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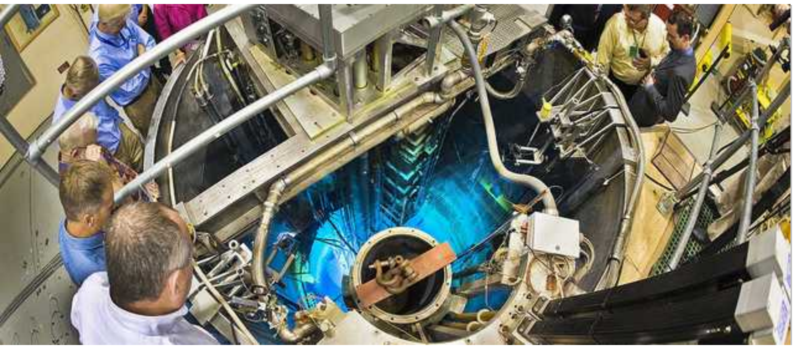

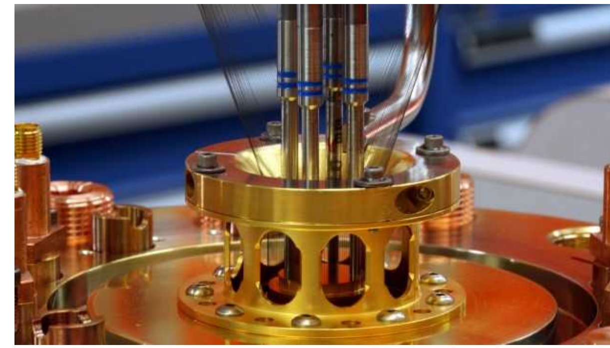

Delayed Fission Gamma-ray Characteristics of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, and ^{239}Pu

Taylor K. Lane

Mentor: Ed Parma

Manager: Ken Reil

Applied Nuclear Technologies, 01384

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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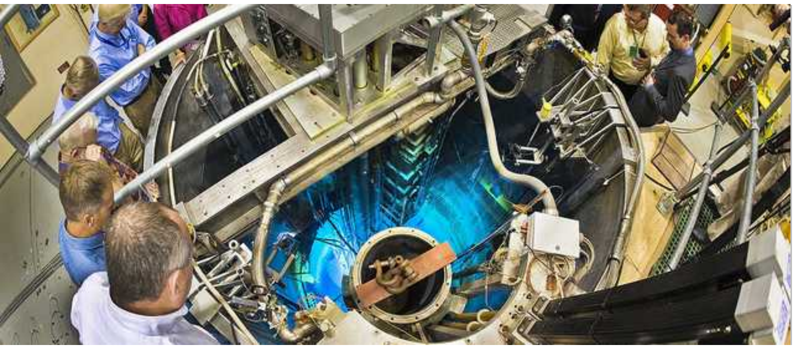

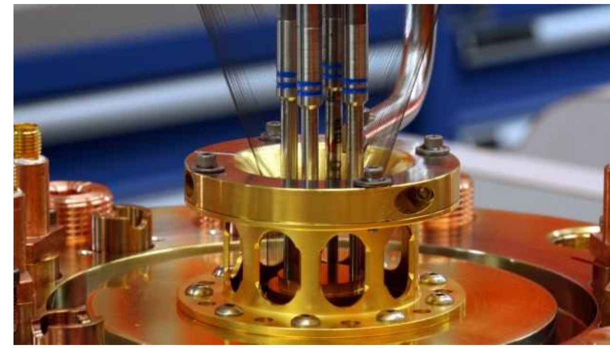

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What am I doing and why does it matter?

- Studying fission gamma-ray emission properties

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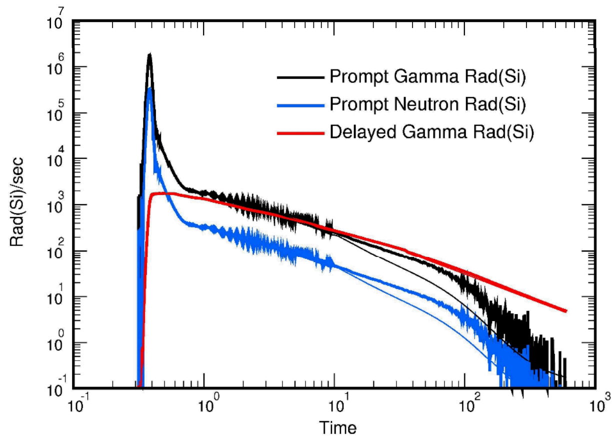

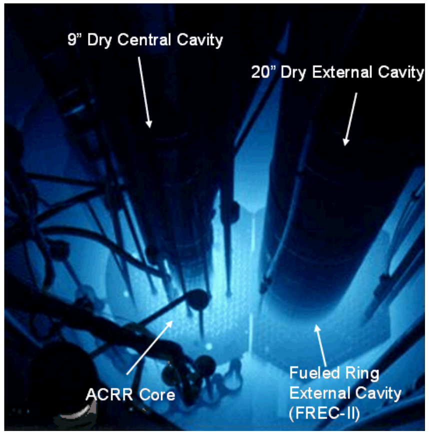

ACRR Shots

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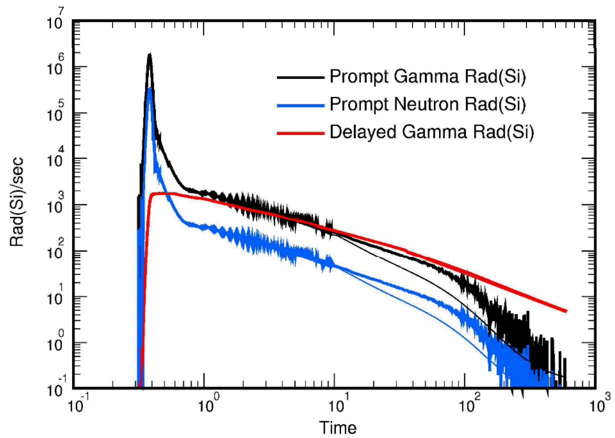
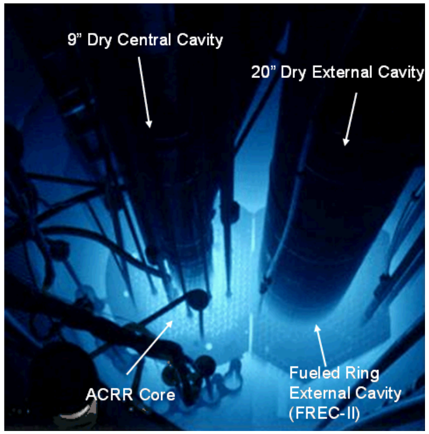




ACRR Shots

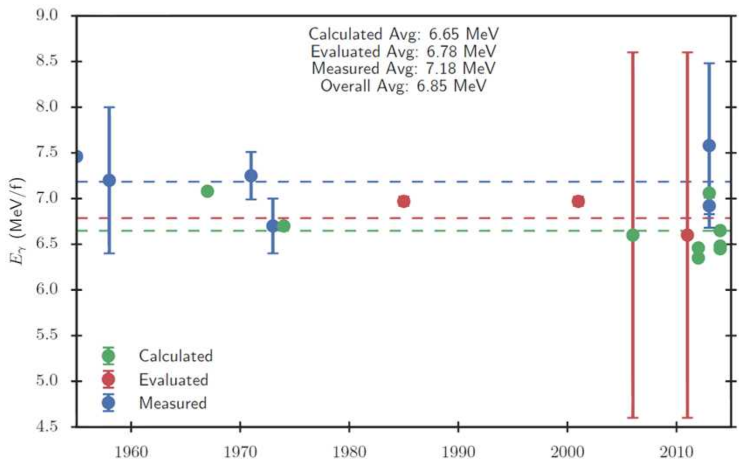
- Increase spectra fidelity (from 48 energy groups)
- Provide time-dependent spectra
- Provide time-dependent energy release curves

What’s available in the literature?

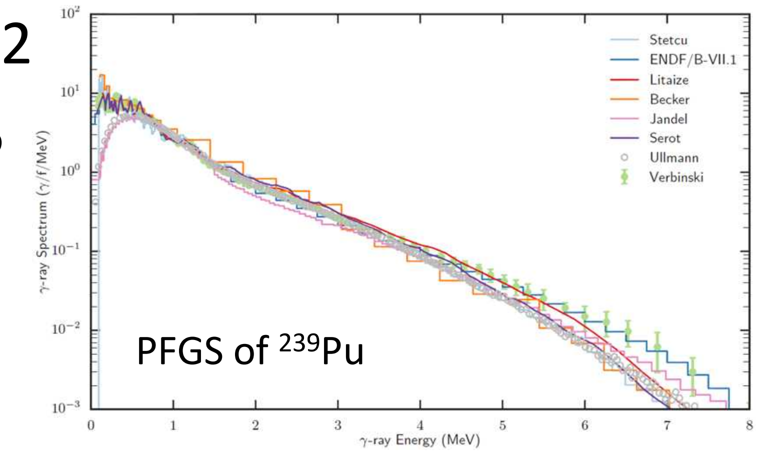
A lot. But it’s a mixed bag.

- Mostly experiments from 1955 – 1982
- Mostly simulations from 2001 – 2015
- Interspersed ENDF “evaluations”

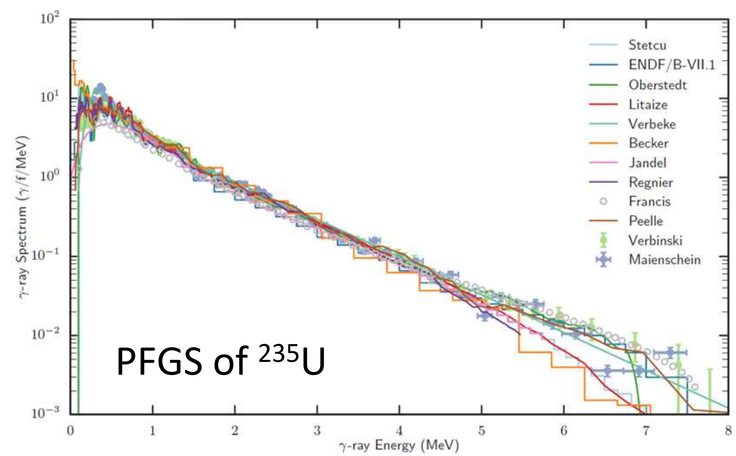
Time	#
‘50s	2
‘60s	3
‘70s	3
‘80s	2
‘90s	1
‘00s	4
‘10s	13



E_γ for (n_{th},f) of ^{235}U



PFGS of ^{239}Pu



PFGS of ^{235}U

Methodology

CINDER2008-SNL

- CINDER is the transmutation code used in MCNP KCODE runs
- Tracks neutron-induced transmutation, natural decay and delayed radionuclide photon release.
- High-Fidelity Gamma Output (7,428 groups) vs 25 groups

Number Density of Isotope *m*

Loss Fraction for Isotope *m*

“Other” Loss or Gain for Isotope *m*

Fraction of Isotope *k* that Transmute to Isotope *m*

$$\frac{dN_m(t)}{dt} = -N_m(t)\beta_m + \bar{Y}_m + \sum_{k\neq m} N_k(t)\gamma_{k\rightarrow m}$$

(g,x) Cross Section for Isotope *m*, resulting in isotope ≠*m*

$$\beta_m = \lambda^m + \phi_n\sigma^m_{n,abs} + \phi_g\sigma^m_{g,abs}$$

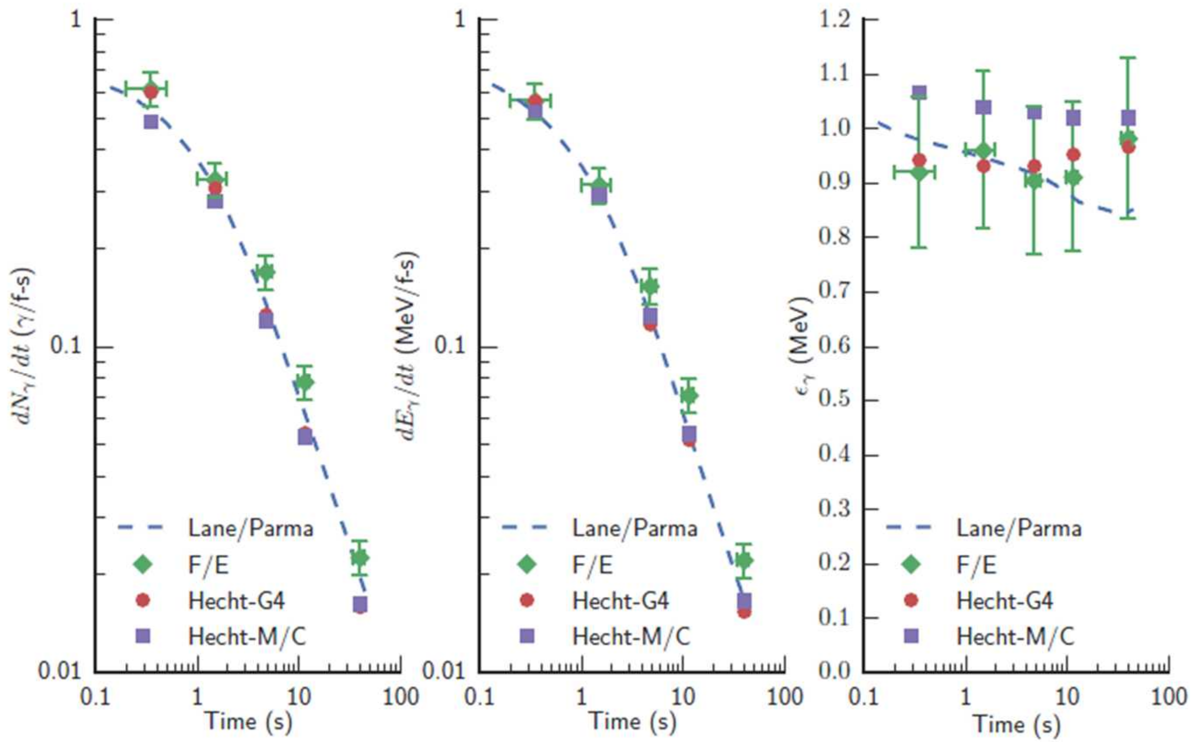
Rate of Natural Decay for Isotope *m*

Neutron Flux

(n,abs) Cross-Section for Isotope *m*

Photoflux

^{235}U – Fisher and Engle Comparison



Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**F**	**0.001 – 30**	**0.2 – 45**	**3.07**	**2.79**	**0.85**
F/E		0.137 – 6.419	0.2 – 45	3.31 ± 0.46	3.18 ± 0.45	0.96 ± 0.14
Hecht-G4			0.2 – 45	2.39	2.58	0.93
Hecht-M/C	F	0 – 25	0.2 – 45	2.46	2.40	1.03

^{235}U – Characteristic Summary

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CINDER	**F**	**0.001 – 30**	**10^{-6} – 10^{8}**	**9.47**	**6.95**	**0.74**
CINDER	**HE**	**0.001 – 30**	**10^{-6} – 10^{8}**	**8.49**	**6.07**	**0.72**
Maienschein, *et al.*		0.3 – 10	5E-8 – 10^{8}	7.4 ± 0.8	7.20 ± 0.80	0.97 ± 0.15
Thomas and Grover				8.2	7.08	0.87
Peelle and Maienschein		0.01 – 10.5	< 69E-9	8.13 ± 0.35	7.25 ± 0.26	0.97 ± 0.05
Peelle and Maienschein		0.14 – 10.0	< 69E-9	7.45 ± 0.32	7.18 ± 0.26	0.96 ± 0.06
Verbinski, *et al.*		0.14 – 10.0	< 10^{-8}	6.51 ± 0.30	6.70 ± 0.30	0.97 ± 0.05
Hoffman and Hoffman				6.49	6.70	1.03
Sher					6.97 ± 0.50	
Frehaut, *et al.*	1.73 ± 0.19			6.78 ± 0.04		
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Madland	2.53E-8				6.60 ± 0.03	
Madland	2				6.76 ± 0.03	
Madland	14				7.69 ± 0.08	
ENDF/B-VII.1		0.025 – 8.1		7.04 ± 2.13	6.60 ± 2.00	0.94
Jandel, *et al.* (PM)		> 0.15		6.2	6.46	1.04
Jandel, *et al.* (CGMF)		> 0.15		6.79	6.35	0.94
Becker, *et al.*		> 0.14		8.05	7.06	0.88
Chyzh, *et al.*		0.15 – 9.5		6.95 ± 0.30	7.58 ± 0.90	1.09 ± 0.12
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Litaize, *et al.*	2.53E-8	0.1 – 4.0	< 10^{-8}	4.57	6.65	0.88
Stetcu, *et al.*		> 0.1		7.41	6.45	0.87

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$$\epsilon_\gamma = \frac{E_\gamma}{N_\gamma}$$

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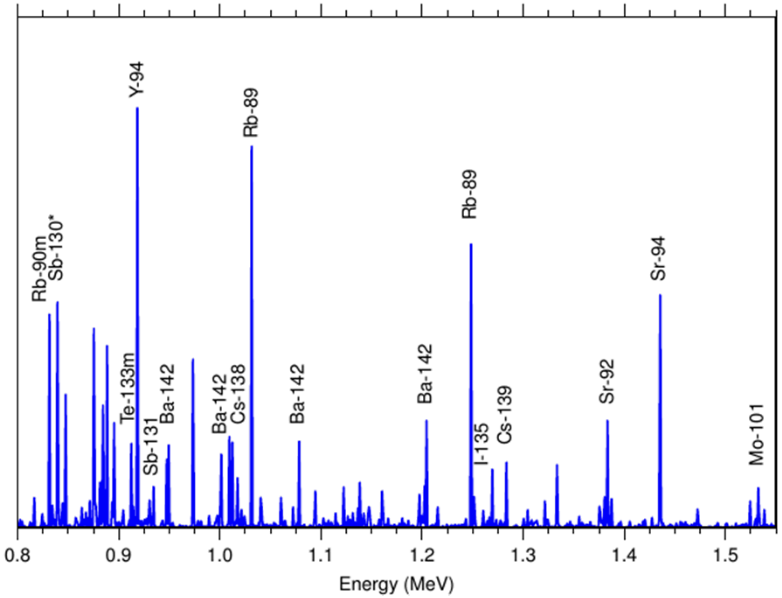
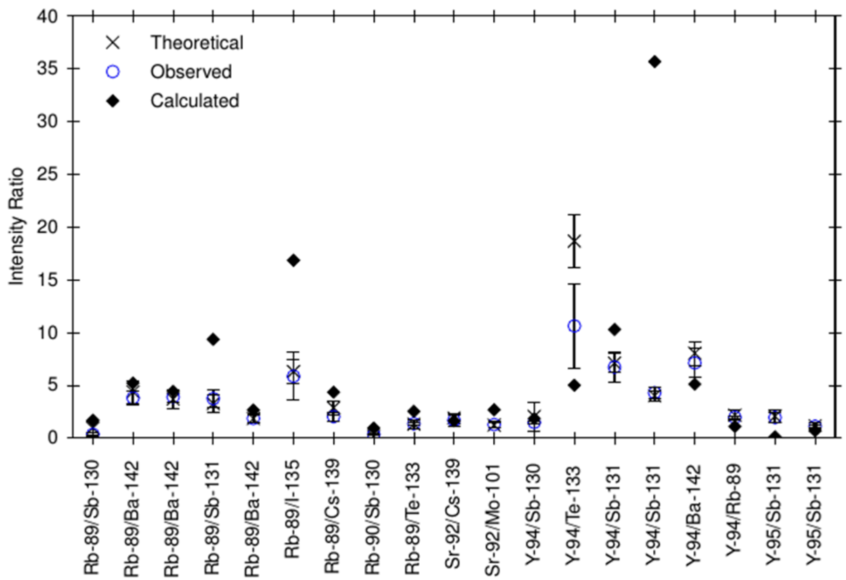
Madland	14				7.69 ± 0.08	
ENDF/B-VII.1		0.025 – 8.1		7.04 ± 2.13	6.60 ± 2.00	0.94
Jandel, *et al.* (PM)		> 0.15		6.2	6.46	1.04
Jandel, *et al.* (CGMF)		> 0.15		6.79	6.35	0.94
Becker, *et al.*		> 0.14		8.05	7.06	0.88
Chyzh, *et al.*		0.15 – 9.5		6.95 ± 0.30	7.58 ± 0.90	1.09 ± 0.12
Jandel, *et al.*		> 0		6.35	6.48	1.03
Oberstedt, *et al.*		0.1 – 6.0		8.18 ± 0.11	6.98 ± 0.09	0.85 ± 0.02
Litaize, *et al.*	2.53E-8	0.1 – 4.0	< 10^{-8}	5.85	6.65	0.88
Stetcu, *et al.*		> 0.1		7.41	6.45	0.87

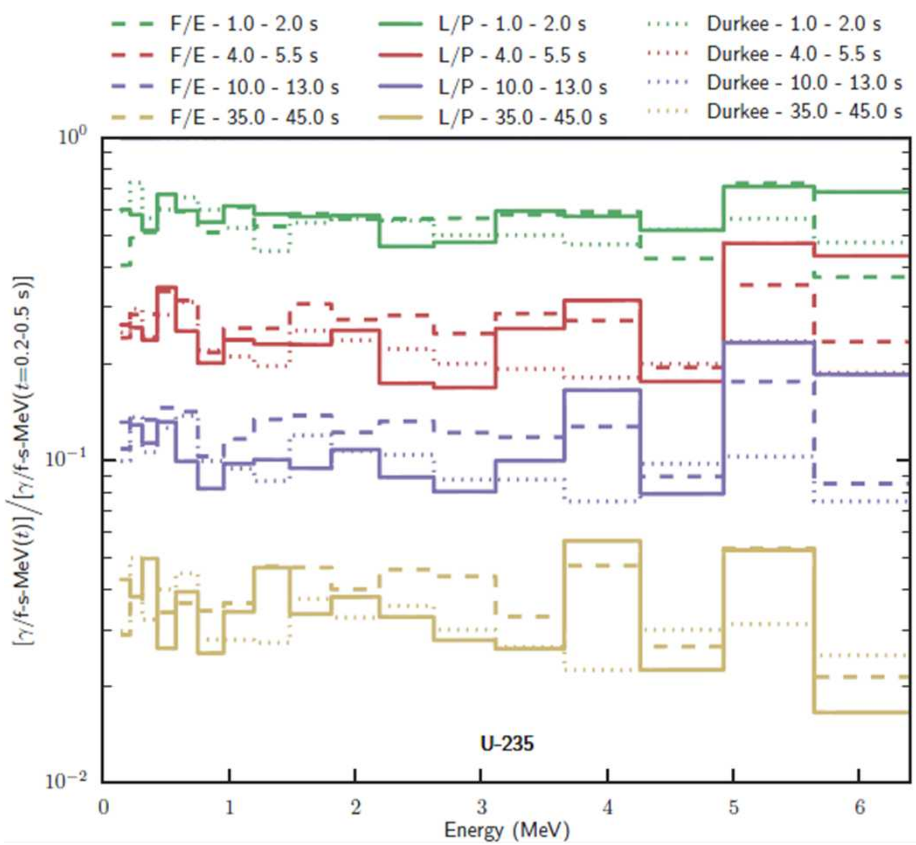
^{235}U – Characteristic Summary

Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**T**	**0.001 – 30**	**$10^{-6} – 10^{8}$**	**9.36**	**6.89**	**0.74**
CINDER	**F**	**0.001 – 30**	**$10^{-6} – 10^{8}$**	**9.47**	**6.95**	**0.74**
CINDER	**HE**	**0.001 – 30**	**$10^{-6} – 10^{8}$**	**8.49**	**6.07**	**0.72**
Maienschein, *et al.*		0.3 – 10	5E-8 – 10^{8}	7.4 ± 0.8	7.20 ± 0.80	0.97 ± 0.15
Thomas and Grover				8.2	7.08	0.87
Peelle and Maienschein		0.01 – 10.5	< 69E-9	8.13 ± 0.35	7.25 ± 0.26	0.97 ± 0.05
Peelle and Maienschein		0.14 – 10.0	< 69E-9	7.45 ± 0.32	7.18 ± 0.26	0.96 ± 0.06
Verbinski, *et al.*		0.14 – 10.0	< 10^{-8}	6.51 ± 0.30	6.70 ± 0.30	0.97 ± 0.05
Hoffman and Hoffman				6.49	6.70	1.03
Sher					6.97 ± 0.50	
Frehaut, *et al.*	1.73 ± 0.19			6.78 ± 0.04		
Frehaut, *et al.*	14.18 ± 0.10			7.91 ± 0.04		
Madland	2.53E-8				6.60 ± 0.03	
Madland	2				6.76 ± 0.03	
Madland	14				7.69 ± 0.08	
ENDF/B-VII.1		0.025 – 8.1		7.04 ± 2.13	6.60 ± 2.00	0.94
Jandel, *et al.* (PM)		> 0.15		6.2	6.46	1.04
Jandel, *et al.* (CGMF)		> 0.15		6.79	6.35	0.94
Becker, *et al.*		> 0.14		8.05	7.06	0.88
Chyzh, *et al.*		0.15 – 9.5		6.95 ± 0.30	7.58 ± 0.90	1.09 ± 0.12
Jandel, *et al.*		> 0		6.35	6.48	1.03
Oberstedt, *et al.*		0.1 – 6.0		8.18 ± 0.11	6.98 ± 0.09	0.85 ± 0.02
Litaize, *et al.*	2.53E-8	0.1 – 4.0	< 10^{-8}	5.85	6.65	0.88
Stetcu, *et al.*		> 0.1		7.41	6.45	0.87

^{235}U – Spectra Comparison

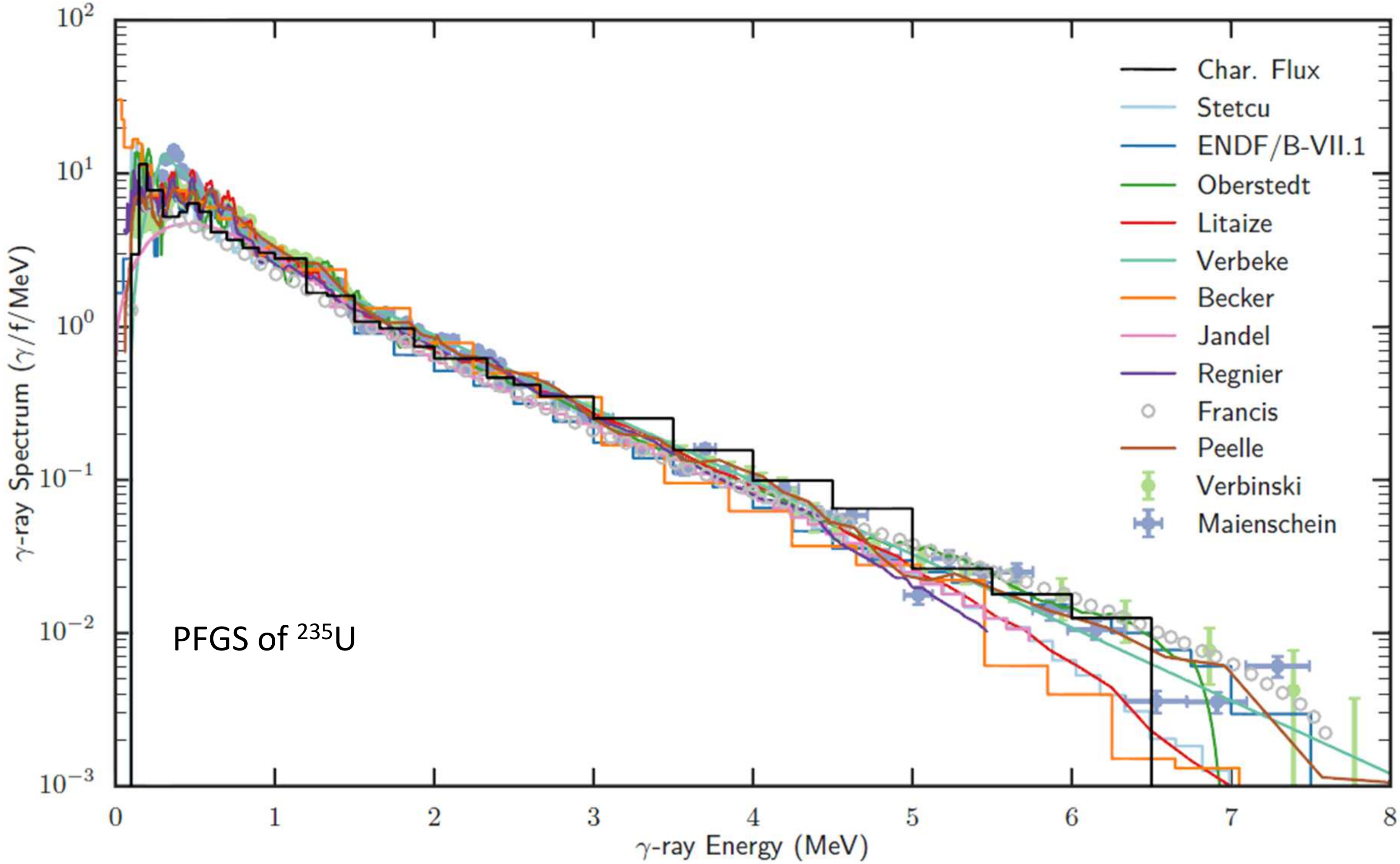






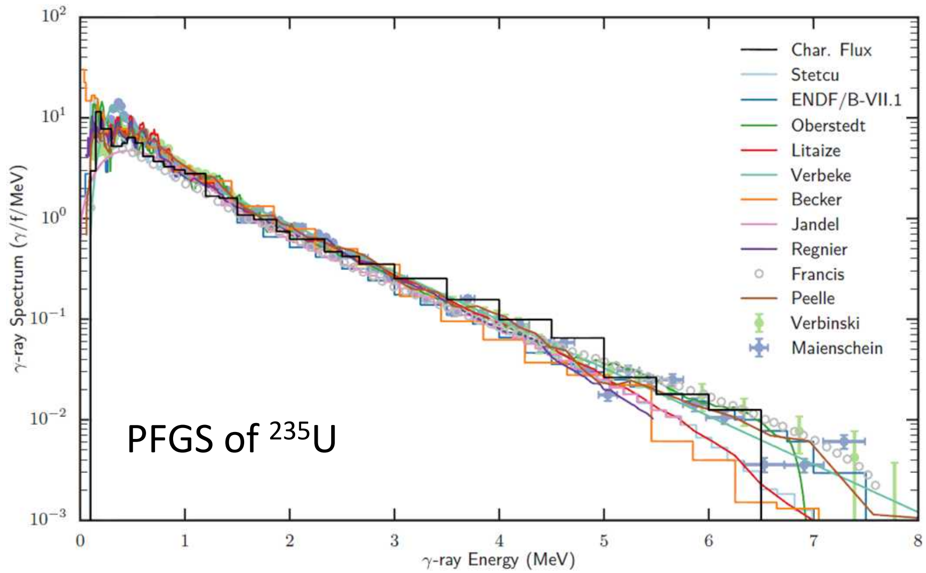
ACRR Characterization

Gamma-ray Spectra



ACRR Characterization

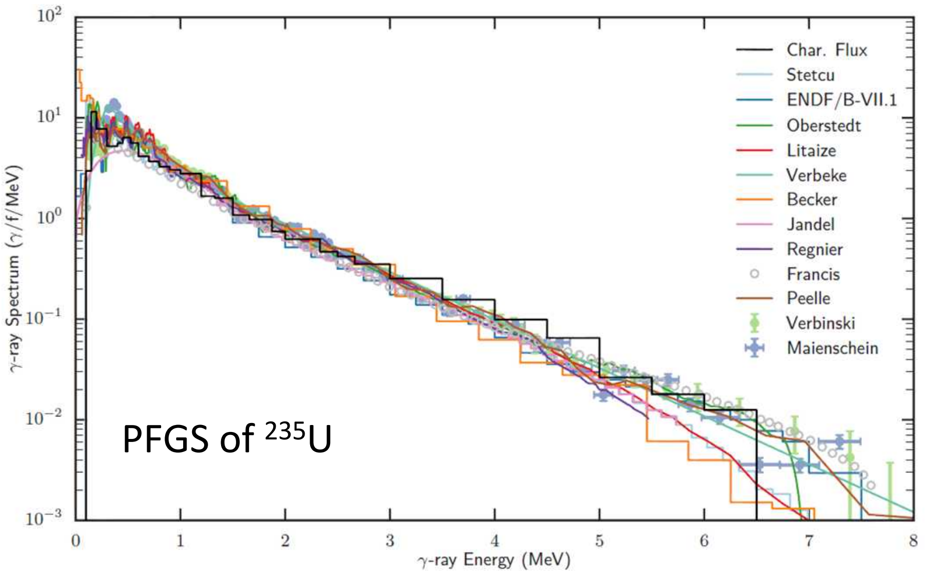
Gamma-ray Spectra



ACRR Characterization

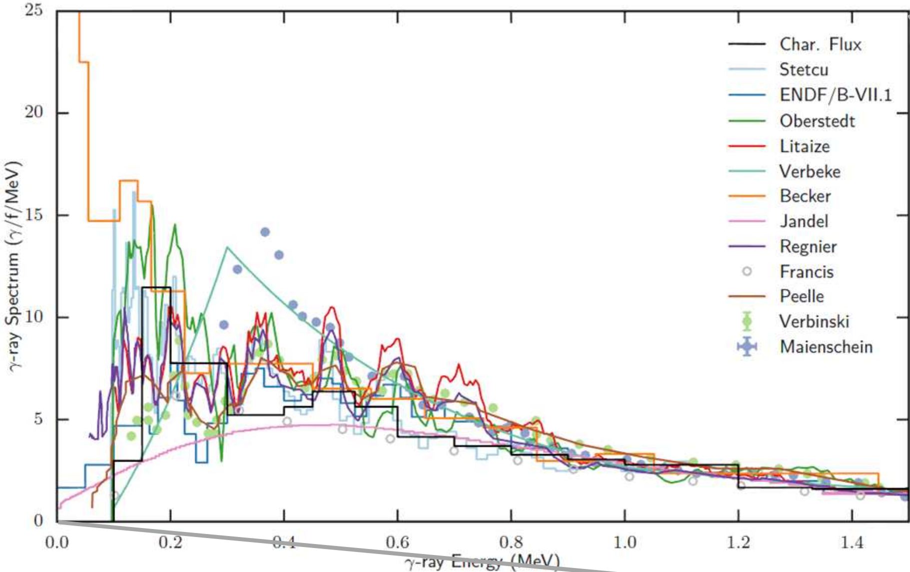
Gamma-ray Spectra

- Char. Flux fits reasonably well to literature
- Char. Flux – DFGS (0.2-0.5 s)
- Lit. Data – PFGS (< 10^{-8} s)

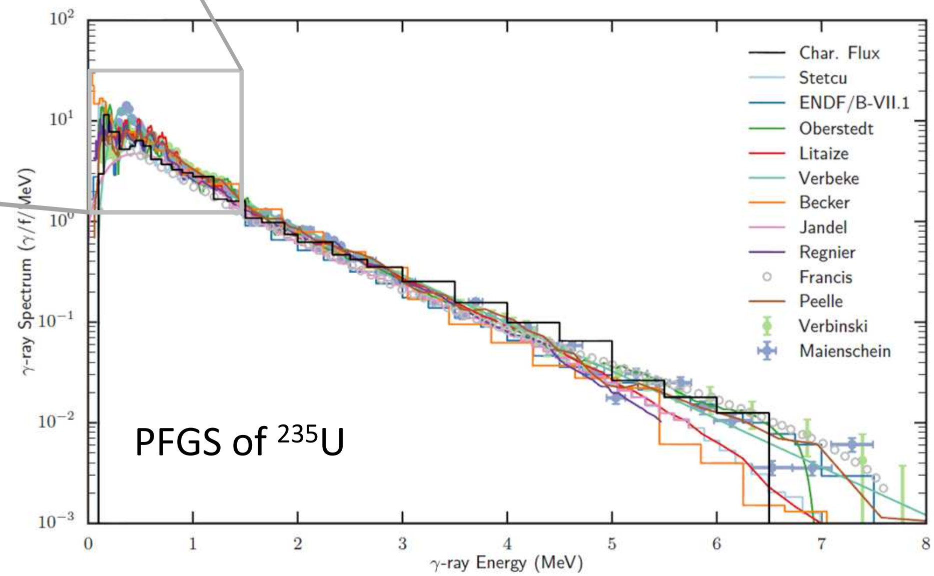


ACRR Characterization

Gamma-ray Spectra

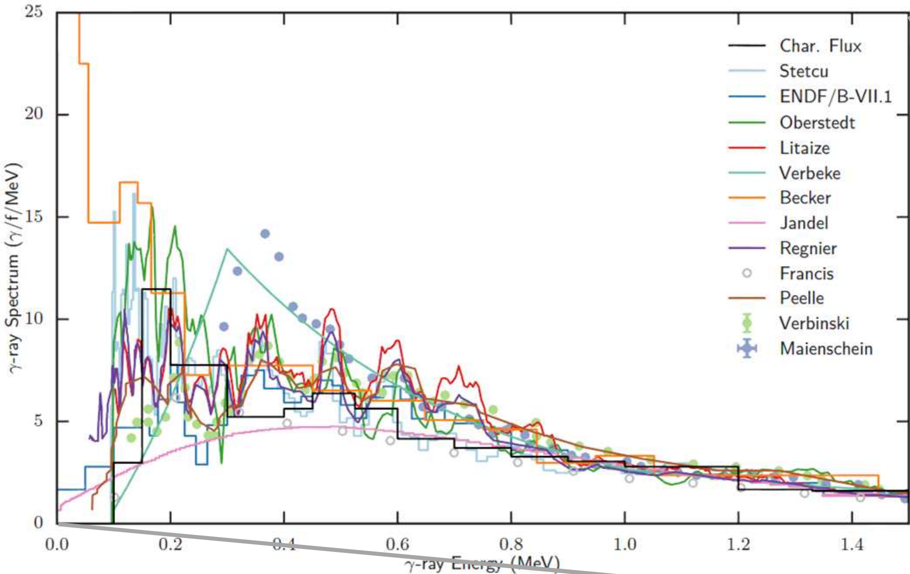


- Char. Flux fits reasonably well to literature
- Char. Flux – DFGS (0.2-0.5 s)
- Lit. Data – PFGS (< 10^{-8} s)

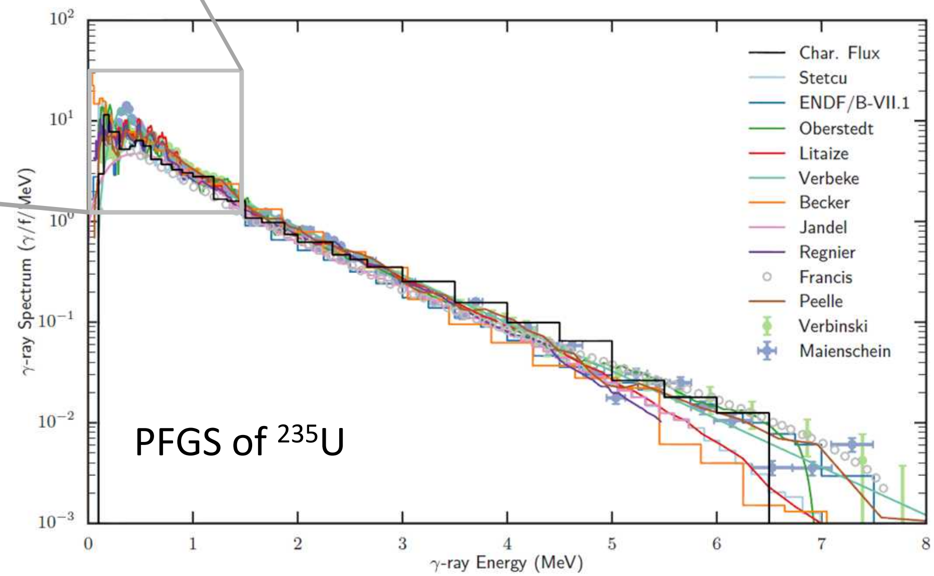


ACRR Characterization

Gamma-ray Spectra



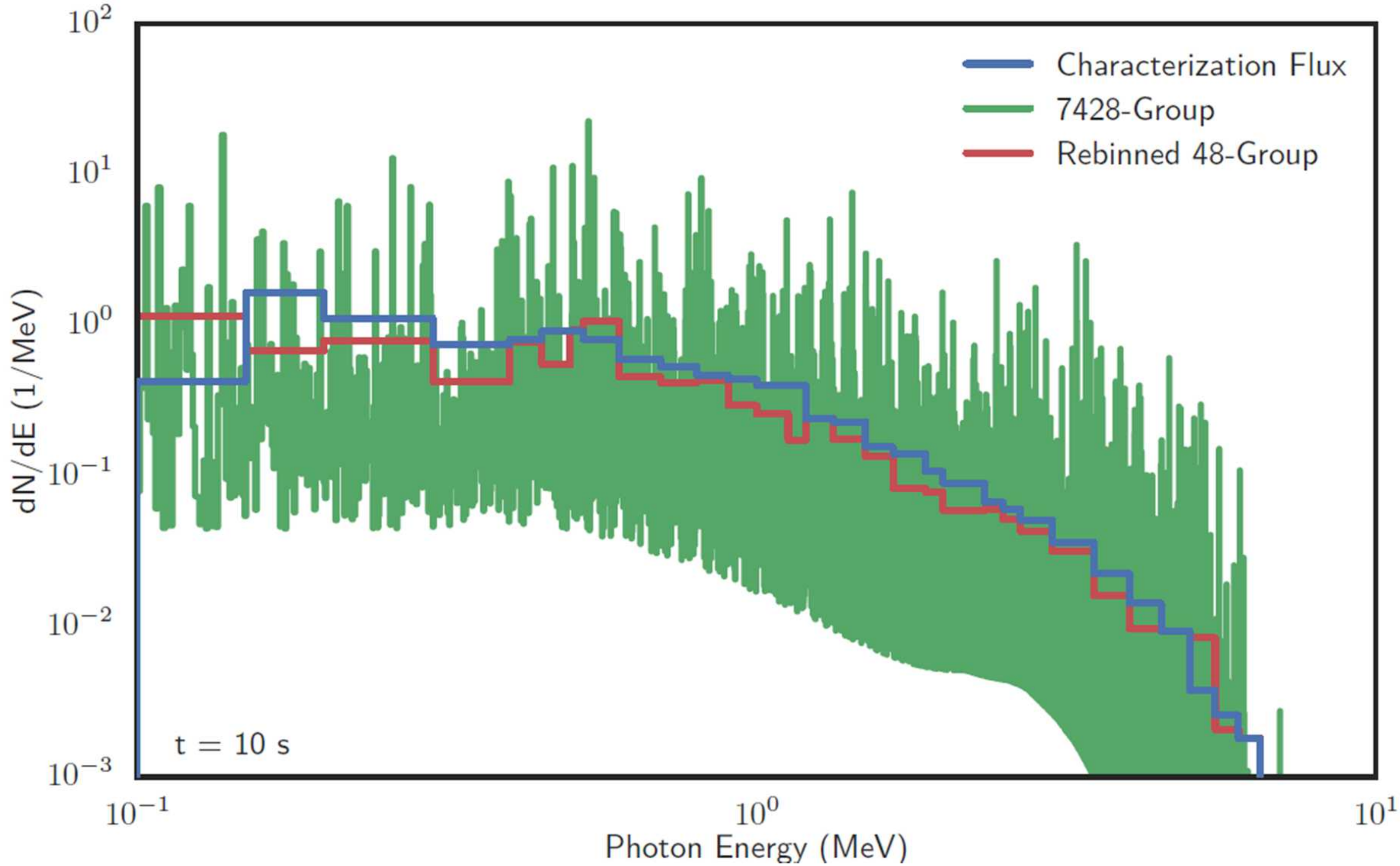
- Char. Flux fits reasonably well to literature
- Char. Flux – DFGS (0.2-0.5 s)
- Lit. Data – PFGS (< 10^{-8} s)



- Spread in low-energy data
- Discrete transitions visible
- Char. Flux too low below 800 keV

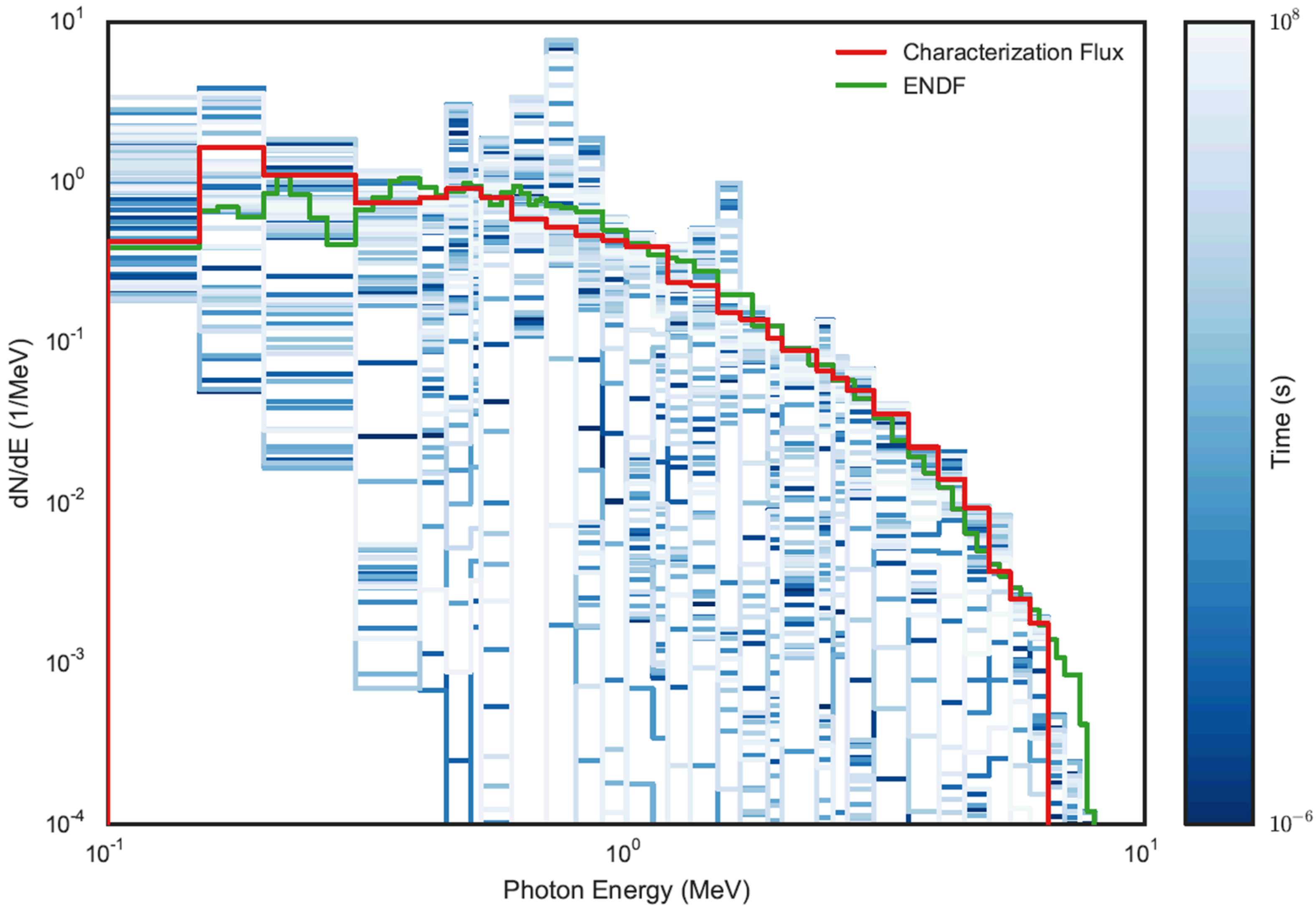
ACRR Characterization

Gamma-ray Spectra



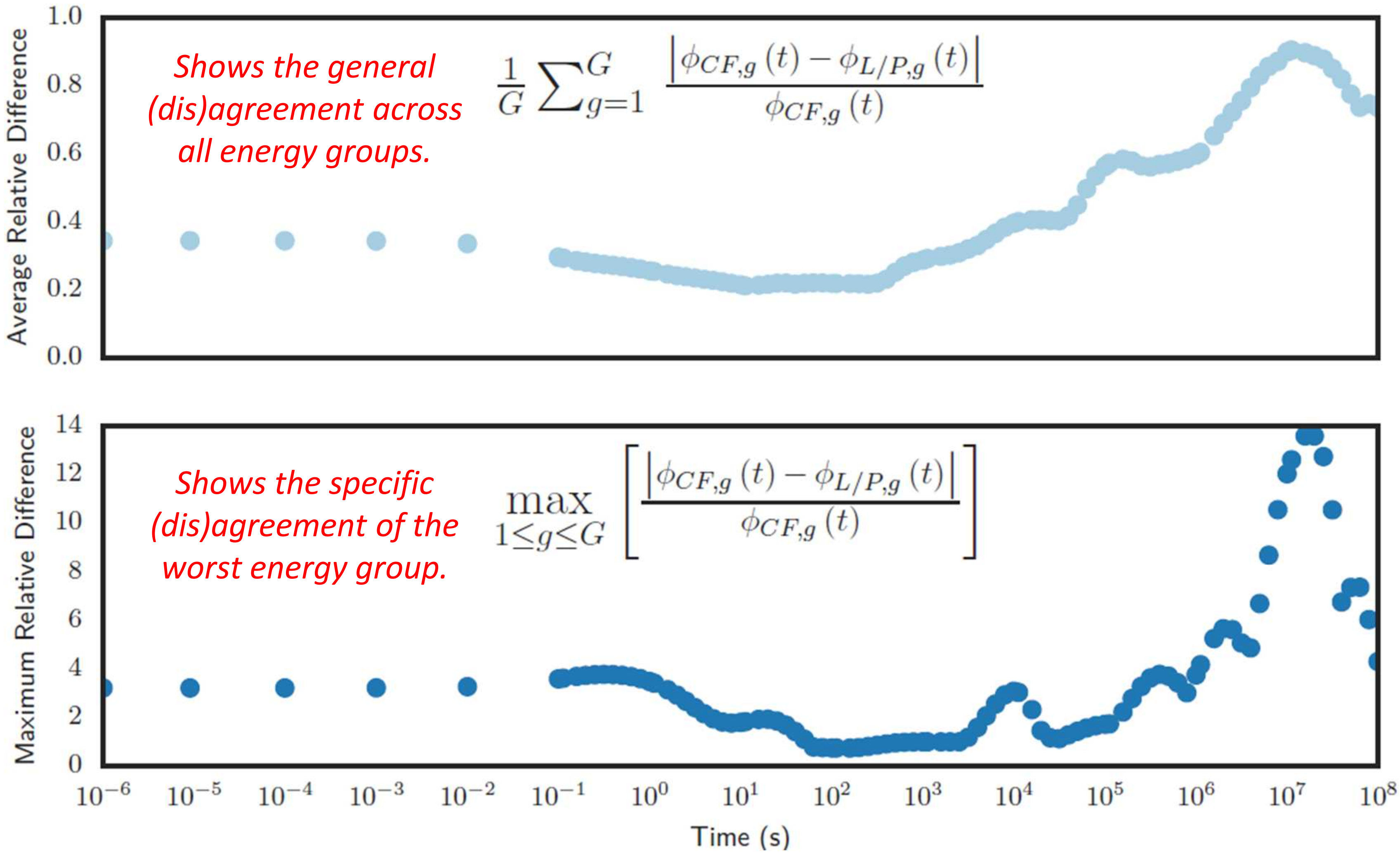
ACRR Characterization

Gamma-ray Spectra



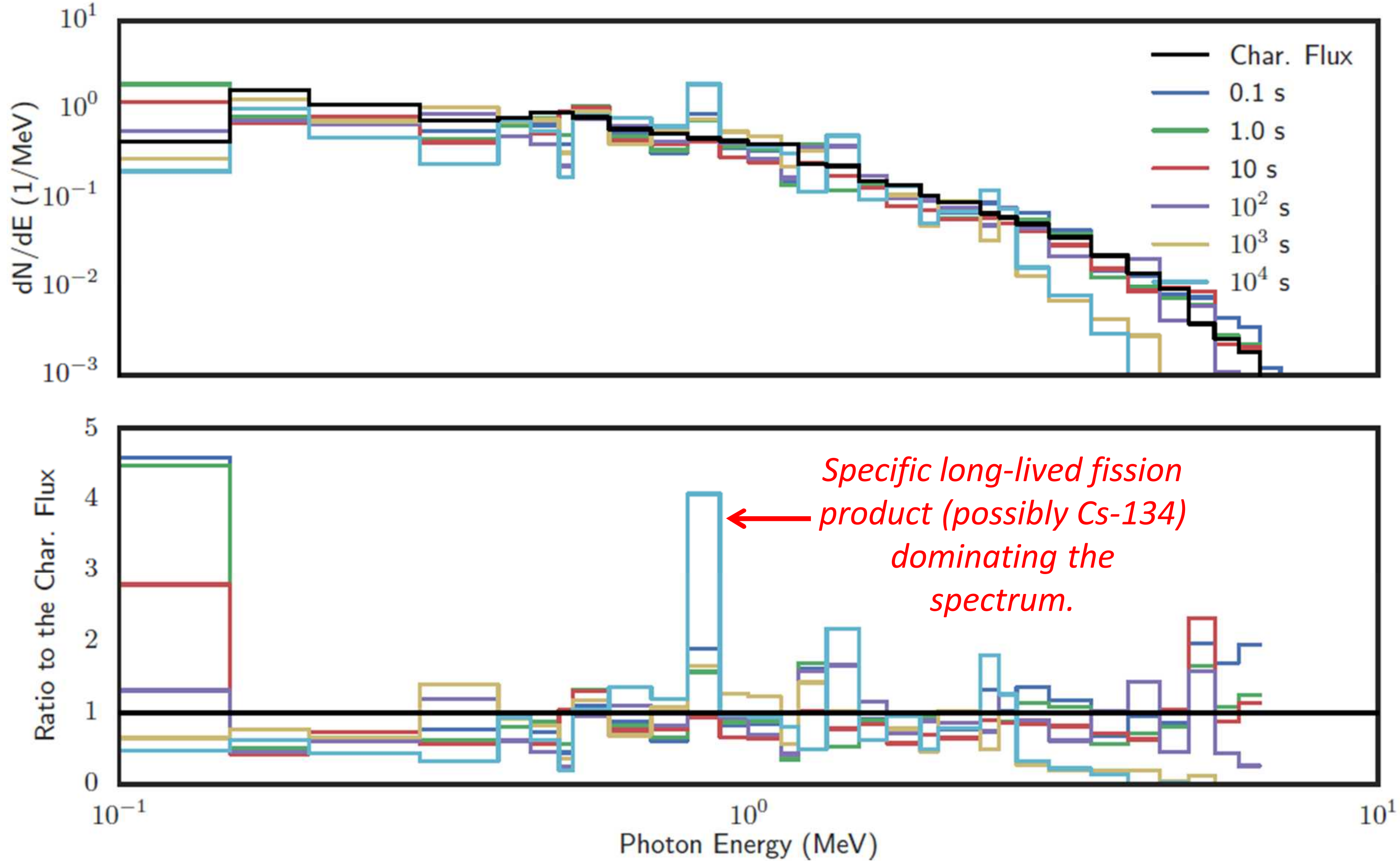
ACRR Characterization

Gamma-ray Spectra



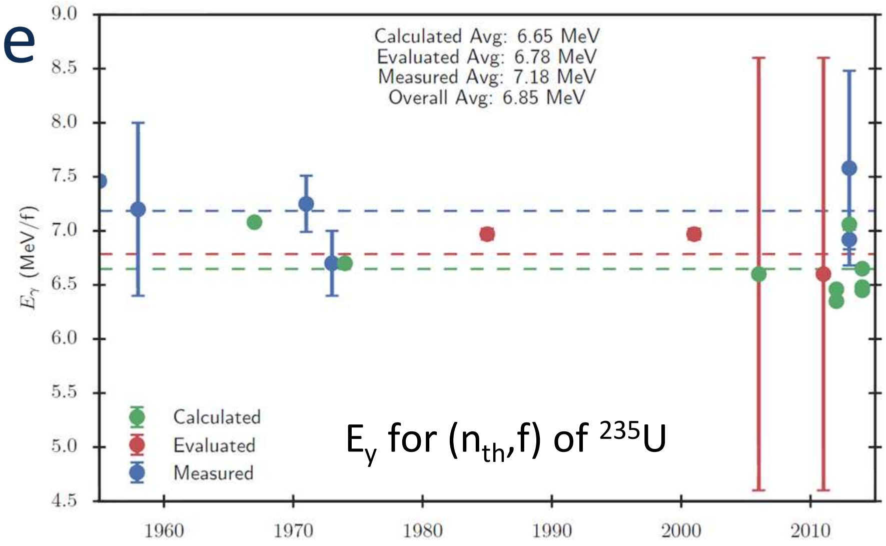
ACRR Characterization

Gamma-ray Spectra



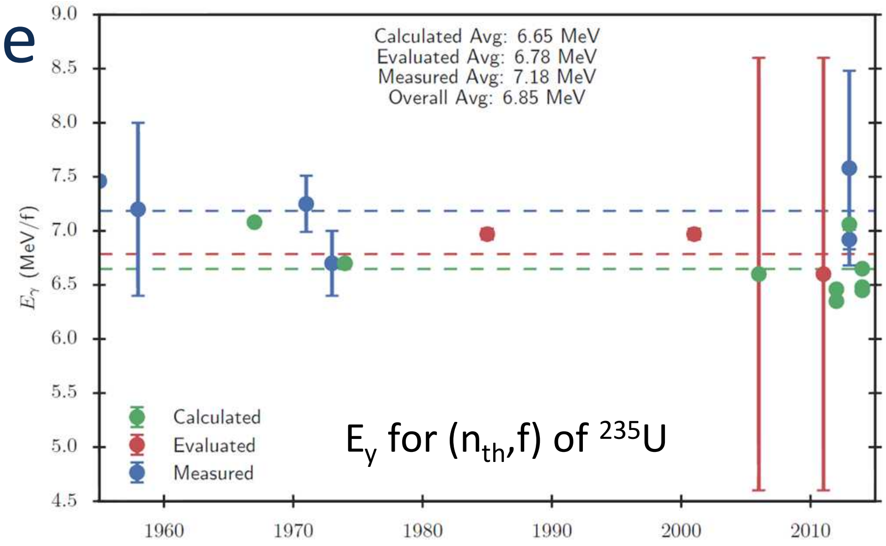
ACRR Characterization

Gamma-ray Energy Release



ACRR Characterization

Gamma-ray Energy Release

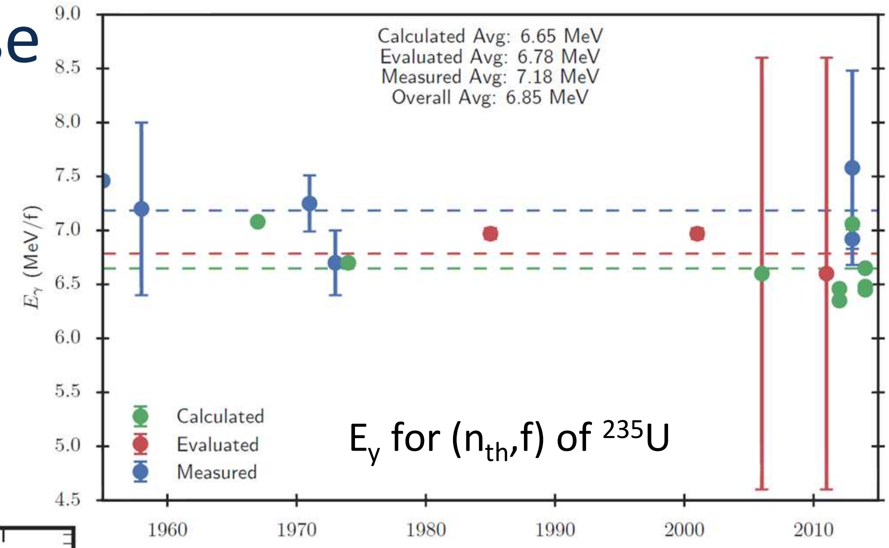


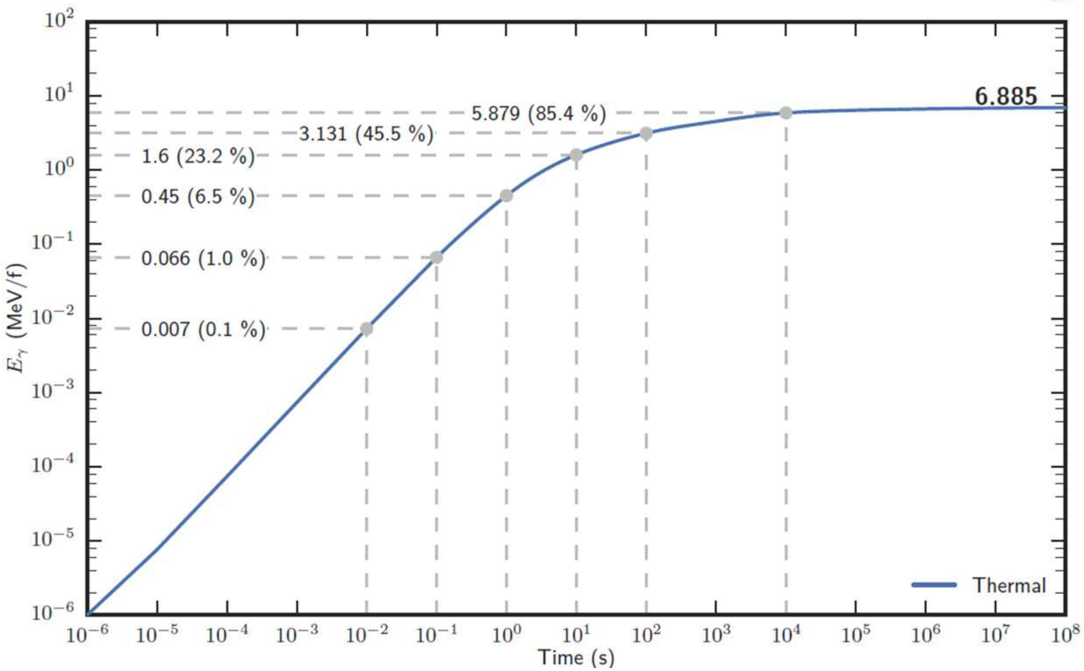
How much energy is released after 1 s? 10 s? 1 min? 1 hr?

ACRR Characterization

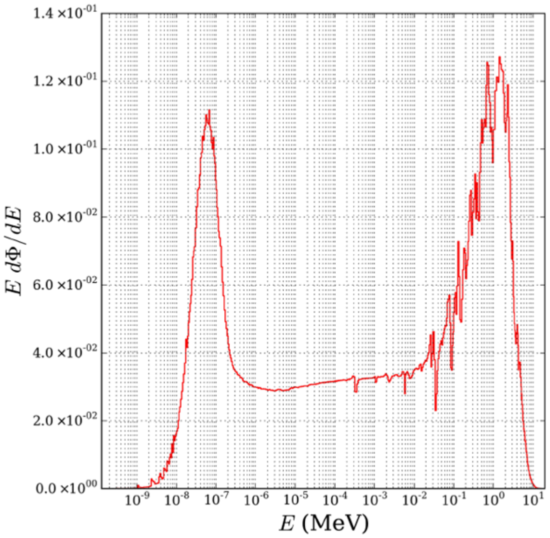
Gamma-ray Energy Release

How much energy is released after 1 s? 10 s? 1 min? 1 hr?

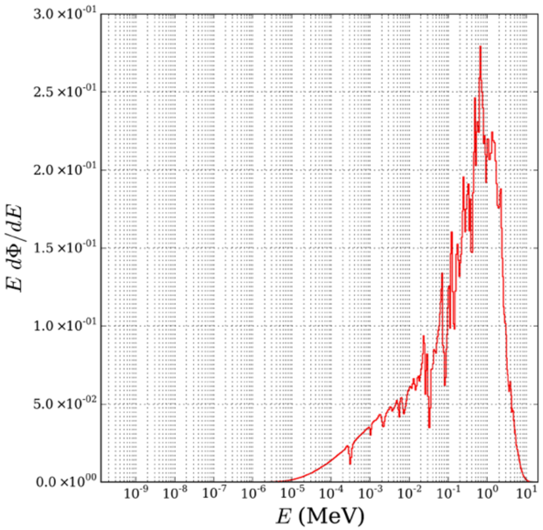




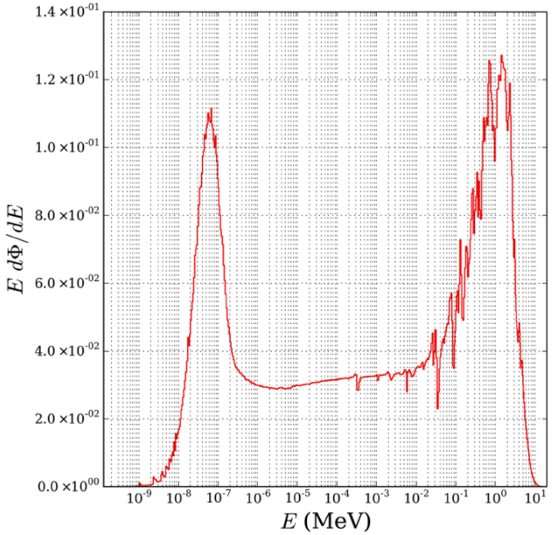
ACRR Characterization

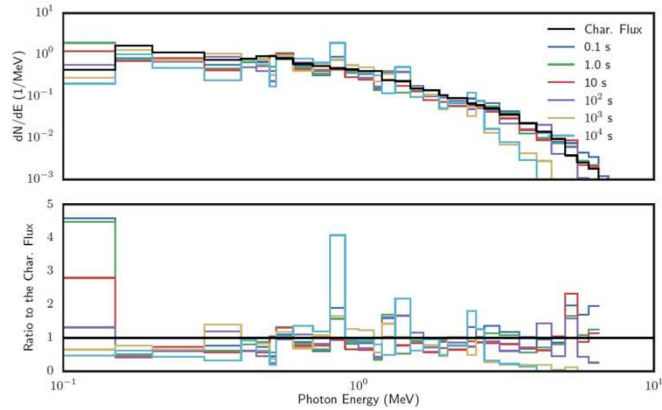


Depending on the n spectrum,

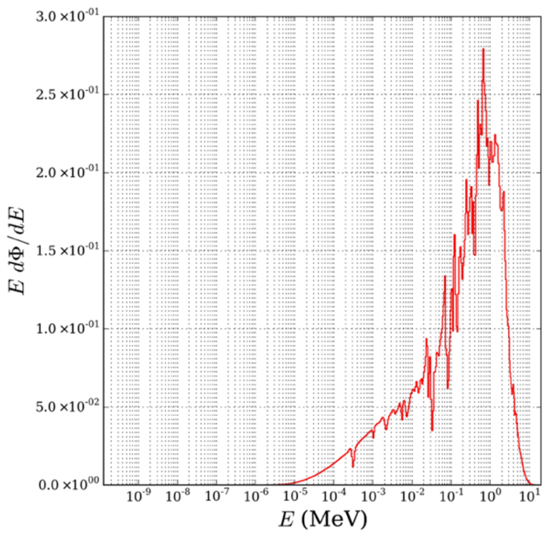


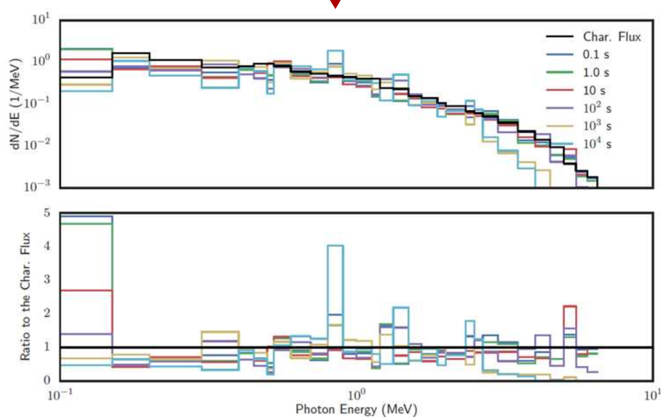
ACRR Characterization



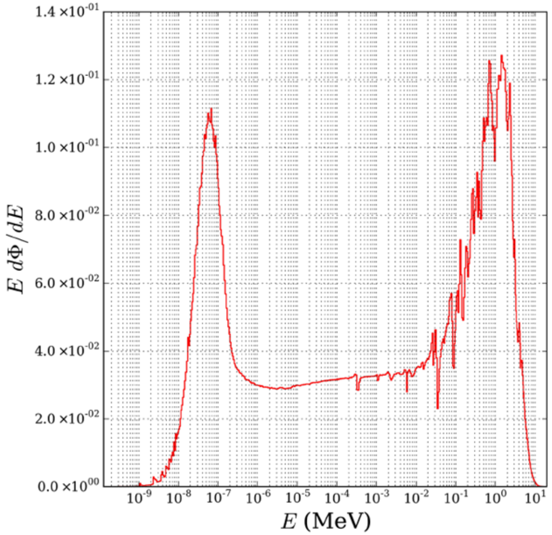


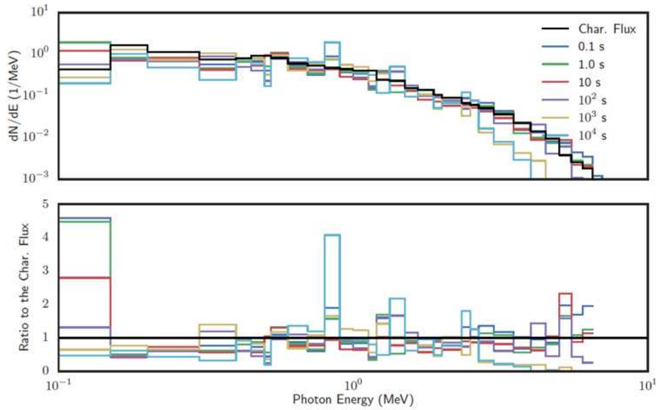
Depending on the n spectrum, average the delayed γ spectrum

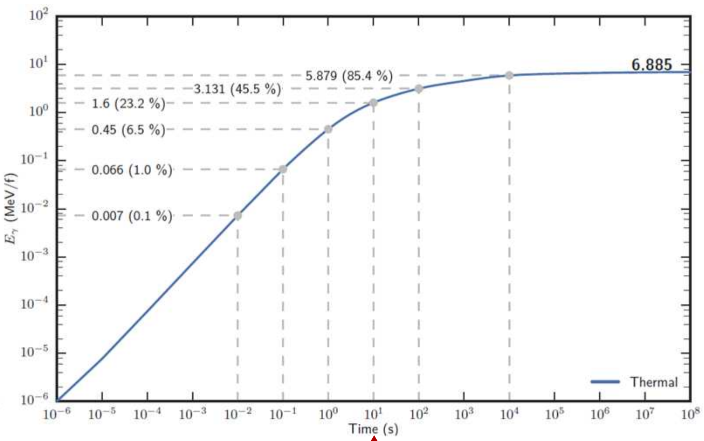




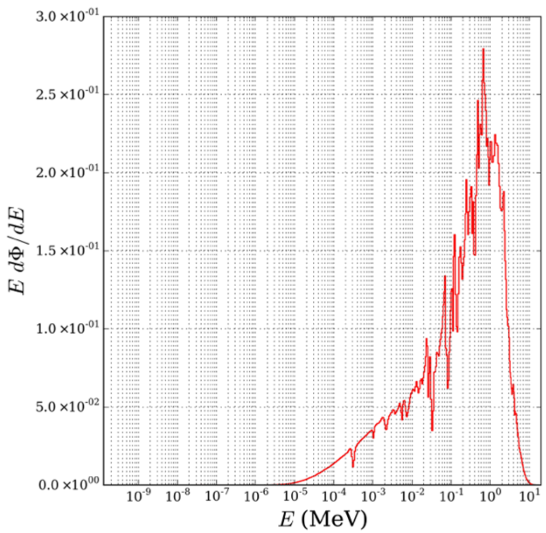
ACRR Characterization

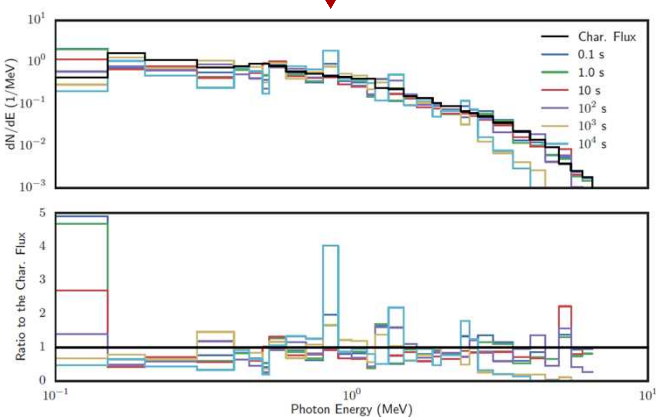


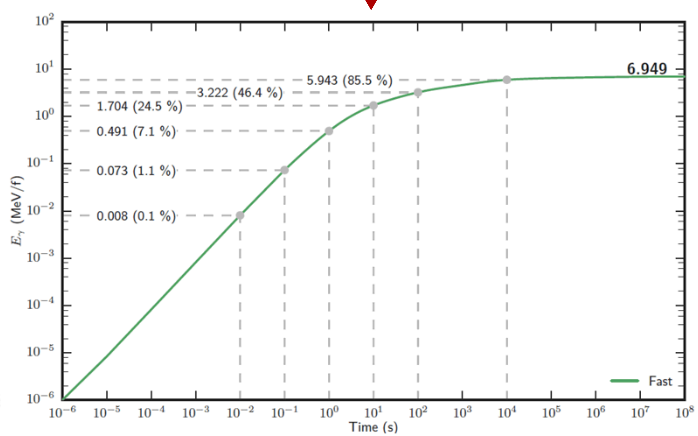




Depending on the n spectrum, average the delayed γ spectrum and the E_γ time profiles.







Questions?

Acknowledgments

Ed Parma

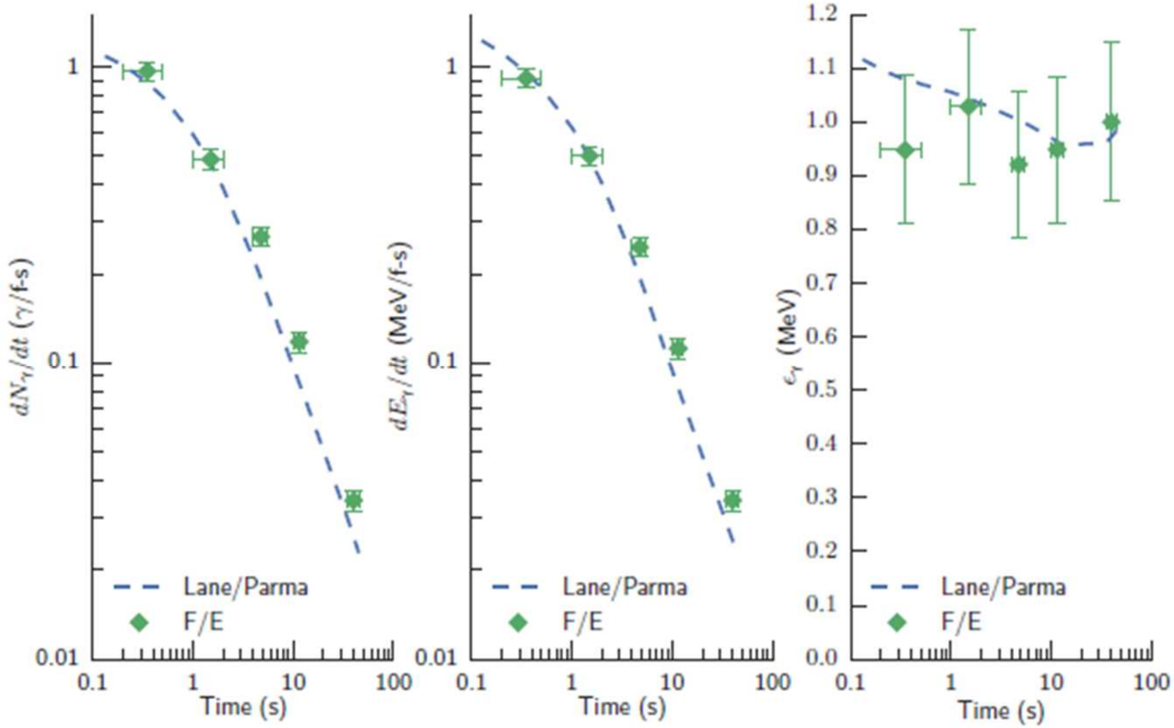
Ken Reil

Billy Martin

Russell Depriest

Rick Vega

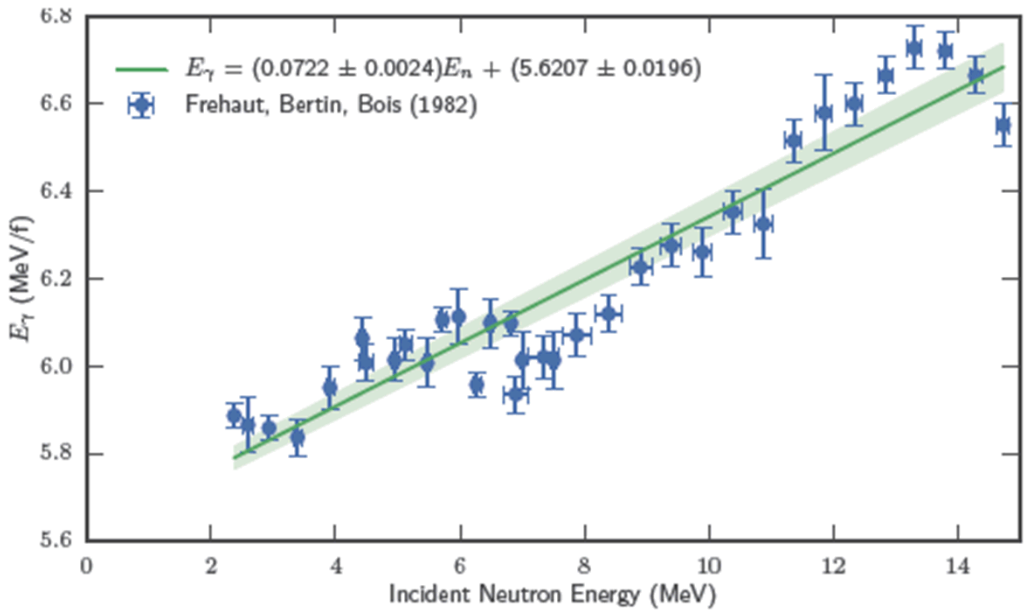
^{232}Th – Fisher and Engle Comparison



Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**F**	**0.001 – 30**	**0.2 – 45**	**4.46**	**4.50**	**0.98**
F/E		0.137 – 6.419	0.2 – 45	5.07 ± 0.71	5.04 ± 0.71	0.99 ± 0.15

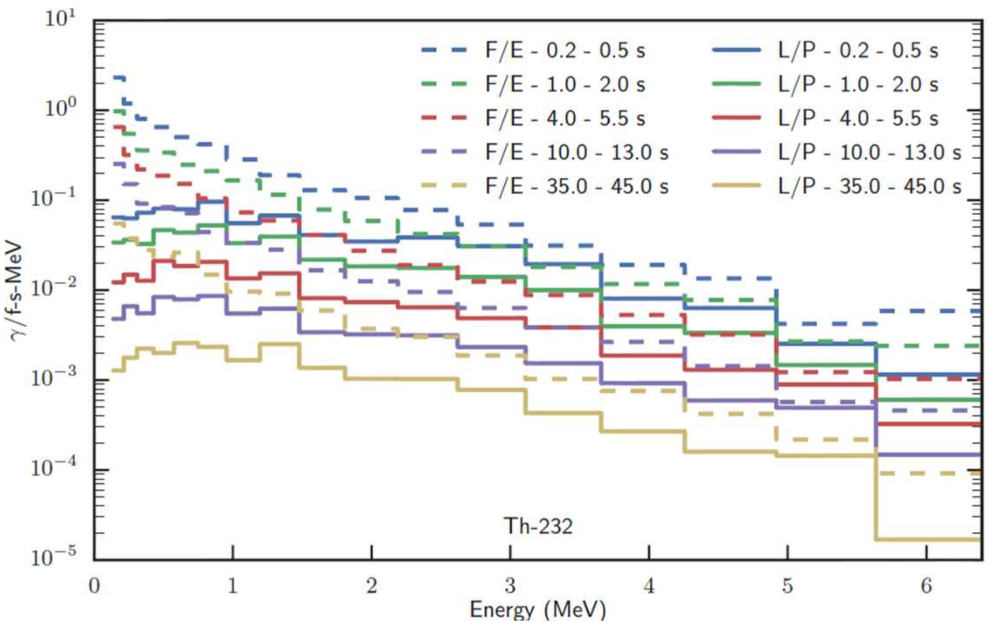
^{232}Th – Characteristic Summary

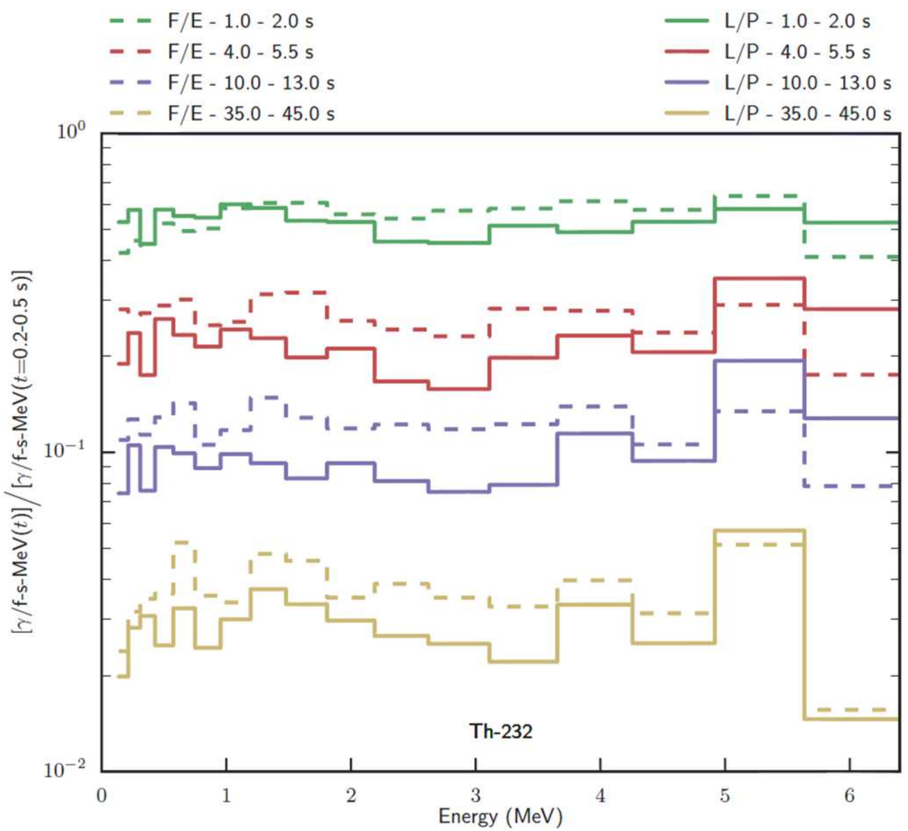
Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**T**	**0.001 – 30**	**10^{-6} – 10^{8}**	**10.38**	**8.88**	**0.86**
CINDER	**F**	**0.001 – 30**	**10^{-6} – 10^{8}**	**10.38**	**8.88**	**0.86**
CINDER	**HE**	**0.001 – 30**	**10^{-6} – 10^{8}**	**9.80**	**8.21**	**0.84**
Linear Model	2.53E-8				5.62 ± 0.02	
Linear Model	2				5.77 ± 0.02	
Linear Model	14				6.63 ± 0.05	
Hoffman and Hoffman				6.16	6.61	1.07
Sher					7.11 ± 0.90	
ENDF/B-VII.1					7.11 ± 0.90	



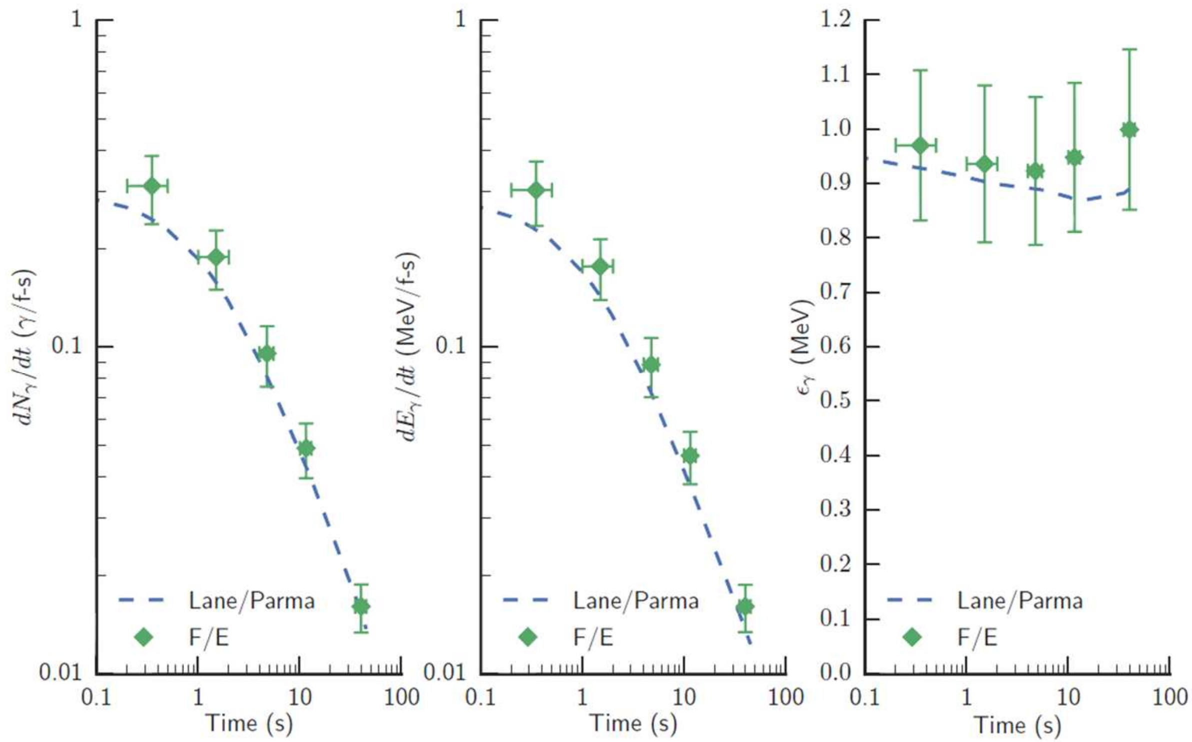
- The trend of the HE library lowering the N_γ and E_γ values disagrees with the Frehaut, Bertin, Bois data.

^{232}Th – Spectra Comparison





^{233}U – Fisher and Engle Comparison



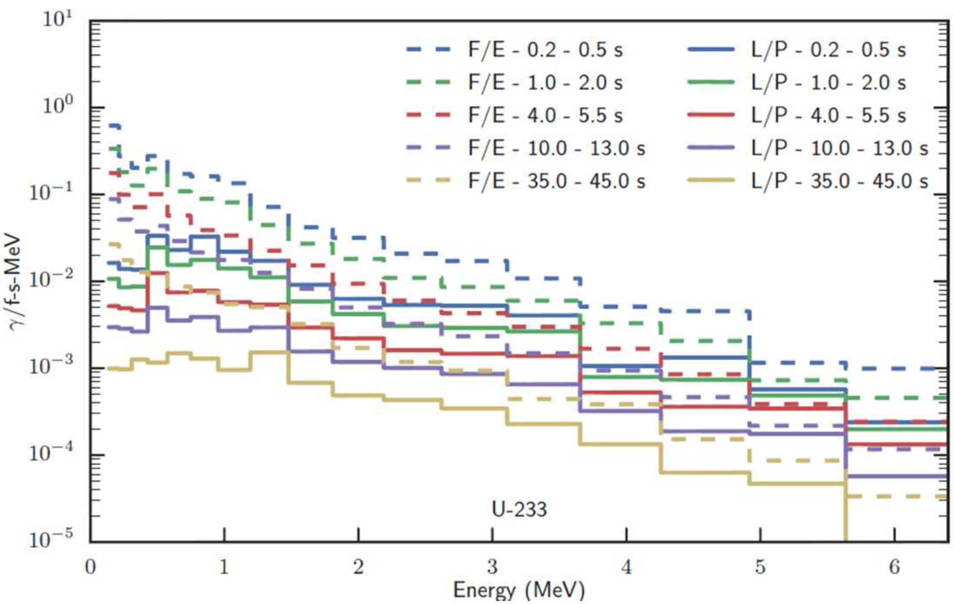
Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**F**	**0.001 – 30**	**0.2 – 45**	**2.45**	**2.01**	**0.71**
F/E		0.137 – 6.419	0.2 – 45	3.26 ± 0.82	2.86 ± 0.71	0.88 ± 0.13

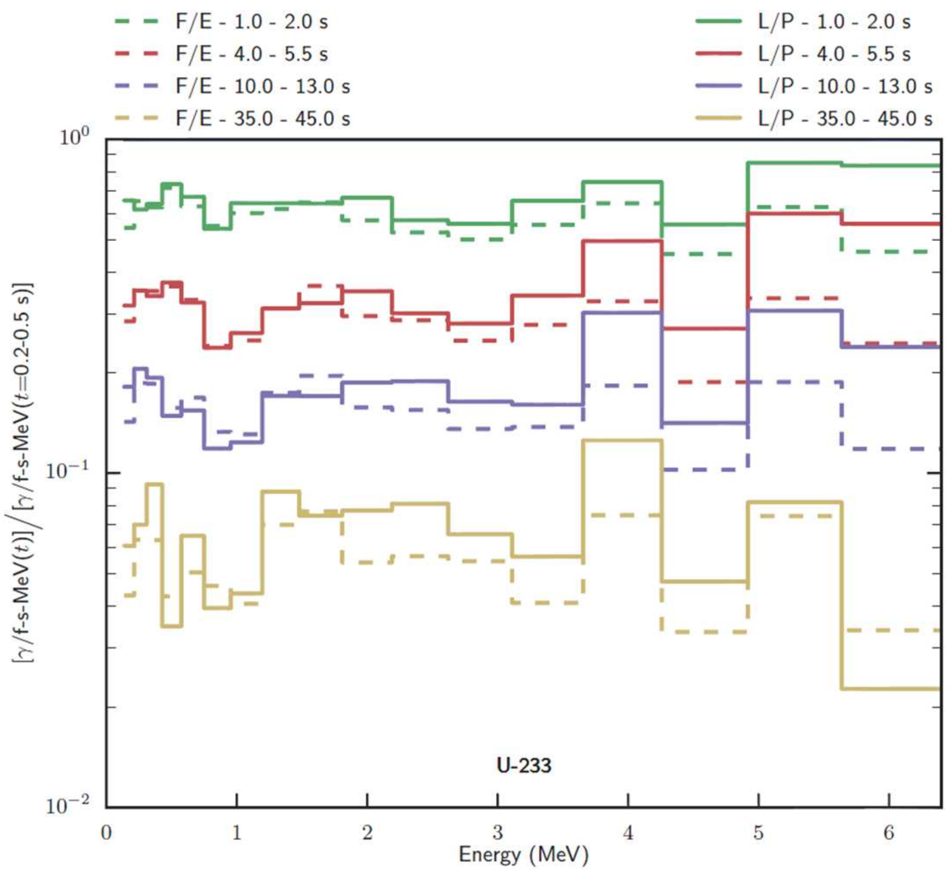
^{233}U – Characteristic Summary

Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**T**	**0.001 – 30**	**$10^{-6} - 10^{8}$**	**6.44**	**5.55**	**0.86**
CINDER	**F**	**0.001 – 30**	**$10^{-6} - 10^{8}$**	**6.47**	**5.58**	**0.86**
CINDER	**HE**	**0.001 – 30**	**$10^{-6} - 10^{8}$**	**5.98**	**5.15**	**0.86**
Pleasonton				6.31 ± 0.30	6.69 ± 0.30	1.06 ± 0.07
Hoffman and Hoffman				6.27	6.64	1.06
Sher					7.73 ± 0.52	
ENDF/B-VII.1		0.025 – 8.1		8.90 ± 0.60	7.72 ± 0.52	0.87
Jandel, *et al.*		> 0		6.76	7.24	1.08

- Most recent ENDF release (2011) still based on data from Sher (1981).
- Poor cross-section data likely culprit for E_γ underestimation.
- Two distinct ε_γ camps (0.86 and 1.06).

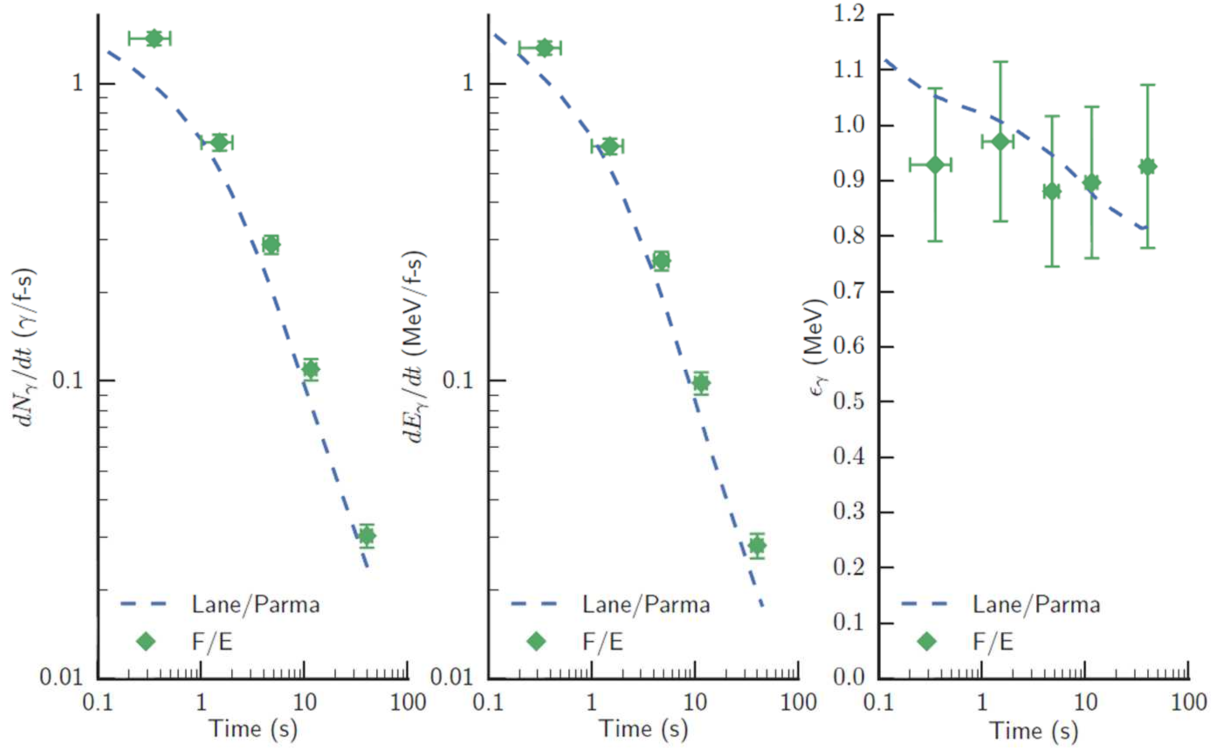
^{233}U – Spectra Comparison





^{238}U – Fisher and Engle Comparison

Sandia National Laboratories



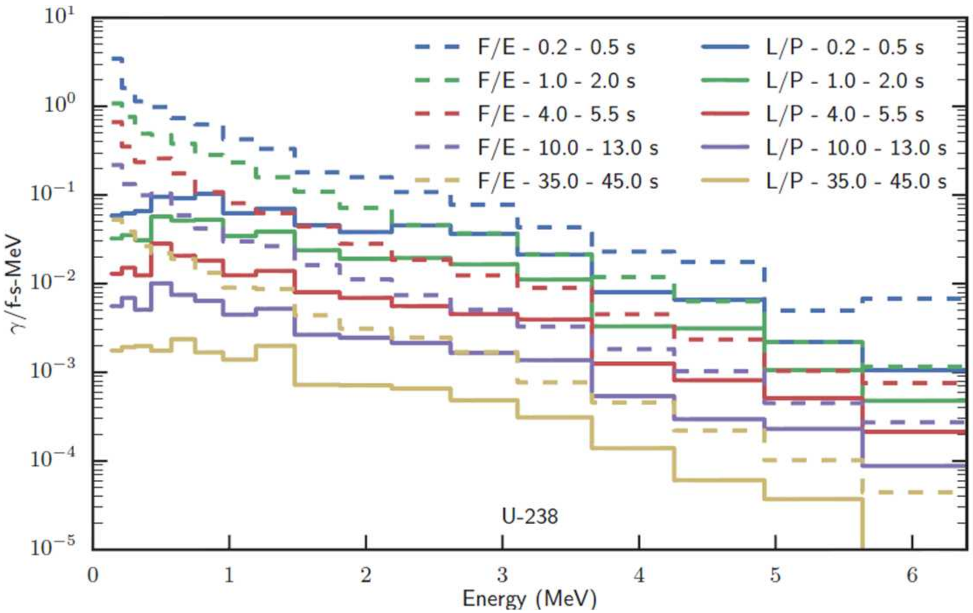
Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**F**	**0.001 – 30**	**0.2 – 45**	**4.62**	**4.37**	**0.82**
F/E		0.137 – 6.419	0.2 – 45	5.50 ± 0.77	5.08 ± 0.71	0.99 ± 0.15

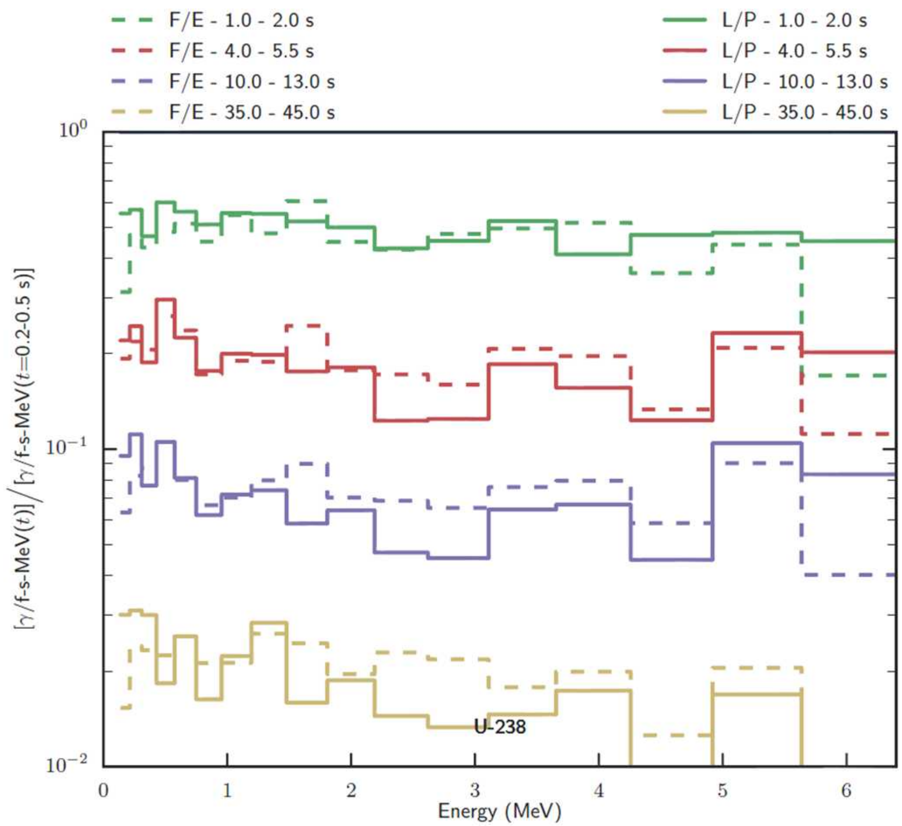
^{238}U – Characteristic Summary

Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**T**	**0.001 – 30**	**10^{-6} – 10^{8}**	**10.08**	**8.26**	**0.82**
CINDER	**F**	**0.001 – 30**	**10^{-6} – 10^{8}**	**10.08**	**8.26**	**0.82**
CINDER	**HE**	**0.001 – 30**	**10^{-6} – 10^{8}**	**9.05**	**7.30**	**0.81**
Hoffman and Hoffman				6.83	6.78	0.99
Sher					6.54 ± 0.53	
Madland	2				6.93	
Madland	14				8.41	
ENDF/B-VII.1	2	0.005 – 7.25		8.99 ± 0.71	6.97 ± 0.55	0.77
ENDF/B-VII.1	14	0.005 – 7.25		10.92 ± 0.92	8.41 ± 0.71	0.77
Litaize, *et al.*	1.8	0.10 – 4.0	< 10^{-8}	9.0	7.04	0.78

- The trend of the HE library lowering the N_γ and E_γ values, is not followed by Madland (and consequently ENDF).

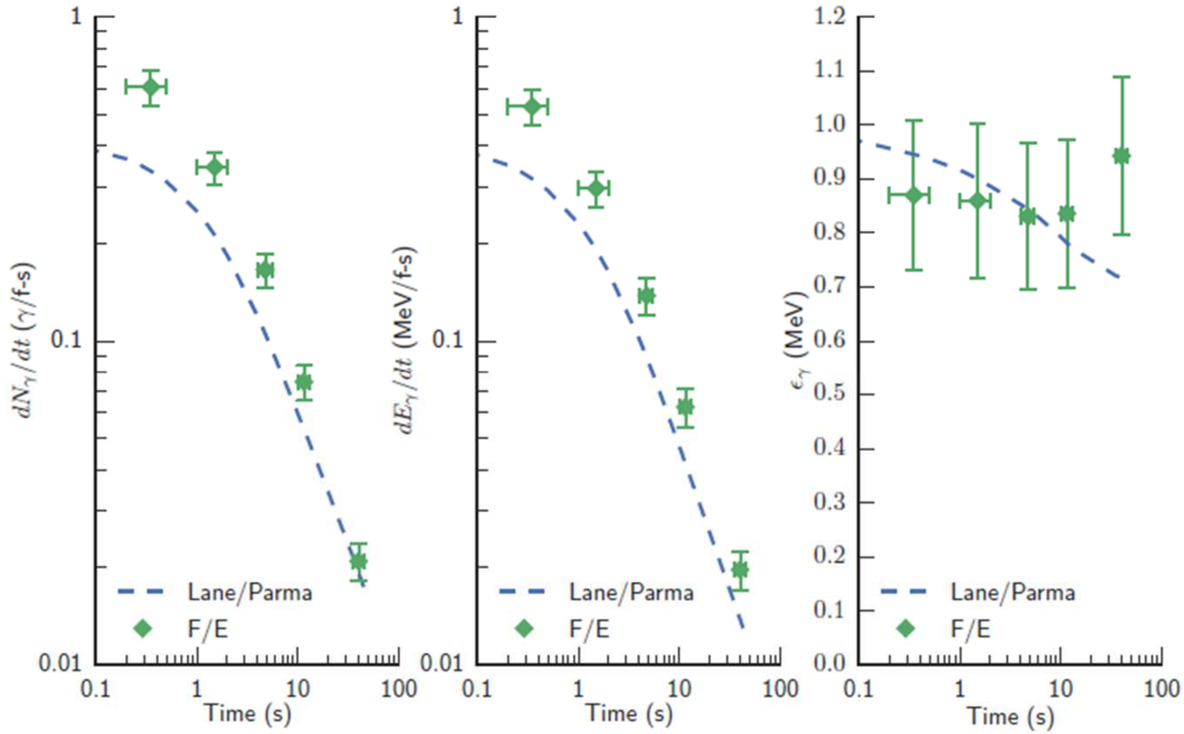
^{238}U – Spectra Comparison





^{239}Pu – Fisher and Engle Comparison

Sandia National Laboratories



Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**F**	**0.001 – 30**	**0.2 – 45**	**2.45**	**2.01**	**0.71**
F/E		0.137 – 6.419	0.2 – 45	3.26 ± 0.82	2.86 ± 0.71	0.88 ± 0.13

^{239}Pu – Characteristic Summary

Source	E_n (MeV)	ΔE (MeV)	Δt (s)	N_γ (γ/f)	E_γ (MeV/f)	ε_γ (MeV/γ)
CINDER	**T**	**0.001 – 30**	**10^{-6} – 10^{8}**	**7.31**	**6.66**	**0.91**
CINDER	**F**	**0.001 – 30**	**10^{-6} – 10^{8}**	**7.28**	**6.67**	**0.92**
CINDER	**HE**	**0.001 – 30**	**10^{-6} – 10^{8}**	**6.14**	**5.65**	**0.92**
Verbinski, *et al.*		0.14 – 10	< 10^{-8}	7.23 ± 0.30	6.81 ± 0.30	0.94 ± 0.01
Pleasonton				6.88 ± 0.35	6.73 ± 0.35	0.98 ± 0.07
Hoffman and Hoffman				6.94	6.81	0.98
Sher					7.76 ± 0.22	
Madland	2.53E-8				6.74 ± 0.02	
Madland	2				6.97 ± 0.02	
Madland	14				8.04 ± 0.04	
ENDF/B-VII.1	2.53E-8	0.025 – 8.1		7.75 ± 0.54	6.74 ± 0.47	0.87
ENDF/B-VII.1	2	0.025 – 8.1		8.01 ± 0.56	6.97 ± 0.49	0.87
ENDF/B-VII.1	14	0.025 – 8.1		9.24 ± 0.68	8.04 ± 0.59	0.87
Becker, *et al.*		> 0.14		8.62	7.67	0.89
Chyzh, *et al.*		0.15 – 9.5		7.50 ± 0.30	7.35 ± 1.09	0.98 ± 0.14
Ullmann, *et al.*		> 0.15		7.15 ± 0.09	7.46 ± 0.06	1.04 ± 0.02
Jandel, *et al.*		> 0		7.10	7.40	1.05
Serot, *et al.*		> 0.14		7.19	6.81	0.95
Stetcu, *et al.*		> 0.10		7.48	6.66	0.89

^{239}Pu – Spectra Comparison