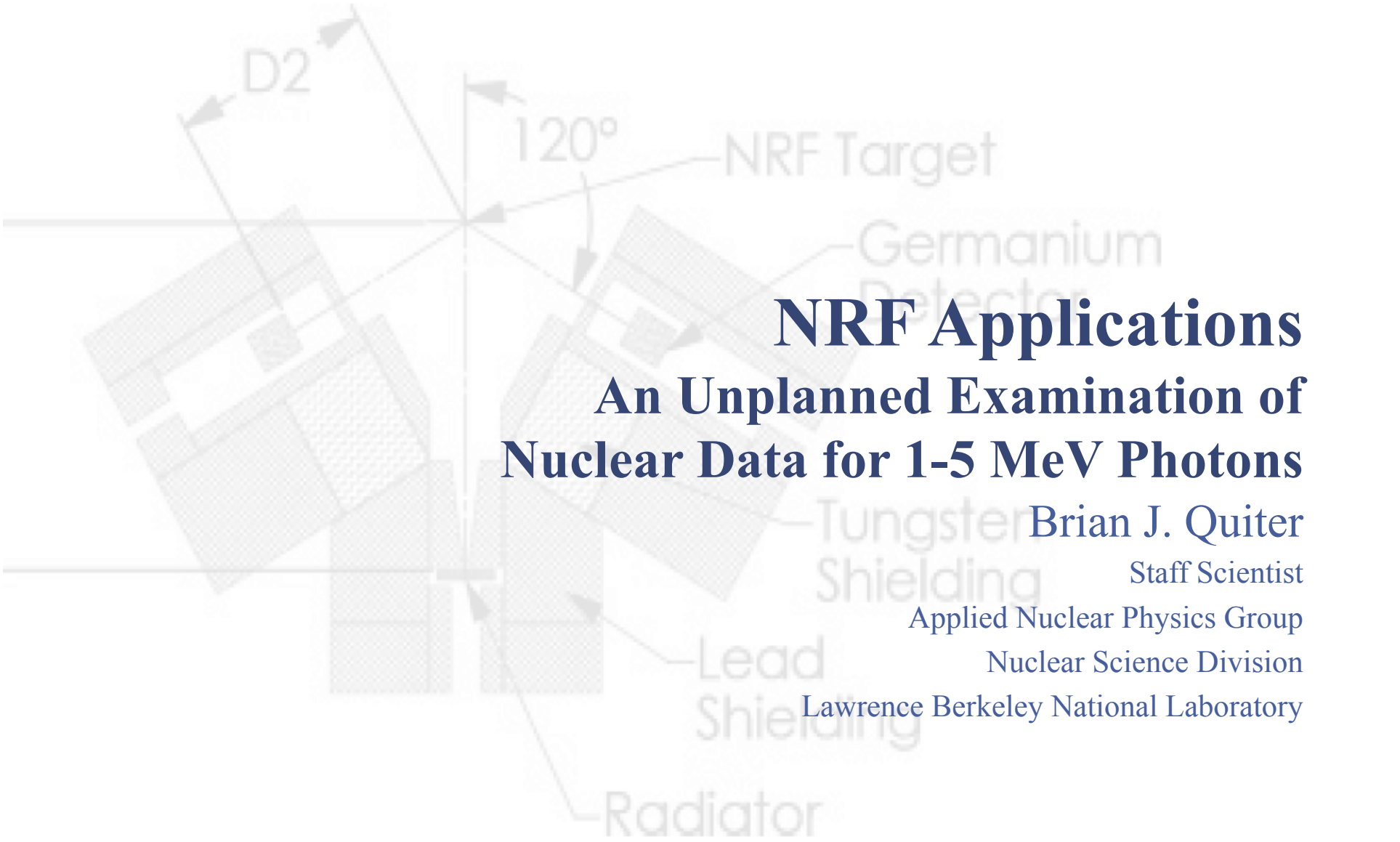

NRF Applications

An Unplanned Examination of Nuclear Data for 1-5 MeV Photons

Brian J. Quiter

Staff Scientist

Applied Nuclear Physics Group

Nuclear Science Division

Lawrence Berkeley National Laboratory

What is Nuclear Resonance Fluorescence?

Photons usually only interact with atomic electrons…

but for resonant photons $\sigma_{NRF} > \sigma_{Atomic}$

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$$t_{1/2} \sim 10 \text{ fs}$$

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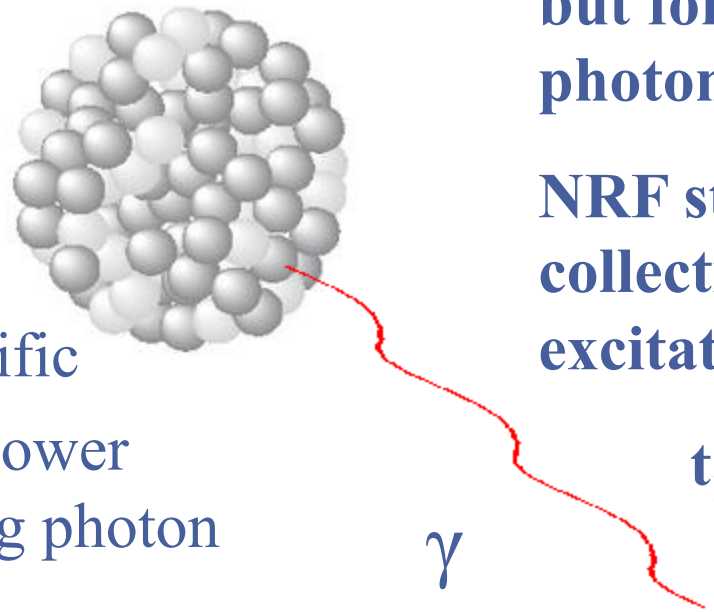

<u>NRF γ rays:</u>

- Nearly isotropic
- Energies are isotope-specific
- Nuclear recoil: γ ray has lower energy than NRF-inducing photon
- Relatively weak signals

What is Nuclear Resonance Fluorescence?

Potential Applications:

- Non-intrusive inspection
- Nuclear materials accountancy
- Treaty verification

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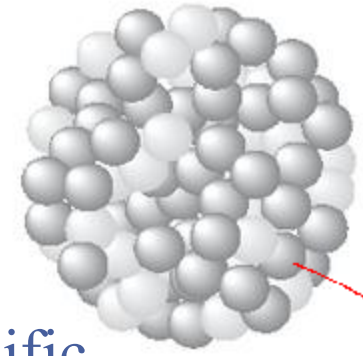


γ

Photons usually only interact with atomic electrons…

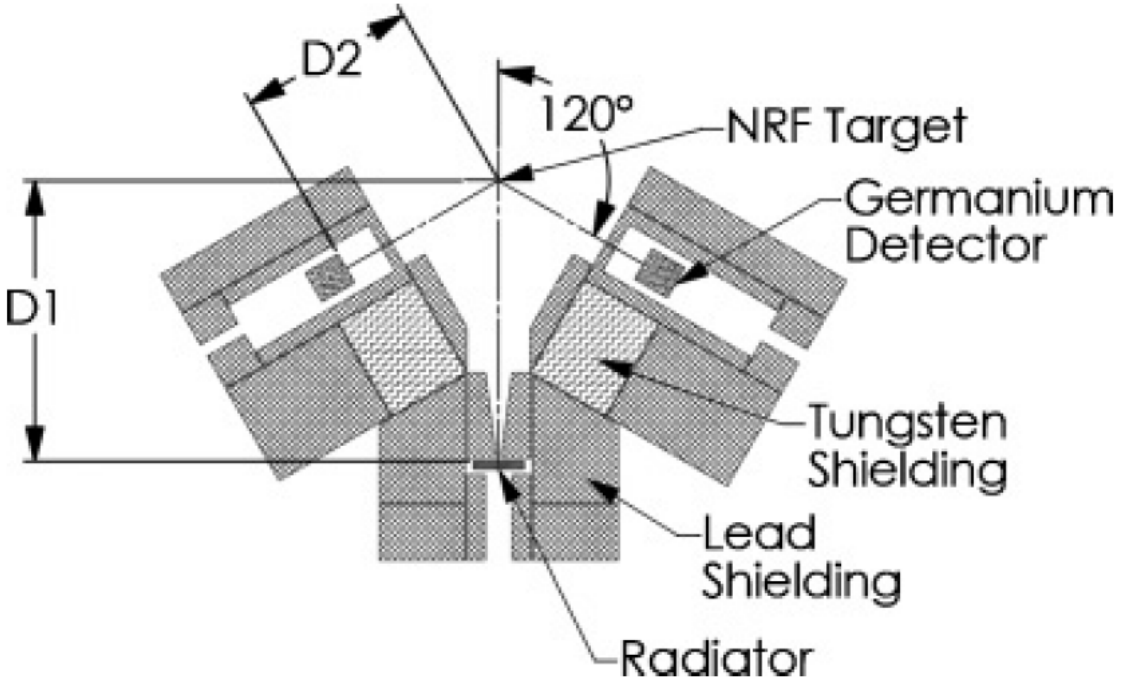
but for resonant photons $\sigma_{NRF} > \sigma_{Atomic}$

NRF states are often collective nucleon excitations

$t_{1/2} \sim 10$ fs

Actinide NRF Measurements

- ^{232}Th and ^{238}U measured in 1987 (Heil et al.)
- ^{235}U and ^{239}Pu measured in 2008 (Bertozzi et al.)
- ^{237}Np measured in 2010 (Angell et al.)
- ^{240}Pu measured in 2012 (Quiter et al.)



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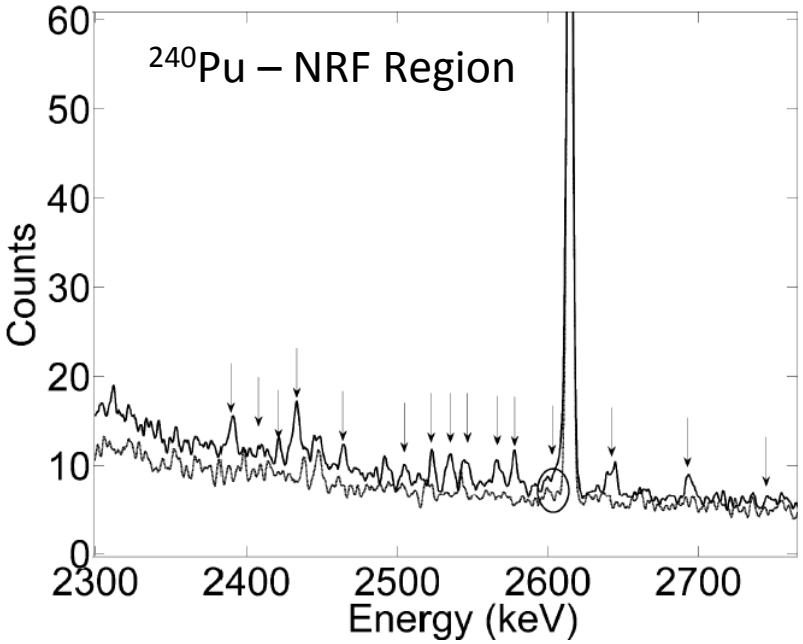
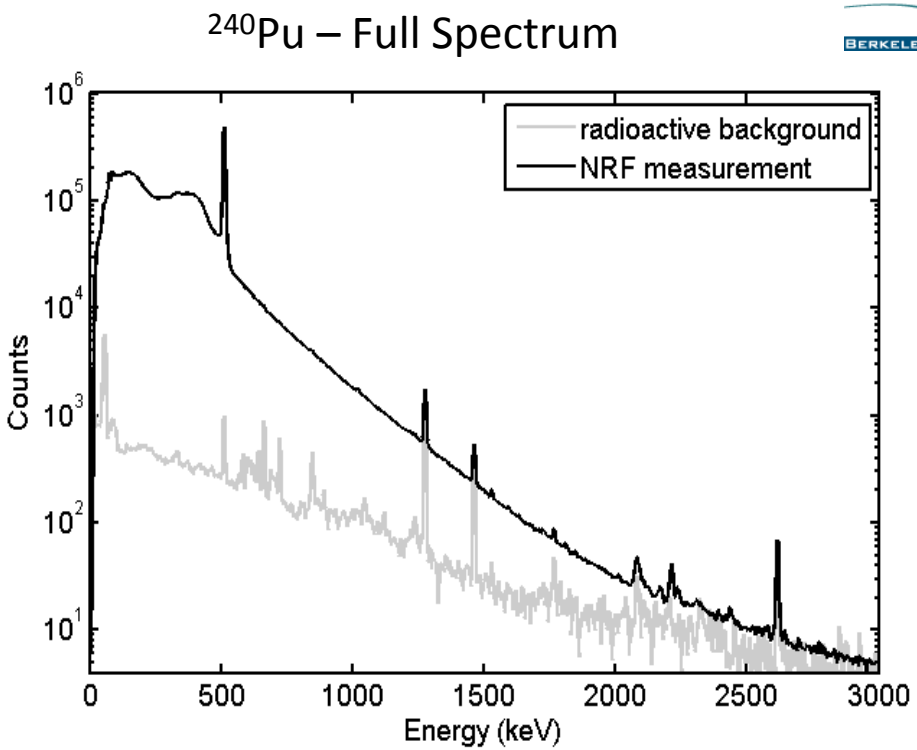
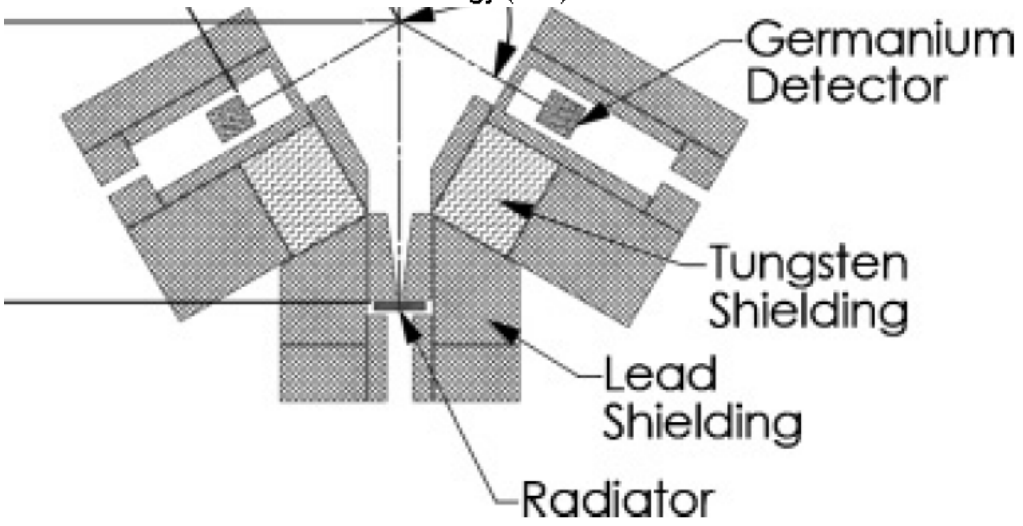


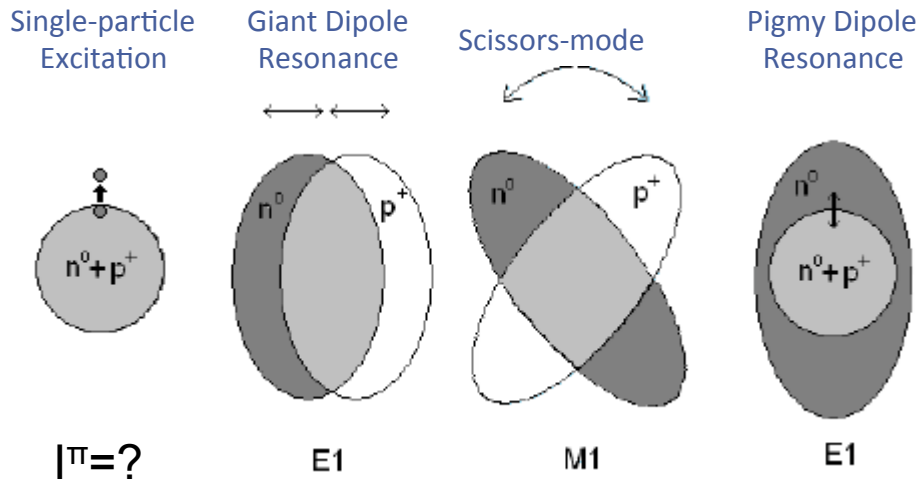




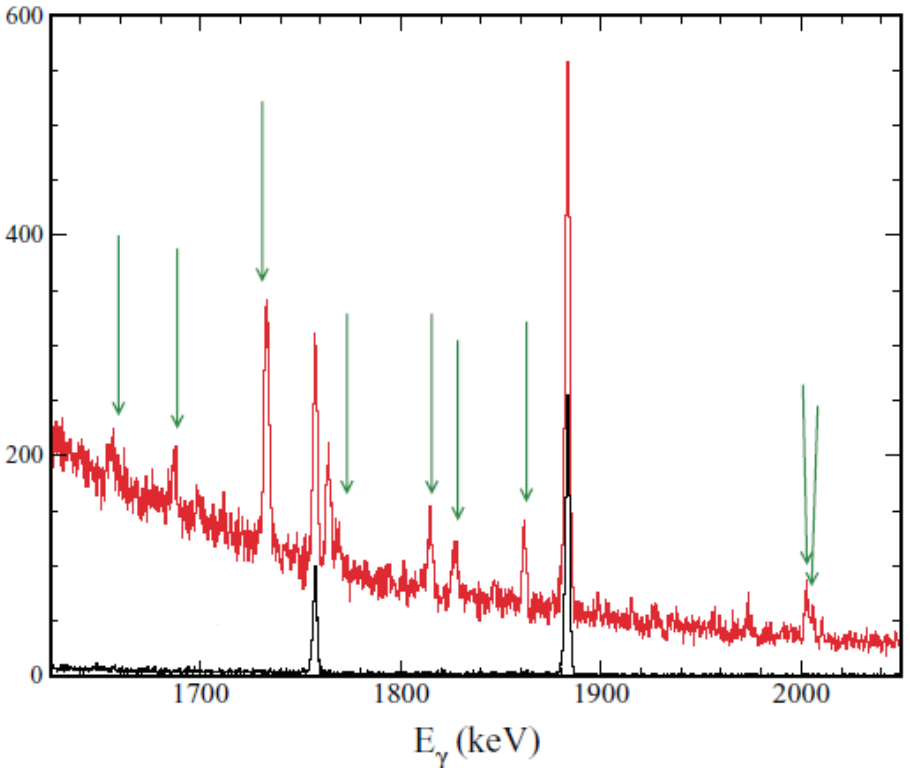
Nuclear Resonance Fluorescence Signatures

- Prolate deformed nuclei tend to have series of M1 resonances at:
  - 1.5-3 MeV (actinides),
  - 4-6.5 MeV (lanthanides/rare earths)

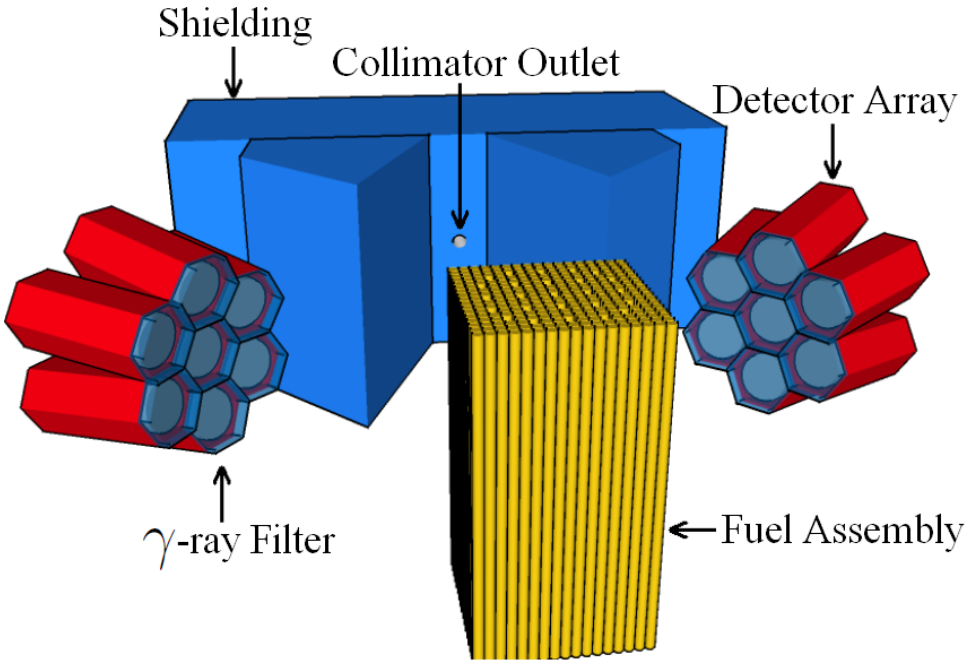
  → Scissors-mode excitation

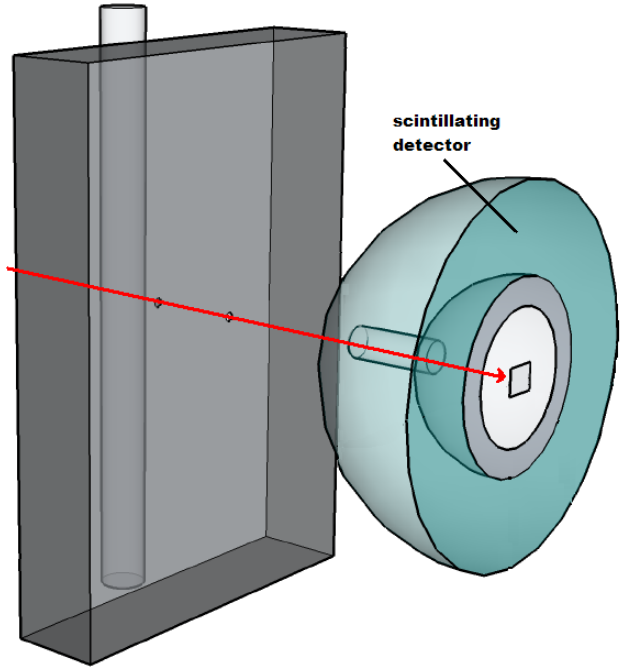


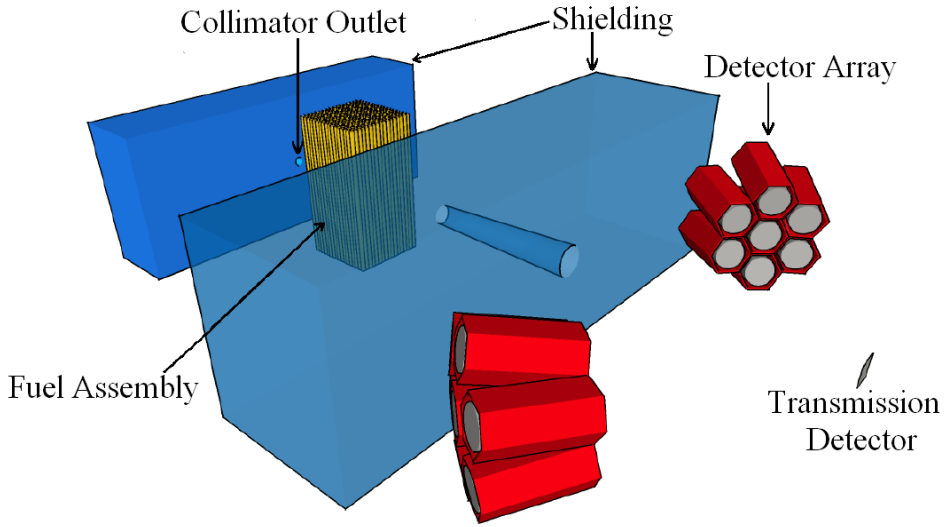
^{235}U NRF Spectrum (Bertozzi et al. 2008)



Total observed strength of 'Scissors-mode' excitation significantly larger for even-A nuclides than for odd-A.


Shielding
Collimator Outlet
Detector Array
γ-ray Filter
Fuel Assembly

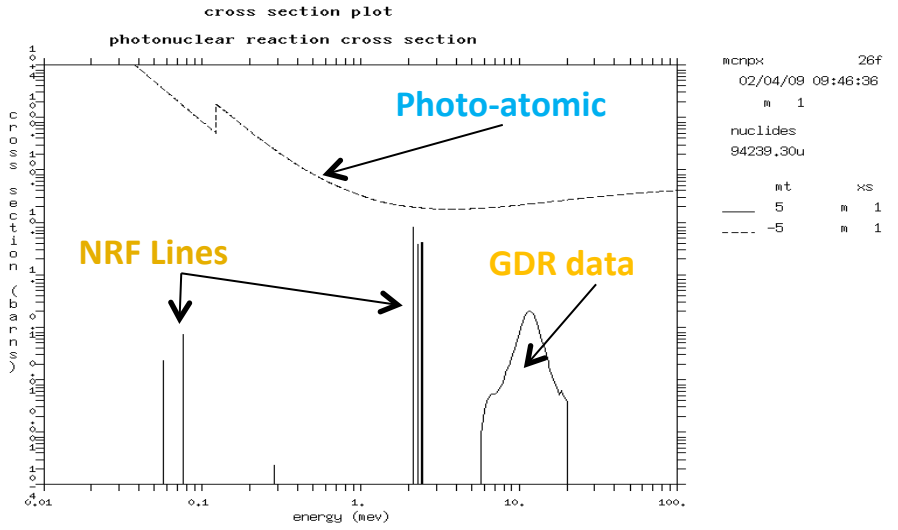

scintillating
detector

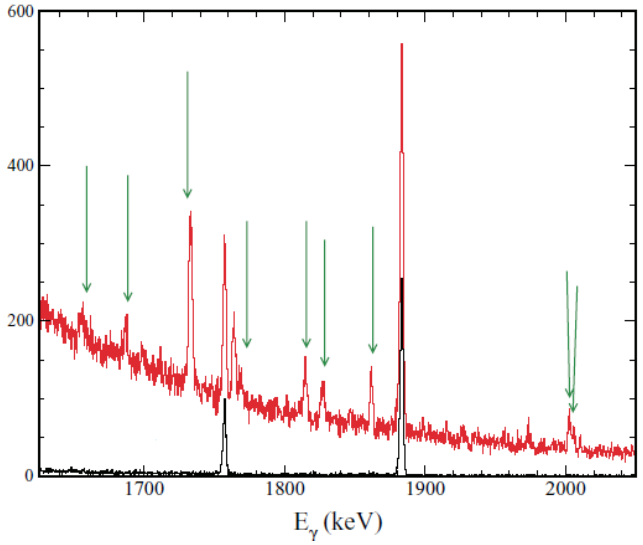

Collimator Outlet
Shielding
Detector Array
Fuel Assembly
Transmission
Detector

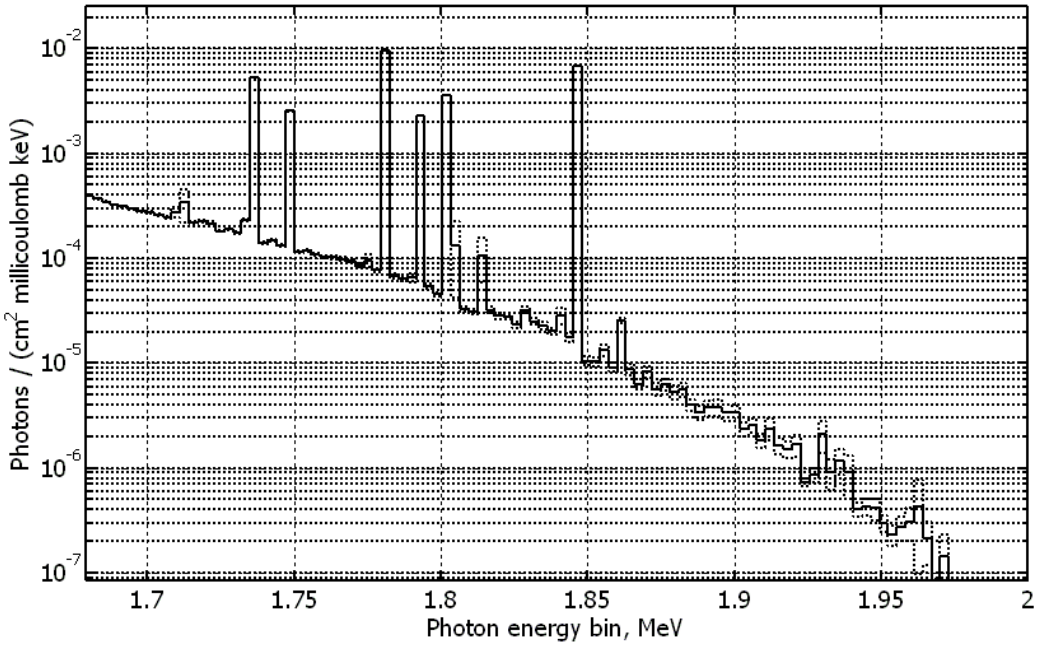
NRF Data into ENDF/MCNP

- Collaborated with LANL
- Data have NRF γ-ray distributions
- Database still contains approximations
  - Isotropic
  - No γ-ray correlations / cascades
  - No polarity

Why do simulations predict better signal vs. background than measurements?!





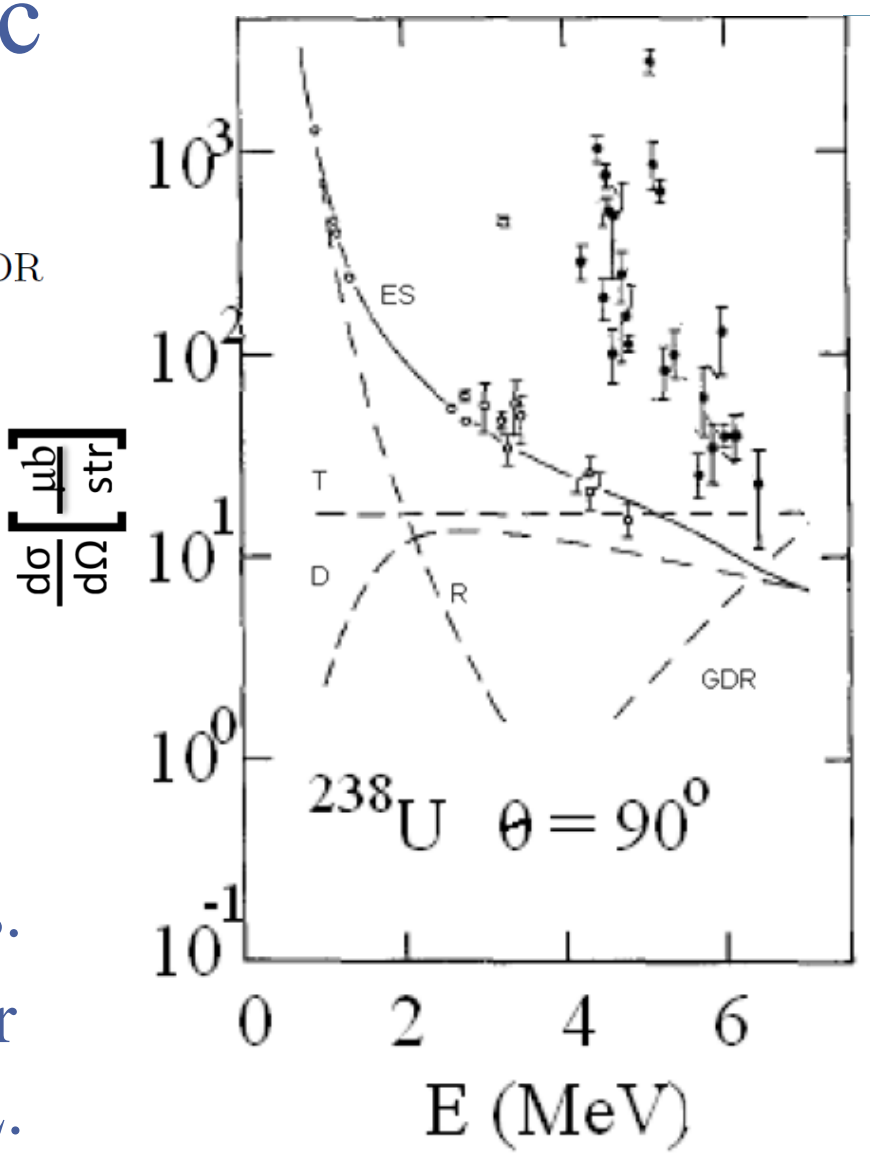


Non-resonant Elastic Photon Scatter

$$A_{\mathrm{Coh}} = A_{\mathrm{Ray}} + A_{\mathrm{Del}} + A_{\mathrm{NT}} + A_{\mathrm{GDR}}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left[|A_{\perp}|^2 + |A_{\parallel}|^2\right]$$

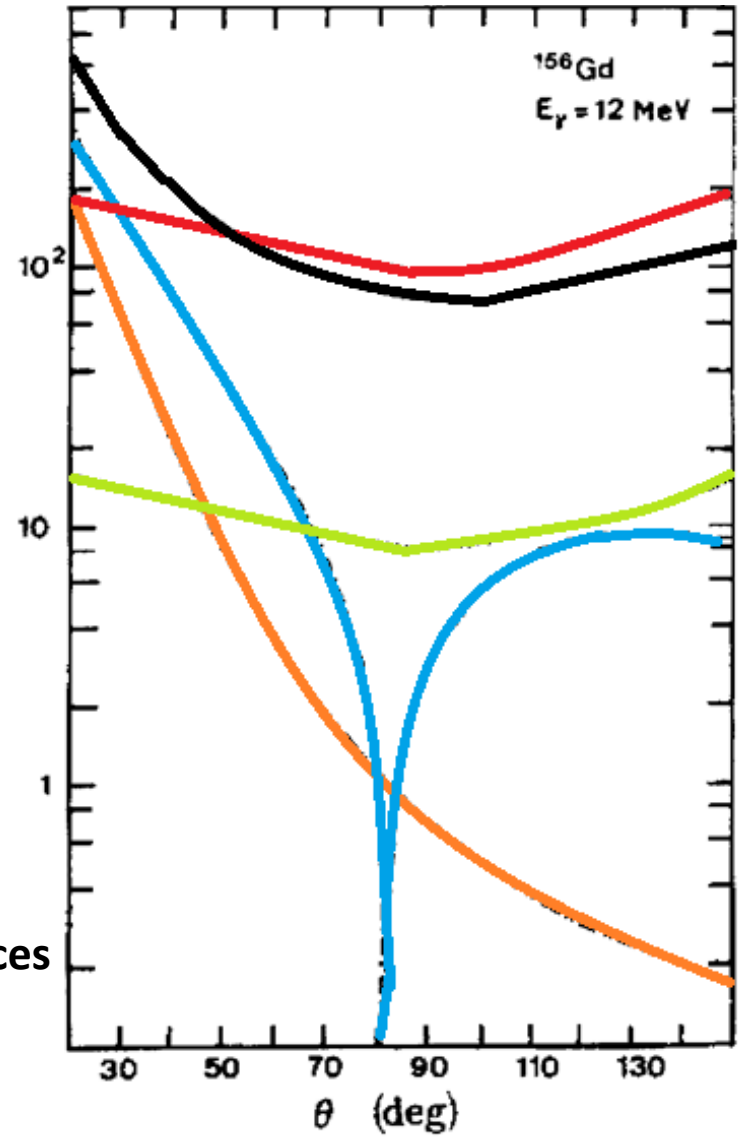
- Rayleigh scatter is majority of σ_{ES} for actinides.
- Also major component of $\frac{d\sigma}{d\Omega}$, even at large angles.
- Also only Rayleigh scatter described in ENDF/EPDL.



Z. Phys. A - Atoms and Nuclei 314, 171–179 (1983)

Photon Scatter Data is not ENDF-ready

- $A_{\mathrm{Coh}} = A_{\mathrm{Ray}} + A_{\mathrm{Del}} + A_{\mathrm{NT}} + A_{\mathrm{GDR}}$ terms all imperfectly predicted by models.
- No systematic measurements.
- A_{Ray}: Rayleigh Scattering tabulation http://adg.llnl.gov/Research/scattering/RTAB.html
  - No longer active link.
- Delbruck research ended in 1990's,
  - Computers took 1 year to calculate Feynman loop integrals…



E. Canetta , "Delbruck and Nuclear Effects in Photon Scattering: Recent Developments" X-RAY SPECTROMETRY 28 357-371 (1999)

Rayleigh Scattering in ENDF

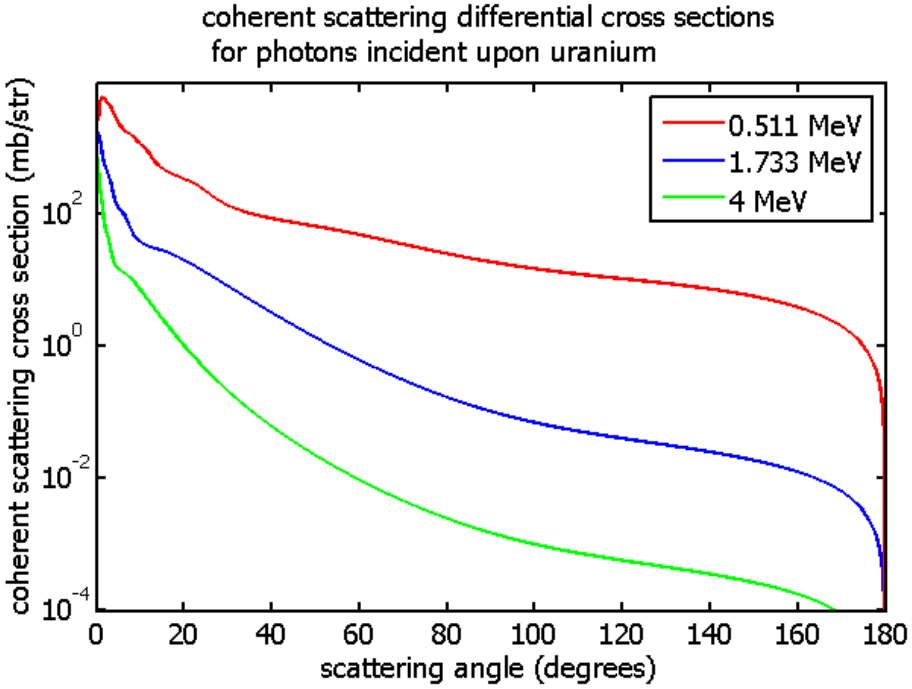
- Form factor multiplication to Thomson scattering on electrons:

$$\sigma_{Ray}\, d\mu = \frac{r_e}{2} C(Z,q)(1+\mu^2) d\mu$$

$$\mu = \cos\theta$$

- Form factor is function of momentum transfer:

$$q = \sqrt{\frac{1-\mu}{2}}\,\frac{E}{hc} = 57.03\,[\mathrm{A}^{-1}]\sqrt{1-\mu}\;E\,[\mathrm{MeV}]$$

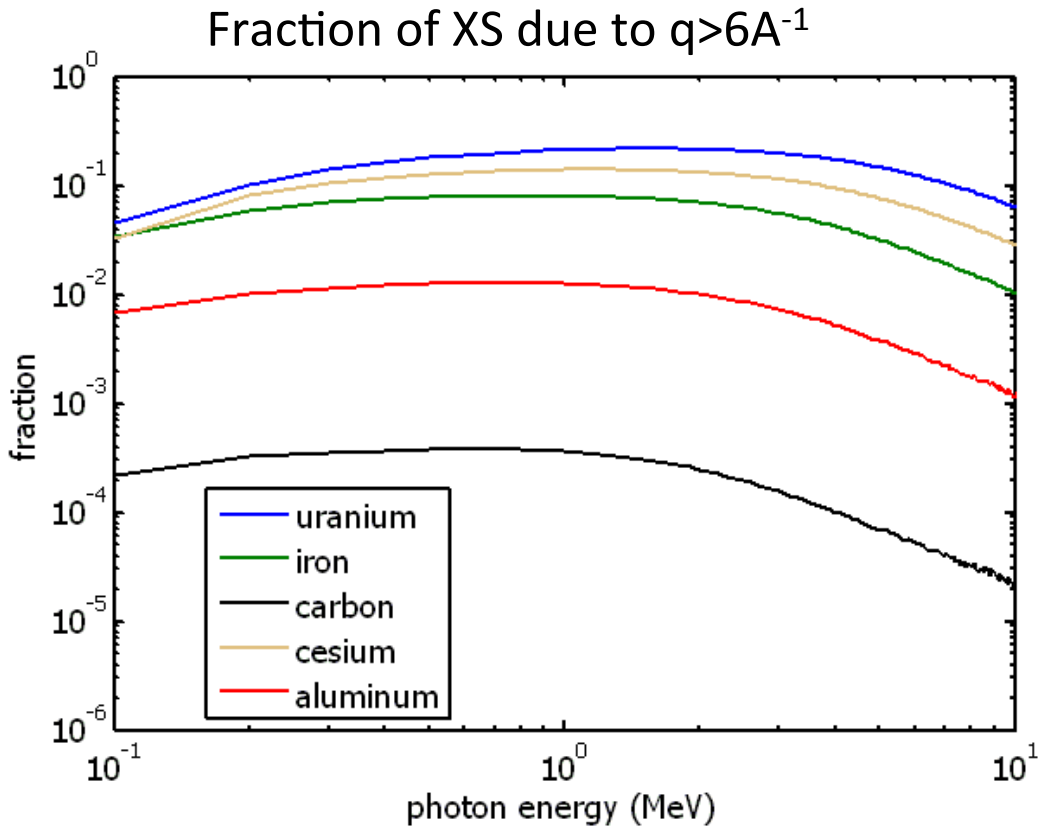


Rayleigh Scattering in MCNP

- Until 2011, form factor functions **had not** been implemented in MCNP for $q \geq 6$ [A^{-1}].

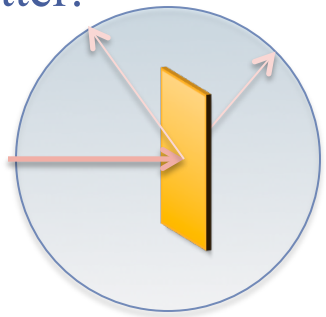
E (keV)	Angle
74.4	180°
105	90°
194	45°
1733	4.9°
2423	3.5°

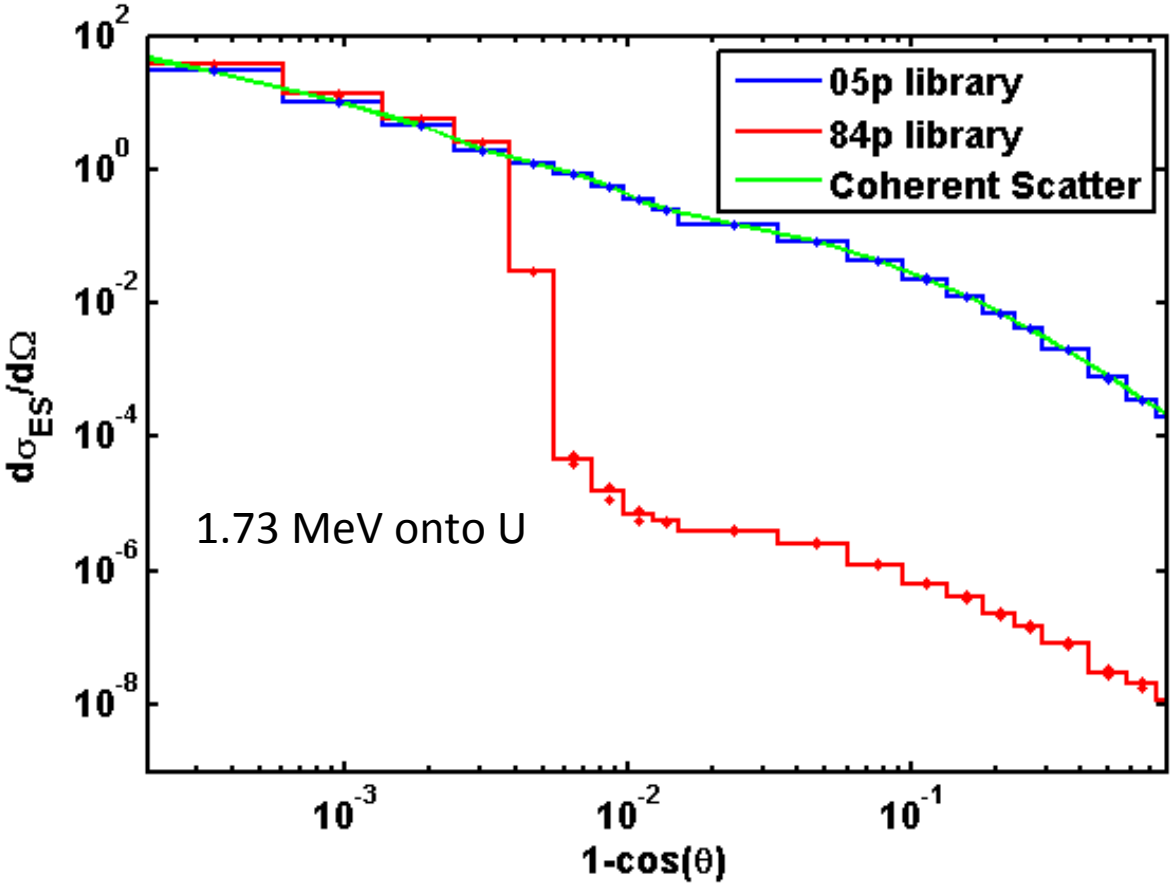
Modified MCNPX source code to fully include Rayleigh scattering



Form Factors in MCNP

- Modified source code and data files to allow ENDF evaluation of photo-elastic scatter.





J.S. Hendricks and **B.J. Quiter**, "Form Factor Upgrade for Improved Photon Transport", J. Nuc. Tech 175 p150 (2011)

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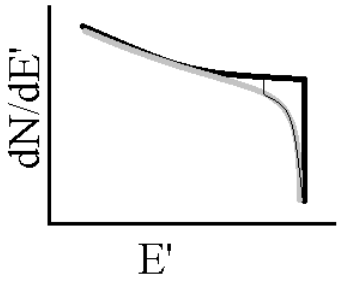
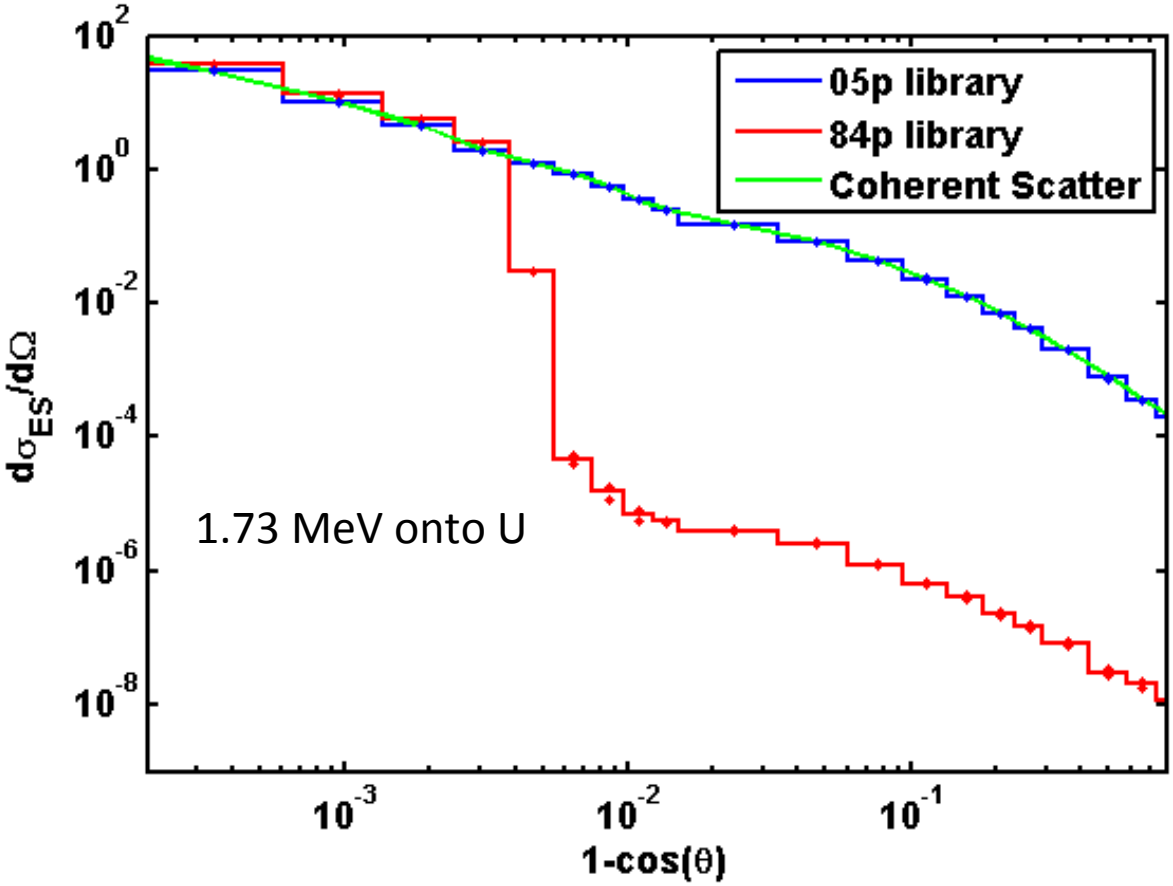


- Also improved incoherent scatter (similar feature for $q \geq 8$ A^{-1}).
- Still no photonuclear elastic scatter
  - No ENDF database
- Improvement not being maintained by nuclear data team at LANL.

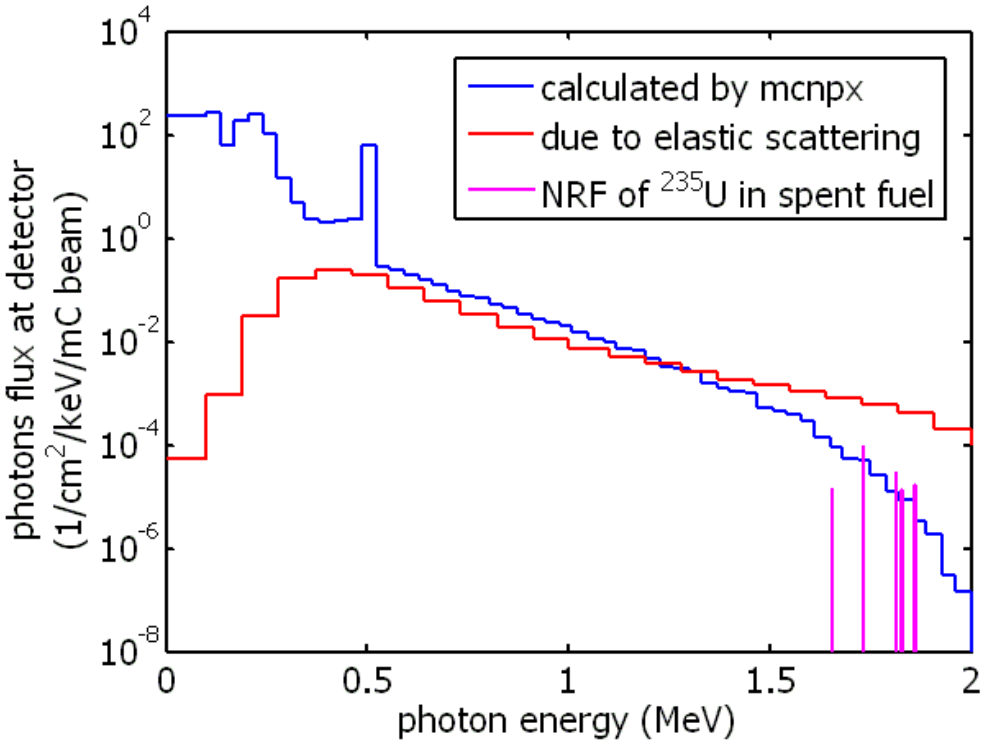


J.S. Hendricks and **B.J. Quiter**, "Form Factor Upgrade for Improved Photon Transport", J. Nuc. Tech 175 p150 (2011)

Summary

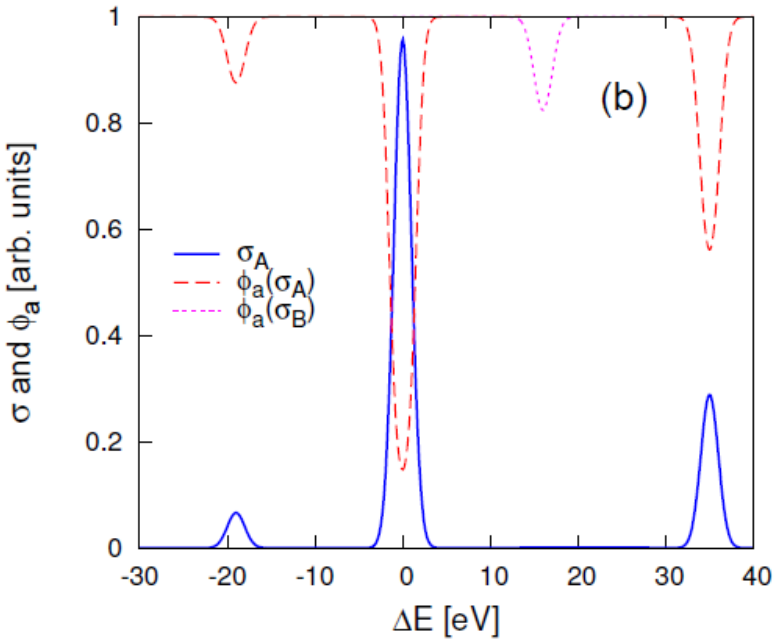
- Added actinide (and more*) NRF data to photonuclear ENDF files,
- Processed using NJOY to create photonuclear ACE files for MCNP,
  - NJOY has bugs, cannot process non-isotropic NRF.

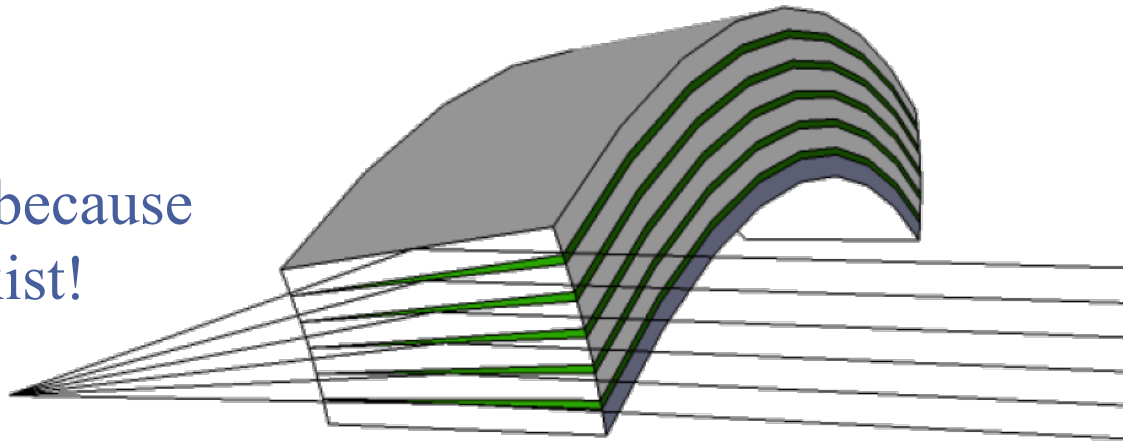
- Photo-elastic scattering is only handled through form factors,
- MCNP has a legacy bug that is also hard-coded into NJOY
  - Impacts coherent and incoherent scatter.
- Narrow energy spread γ-ray beams are coming!



Other Applications

- NRF assays using unresolved resonances
  - Data does not exist, systematic measurements would inform whether highly valuable, potentially useful, or useless.
- Gamma-ray mirrors:
  - Bragg diffraction
  - Modeling is not used because physics data do not exist!





Thanks!

I'd like to thank:

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LLNL: Lynn Kissel

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- Department of Homeland Security, TAR
- Advanced Fuel Cycle Initiative of the Office of Nuclear Energy (DOE NE)