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 $\sigma_{\text{NRF}} > \sigma_{\text{Atomic}}$
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$t_{1/2} \sim 10 \text{ fs}$
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**NRF γ rays:**
- Nearly isotropic
- Energies are isotope-specific
- Nuclear recoil: γ ray has lower energy than NRF-inducing photon
- Relatively weak signals

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Potential Applications:
- Non-intrusive inspection
- Nuclear materials accountancy
- Treaty verification

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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

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

\[ A_{\text{Coh}} = A_{\text{Ray}} + A_{\text{Del}} + A_{\text{NT}} + A_{\text{GDR}} \]

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

- Rayleigh scatter is majority of \( \sigma_{\text{ES}} \) for actinides.
- Also major component of \( \frac{d\sigma}{d\Omega} \), even at large angles.
- Also only Rayleigh scatter described in ENDF/EPDL.
Photon Scatter Data is not ENDF-ready

- $A_{Coh} = A_{Ray} + A_{Del} + A_{NT} + A_{GDR}$ 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  - No longer active link.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…

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:

\[ q = \sqrt{\frac{1 - \mu}{2}} \frac{E}{hc} = 57.03 \ [A^{-1}] \sqrt{1 - \mu} \ E[MeV] \]
Rayleigh Scattering in MCNP

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

<table>
<thead>
<tr>
<th>E (keV)</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>74.4</td>
<td>180°</td>
</tr>
<tr>
<td>105</td>
<td>90°</td>
</tr>
<tr>
<td>194</td>
<td>45°</td>
</tr>
<tr>
<td>1733</td>
<td>4.9°</td>
</tr>
<tr>
<td>2423</td>
<td>3.5°</td>
</tr>
</tbody>
</table>

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.

Form Factors in MCNP

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- Also improved incoherent scatter (similar feature for $q \geq 8\ \text{Å}^{-1}$).

- Still no photonuclear elastic scatter
  - No ENDF database

- Improvement not being maintained by nuclear data team at LANL.

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 $\gamma$-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:
LANL: John Hendricks, Morgan White, Laurie Waters and Steve Tobin
LBNL: Bernhard Ludewigt, Scott Ambers, Jim Siegrist, and Vladimir Mozin
LLNL: Lynn Kissel

This work received support from:
• The Offices of Proliferation Detection and Nonproliferation & International Security of the National Nuclear Security Administration, (NA-221)
• Next Generation Safeguard Initiative of the Office of Nonproliferation and International Security (DOE NA-241)
• Department of Homeland Security, TAR
• Advanced Fuel Cycle Initiative of the Office of Nuclear Energy (DOE NE)