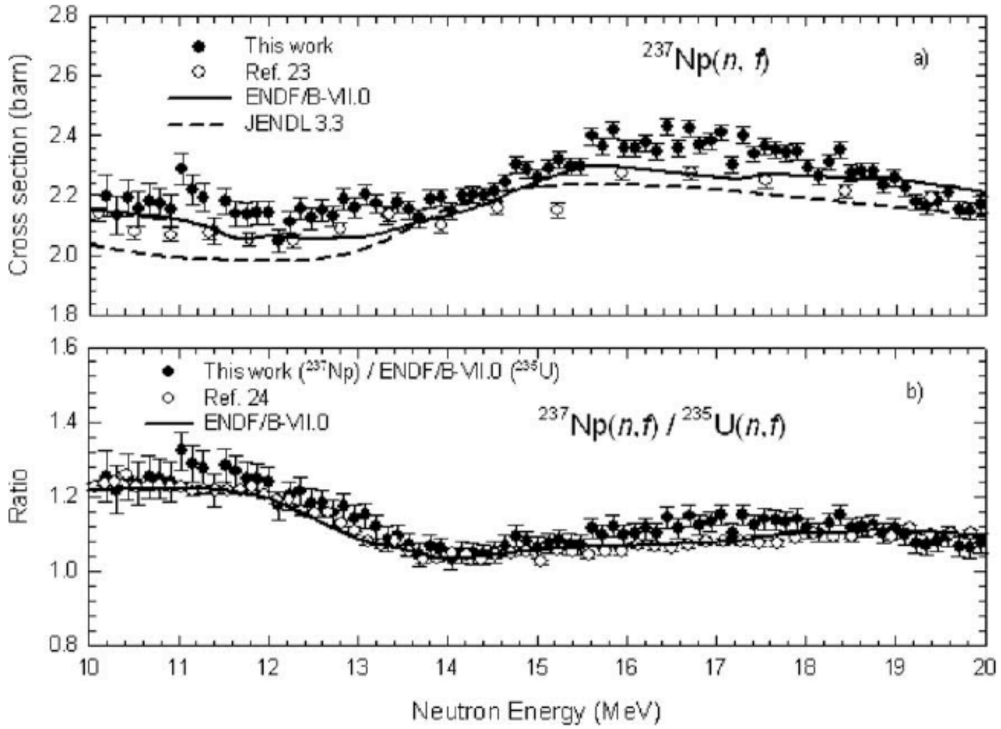
Neutron induced fission cross section of ^{237}Np from 100 keV to 200 MeV

F. Tovesson[*] and T. S. Hill

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

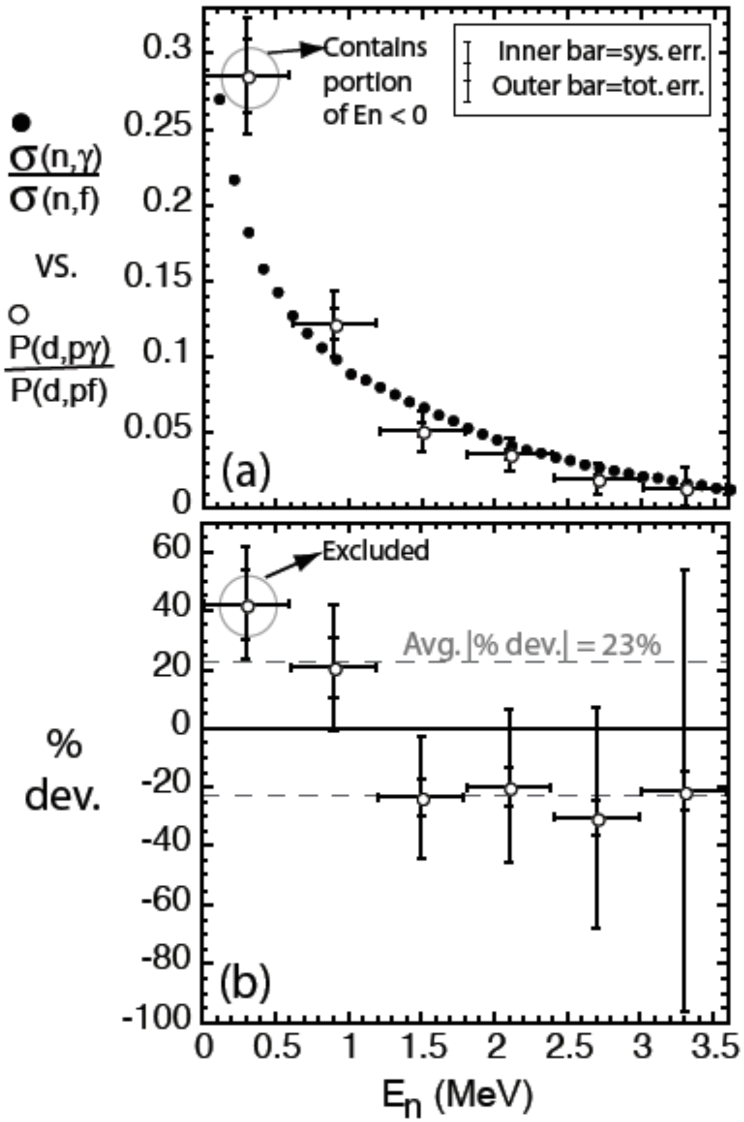
(Received 16 November 2006; published 20 March 2007)

First test of the absolute surrogate method at high E_x



Basunia *et al.* NIM B **267**, 1899 (2009)

Internal Ratio Result for ^{235}U(n,g)



ENDF: solid

STARS/LIBERACE: open

^{235}U(d,p)

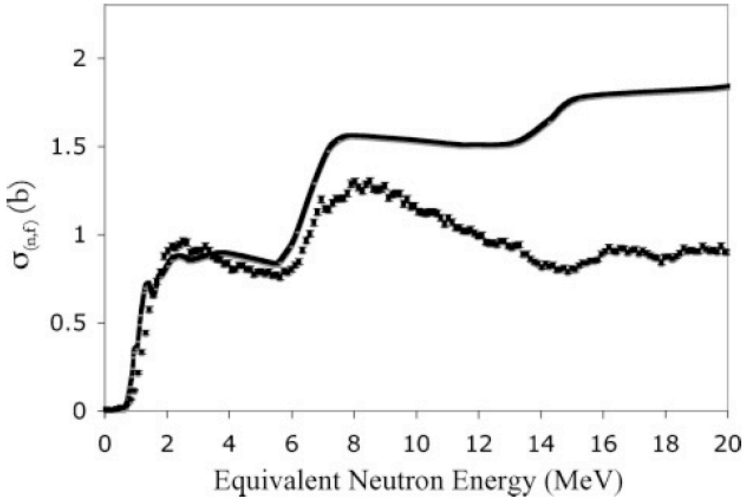
J. M Allmond *et al.* Phys. Rev. C **79**, 054610 (2009)

Examining the effects J^{π} differences (0^{+} vs. $7/2^{-}$): ^{236}U(n,f) from ^{238}U(^{3}He,α'f)/^{235}U(^{3}He,α'f) (external ratio and absolute)

Ph.D. thesis project
Bethany Lyles

Failed because of contaminants in the target

Absolute



Ratio

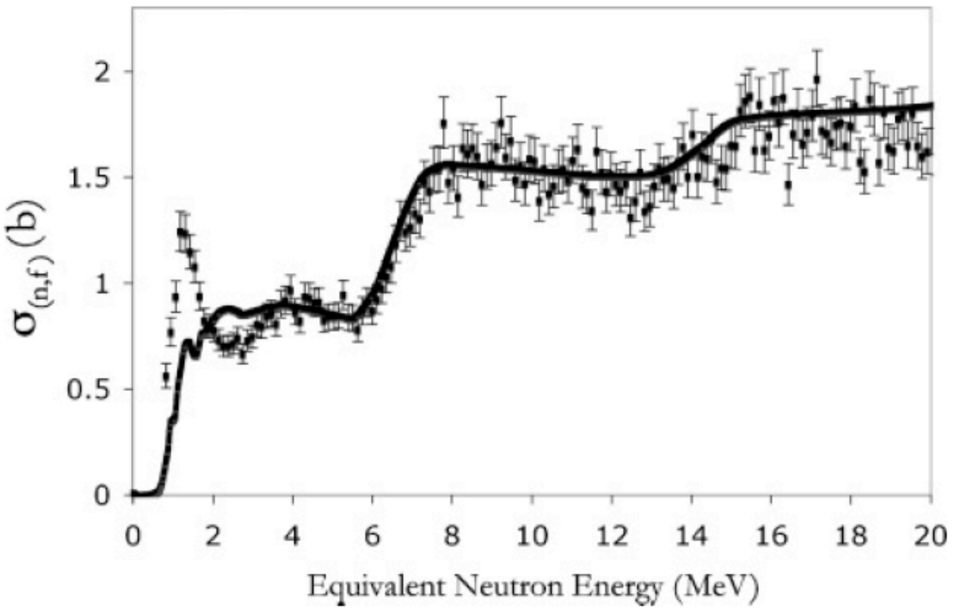
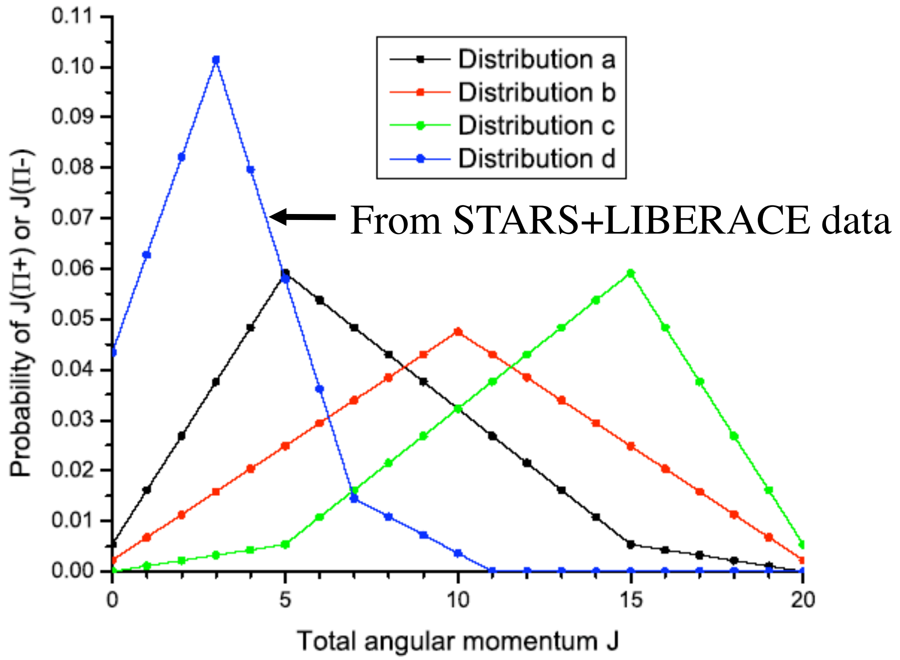


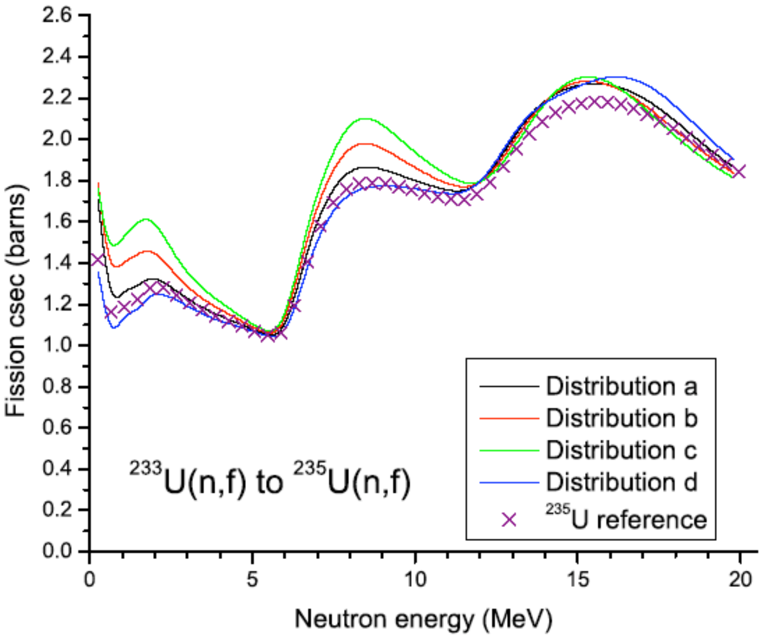
FIG. 12. The ^{236}U(n, f) cross section determined using the SRM relative to the ^{233}U(n, f) cross section as a function of equivalent neutron energy. The solid line is the ENDF/B-VII library evaluation for this cross section.

The External Ratio approach works for (n,f) for suitable spin distributions

J. Escher & F.S. Dietrich, PRC 74 054601 (2006)



From STARS+LIBERACE data



Ratios are relatively insensitive to spin differences

between the actual and surrogate reactions

Collaboration publications

Experiment	Principle Investigator	Publication
^{235}U(d,pg) and (d,pf) for (n,g) and (n,f)	J. M. Allmond	Phys. Rev. C **79**, 054610 (2009)
^{234,236}U(a,a' f) for (n,f)	S. R. Lesher	Phys. Rev. C **79**, 044609 (2009)
^{238}U(^{3}He,tf) for (n,f)	M. S. Basunia	Nucl. Inst. & Meth. B **267**, 1899 (2009)
^{235,238}U(^{3}He,af) for (n,f)	B. F. Lyles	Phys. Rev. C. **76**, 014606 (2007)
^{238}U(a,a' f) for ^{237}U(n,f)	J. T. Burke	Phys. Rev. C **73**, 054604 (2006)
^{232}Th(^{3}He,^{3}He'f) and ^{232}Th(^{3}He,af) for ^{230,231}Th(n,f)	B. L. Goldblum	To be submitted to Phys. Rev. C
^{171,173}Yb(d,pg) for (n,g)	R. Hatarik	To be submitted to Phys. Rev. C

Applications

- Stockpile stewardship
- Reactor designs
- Nuclear astrophysics
  - s-process

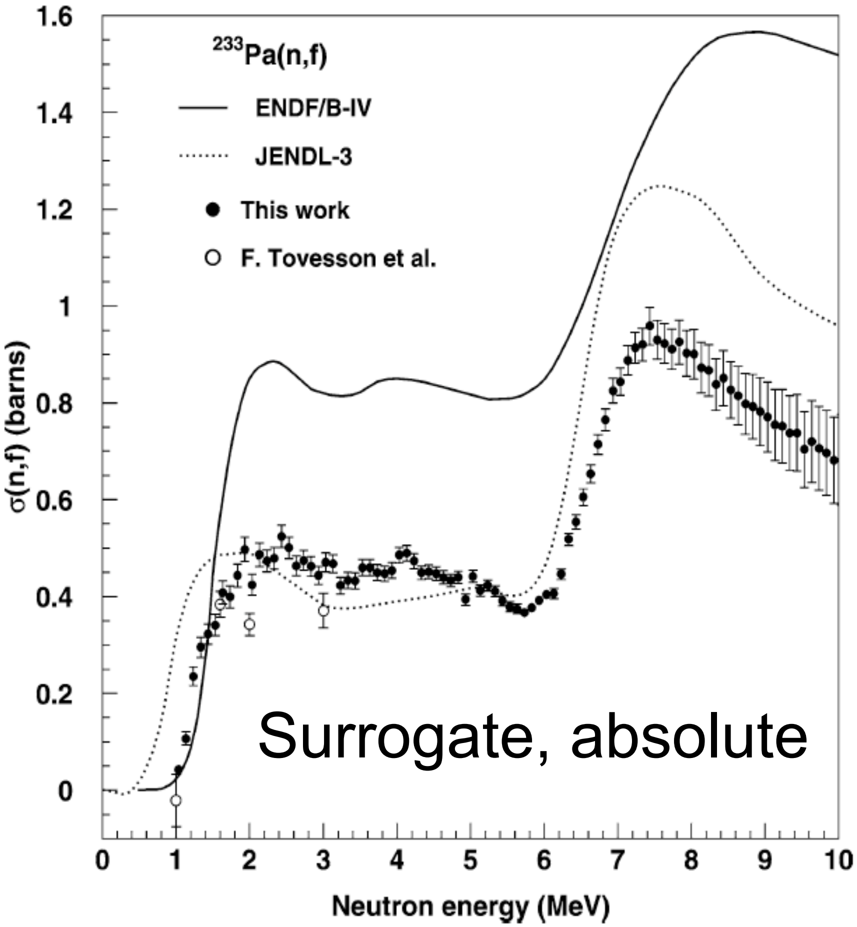
Example: Th fuel cycle

- ^{233}Pa(*n,f*) controls production of ^{233}U
- Recent measurements at Orsay

^{232}Th

(^{3}He,*p*) ^{234}Pa
(^{3}He,*d*) ^{233}Pa
(^{3}He,*t*) ^{232}Pa
(^{3}He,) ^{231}Th

M. Petit et al. / Nuclear Physics A 735 (2004) 345–371



Surrogate, absolute

^{230}Th(n, f) Cross Section Using the SRM

^{232}Th(^{3}He,af)

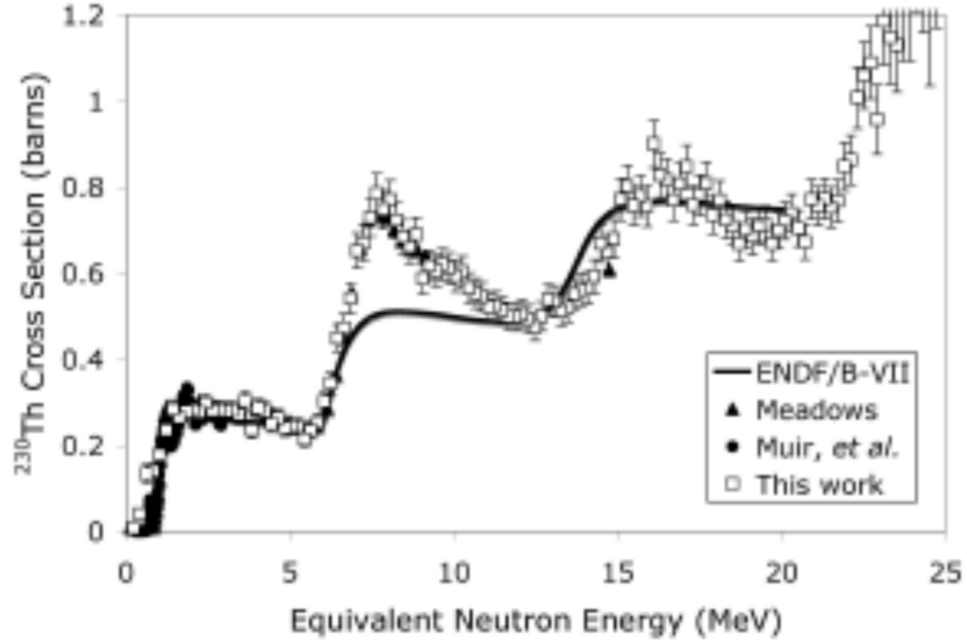


FIG. 2: The ^{230}Th(n,f) cross section in the equivalent neutron energy range of 0 to 25 MeV. The error bars on the surrogate data represent both the statistical and systematic uncertainty. For comparison, evaluated and directly-measured ^{230}Th(n,f) cross section data are shown.

^{231}Th(n, f) Cross Section Using the SRM

^{232}Th(^{3}He,^{3}He'f)

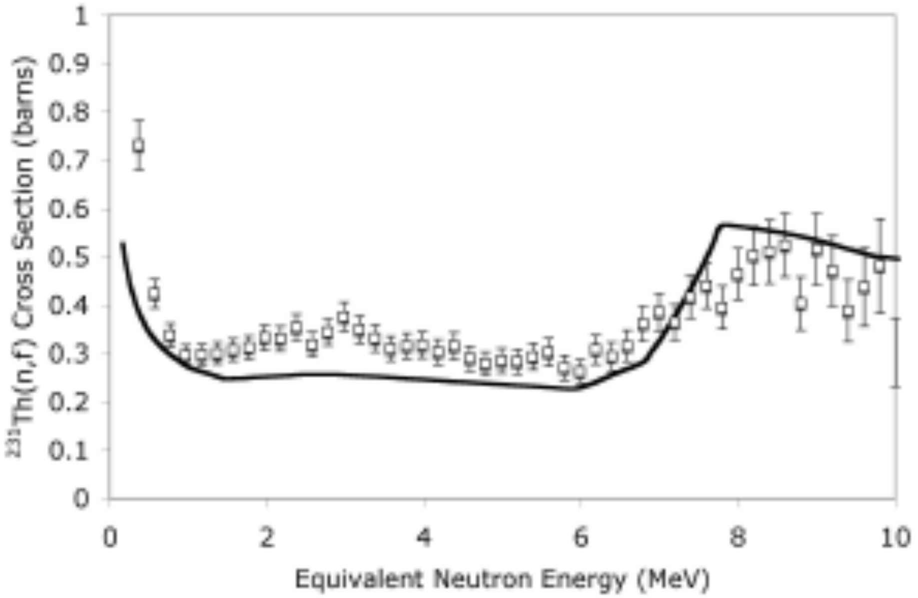
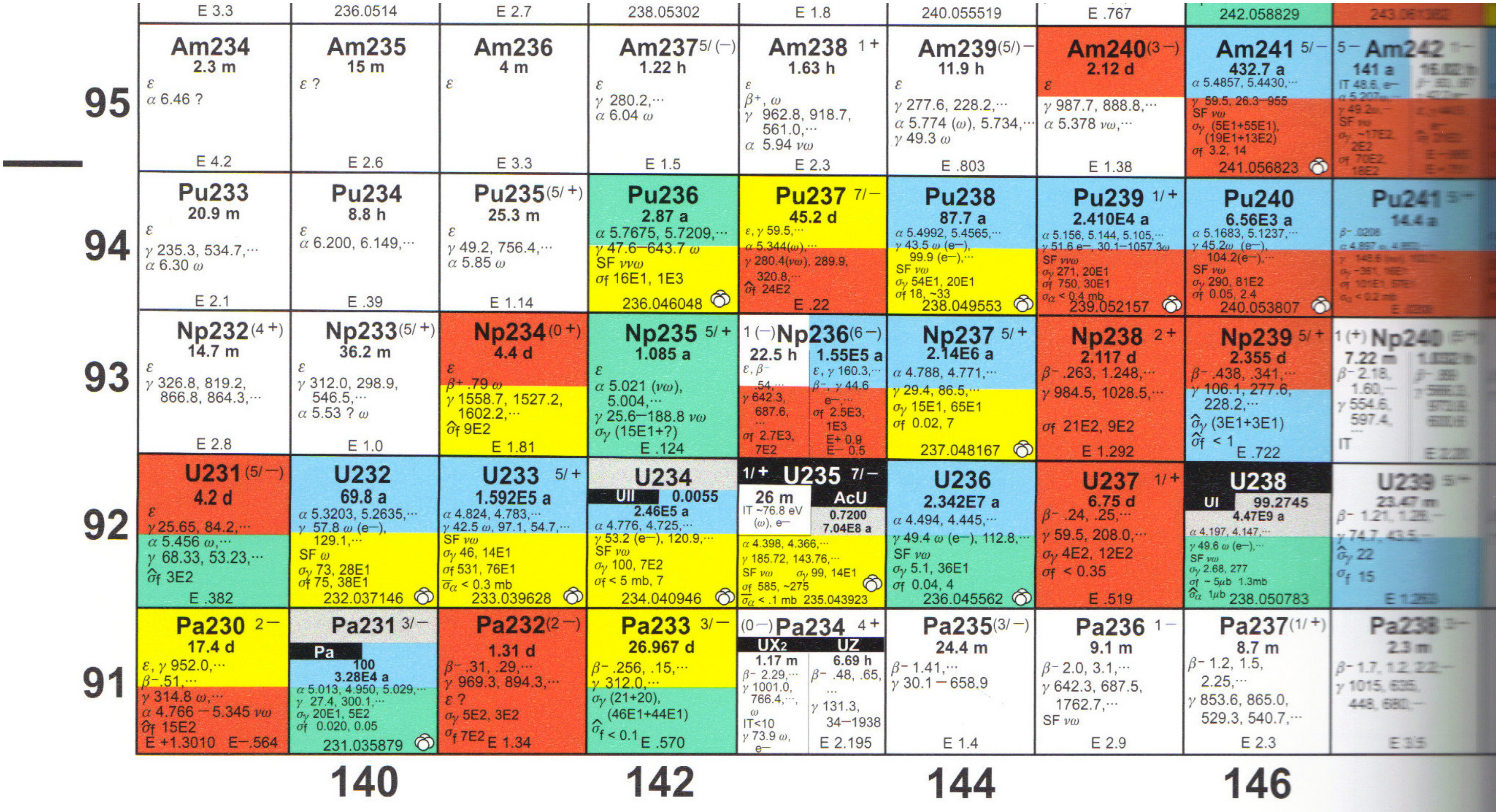


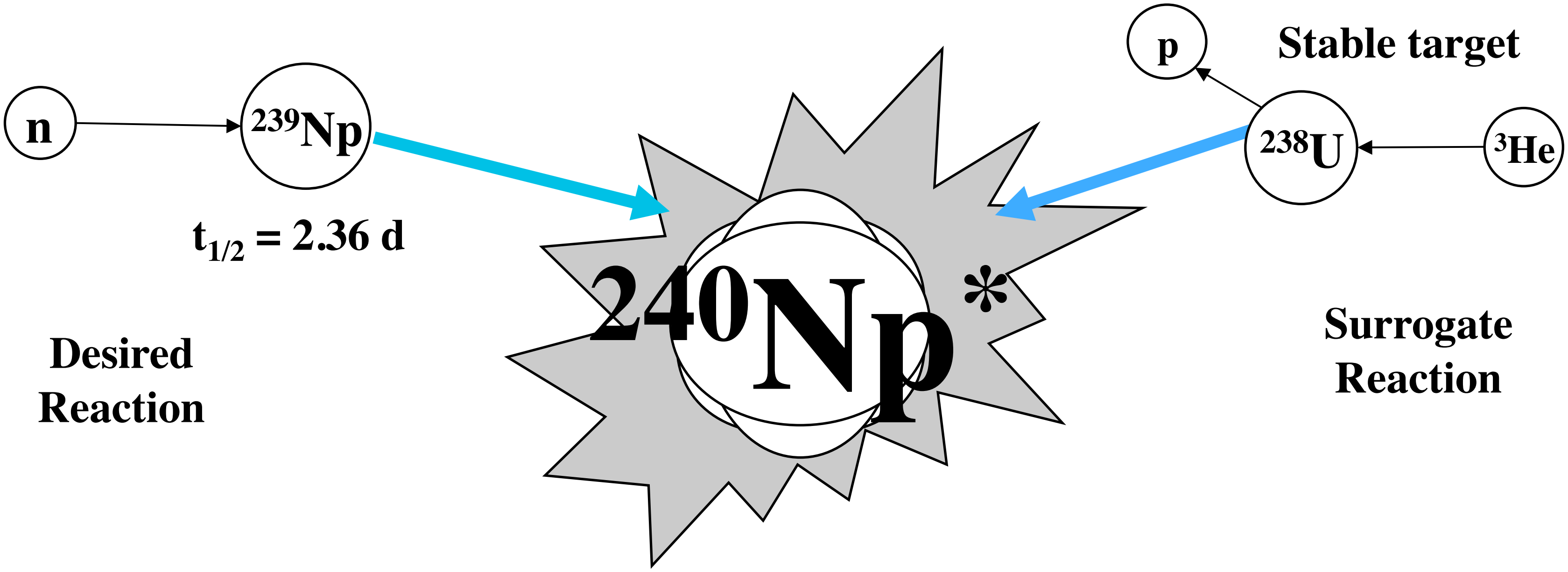
FIG. 4: The ^{231}Th(n,f) cross section extracted using the SRM, relative to the evaluated ^{235}U(n,f) cross section obtained from ENDF/B-VII, as a function of equivalent neutron energy is given by the open squares. The error bars represent both the statistical and systematic uncertainty. For comparison, the evaluated ^{231}Th(n,f) cross section from ROSFOND is denoted by the solid line.

^{239}Np(n,f) and ^{239}Pu breeding in reactors



	E 3.3	236.0514	E 2.7	238.05302	E 1.8	240.055519	E .767	242.058829	
95	**Am234** 2.3 m ε α 6.46 ? E 4.2	**Am235** 15 m ε ? E 2.6	**Am236** 4 m ε E 3.3	**Am237** 5/ (−) 1.22 h ε γ 280.2,··· α 6.04 ω E 1.5	**Am238** 1 + 1.63 h ε β^+, ω γ 962.8, 918.7, 561.0,··· α 5.94 $\nu\omega$ E 2.3	**Am239** (5/) − 11.9 h ε γ 277.6, 228.2,··· α 5.774 (ω), 5.734,··· γ 49.3 ω E .803	**Am240** (3 −) 2.12 d ε γ 987.7, 888.8,··· α 5.378 $\nu\omega$,··· E 1.38	**Am241** 5/ − 432.7 a α 5.4857, 5.4430,··· γ 59.5, 26.3−955 SF $\nu\omega$ σ_γ (5E1+55E1), (19E1+13E2) σ_f 3.2, 14 241.056823	5 − **Am242** 141 a IT 48.6, e− SF 2E2 18E2
94	**Pu233** 20.9 m ε γ 235.3, 534.7,··· α 6.30 ω E 2.1	**Pu234** 8.8 h ε α 6.200, 6.149,··· E .39	**Pu235** (5/ +) 25.3 m ε γ 49.2, 756.4,··· α 5.85 ω E 1.14	**Pu236** 2.87 a α 5.7675, 5.7209,··· γ 47.6−643.7 ω SF $\nu\nu\omega$ σ_f 16E1, 1E3 236.046048	**Pu237** 7/ − 45.2 d ε, γ 59.5,··· α 5.344(ω),··· γ 280.4($\nu\omega$), 289.9, 320.8,··· $\hat{\sigma}_f$ 24E2 E .22	**Pu238** 87.7 a α 5.4992, 5.4565,··· γ 43.5 ω (e−), 99.9 (e−),··· SF $\nu\omega$ σ_γ 54E1, 20E1 σ_f 18, ~33 238.049553	**Pu239** 1/ + 2.410E4 a α 5.156, 5.144, 5.105,··· γ 51.6 e−, 30.1−1057.3ω SF $\nu\nu\omega$ σ_γ 271, 20E1 σ_f 750, 30E1 σ_α < 0.4 mb 239.052157	**Pu240** 6.56E3 a α 5.1683, 5.1237,··· γ 45.2ω (e−), 104.2(e−),··· SF $\nu\omega$ σ_γ 290, 81E2 σ_f 0.05, 2.4 240.053807	**Pu241** 14.4 a β^- .0208
93	**Np232** (4 +) 14.7 m ε γ 326.8, 819.2, 866.8, 864.3,··· E 2.8	**Np233** (5/ +) 36.2 m ε γ 312.0, 298.9, 546.5,··· α 5.53 ? ω E 1.0	**Np234** (0 +) 4.4 d ε β^+ .79 ω γ 1558.7, 1527.2, 1602.2,··· $\hat{\sigma}_f$ 9E2 E 1.81	**Np235** 5/ + 1.085 a ε α 5.021 ($\nu\omega$), 5.004,··· γ 25.6−188.8 $\nu\omega$ σ_γ (15E1+?) E .124	1 (−) **Np236** (6 −) 22.5 h ε, β^- .54,··· γ 642.3, 687.6, ··· σ_f 2.7E3, 7E2 1.55E5 a ε, γ 160.3,··· β^-, γ 44.6 e−,··· σ_f 2.5E3, 1E3 E+ 0.9 E− 0.5	**Np237** 5/ + 2.14E6 a α 4.788, 4.771,··· γ 29.4, 86.5,··· σ_γ 15E1, 65E1 σ_f 0.02, 7 237.048167	**Np238** 2 + 2.117 d β^- .263, 1.248,··· γ 984.5, 1028.5,··· σ_f 21E2, 9E2 E 1.292	**Np239** 5/ + 2.355 d β^- .438, .341,··· γ 106.1, 277.6, 228.2,··· $\hat{\sigma}_\gamma$ (3E1+3E1) $\hat{\sigma}_f$ < 1 E .722	1 (+) **Np240** 7.22 m β^- 2.18, 1.60, γ 554.6, 597.4, IT
92	**U231** (5/ −) 4.2 d ε γ 25.65, 84.2,··· α 5.456 ω,··· γ 68.33, 53.23,··· $\hat{\sigma}_f$ 3E2 E .382	**U232** 69.8 a α 5.3203, 5.2635,··· γ 57.8 ω (e−), 129.1,··· SF ω σ_γ 73, 28E1 σ_f 75, 38E1 232.037146	**U233** 5/ + 1.592E5 a α 4.824, 4.783,··· γ 42.5 ω, 97.1, 54.7,··· SF $\nu\omega$ σ_γ 46, 14E1 σ_f 531, 76E1 $\bar{\sigma}_\alpha$ < 0.3 mb 233.039628	**U234** UII 0.0055 2.46E5 a α 4.776, 4.725,··· γ 53.2 (e−), 120.9,··· SF $\nu\omega$ σ_γ 100, 7E2 σ_f < 5 mb, 7 234.040946	1/ + **U235** 7/ − 26 m IT ~76.8 eV (ω), e− AcU 0.7200 7.04E8 a α 4.398, 4.366,··· γ 185.72, 143.76,··· SF $\nu\omega$ σ_γ 99, 14E1 σ_f 585, ~275 $\bar{\sigma}_\alpha$ < .1 mb 235.043923	**U236** 2.342E7 a α 4.494, 4.445,··· γ 49.4 ω (e−), 112.8,··· SF $\nu\omega$ σ_γ 5.1, 36E1 σ_f 0.04, 4 236.045562	**U237** 1/ + 6.75 d β^- .24, .25,··· γ 59.5, 208.0,··· σ_γ 4E2, 12E2 σ_f < 0.35 E .519	**U238** UI 99.2745 4.47E9 a α 4.197, 4.147,··· γ 49.6 ω (e−),··· SF $\nu\omega$ σ_γ 2.68, 277 σ_f ~ 5μb 1.3mb $\hat{\sigma}_\alpha$ 1μb 238.050783	**U239** 23.47 m β^- 1.21, 1.28, γ 74.7, 43.5, $\hat{\sigma}_\gamma$ 22 σ_f 15
91	**Pa230** 2 − 17.4 d ε, γ 952.0,··· β^- .51,··· γ 314.8 ω,··· α 4.766 − 5.345 $\nu\omega$ $\hat{\sigma}_f$ 15E2 E +1.3010 E−.564	**Pa231** 3/ − Pa 100 3.28E4 a α 5.013, 4.950, 5.029,··· γ 27.4, 300.1,··· σ_γ 20E1, 5E2 σ_f 0.020, 0.05 231.035879	**Pa232** (2 −) 1.31 d β^- .31, .29,··· γ 969.3, 894.3,··· ε ? σ_γ 5E2, 3E2 σ_f 7E2 E 1.34	**Pa233** 3/ − 26.967 d β^- .256, .15,··· γ 312.0,··· σ_γ (21+20), (46E1+44E1) $\hat{\sigma}_f$ < 0.1 E .570	(0 −) **Pa234** 4 + UX2 1.17 m β^- 2.29,··· γ 1001.0, 766.4,···, ω IT<10 γ 73.9 ω, e− UZ 6.69 h β^- .48, .65, ··· γ 131.3, 34−1938 E 2.195	**Pa235** (3/ −) 24.4 m β^- 1.41,··· γ 30.1 − 658.9 E 1.4	**Pa236** 1 − 9.1 m β^- 2.0, 3.1,··· γ 642.3, 687.5, 1762.7,··· SF $\nu\omega$ E 2.9	**Pa237** (1/ +) 8.7 m β^- 1.2, 1.5, 2.25,··· γ 853.6, 865.0, 529.3, 540.7,··· E 2.3	**Pa238** 2.3 m β^- 1.7, 1.2, 2.2 γ 1015, 635, 448, 680,
		140		142		144		146	

Next proposed experiment at 88” Cyclotron



n → ^{239}Np

$t_{1/2}$ = 2.36 d

Desired Reaction

^{240}Np*

p

Stable target

^{238}U ← ^{3}He

Surrogate Reaction

$$^{238}\mathrm{U}(^3\mathrm{He},p\mathit{f}) \rightarrow {}^{240}\mathrm{Np}^* \rightarrow \mathbf{{}^{239}Np(n,\mathit{f})}$$

$$^{236}\mathrm{U}(^3\mathrm{He},p\mathit{f}) \rightarrow {}^{238}\mathrm{Np}^* \rightarrow {}^{237}\mathrm{Np}(n,\mathit{f})$$

The surrogate ratio method can also be applied to other areas: Generation-IV reactor design

Target	**Surrogate Reactions**	**Ratio Reactions**	**Reactor Type**[*]
^{238}Pu	^{239}Pu(α,α’)	^{235}U(α,α’)	LFR,SFR
^{239}Pu	^{239}Pu(d,p), ^{240}Pu(α,α’)	^{235}U(d,p), ^{236}U(α,α’)	GFR,LFR,SFR,EFR
^{240}Pu	^{240}Pu(d,p), ^{242}Pu(^{3}He,α)	^{236}U(d,p), ^{236,238}U(^{3}He,α)	GFR,LFR,SFR,EFR
^{241}Pu	^{242}Pu(α,α’)	^{236}U(α,α’)	GFR,LFR,SFR,EFR
^{241}Am	^{243}Am(^{3}He,α), ^{240}Pu(^{3}He,d)	^{235}U(^{3}He,α), *none yet*	GFR,LFR,SFR
^{242m}Am	^{242}Pu(^{3}He,t), ^{243}Am(α,α’)	^{238}U(^{3}He,t), ^{235}U(α,α’)	LFR,SFR
^{243}Am	^{243}Am(d,p), ^{242}Pu(^{3}He,d)	^{239}Pu(d,p), *none yet*	SFR
^{242}Cm	^{243}Am(^{3}He,t)	*^{238}U(^{3}He,t)*	EFR
^{243}Cm	^{245}Cm(^{3}He,α), ^{243}Am(^{3}He,t)	^{235}U(^{3}He,α), ^{238}U(^{3}He,*t*)	GFR,EFR
^{244}Cm	^{245}Cm(α,α’), ^{243}Am(^{3}He,d)	^{235}U(α,α’), *none yet*	GFR,LFR,SFR,EFR
^{245}Cm	^{247}Cm(^{3}He,α), ^{245}Cm(d,p)	^{235}U(^{3}He,α), ^{235}U(d	FR R

[*] from Aliberti *et al.*,

Surrogates for nuclear astrophysics: the s-process (slow neutron capture)

- <u>s-process:</u> slow neutron capture moves along valley of stability with **branch points** where β-decay competes with capture.

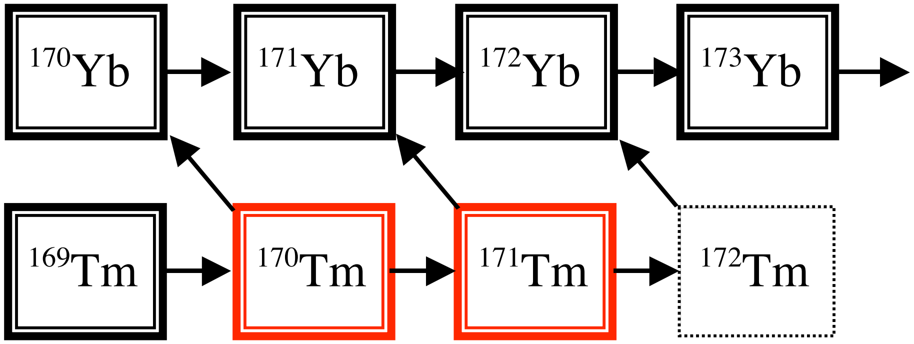
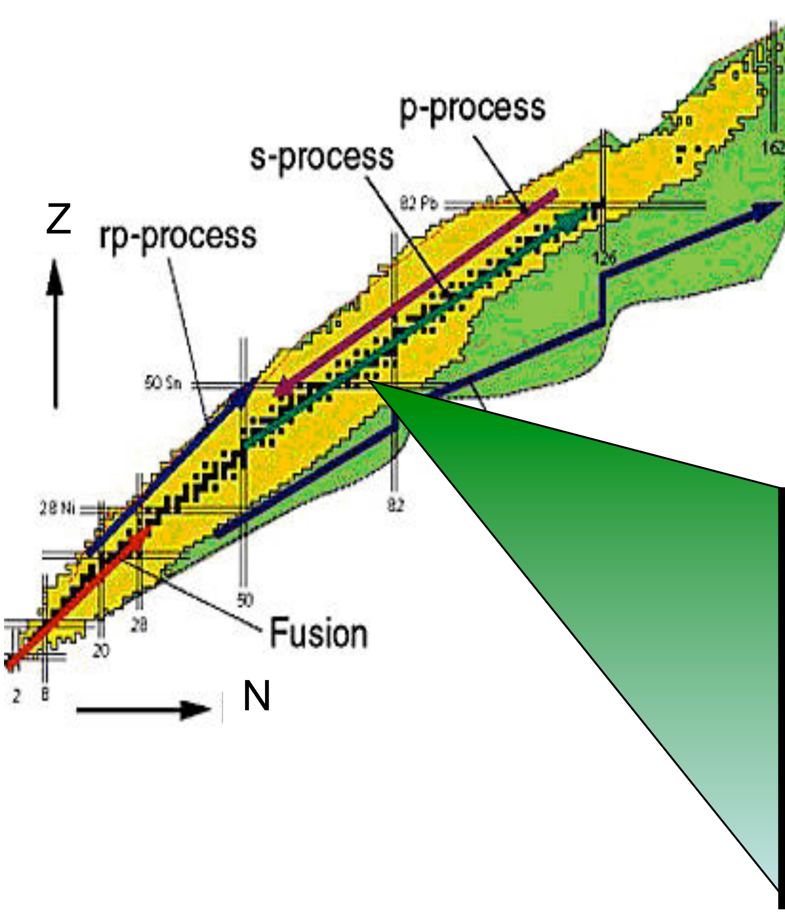


Figure 1 The s-process pathway from ^{169}Tm to ^{173}Yb from [2]. Branch-point nuclei are outlined in red.

HEDP-induced population of low-lying states in s-process branch point nuclei could affect nucleosynthesis

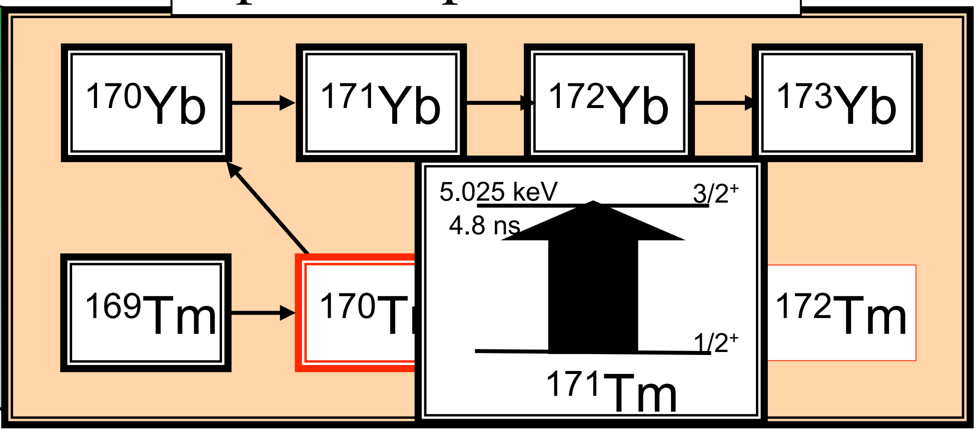


S-process conditions

$k_BT \approx 8, 30$ keV

$\rho \approx$ 50-100 g/cm^3

s-process path near Tm

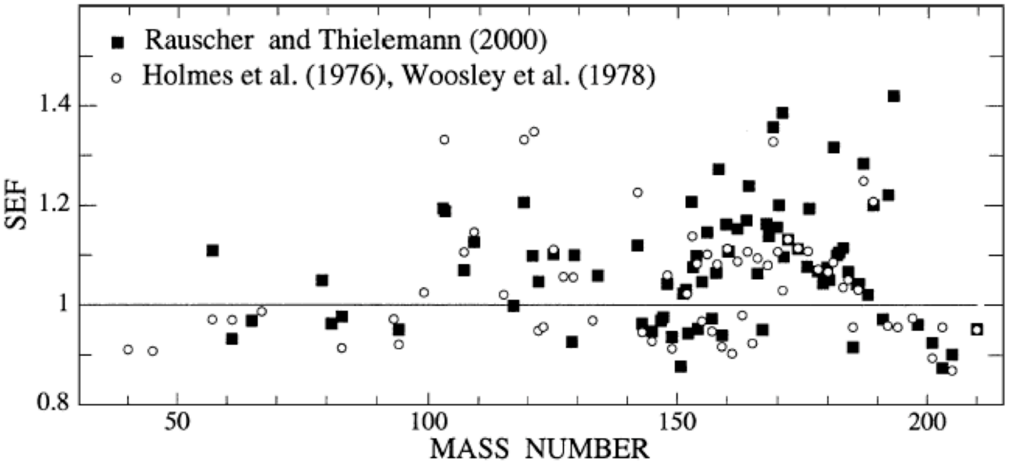


Equilibrium population of the excited state is ≈ 36%

s-process, surrogate measurement “issues”

- Difficult targets
- Low energy neutrons, high intensity
- Dense plasma environment
  - Screening
  - Population of low lying excited states
    - Affects □ decay lifetimes
    - Affects (n,□) cross sections (Stellar enhancement factors)

Stellar enhancement factors (SEF)



- No data exists for (n,) cross sections on two different states of the same nucleus at stellar s-process energies (tens keV)
- Surrogate reactions will allow us to address the J mismatch issue

Important s-process branch points

Branch Point	Ground State J^{π}	1st Exc. State E_x (keV)	1st Exc. State J^{π}	STARS/LIBERACE reaction
^{79}Se	$7/2^+$	95.77	$1/2^-$	^{76}Ge(^{6}Li,d)^{80}Se*
^{85}Kr	$9/2^+$	304.871	$1/2^-$	^{87}Rb(d,^{3}He)^{86}Kr*
^{147}Pm	$7/2^+$	91.1	$5/2^+$	^{149}Sm(d,^{3}He)^{148}Pm*
^{151}Sm	**$5/2^-$**	**4.821**	**$3/2^-$**	^{152}Sm(α,α')^{152}Sm*
^{163}Ho	$7/2^-$	100.03	$9/2^-$	^{165}Ho(^{3}He,α)^{164}Ho*
^{170}Tm	**1^-**	**38.7139**	**2^-**	^{171}Yb(d,^{3}He)^{171}Tm*
^{171}Tm	**$1/2^+$**	**5.0361**	**$3/2^+$**	^{172}Yb(d,^{3}He)^{172}Tm*
^{179}Ta	**$7/2^+$**	**30.7**	**$9/2^+$**	^{181}Ta(^{3}He,α)^{180}Ta*
^{204}Tl	2^-	414.1	4^-	^{205}Tl(α,α)^{205}Tl*
^{205}Pb	$5/2^-$	703.3	$7/2^-$	^{207}Pb(^{3}He,α)^{206}Pb
^{185}W	**$3/2^-$**	**23.547**	**$1/2^-$**	^{186}W(α,α')^{186}W

Table I: Important s-process branch point nuclei from [1]. Potential STARS/LIBERACE reactions are in the right-most column.

Surrogate measurements will only take you so far.

Some speculative ideas

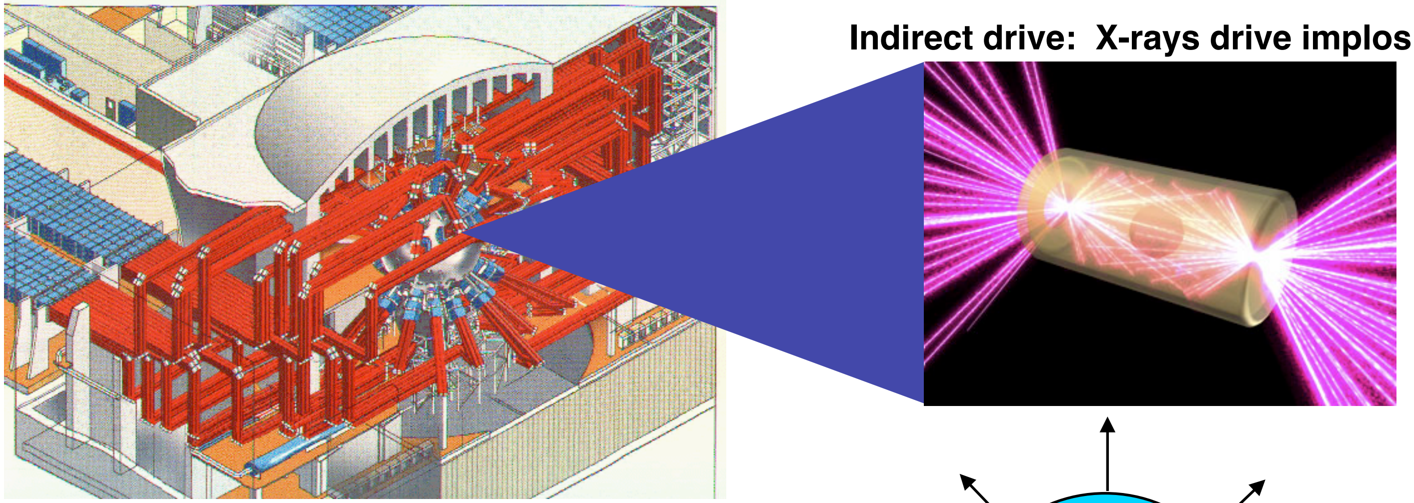
- Regarding the possible complementary measurements for the surrogate method:
    - Average cross section measurements at NIF

The National Ignition Facility (NIF):
A new kind of nuclear laboratory

NIF is designed to implode D-T (or other) pellets to achieve thermonuclear fusion

Standard ignition configuration: 192 beams, 1.8MJ in 3ω light

Indirect drive: X-rays drive implosion



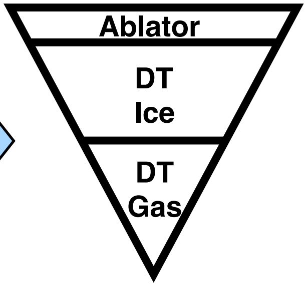
Hohlraum ~ 10 mm long

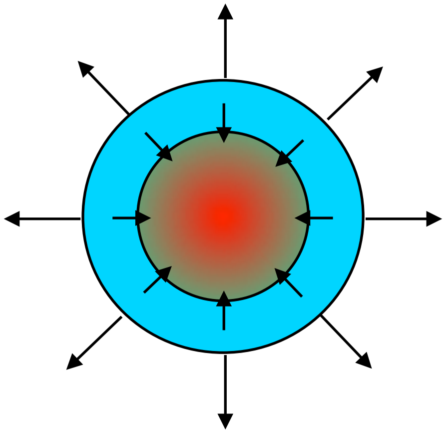
Target ~ 1 mm radius

Optical pulse ~ few ns

Burn ~ few ps

Can insert $\leq 10^{15\text{-}20}$ nuclei

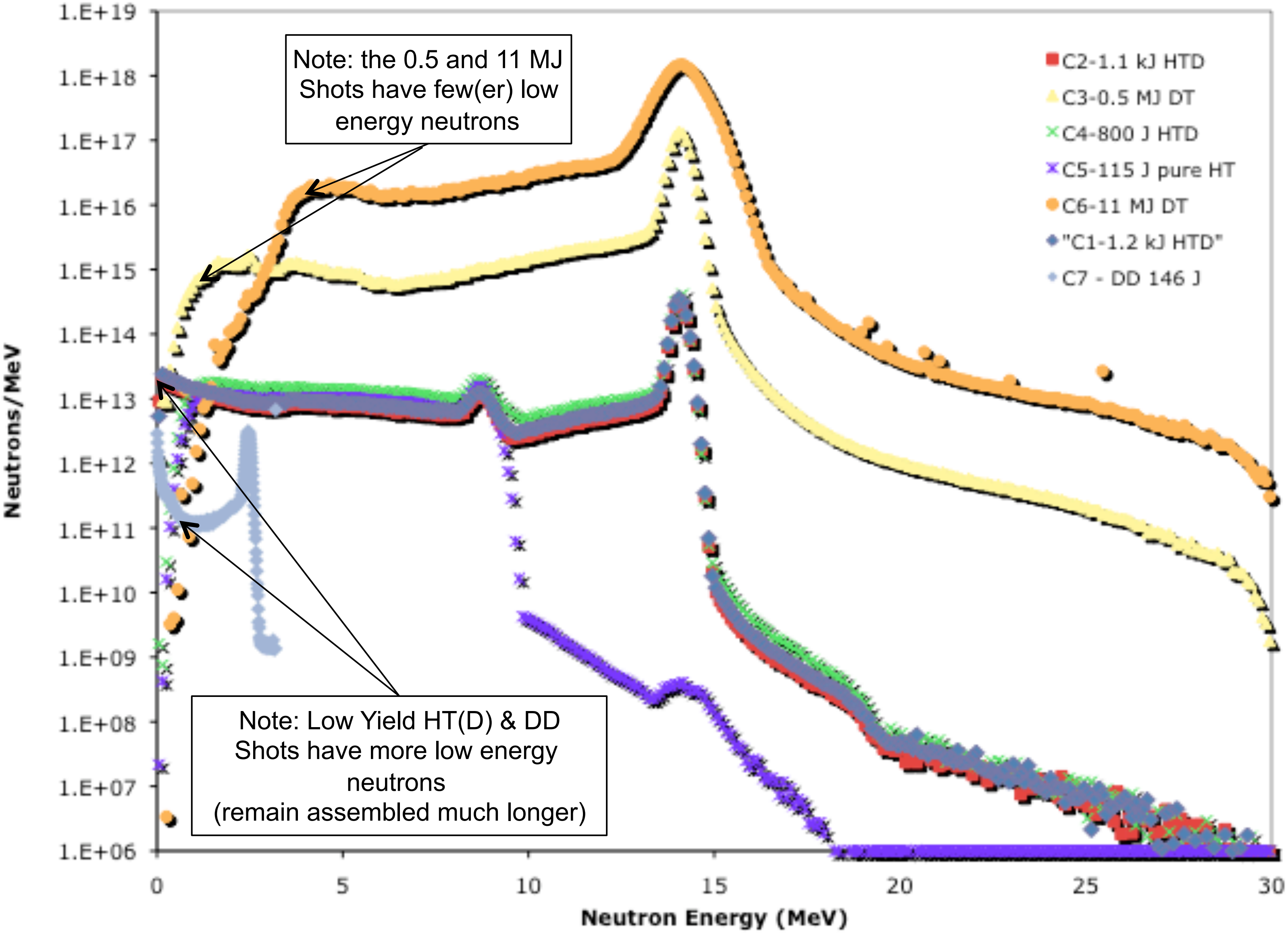




$$r_{initial} = 1\ \text{mm}$$
$$r_{final} = 30\ \mu\text{m}$$

Up to 300 shots/year with ≈15% dedicated for basic science (Ride-along also possible)

What do the NIF neutron spectra look like (Modeling courtesy of C. Cerjan)



Note: the 0.5 and 11 MJ Shots have few(er) low energy neutrons

Note: Low Yield HT(D) & DD Shots have more low energy neutrons
(remain assembled much longer)

Stellar reaction cross section measurements are enhanced by $(\square_{areal}\square)^2$ at NIF compared to accelerator-based experiments

Assumptions

- 1 mm diameter initial pellet size with density≈0.1 g/cm^3 Compression to 30 μm diameter
- No fuel loaded. 50/50 mix of *A* and *B*

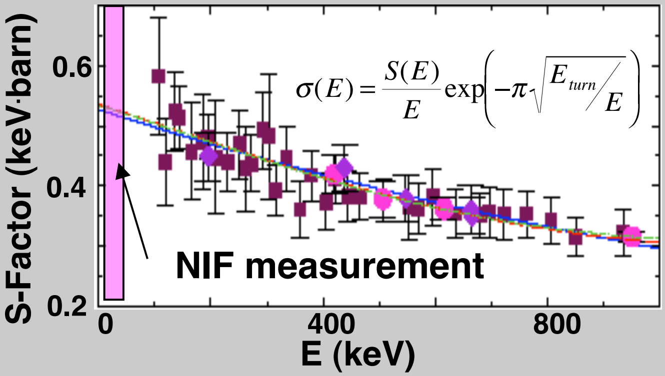
Consider the reaction $A(B,X)Y$

$$N_Y = \sigma_{(b,x)}(N_A N_B / area)$$

$$for\, \sigma_{(b,x)} = 0.01pb\ (10^{-38}cm^2)$$

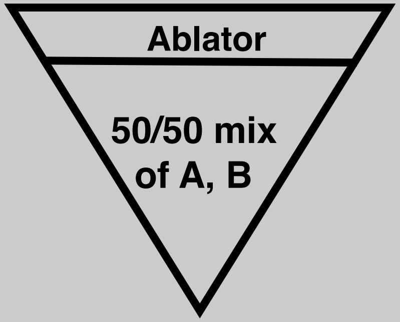
$$N_Y = 10^{-38}cm^2\left(10^{20} \bullet 10^{20} / 4\pi(30\mu m)^2\right) \approx \mathbf{10^6} +$$

Accelerator-Based Experiments



- √ Mono-energetic
- □ Low event rate (few events/month)
- □ Significant screening corrections needed
- □ Not performed at relevant energies

NIF-Based Experiments



- √ High Count rate (3x10^5 atoms/shot)
- √ Small, manageable screening
- √ Energy window is better
- □ Integral experiment
- □ ^{7}Be background

Conclusions

- Neutron-induced reactions are of interest for a variety of applied and basic science reasons
  - s process
  - Reactor designs
  - Stockpile stewardship
- Surrogate reaction often the only way to estimate these cross sections
- NIF represents unique opportunities and challenges