Gamma-Ray Emission Spectra as a Constraint on Calculations of ^{234,236,238}U Neutron-Capture Cross Sections

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Capture cross-sections and spectra important

- Neutron capture cross sections in the "continuum" region >≈ 1 keV and gamma-emission spectra of importance to basic science and many applied fields
  - Defense
  - Nuclear security, safeguards, and forensics
  - Nuclear power
  - r- and s- process nucleosynthesis
- Careful measurements have been made on most common stable nuclides
- But must rely on calculations (or "surrogate" reactions) for rare or unstable nuclides
- Must benchmark calculations against measurements
  - Cross sections
  - Another observable: gamma-ray spectrum
  - $\langle \Gamma_\gamma \rangle$

Digression: Some theory background

Ultimate Goal: Calculate capture cross sections
(Especially true – unstable nuclides)

Capture cross section calculated by Hauser-Feshbach approximation;

$$\sigma_\gamma \approx \frac{T_{in}}{k^2}\pi W \frac{\sum_{Discrete} T_{out}(\varepsilon_\gamma) + \int_{E_{crit}}^{T_{neut}+Q} T_{out}(E-E_x)\rho(E_x)dE_x}{\sum T_{out}}$$

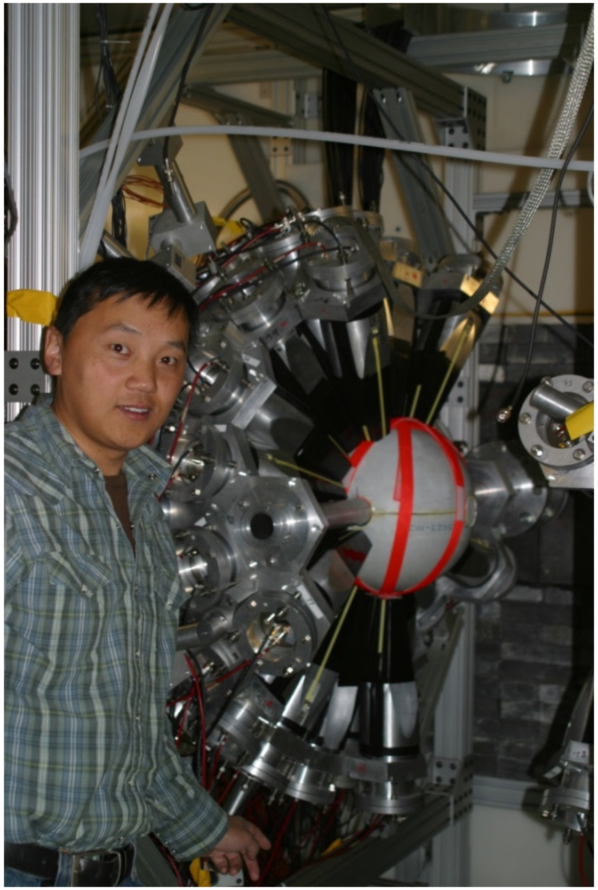
$$T_{XL}(\varepsilon_\gamma) = 2\pi\varepsilon_\gamma^{2L+1} f_{XL}(\varepsilon_\gamma)$$

Shape usually OK, magnitude often X2 to X10 error

Strength function normalized to measured average capture width $<\Gamma_\gamma>$
> Need to know $<\Gamma_\gamma>$!!

$$\frac{2\pi}{D_o}\langle\Gamma_\gamma\rangle = C\int_0^E d\varepsilon_\gamma (2\pi\varepsilon_\gamma^3) f_{E1}(\varepsilon_\gamma)\rho(E-\varepsilon_\gamma)$$

The DANCE array

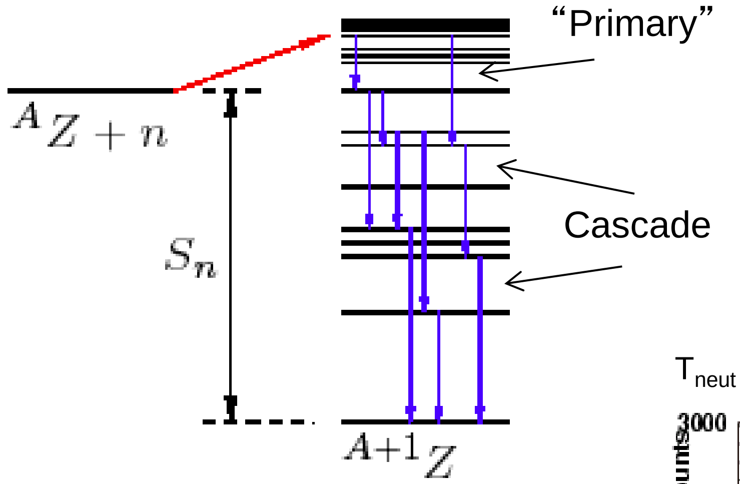


Half of DANCE array with ^{6}LiH ball

Detector for Advanced Neutron Capture Experiments

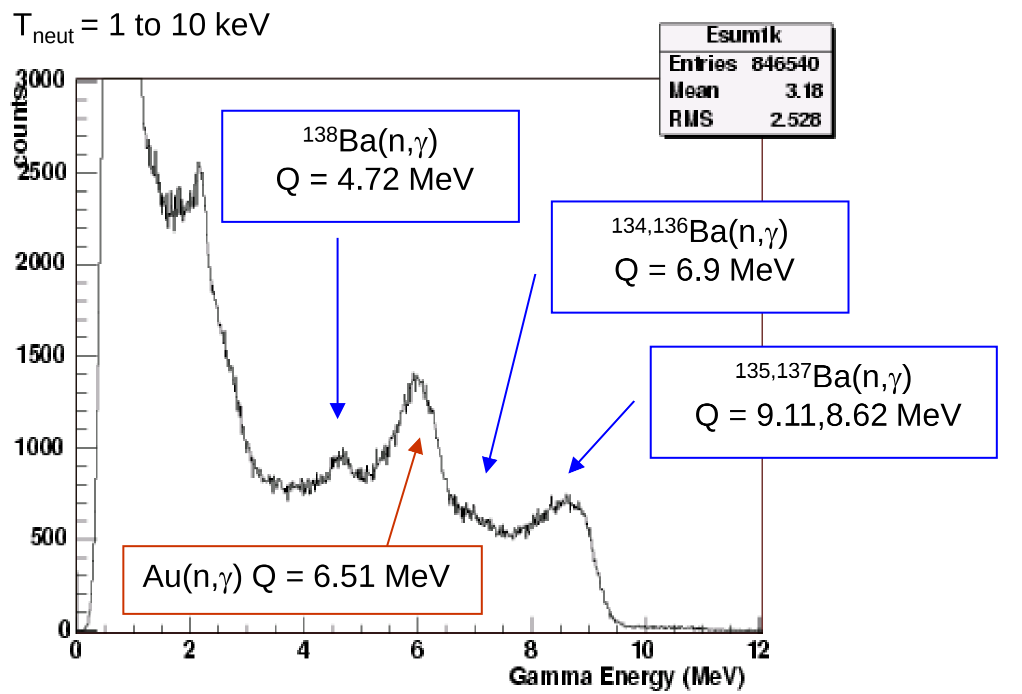
- 162 segments with 4 different shape crystals (160 segments with crystals)
- Calorimetric detector (nearly 4π) – detects full energy of decay cascade
- High efficiency and high neutron flux allows measurements on milligram samples
- Highly segmented to allow detection of radioactive targets
- Inner radius = 17 cm
- Crystal depth = 15 cm
- State-of-the-art fast transient digitizers for data acquisition – CAEN VX1730B
- ^{6}LiH inner sphere to absorb scattered neutrons

Neutron Capture



Detect ALL gammas-

- Summed energy is Q value (Sn) + neutron cm T
- $E_x = T_n(1+M_n/M_A)+Q$



Neutron Flux Measurement

3 Neutron Monitors

^{6}Li(n,αt) 22.60 m

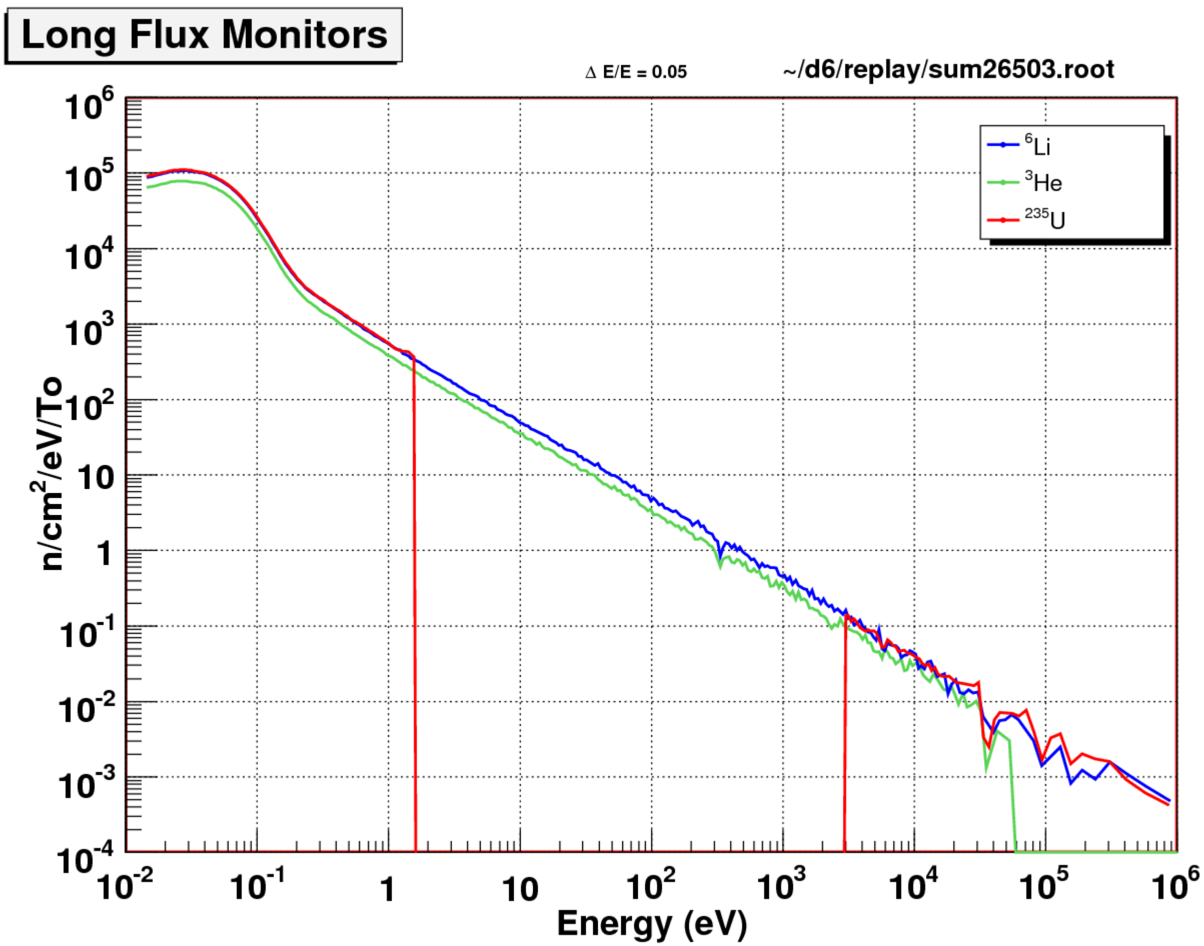
^{10}B(n,α) 22.76 m

^{235}U(n,f) 22.82 m

Flux from ^{6}Li:
~547 $E^{-1.04}$
n/cm^{2}/eV/To
(at monitor)
I = 100 μA
(5-Aug-10)

Monitors are 2 m downstream of target

- Attenuation by target
- Geometric solid angle
- Targets often < beam



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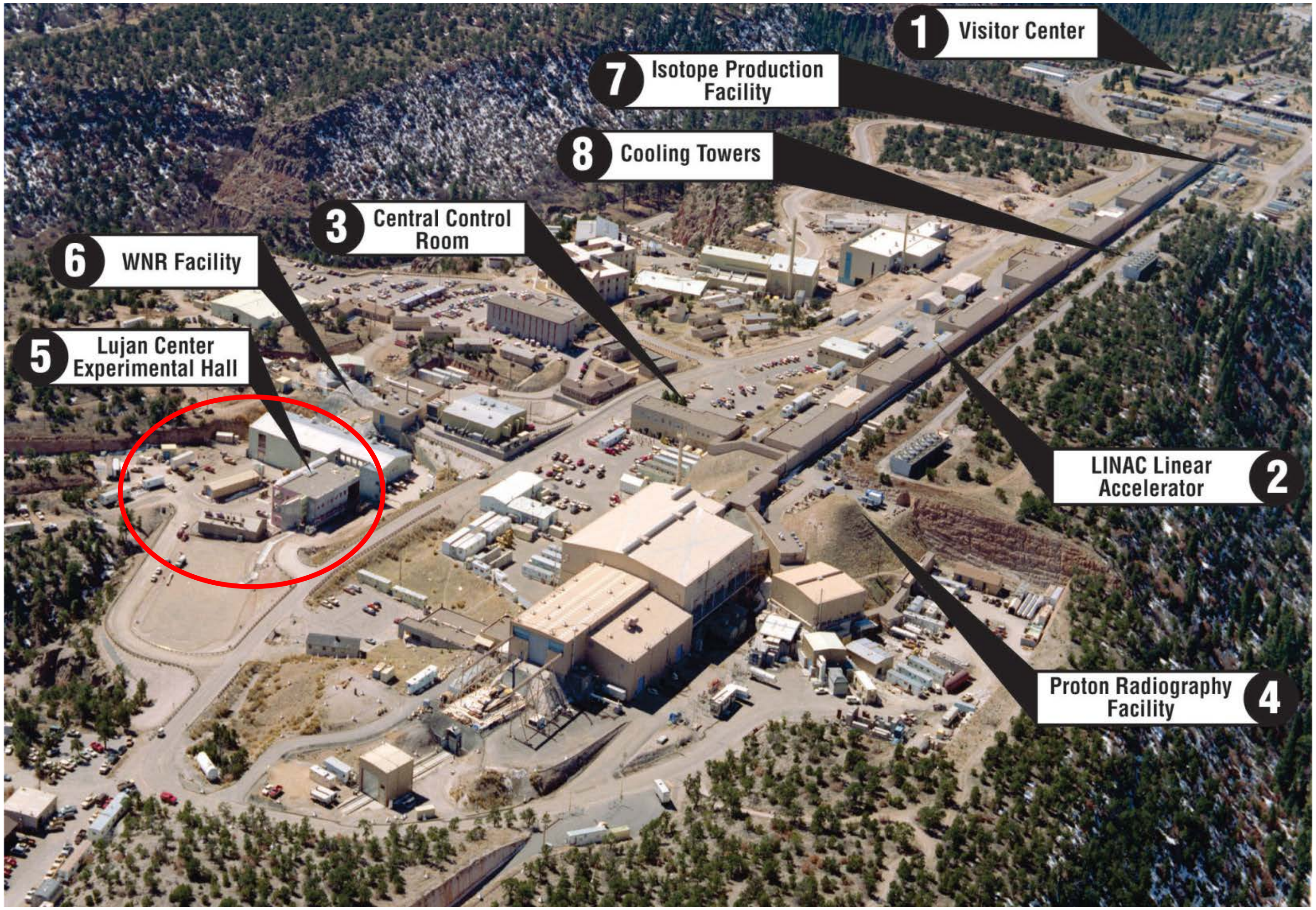


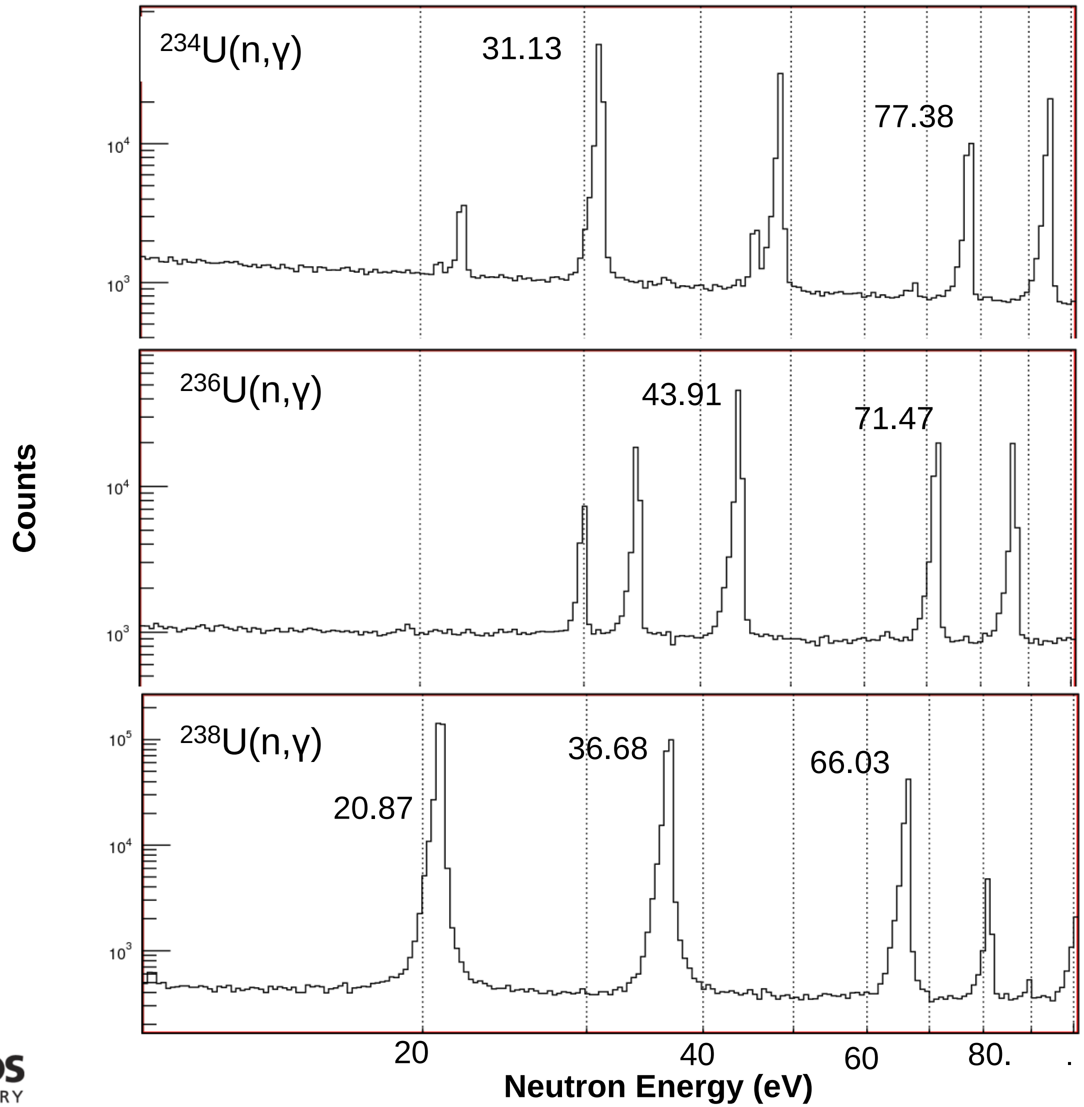
Summary – measurements on $^{234,236,238}U(n,\gamma)$

- Gamma-ray spectrum measurements from resolved resonances made with 1 -2 mg/cm^2 thick targets
- Cross sections > 1 keV measured using thicker targets

Uranium Measurements

Isotope	234	236	238
Q window (MeV)	5.30 ± 0.50	5.13 ± 0.50	4.81± 0.65
γ-spectrum target	1.0 mg/cm^2	1.29 mg/cm^2	2.27 mg/cm^2
σ target	(2015)	2014 – Analysis In progress	48 mg/cm^2 PRC 89,034603

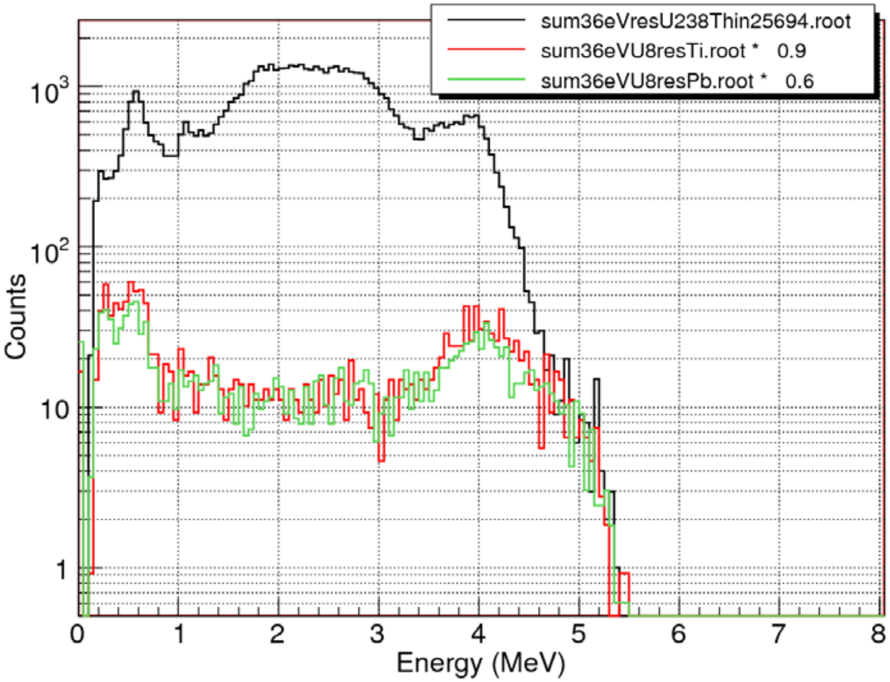
Uranium s-wave resonances



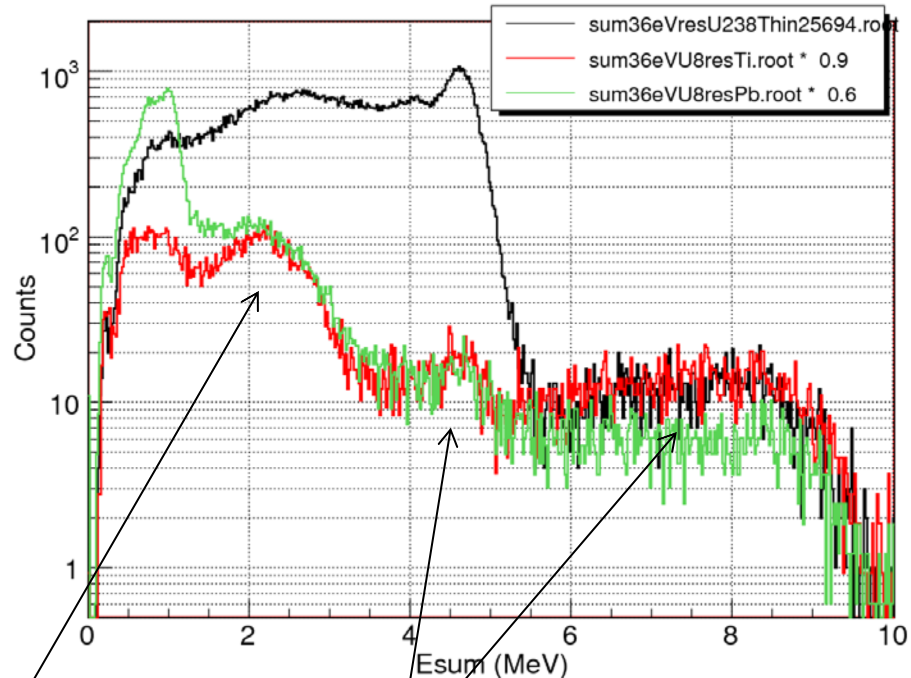
$\ell=0 \quad \frac{1}{2}^+$

^{238}U Background subtraction – 36 eV resonance (M=2)

$E_{cluster}$ (gated by Q,T_{neut})



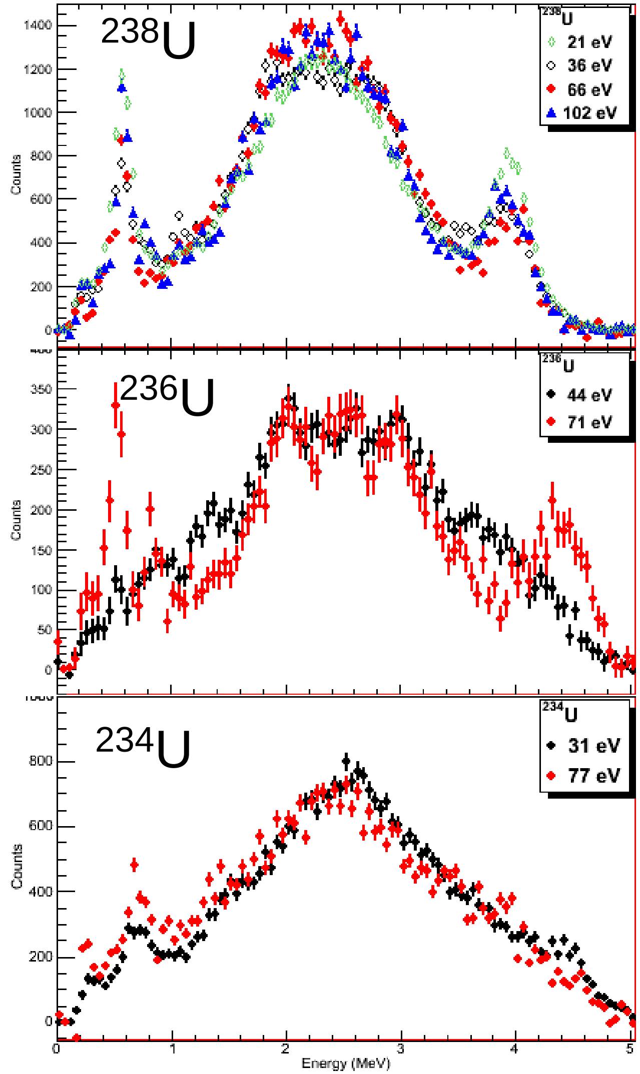
Esum (gated by T_{neut})



Principal Backgrounds

- β⁻ decay ^{226}Ra chain
  - ^{214}Bi Q=3.27 MeV
  - ^{214}Pb Q=1.03 MeV
- Ba(n,γ)
  - Scattered neutrons
  - ^{138}Ba Q=4.72 MeV

Multiplicity = 2 Gamma ray spectra



Calculate capture gamma-ray spectrum

Formula for spectrum – Monte Carlo DICEBOX algorithm

Level density – Constant Temperature

Parameters from von Egidy and Bucurescu Phys Rev C 72, 044311 (2005)

Radiative strength function – Simplest model is E1 only

- Parameters usually taken from (Υ,n)
- Q value (Sn) ≈ 4.81 MeV (^{238}U)
- What is function between GS and Sn?
- Different models – (Kopecky and Uhl, Phys Rev C**41**, 1941 (1990))
- Use "Modified Generalized Lorentzian" (MGLO)

Kroll, Phys. Rev. C**88**, 034317 (2013)

$$f(\varepsilon_\gamma) = \frac{\sigma_r \Gamma_r}{3\pi^2(\hbar c)^2}\left[\frac{\varepsilon_\gamma \Gamma_\gamma(\varepsilon_\gamma, T)}{(\varepsilon_\gamma^2 - \varepsilon_r^2)^2 + \varepsilon_\gamma^2 \Gamma_\gamma^2(\varepsilon_\gamma, T)} + \frac{(0.7)4\pi^2\ \Gamma_r T^2}{\varepsilon_r^5}\right]$$

Calculate capture gamma-ray spectrum

Nucleus rich in different collective modes of vibration

M1 Scissors

M1 Gamow-Teller

E1 Pygmy

Usually parameterized as "Standard Lorentzian" (SLO)

$$f(\varepsilon_\gamma) = \frac{1}{3\pi^2(\hbar c)^2} \frac{\sigma_r \varepsilon_\gamma \Gamma_r^2}{(\varepsilon_\gamma^2 - \varepsilon_r^2)^2 + \varepsilon_\gamma^2 \Gamma_r^2}$$

- Lots of work to characterize these modes using different probes
  Probes have varying sensitivity
- Parameters determined by "Oslo Method" appear to provide consistent description of neutron capture (MK)
- Comparing results from different probes leads to question:
  "Is there a universal strength function?"

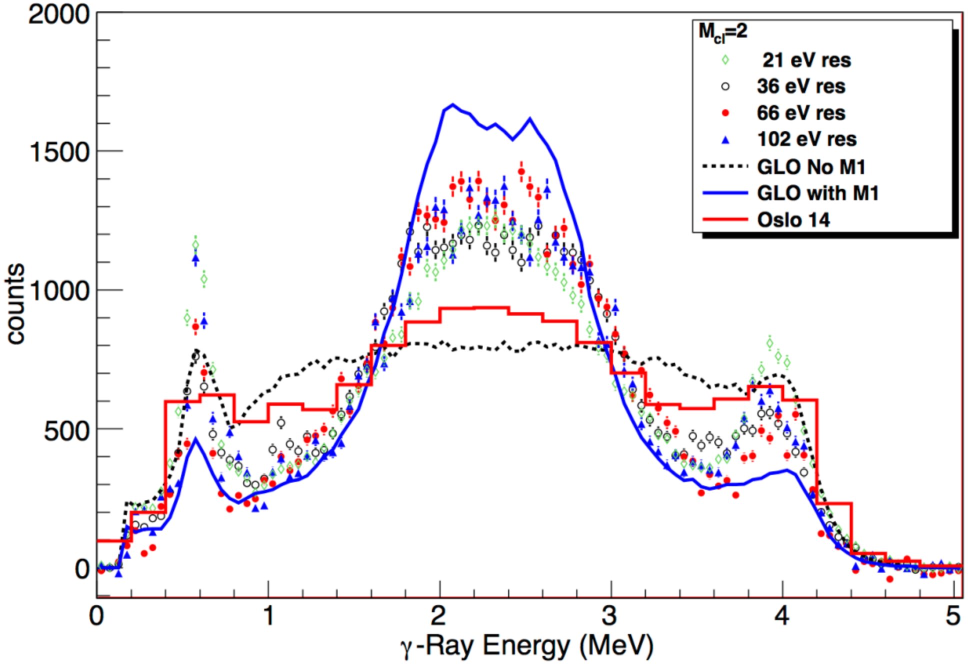
Gamma spectrum provides constraint on RSF

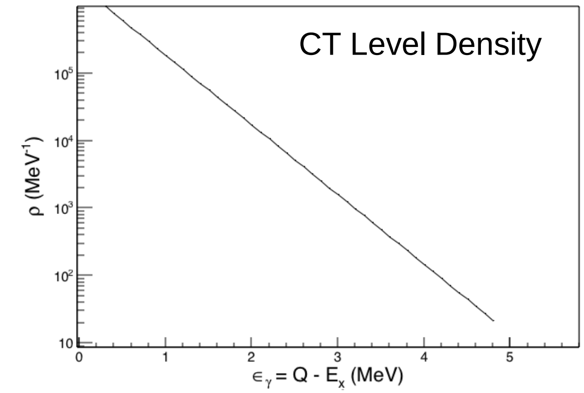
Test radiative strength function by "Spectrum Fitting Method"

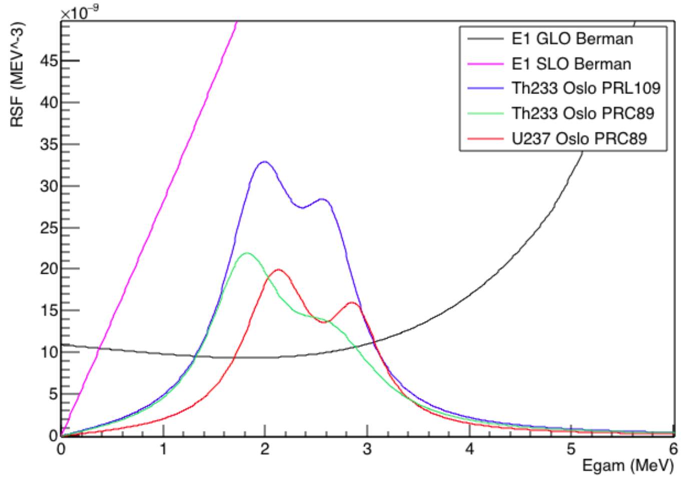
- Assume form of Radiative Strength Function
- Generate gamma cascades using Monte Carlo
  - DICEBOX (F. Bečvář, NIM A **417**, **434** (1998).)
  - Uses level density above E_{crit} (~ 0.5 MeV)
  - Tabulated level information below E_{crit}
- Process cascades through GEANT4 model of DANCE
  - Use formulation of Jandel
    (M. Jandel, et al., NIM B **261**, 1117 (2007).)
  - Based on original model by Reifarth and Heil
    (M. Heil, R. Reifarth, et al., NIM A **459**, **229**(2001).)
- Compare to observed gamma-ray spectra – qualitative!!
  - Consider low-lying resolved resonances and gate on Q-value (summed energy) spectrum to reduce backgrounds
  - Background subtraction still needed

^{238}U Capture Results – M_{cl} = 2

^{238}U(n,ϒ) M_{cl}=2 Spectrum

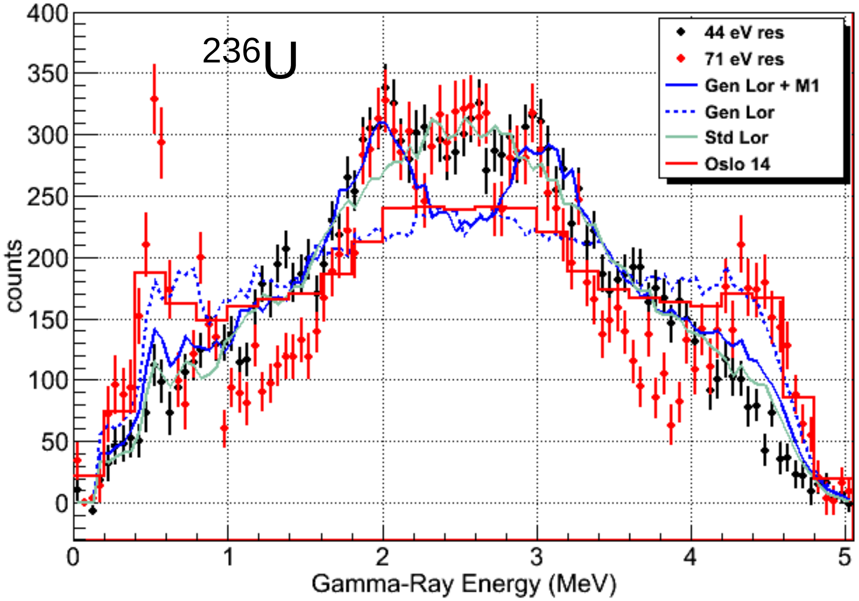


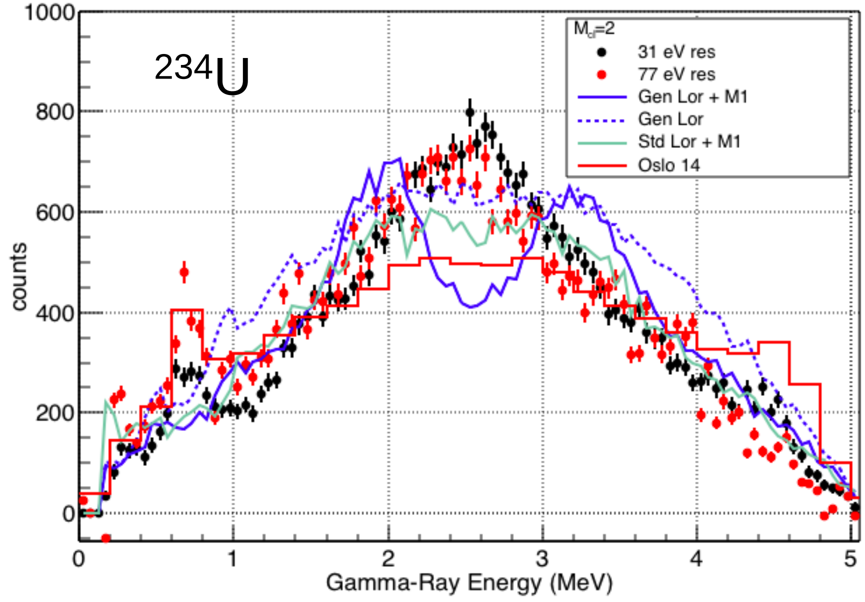


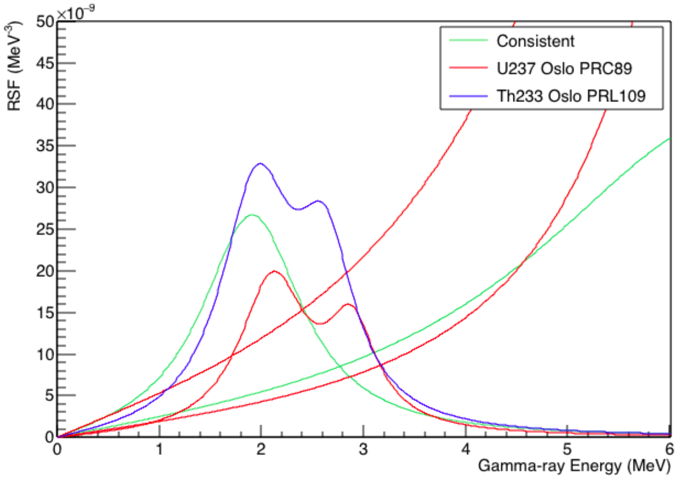


	E1	σ1	Γ1	E2	σ2	Γ2
GDR Berman (RIPL-3)	11.28	325.0	2.48	13.73	384.0	4.25
M1 Scissors Oslo PRL 109 (^{233}Th)	2.00	0.65	0.85	2.65	0.60	0.70
M! Scissors Oslo PRC 89 (^{237}U)	2.15	0.45	0.80	2.90	0.40	0.60
M! Spin Oslo PRC 89 (^{237}U)	6.61	7.00	4.00			
E1 Pygmy Oslo PRC 89 (^{237}U)	7.30	15.00	2.00			

M_{cl} =2 Gamma-ray spectra Calculations



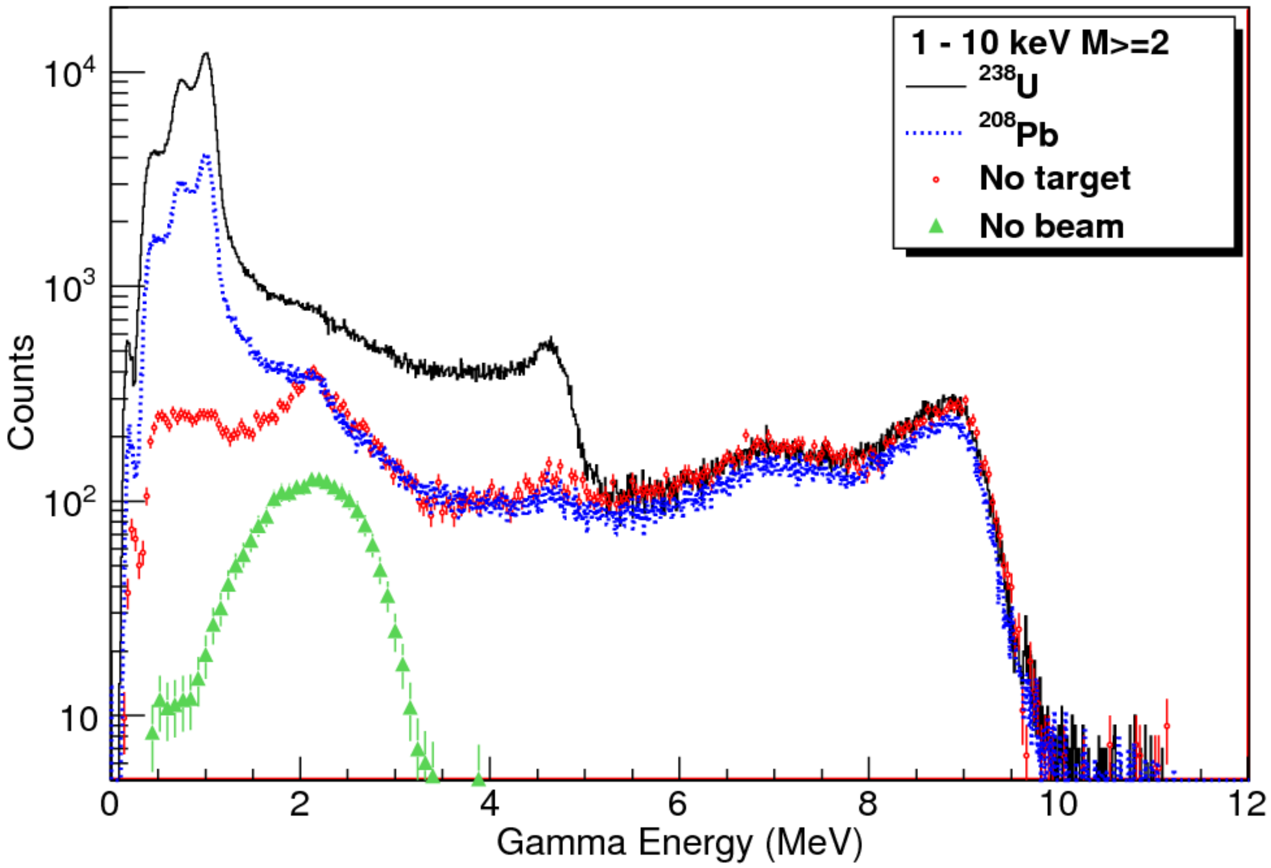




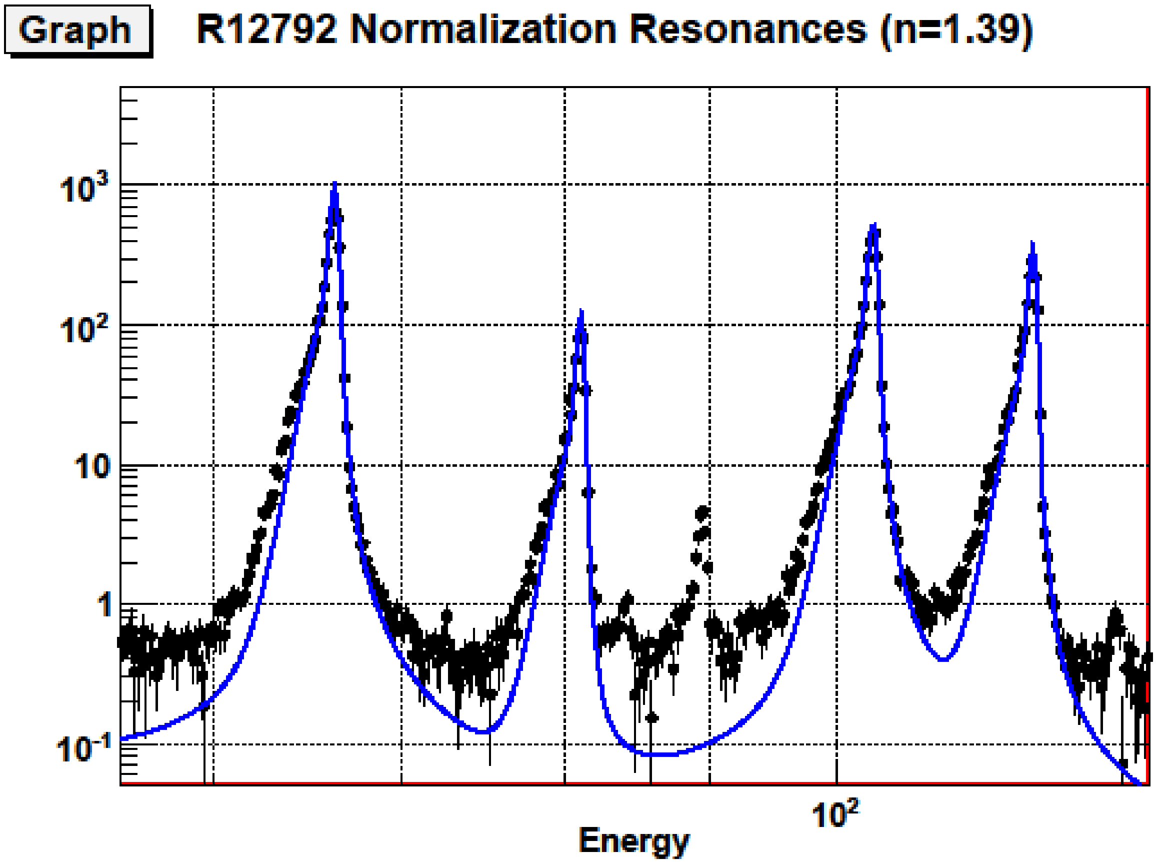
	E1	σ1	Γ1
"Consistent" M1 Scissors	2	0.60	4.7
"Consistent" M1 GT	7	3.00	4.7

+ SLO E1 GDR

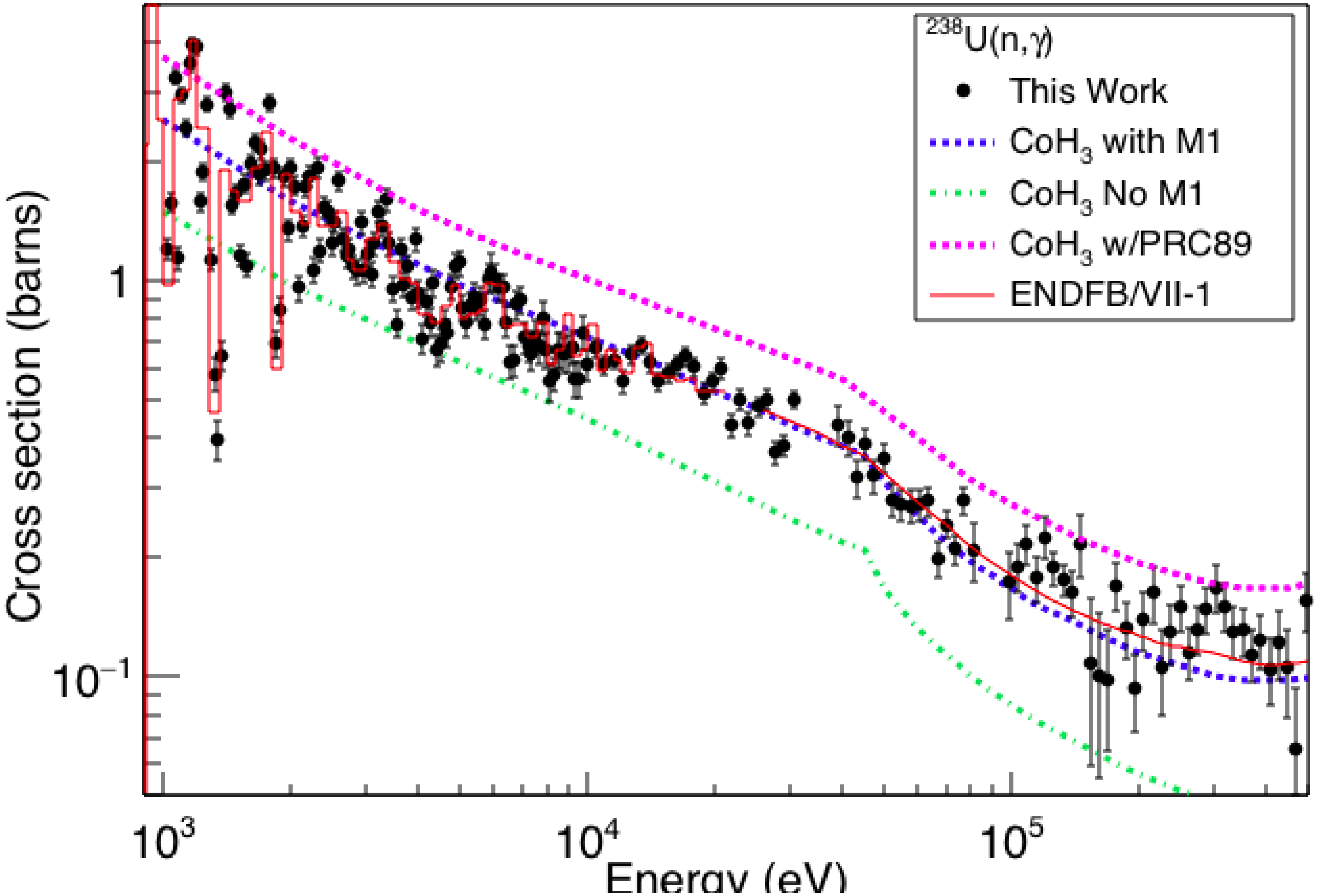
Background subtraction – 1 – 10 KeV



Normalize to weak resonances

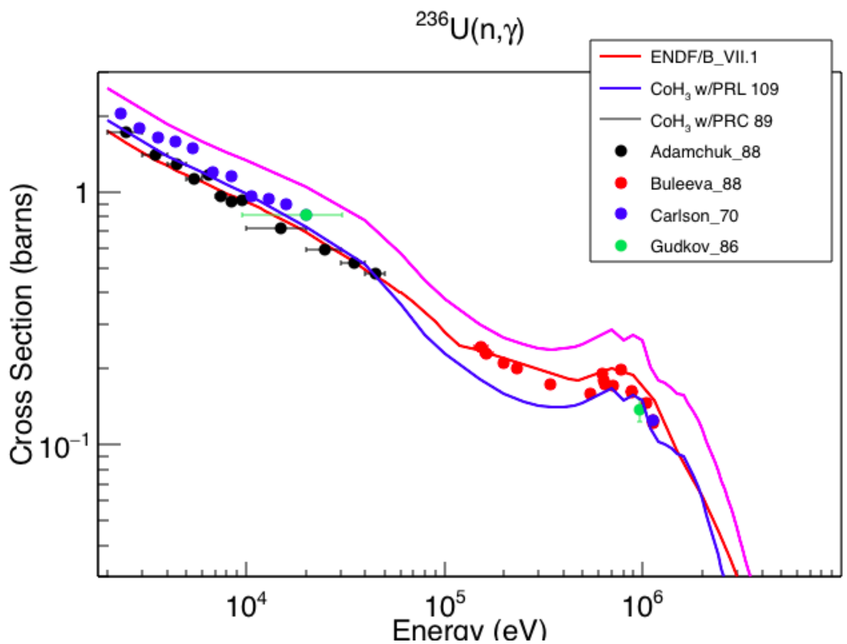


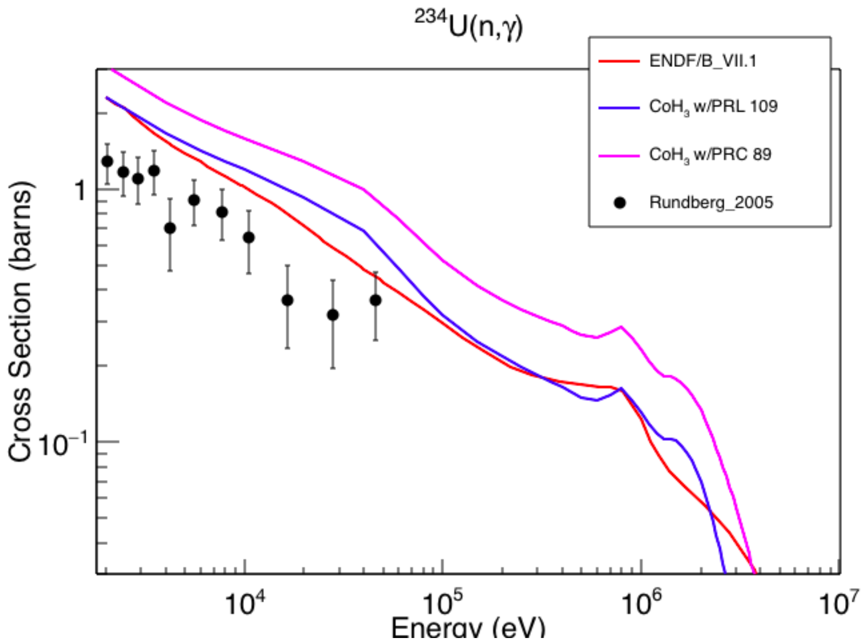
Cross Sections



J.L.U. et al, Phys. Rev. *C* **89**, 034603 (2014)

Cross Sections





Results

- Shape of capture cross section vs neutron energy is not sensitive to form of strength function (although magnitude is)
- Generalized Lorentzian E1 strength function is not sufficient to describe shape of observed gamma-ray spectra
- MGLO + "Oslo M1" parameters produces quantitative agreement with measured $^{238}U(n,\gamma)$ cross section.
- Additional strength at low energies (~ 3 MeV) – likely M1- is required (See also Guerrero (nTOF): Jour. Korean Phys. Soc. **59**, 1510 (2011) (ND2010))
- Careful study of complementary results on low-lying giant resonance strength is needed to consistently describe observations
  - Kwan – NRF (E. Kwan, et al., Phys. Rev. C **83**, 041601(R)(2011))
  - M1 – (Heyde, Rev. Mod. Phys. **82**, 2365, 2010)
  - Pygmy E1 dipole

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