What theoretical improvements are needed to model photonuclear reactions?

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Much of nuclear data is devoted to particles, i.e., neutrons – But photons matter too

- Reactions induced by the interaction of photons with nuclei are important for applications and fundamental science
  - Radiation shielding and radiation transport
  - Safeguards and inspection technologies
  - Nuclear waste transmutation
  - Fission and fusion reactors
  - Activation analyses
  - Dosing for radiotherapy
  - Stockpile stewardship
  - Nucleosynthesis in the cosmos

- Evaluated data in needed for photon-induced reactions on wide range of nuclei (nearly, the entire chart of the nuclides) with energies ranging from 0-200 MeV

Recent review: T. Kawano et al., Nucl. Data Sheets 163, 109 (2020)
Photons are different that particles

- **Particles interact strongly**
  - Reaction cross sections are computed using the optical potential
  - At high energies, particles can bring in high angular momentum

- **Photons interact electromagnetically**
  - These reactions are weaker than strong interactions
  - Photo-absorption is dominated by the E1 component
    - Angular momentum: \( J_{CN} = J_T \pm 1 \)
    - Parity switches: \( \Pi_{CN} = -\Pi_T \)
  - Structure can affect absorption for low-energy photons (nuclear fluorescence), especially for light nuclei
Nuclear data evaluations are driven by experimental data

- Several different experimental approaches
  - Mono-energetic beams
  - Bremsstrahlung
    - Photo-absorption cross section must be unfolded

- Complete channels can be difficult to separate
  - Neutron channels dominate
    - Charged particles are often lumped together in the neutron channels
    - Sometimes explicit neutron channels are not identified
    - Sometimes the neutron multiplicities are misidentified

- Experimental data can be incomplete or inconsistent
  - Modeling is needed for a complete evaluation
    - Resolve experimental discrepancies
    - Disentangle various channels
    - Fill in gaps from experiment
  - Modeling is needed for exotic nuclei

Modeling is only as good as the theory built into the models
Modeling of photonuclear reactions

- Hauser-Feshbach formalism
  - Compound nucleus decay
  - Pre-equilibrium emission

- Codes
  - EMPIRE
  - TALYS
  - CCONE
  - MEND-G
  - GLUNF
  - CoH₃
  - YAHFC

Codes mostly use the same physics with different implementations
Modeling of photonuclear reactions: Photo-absorption cross section

- Absorption is governed by the giant-dipole resonance (GDR) + quasi-deuteron photo-absorption (QD) (high-energy photons)
  \[ \sigma_{abs} = \sigma_{GDR} + \sigma_{QD} \]

- GDR component:
  - Collective resonance with energy: \( E_0 \sim 80 \ A^{1/3} \)
    - Strength function is generally inferred from photo-absorption data \( \sigma(\gamma, n) \)
    - Theory can give guidance for resonance energies, RPA, etc
  - Resonance widths \( \Gamma_i \)
    - \( \sim 4\text{-}6 \ MeV \)
    - Very difficult to compute theoretically

Cataloged ground-state resonance parameters for over 200 nuclei
The GDR is a collective mode generally described with Lorentzian functions

\[ \sigma_{GDR}(E_\gamma) = \sum_{i}^{N_R} \sigma_i \frac{E_\gamma^2 \Gamma_i^2}{(E_i^2 - E_\gamma^2)^2 + E_\gamma^2 \Gamma_i^2} \]

- For spherical nuclei, \( N_R=1 \)
- For deformed nuclei \( N_R=2 \)

\( N_R > 1 \) is due to deformation
- Dipole is composed of three collective modes along each of the three principal axes

\[ E_k = E_0 \frac{R}{R_k} \]

\[ = E_0 e^{-\sqrt{\frac{5}{4\pi}}\beta \cos(\gamma + \frac{2\pi k}{3})} \]

- Angular momentum can induce deformation and split the dipole

Resonance parameters are nucleus dependent

The GDR depends on the nucleus – can’t just plug and play
Modeling of photonuclear reactions: Advanced treatments of the GDR

- Beyond simple Lorentzian
  - $\Gamma_\gamma$ for neutron capture tells us something about the low-energy behavior
  - Simple Lorentzian is usually inadequate at low energy
    - Modifications to the Lorentzian – increase EM strength function for $E_\gamma < S_n$
      - Simple modified Lorentzian [At. Nucl. Data Tables 97, 567 (2011)]
  - Effects:
    - $(n,\gamma)$ cross section
    - Low-energy photonuclear reactions, $E_\gamma < S_n$
    - Determines the emitted $\gamma$-spectra
  - Are these modifications E1 or M1?
    - Shell model calculations in the fp-shell indicate that it might be M1 and reasonably describe experimental observations
  - Slight caveat: This is also tangled up with level density models and neutron transmission coefficients

Better understanding of low-energy behavior is needed
Modeling of photonuclear reactions: More advanced treatments of the GDR

- **Warning!** For lighter nuclei, the GDR might not be well represented by the simple sum of a few Lorentzians
  - For $^{40}$Ca data 10 resonances are needed to reconstruct the data

- Microscopic theories for nuclei with no data:
  - Resonance energies
    - RPA
    - Ab initio theories based on coupled-clusters
  - Width is more difficult as it is beyond 1p-1h
  - Difficult to do properly as these 1p-1h excitations

Better microscopic theories could be helpful for light nuclei
Modeling of photonuclear reactions: Quasi-deuteron photo-absorption

- Quasi-deuteron photo-absorption
  \[ \sigma_{QD}(E_\gamma) = L \frac{NZ}{A} \sigma_d P_b \]
  - \( L=6.5 \), adjusted to data and is rarely fine-tuned for specific cases
  - The deuteron photo-disintegration cross section, \( \sigma_d \)
  - Pauli-blocking factor, \( P_b \). (fit to an expensive full-scale calculation)

Modeling of photonuclear reactions: Nuclear Decay

- Two decay components
  - Compound
  - Pre-equilibrium

- Compound nucleus emission
  - Statistical decay with Hauser-Feshbach
    - Level densities
    - Transmission coefficients for particle emission
      - Optical potentials work well
    - EM strength functions
      - Same as for photo-absorption
      - Transition from continuum to discrete states
    - Fission model
      - Fission models are not predictive
      - Try to reproduce \((n,f)\) and \((\gamma,f)\) simultaneously
        - Also, across isotopic chains

Photonuclear reactions use the same physics as neutron reactions
Pre-equilibrium emission
- Most modeling codes use the exciton model
- Many codes use neutron pre-equilibrium as a surrogate, i.e., they take the initial configuration as 1p-0h or 2p-1h
- CoH₃ starts at 1p-1h for GDR and 2p-2h for QD
- Note though that overall, the pre-equilibrium component is small relative to the total

There is a general weakness in HF modeling for pre-equilibrium and neutron inelastic scattering

Consistency is needed – and perhaps a better model

FIG. 7. (Color online) Calculated $^{183}$Ta(γ, n) and (γ, 2n) cross section when the initial exciton configuration is 1p-0h (solid), 1p-1h (dashed), and 2p-1h (dot-dashed). The calculated cross sections are shown by the ratios to the CoH₃ default calculation.

Modeling of nuclear reactions: Modeling $^{238}\text{U}$: n and $\gamma$ reactions

Often photonuclear has better data for “absorption” cross section
Modeling of nuclear reactions:
Modeling $^{238}$U: n and $\gamma$ reactions

Fission parameters “fit” to (n,f) only, but derived from $^{238}$U (n,f), $^{237}$U (n,f), and $^{236}$U (n,f) data

Consistency between (n,f) and ($\gamma$,f) to $\sim$ 10-15%
Modeling of nuclear reactions: Modeling $^{238}\text{U}$: n and $\gamma$-2n reactions

![Graph](image_url)
Modeling of nuclear reactions: Role of the GDR absorption cross section

Uncertainties in $\sigma_{GDR}$ limits ability to predict where there is no data
GDR strength function at high excitation energy and angular momentum

- GDR at high excitation energy and high angular momentum
  - Axel-Brink hypothesis states that the GDR is built on all states
    - Depends on the properties of the state, i.e., is it deformed?
  - Intrinsic width might have a weak dependence on excitation energy
  - State density is high and is composed of all deformations
    - The GDR is an ensemble of the for all the states, including deformation weighted by Free energy

Phys. Rev. Lett. 76, 2025 (1993);
Summary

- Better understanding of the photo-absorption cross section to provide better local accuracy – centroids, widths, and strength
  - Low-energy enhancements to strength function
    - Microscopic theories
  - Strength function for high excitation energy

- Compound decay relies on the same physics as neutron reactions
  - Level densities
  - Particle transmission coefficients
  - EM strength functions
  - Fission models
  - Transition from continuum gamma rays to discrete states
  - Possibility of isospin and K conservation

- Pre-equilibrium decay
  - Better understanding and consistency for initial configurations
  - But we should do better than the exciton model
    - Could be computationally expensive
    - Will also improve our understanding of neutron inelastic scattering

Need improved understanding of $E_x$ and $J$ dependence in models