Recent developments in neutron capture on actinides using the DANCE detector

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Other DANCER's

B. Baramsai, T.A. Bredeweg, A.J. Couture, R.C. Haight, M. Jandel, T. Kawano, A.L. Keksis, S. Mosby, J.M. O'Donnell, R.S. Rundberg, G. Rusev, D.J. Vieira, C. Walker, J.B. Wilhelmy

Los Alamos National Laboratory

C.-Y. Wu, J.A. Becker

Lawrence Livermore National Laboratory

A. Chyzh, G.E. Mitchell

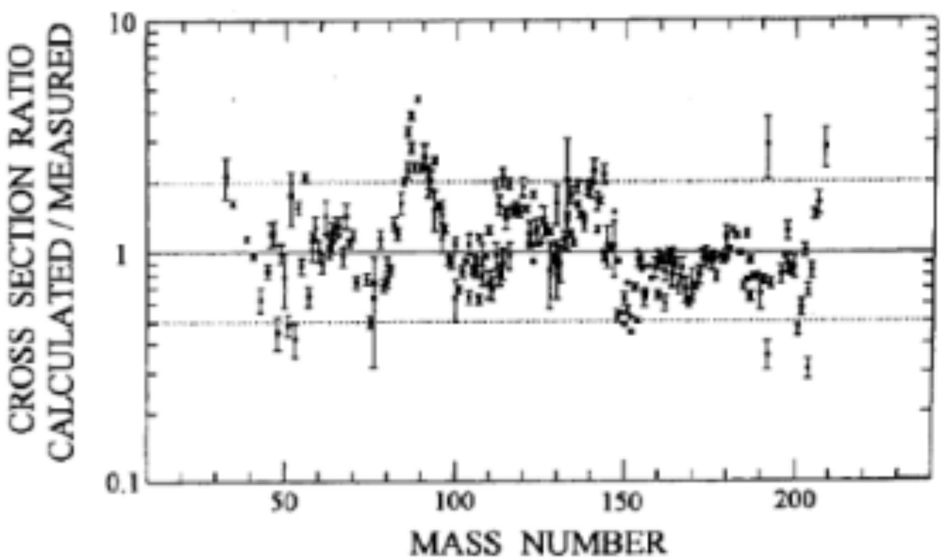
North Carolina State University

M. Krticka

Charles University, Prague

Capture cross-sections and spectra important

- Neutron capture cross sections and gamma-emission spectra of importance to basic science and many applied fields

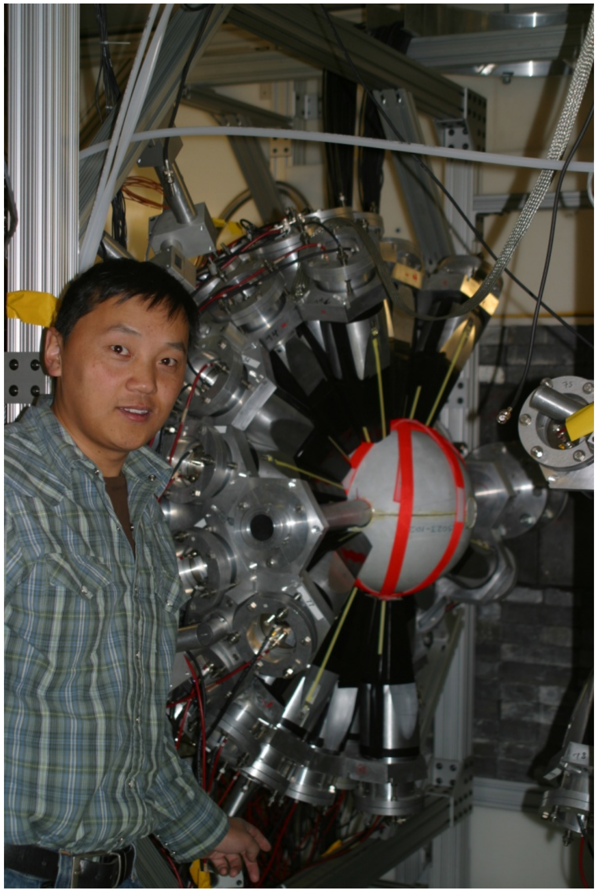


Stellar capture cross sections calculated with the statistical model code NON-SMOKER compared with available experimental data.

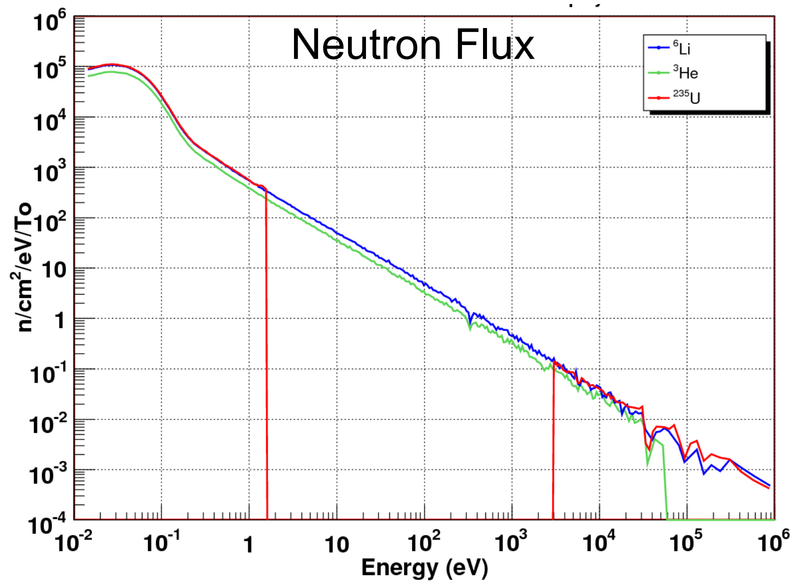
(From Rauscher and Thielemann, *Atomic and Nuclear Astrophysics*, IOP, 1998)

- Capture cross sections difficult to calculate, rely on measurements
- Careful measurements have been made on most common stable nuclides
- Must rely on calculations for rare or unstable nuclides
- Benchmark calculations against measurements
  - Cross sections
  - Gamma-ray spectrum

Detector for Advanced Neutron Capture Experiments



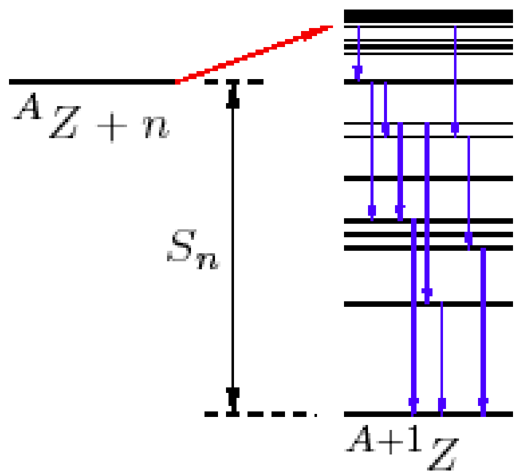
- Nearly 4π coverage (≈3.5π)
- 160 BaF_2 crystals - 4 different shapes
- High efficiency - milligram samples
- Highly segmented - radioactive targets
- ^{6}LiH inner sphere to absorb scattered neutrons
- 20.25 m from water moderator
- LANSCE spallation source – 800 MeV p @ 100 μA

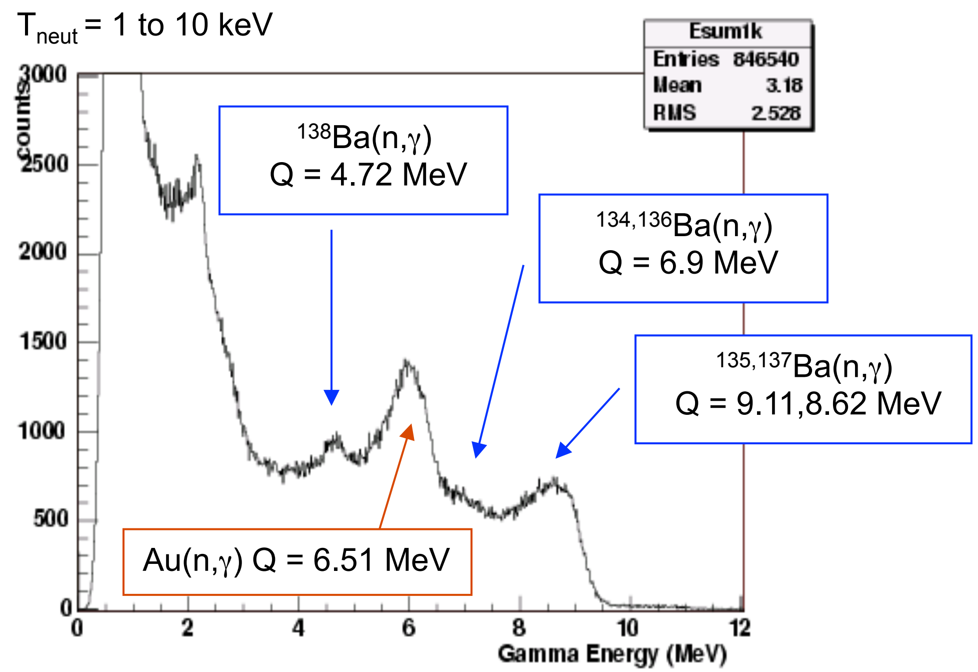


$\Phi = 550E^{-1.04}$ n/cm^2/eV/To at 22.6 m

DANCE Calorimeter

- Calorimetric => Summed Gamma Energy ≈ Q value (S_n)
- Permits ID of target!
- $E_x = T_n(1+M_n/M_A)+Q$





Calculations – some formula's

Hauser-Feshbach

$$\sigma_{capt}(E_n) = \frac{\pi}{k_n^2} \sum_{J\Pi} g_c \frac{T_n T_\gamma}{T_n + T_\gamma} W_{n\gamma},$$

Gamma transmission coefficient

$$T_\gamma = \sum_{j^\pi XL} \int_0^{E'} 2\pi E_\gamma^{(2L+1)} f_{XL}(E_\gamma) \rho(E_x, j^\pi)\, dE_x$$

Normalized γ transmission (s-wave)

$$T_\gamma = 2\pi \frac{\langle \Gamma_\gamma \rangle}{D_0}.$$

DICEBOX

$$\Gamma_{ab} = \sum_{XL} y_{XL}^2 [E_a - E_b]^{2L+1} \frac{f_{XL}(E_a - E_b)}{\rho(E_a, J_a^\pi)}$$

$^{238}U(n,\gamma)$ Spectrum Simulations

Kopecky and Uhl
(Phys. Rev. C **41**, 1941 (1990))
f = GLO + SLO(SF) + SLO(E2)

SLO (Standard Lorentzian)

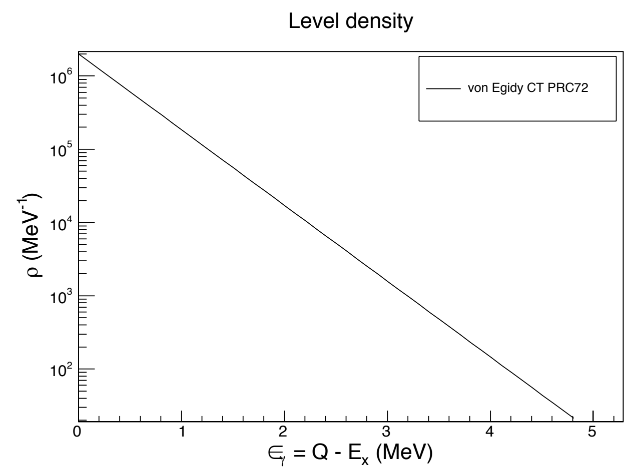
$$f^{SLO}(\varepsilon_\gamma) = \frac{1}{3\pi^2(\hbar c)^2} \frac{\sigma_R \varepsilon_\gamma \Gamma_R^2}{(\varepsilon_\gamma^2 - E_R^2)^2 + \varepsilon_\gamma^2 \Gamma_R^2}$$

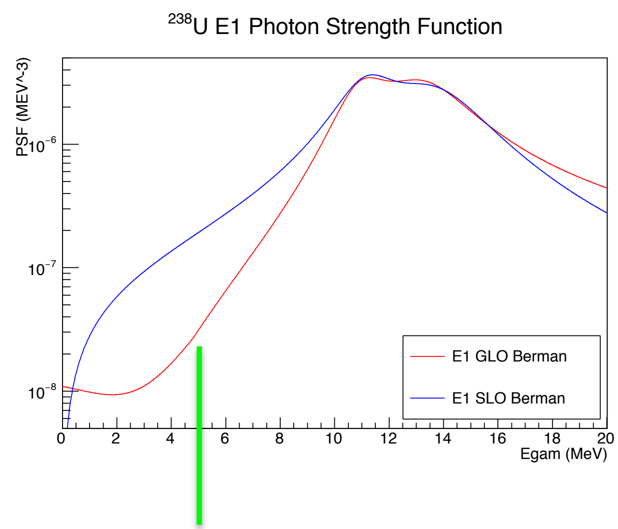
GLO (Generalized Lorentzian)

$$f^{GLO}(\varepsilon_\gamma) =$$

$$\frac{\sigma_R \Gamma_R}{3\pi^2(\hbar c)^2} \left[\frac{\varepsilon_\gamma \Gamma_K(\varepsilon_\gamma, T)}{(\varepsilon_\gamma^2 - E_R^2)^2 + \varepsilon_\gamma^2 \Gamma_K^2(\varepsilon_\gamma, T)} + 0.7 \frac{\Gamma_K(0,T)}{E_R^3} \right]$$

$$\Gamma_K(\varepsilon_\gamma, T) = (\varepsilon_\gamma^2 + 4\pi^2 T^2) \frac{\Gamma_R}{E_R^2} \qquad T = \sqrt{\frac{S_n - \varepsilon_\gamma}{a}}$$





S_n = 4.8 MeV

^{238}U(n,γ) M=2 Gamma-ray spectrum

Kopecky and Uhl
(Phys. Rev. C **41**, 1941 (1990))

f_{XL} = GLO(E1) + SLO(SF) + SLO(E2)

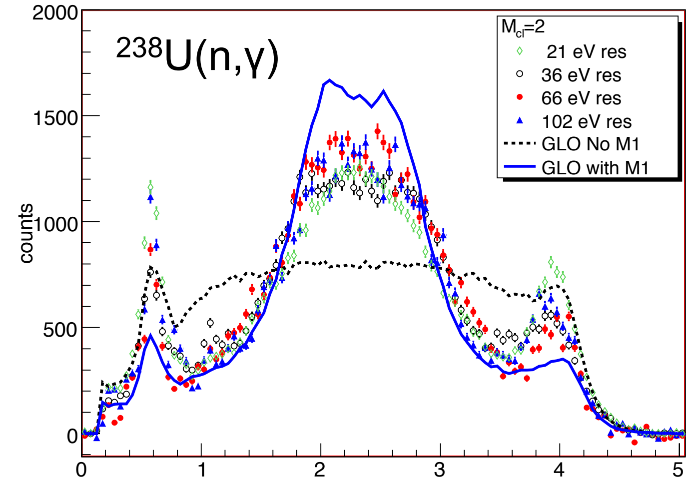
(SF and E2 Parameters from RIPL)

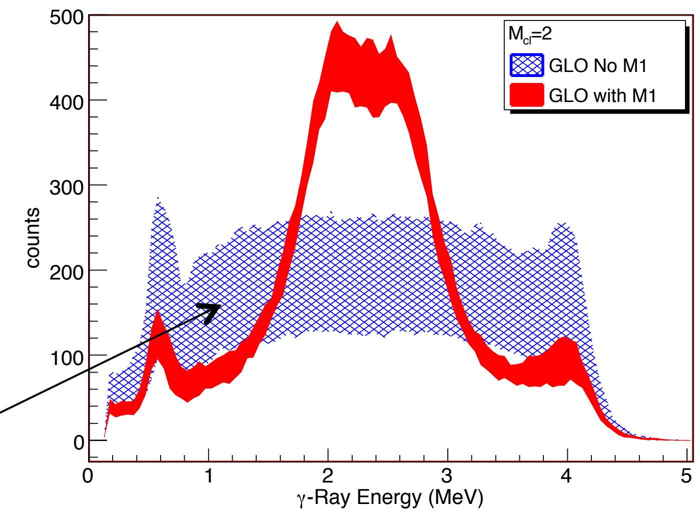
DICEBOX calculation

$$\Gamma_{ab} = \sum_{XL} y_{XL}^2 [E_a - E_b]^{2L+1} \frac{f_{XL}(E_a - E_b)}{\rho(E_a, J_a^\pi)}$$

MC cascades -> GEANT model
("forward modeling")

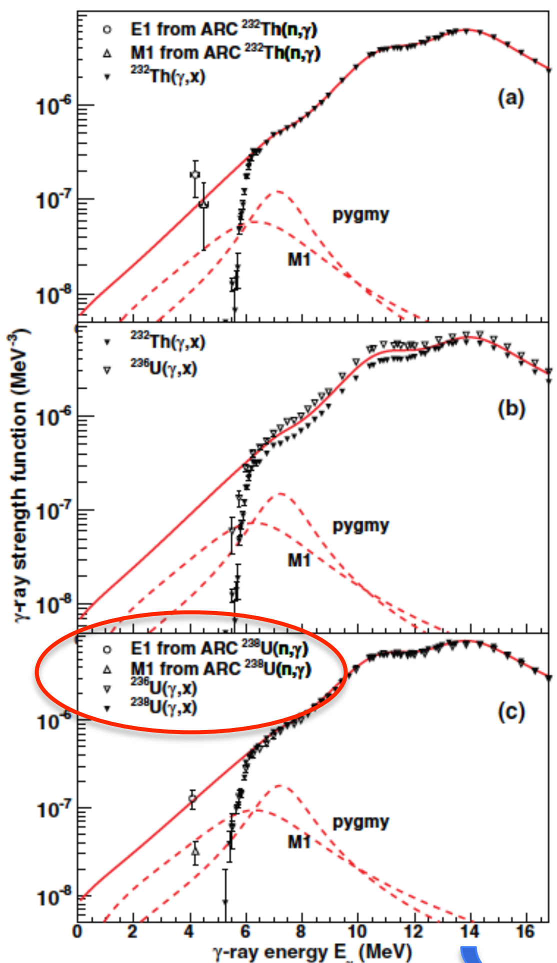
"Realizations" band



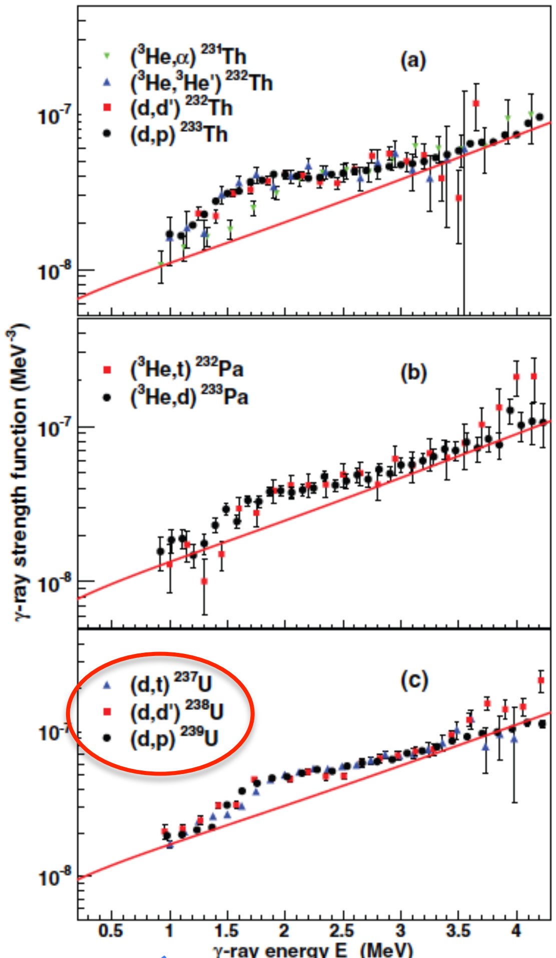


Oslo-method strength function

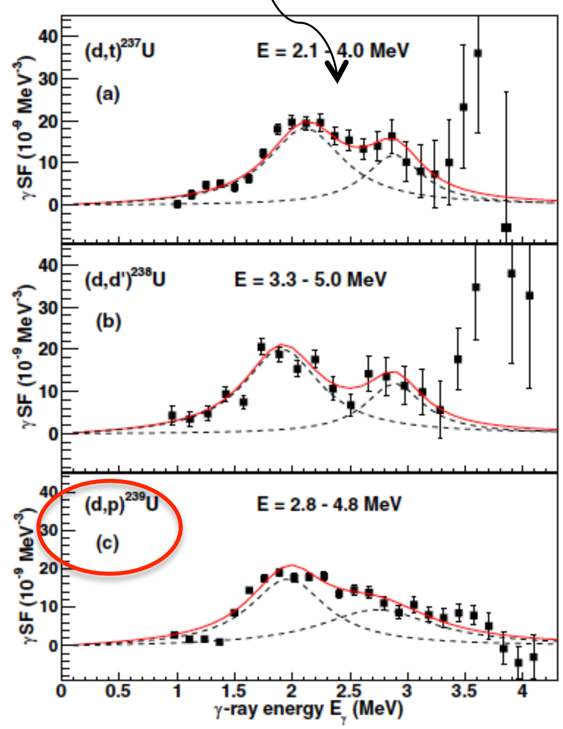
Fit to GDR (photoneutron yield)



Oslo method f_{xl}

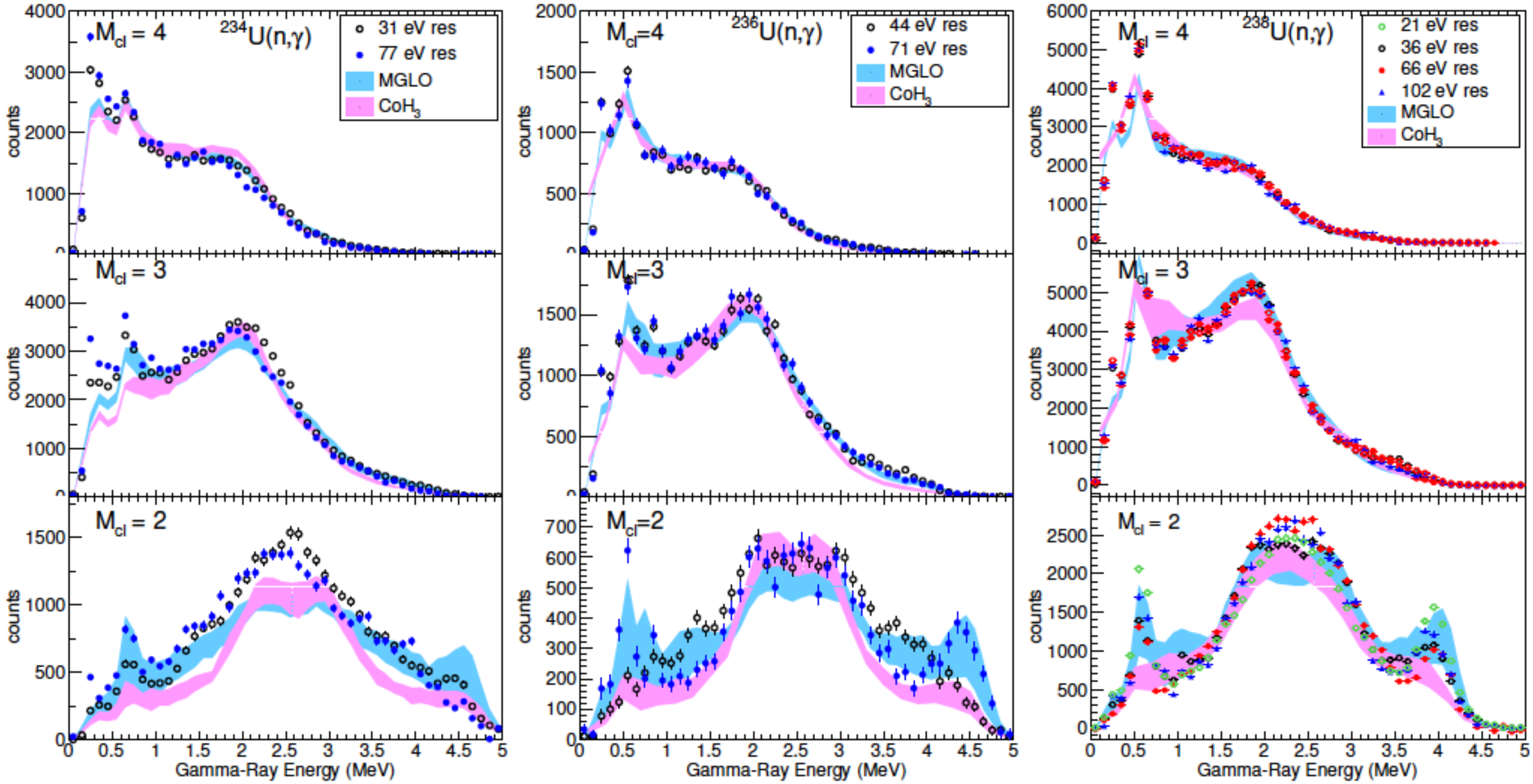


2 component M1

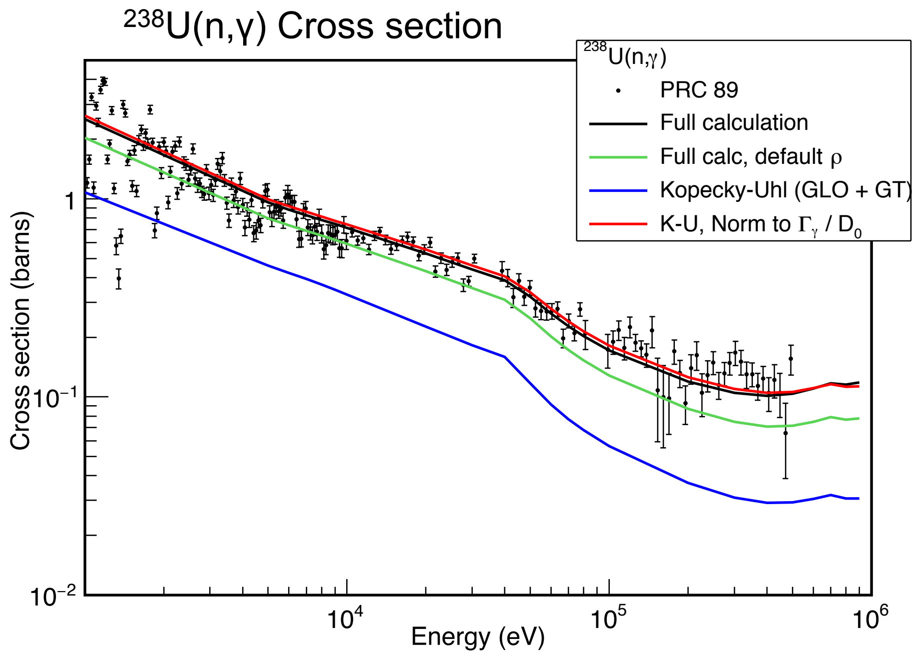


Guttormsen, Phys. Rev. **C** 89, 014302 (2014)

$^{234,236,238}U(n,\gamma)$ Gamma Ray Spectra



Cross-section calculation with CoH_3

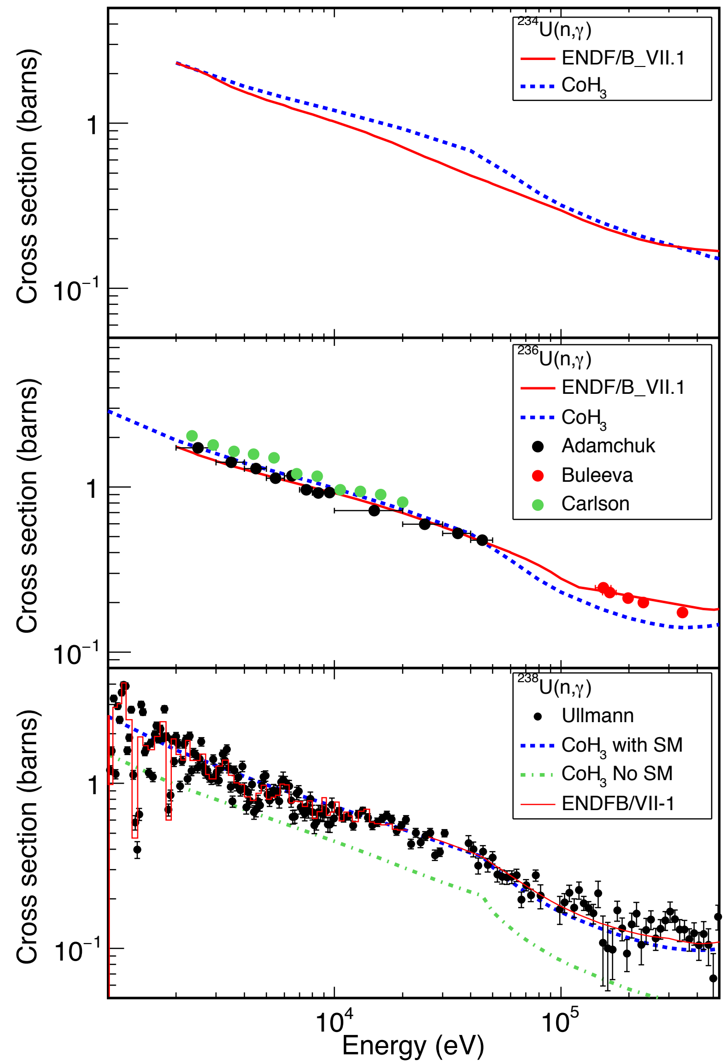


GDR: Herman/EMPIRE (CoH_3)

ρ: Gilbert-Cameron (Kawano, J. Nucl. Sci. Tech. **43**, 1 (2006))

Scissors: E and Γ from Guttormsen, Phys. Rev. C **89**, 014302 (2014); Strengths adjusted

M1(SF), E2: RIPL-3



Sensitivity of $\langle\Gamma\gamma\rangle$ to parameters

Calculate $\langle\Gamma_\gamma\rangle$ with different ρ, strength function parameters

	Model		Γ_γ (meV)		
	PSF	NLD	^{235}U	^{237}U	^{239}U
Vary ρ Von Egidy CT PRC 72	CoH_3	[17]	23.7(5)	19.0(5)	16.6(5)
Von Egidy CT PRC 80	CoH_3	[18]	27.4(18)	17.5(4)	13.4(6)
Kawano GC JNST 43	CoH_3^*	[19]	26.5(6)	23.3(7)	23.3(6)
Vary strength fcn	Oslo*		20.0(3)	21.2(8)	18.9(5)
	Oslo Renorm*		29.5(7)	24.1(9)	22.0(7)
	MGLO*	[17]	21.5(6)	17.5(6)	16.2(5)
Mughabghab	Evaluation	[38]	25.3(10)	23.4(8)	23.36(31)

CoH_3 parameters from M. Herman, EMPIRE INDC-0603 (2013)

Vary E1 GDR parameters (NLD, M1, E2 fixed)

CoH_3
Veyssiere (Nucl.Phys. **A227**, 513 (1974))
Gurevich (Nucl. Phys. **A273**, 326 (1976))
Dietrich (At. Data Nucl. Data Tab. **28**, 299 (1988))

E1 = 6 – 10 meV
M1 + E2 = 16 meV

Generalization to all nuclei

$E_{sm} = 80\ \beta_2 / A^{1/3}$ MeV $\sigma_{sm}\Gamma_{sm} = K\ \beta_2^2$ mb-MeV (Γ = 1.5 MeV)

K = 42.4 ± 5.0 (Fit to 106 FP's A < 200)

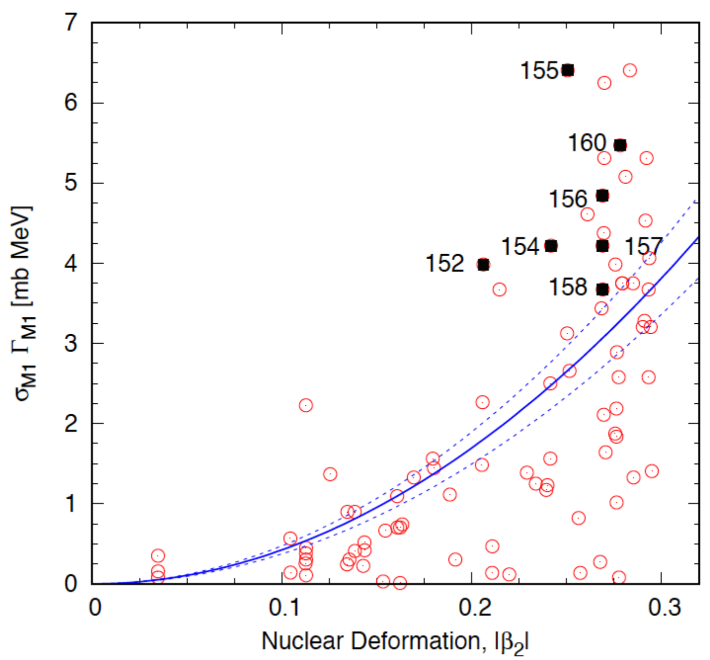


FIG. 1. Ratios of the calculated capture cross sections at 200 keV to the selected evaluated cross sections in ENDF/B-VII.1 and JENDL-4. The triangles show the case when the Hauser-Feshbach calculations do not include the M1 scissors mode. The circles are with the scissors mode.

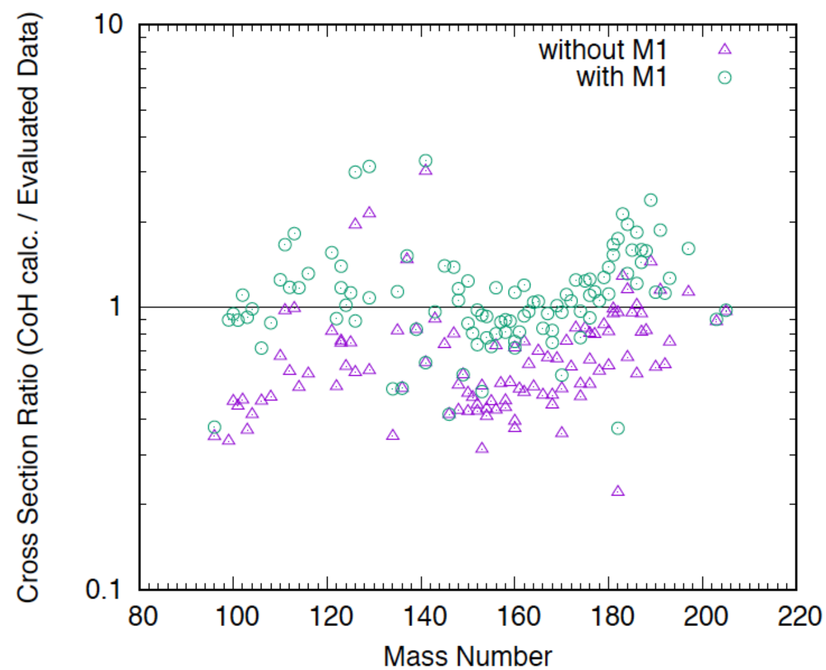
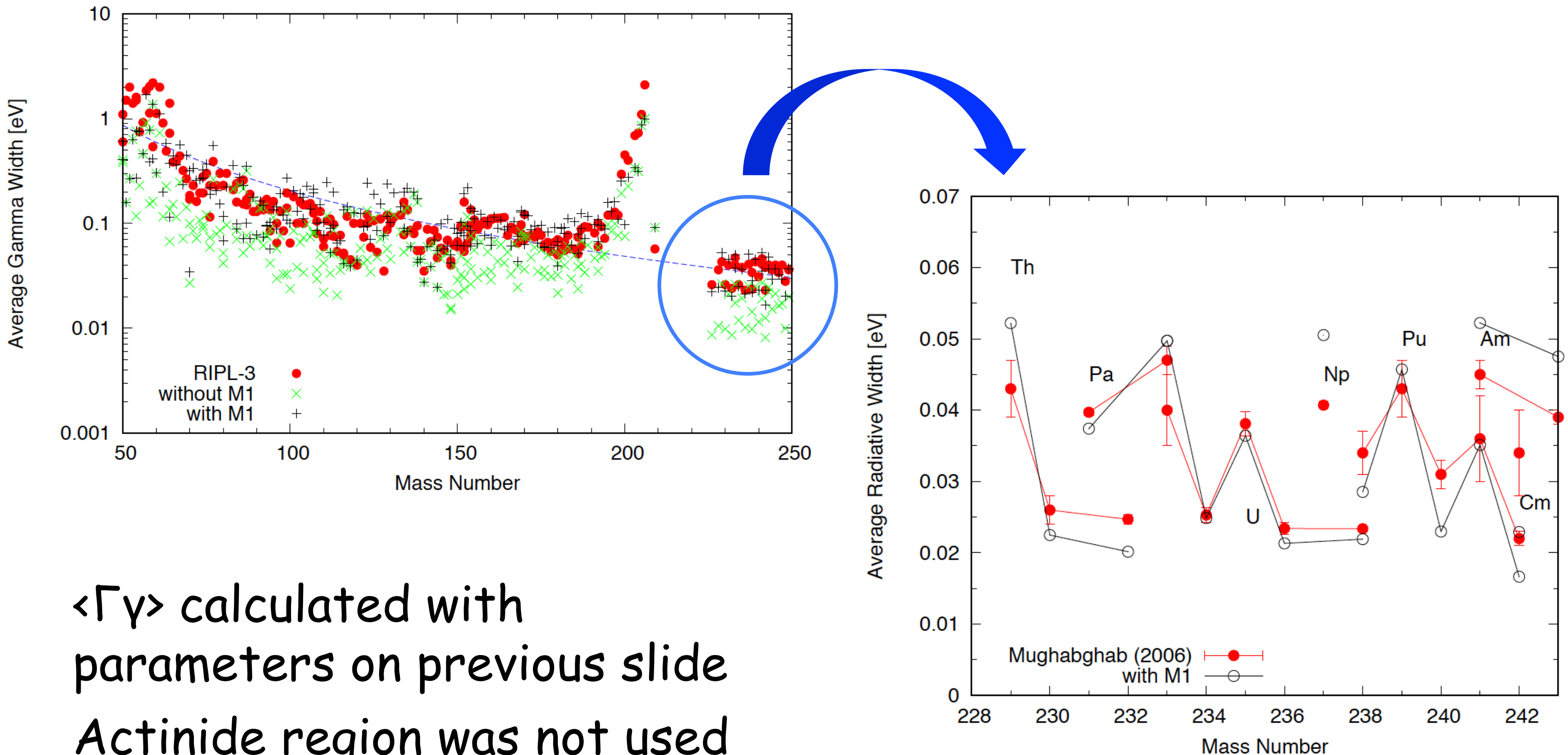


FIG. 2. Additional M1 strength $\sigma_{M1}\Gamma_{M1}$ GDR required to reproduce the evaluated capture cross section at 200 keV for selected nuclei in the fission product region. The quadratic curve is the least-squares fitting to the symbols, and the dashed curves are the 1-σ band. The filled points are for the Gd isotopes.

Kawano, APS DNP 2015
Mumpower, Kawano, et al., submitted to Phys. Rev. C

Compare measured <Γγ> to Calculated

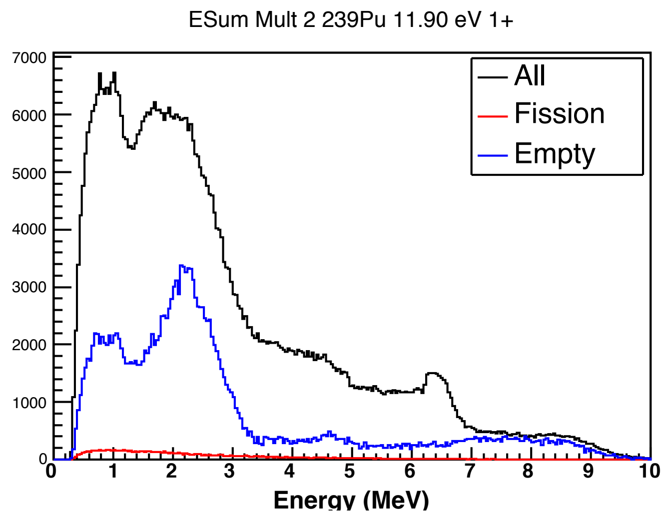


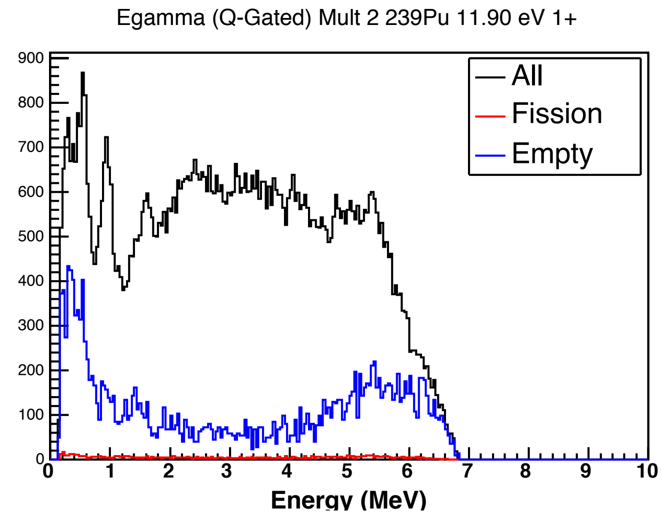
<Γγ> calculated with parameters on previous slide

Actinide region was not used in determining K

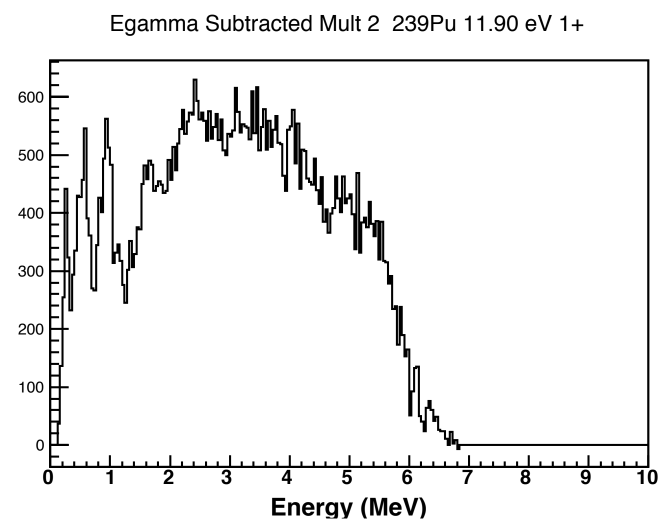
Kawano, APS DNP 2015
Mumpower, Kawano, et al., submitted to Phys. Rev. C

^{239}Pu capture – gamma-ray spectra





- ^{239}Pu(n,γ) S_n = 6.53 MeV
- Fission tagging with PPAC
- Analysis underway
    - 11.90 eV 1^+ resonance

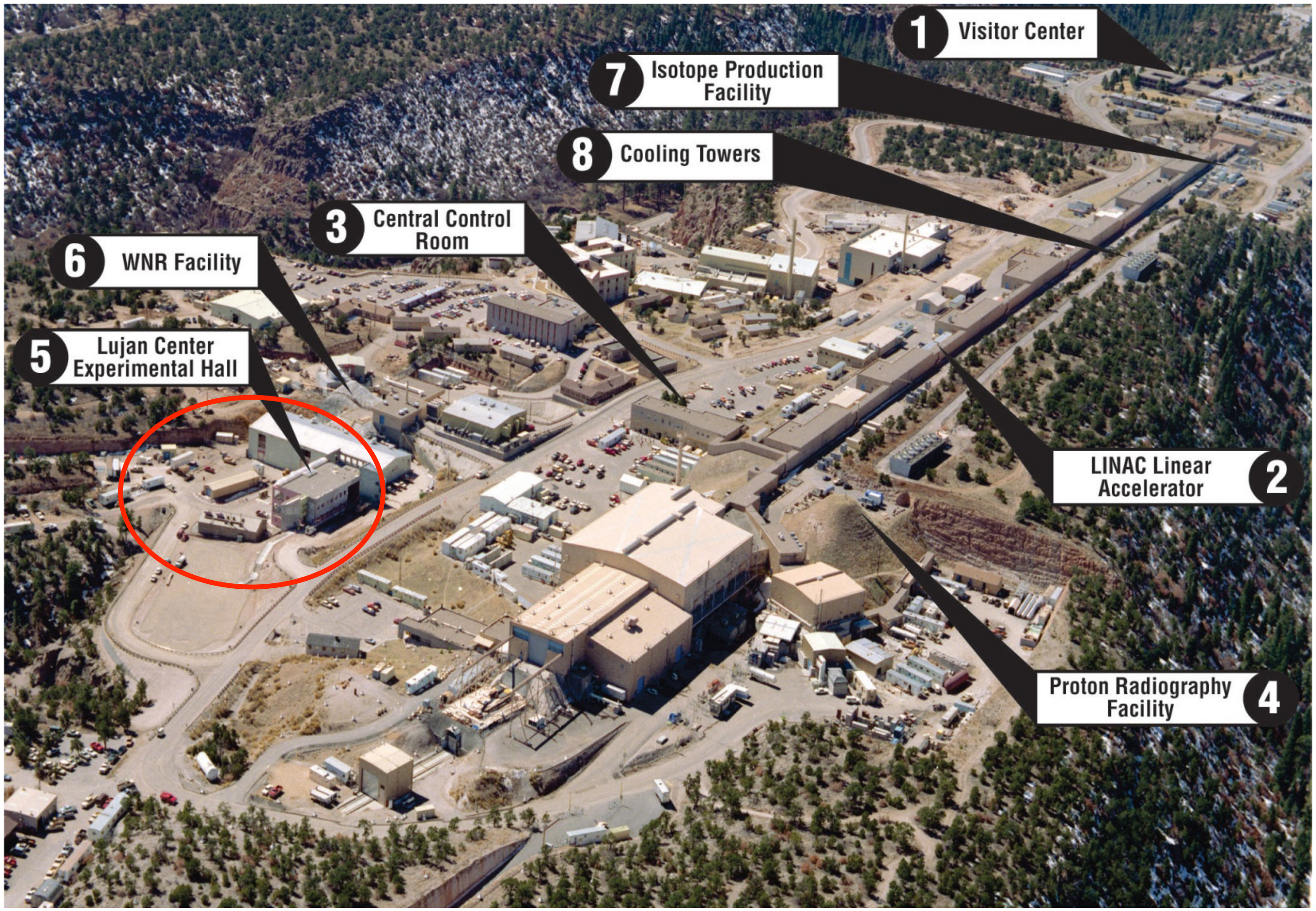


Results

- Shape of capture cross section vs neutron energy is not sensitive to exact form of strength function (although magnitude is)
- Kopecky-Uhl prescription (GLO (E1) + SLO (M1SF) + SLO (E2)) is not sufficient to describe shape of observed gamma-ray spectra
- Additional strength at low energies (2 ~ 3 MeV) – likely M1 Scissors Mode- is required
- Accurate calculations of capture cross section for $^{234,236,238}U$ can be made when including SM – with proper choice of ρ and PSF
- Extending study to odd-mass actinides (^{235}U, ^{239}Pu) and additional nuclei

Extra slides

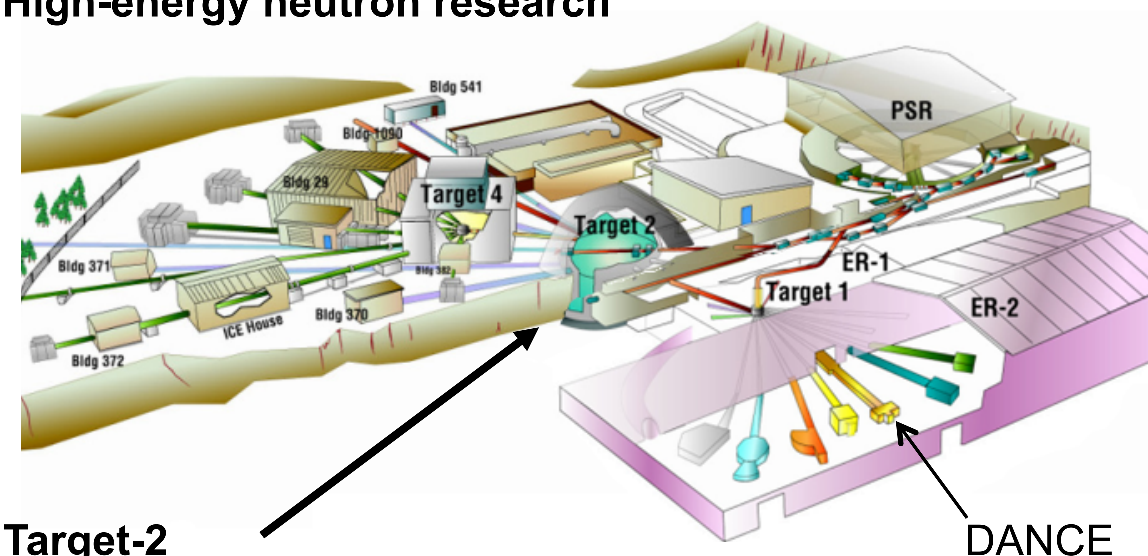
Los Alamos Neutron Science Center *(LANSCE)*



Neutron Research facilities at LANSCE

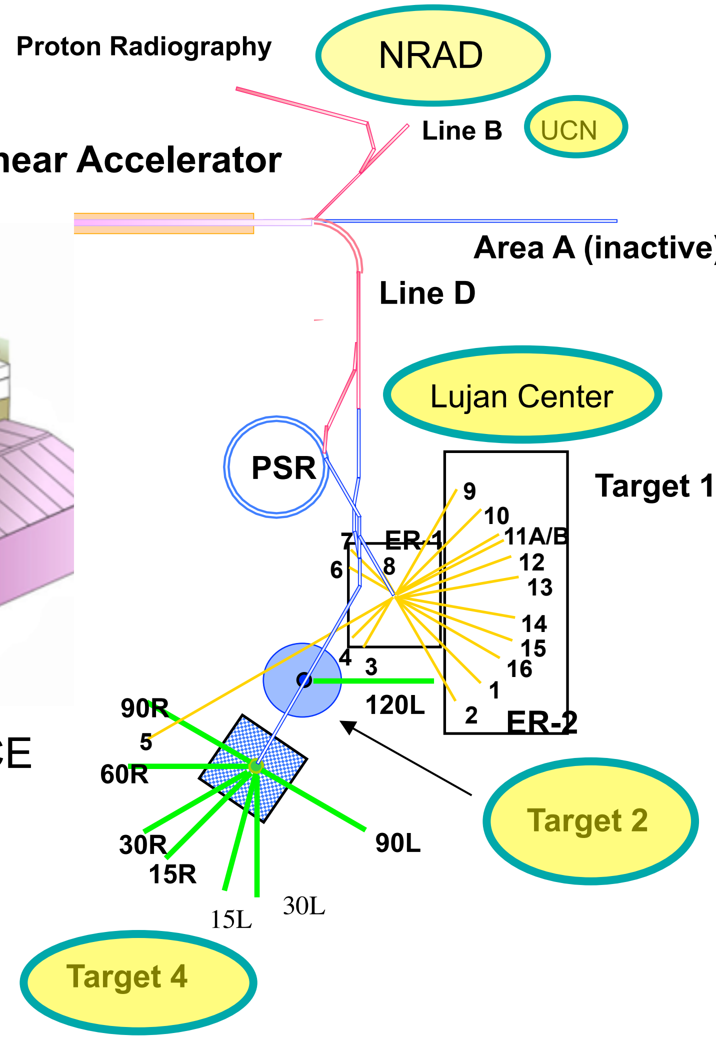
Weapons Neutron Research Facility

Target-4
High-energy neutron research

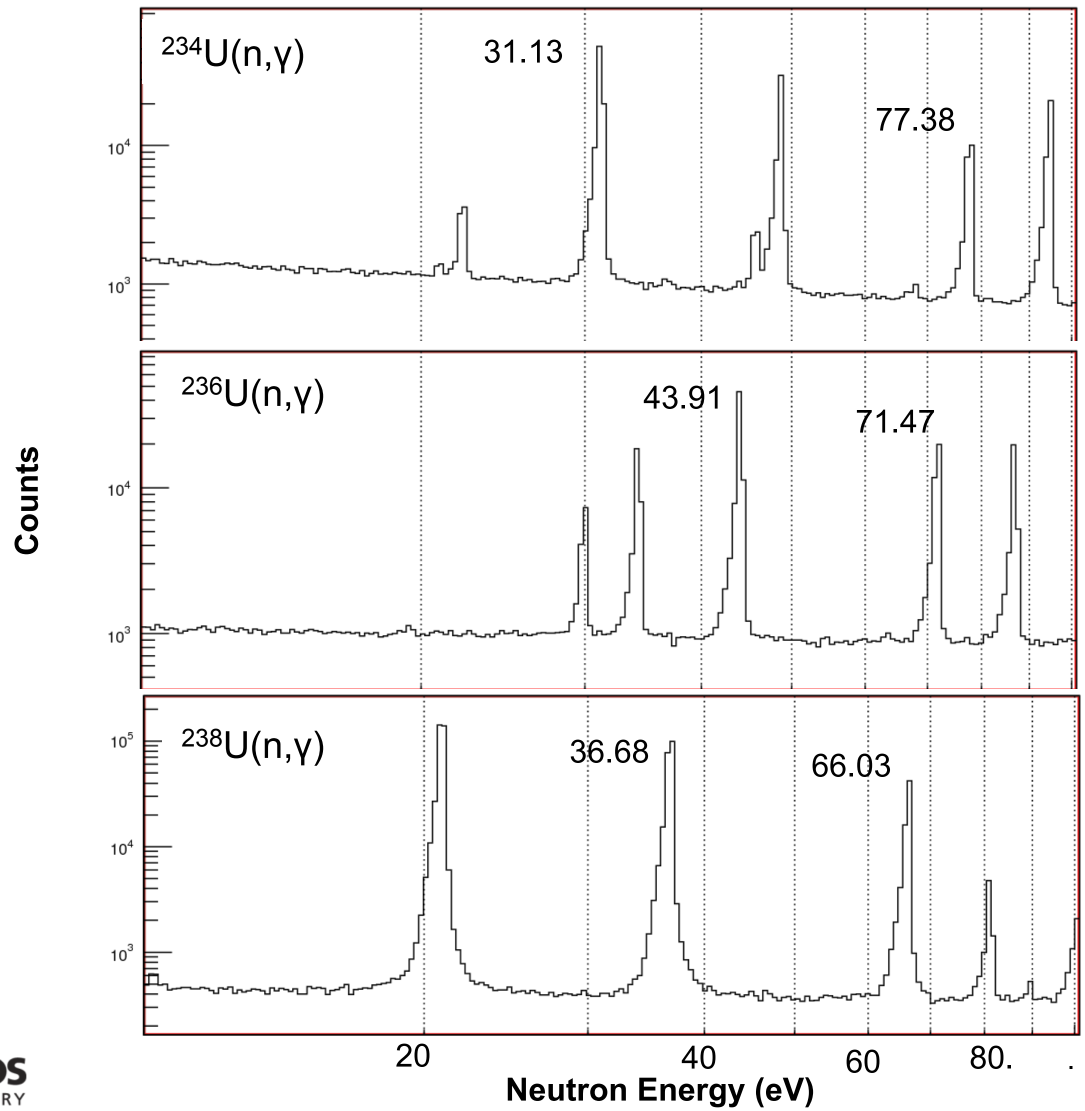


Target-2
- Proton-induced reactions
- Single-pulse experiments

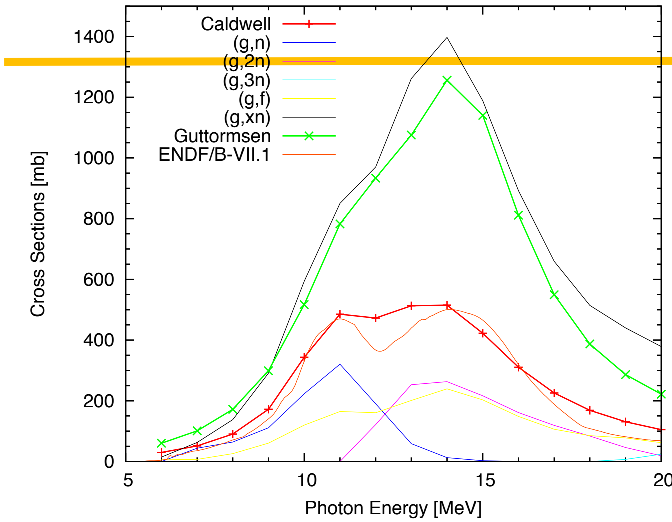
Lujan Center
Low-energy neutrons
- **Material science**
- **Nuclear science**

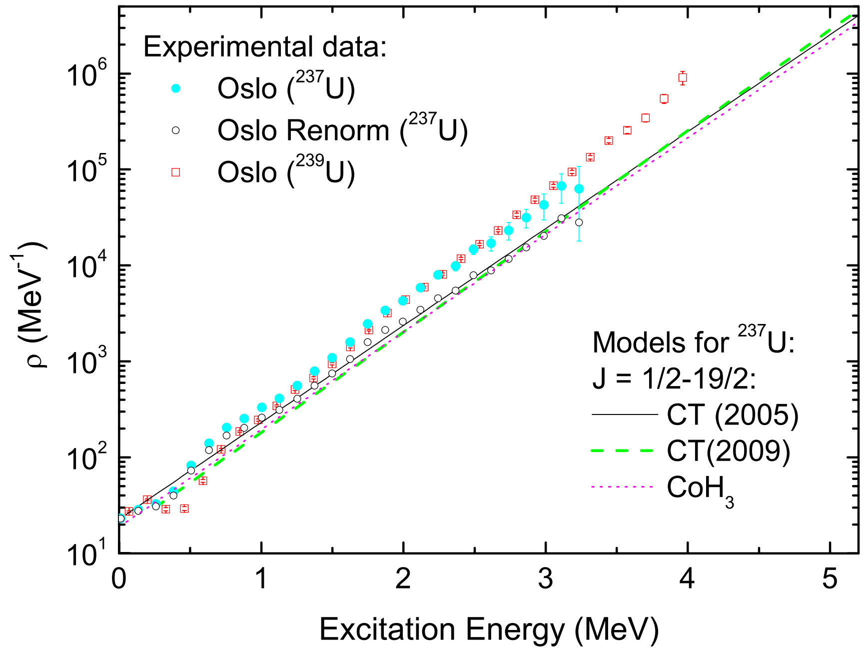


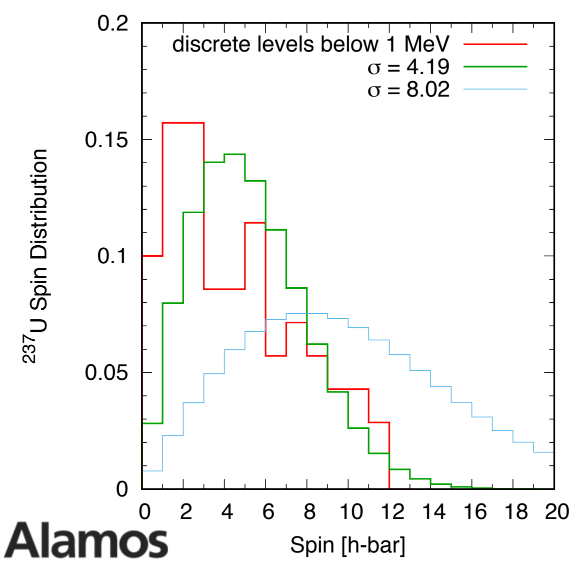
Uranium resonances



$\ell=0$ ½+


Caldwell
(g,n)
(g,2n)
(g,3n)
(g,f)
(g,xn)
Guttormsen
ENDF/B-VII.1
Cross Sections [mb]
Photon Energy [MeV]


Experimental data:
Oslo (^{237}U)
Oslo Renorm (^{237}U)
Oslo (^{239}U)
Models for ^{237}U:
J = 1/2-19/2:
CT (2005)
CT(2009)
CoH$_3$
ρ (MeV^{-1})
Excitation Energy (MeV)


discrete levels below 1 MeV
σ = 4.19
σ = 8.02
^{237}U Spin Distribution
Spin [h-bar]