What theoretical improvements are needed to model photonuclear reactions?

WANDA 2022

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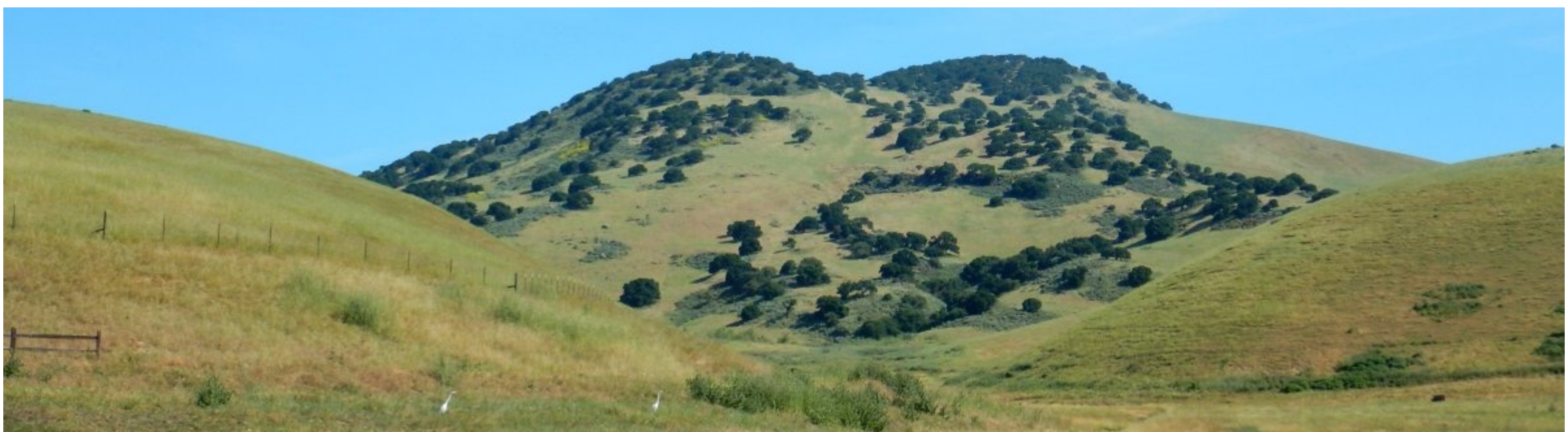
March 2, 2022



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
  - CoH_3
  - 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 Γ_i
    - ~ 4-6 MeV
    - Very difficult to compute theoretically

Cataloged ground-state resonance parameters for over 200 nuclei

Modeling of photonuclear reactions: Giant Dipole Resonance

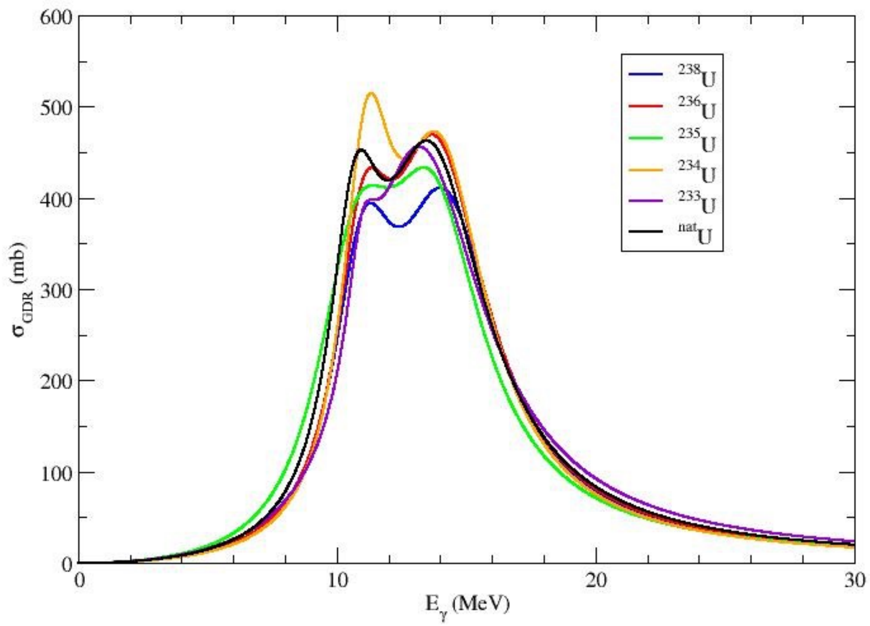
- The GDR is a collective mode generally described with Lorentzian functions

$$\sigma_{GDR}(E_\gamma) = \sum_i^{N_R} \sigma_i \frac{E_\gamma^2 \Gamma_i^2}{\left(E_i^2 - E_\gamma^2\right)^2 + E_\gamma^2 \Gamma_i^2}$$

  - 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

$$E_k = E_0\, R/R_k$$
$$= E_0 e^{-\sqrt{\frac{5}{4\pi}}\beta\cos\left(\gamma+\frac{2\pi k}{3}\right)}$$

    - 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

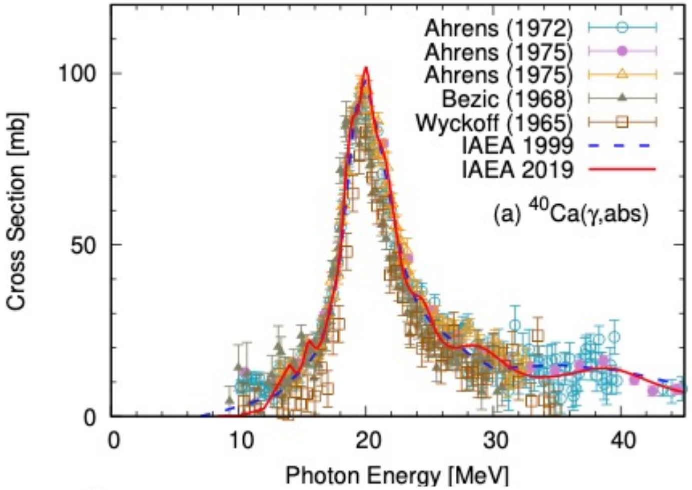
Modeling of photonuclear reactions: Advanced treatments of the GDR

- Beyond simple Lorentzian
  - Γ_γ 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 $E_\gamma < S_n$
      - Generalized Lorentzian [Phys. Rev. C 47, 312 (1993)]
      - Simple modified Lorentzian [At. Nucl. Data Tables 97, 567 (20111)]
  - Effects:
    - (n,γ) cross section
    - Low-energy photonuclear reactions, $E_\gamma < S_n$
    - Determines the emitted γ-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

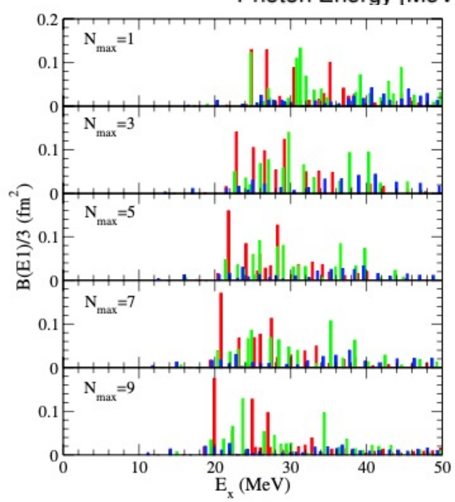
Better understanding of low-energy behavior is needed

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



Nucl. Data Sheets **163**, 109 (2020)



NCSM calculation of the ^{10}B GDR strength, M. Kruse, *et al.*, Eur. Phys. J. A 55, 225 (2019)

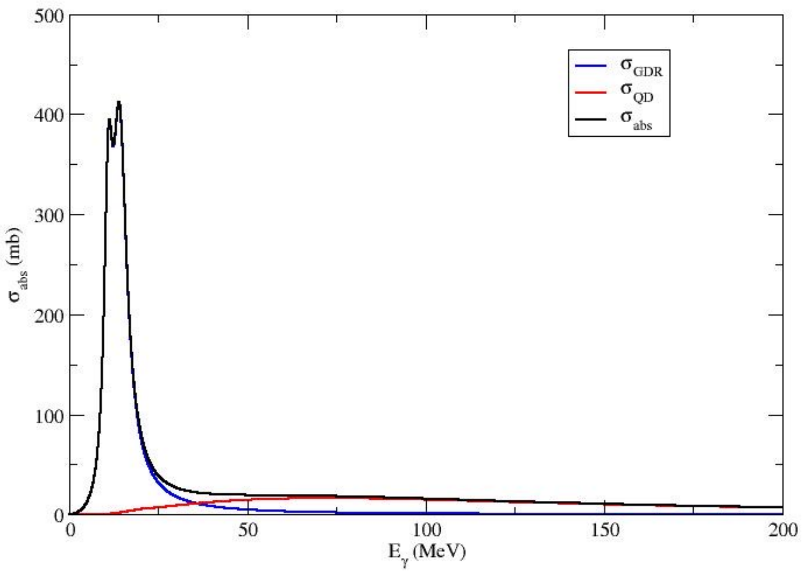
Better microscopic theories could be helpful for light nuclei

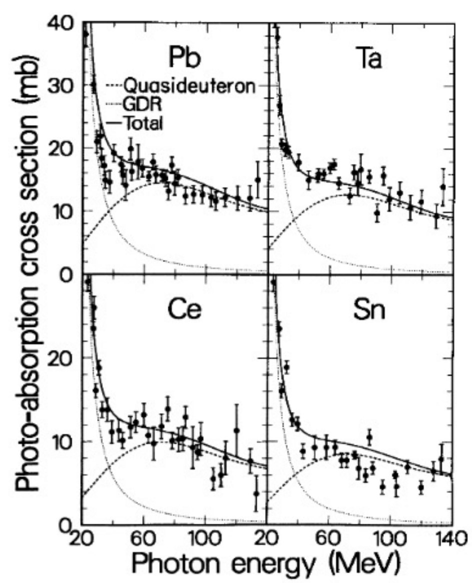
Modeling of photonuclear reactions: Quasi-deuteron photo-absorption

- 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 fined tuned for specific cases
  — The deuteron photo-disintegration cross section, σ_d
  — Pauli-blocking factor, P_b, (fit to an expensive full-scale calculation)

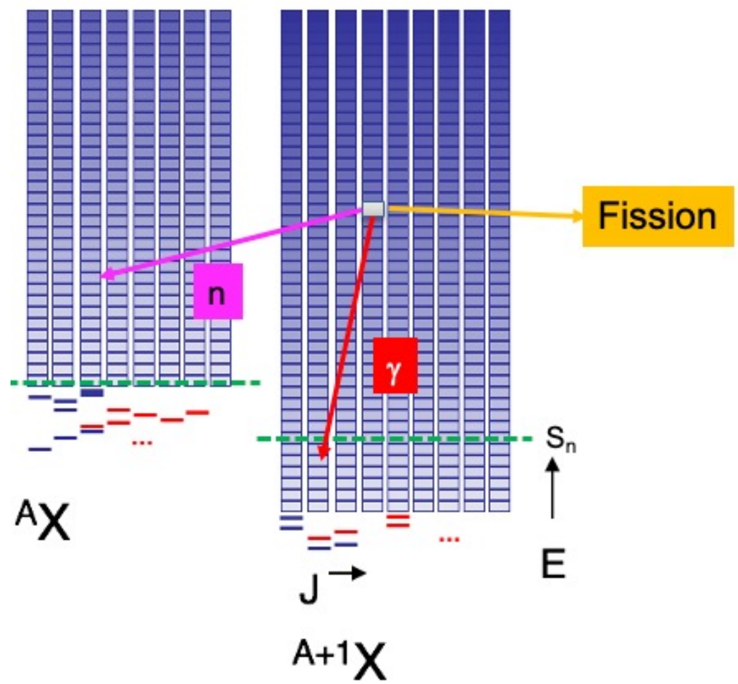




M. Chadwick, *et al.*, Phys. Rev. C **44**, 814 (1991)

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 (γ,f) simultaneously
        - Also, across isotopic chains



Photonuclear reactions use the same physics as neutron reactions

Modeling of photonuclear reactions: Nuclear Decay – Pre-equilibrium

- 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
  - CoH_3 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

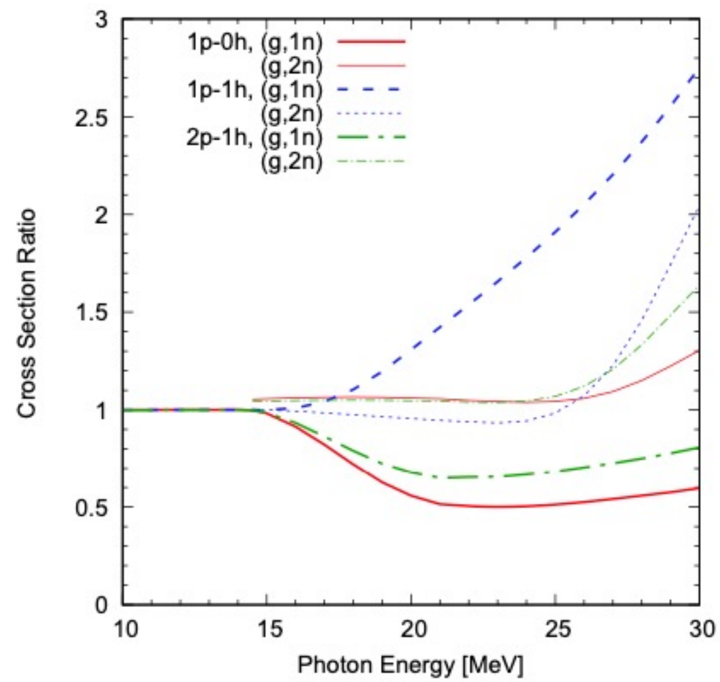
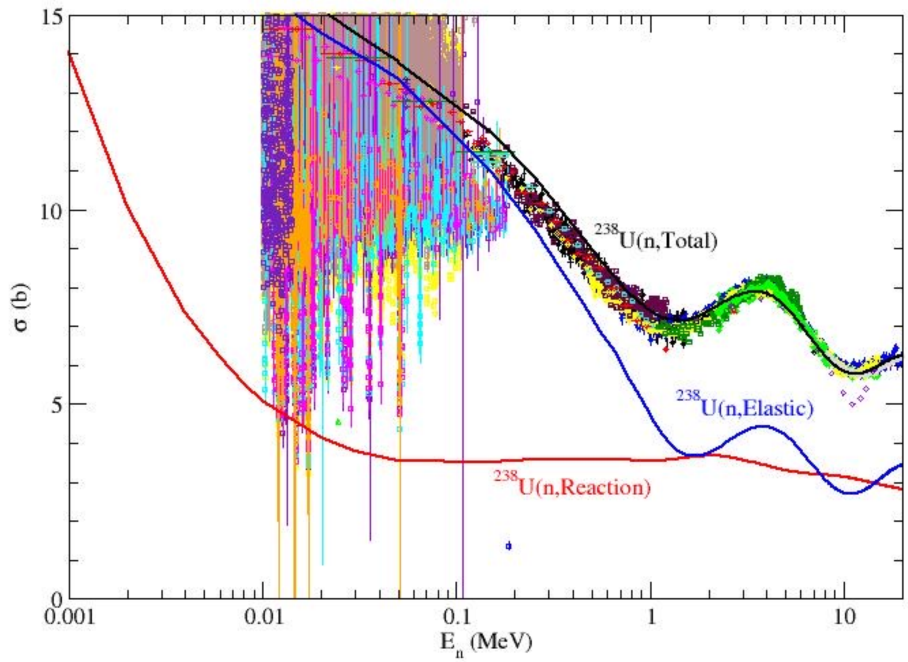


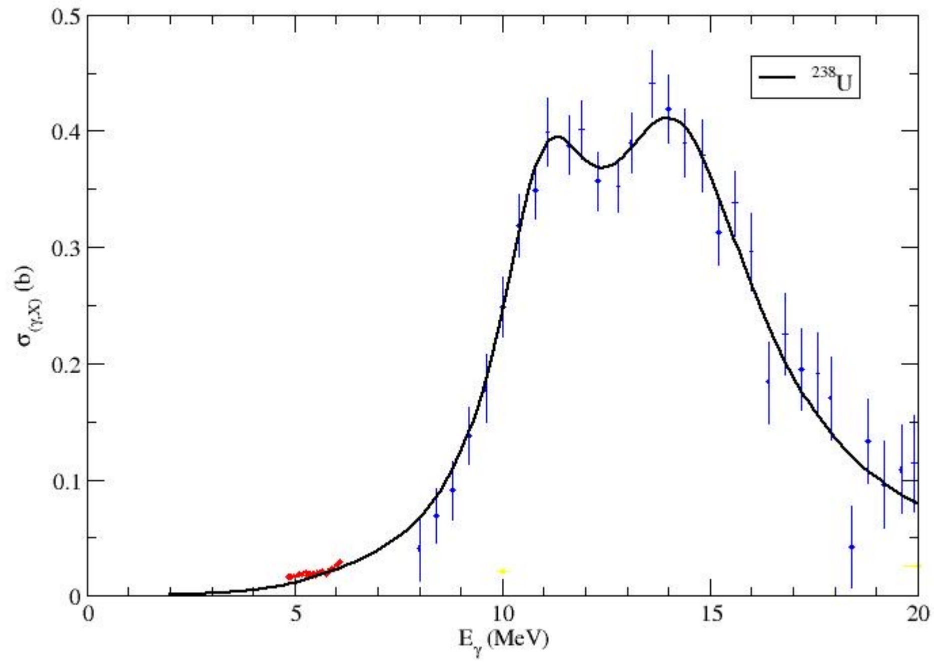
FIG. 7. (Color online) Calculated ^{181}Ta(γ, n) and ($\gamma, 2n$) cross section when the initial exciton configuration is $1p$-$0h$ (solid), $1p$-$1h$ (dashed), and $2p$-$1h$ (dot-dashed). The calculated cross sections are shown by the ratios to the CoH_3 default calculation.

T. Kawano, *et al.*, Nucl. Data Sheets 163, 109 (2020)

Consistency is needed – and perhaps a better model

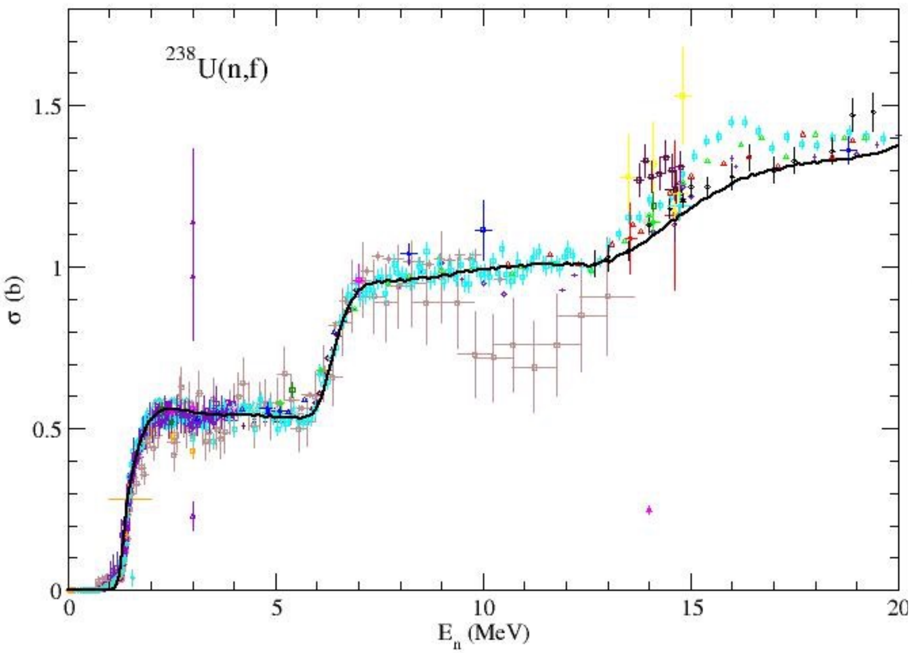
Modeling of nuclear reactions:
Modeling ^{238}U: n and γ reactions

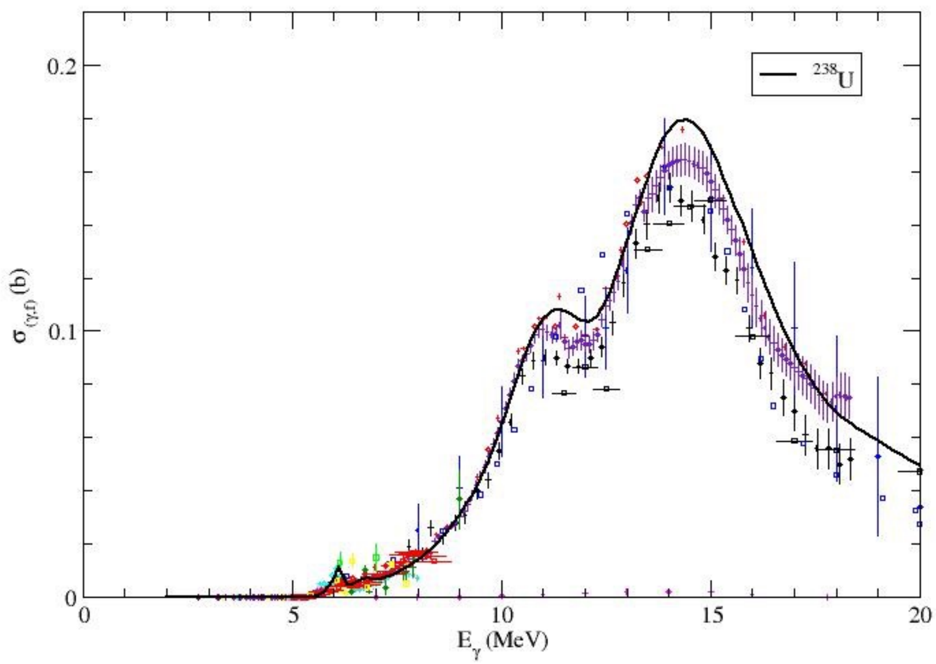




Often photonuclear has better data for "absorption" cross section

Modeling of nuclear reactions: Modeling ^{238}U: n and γ reactions

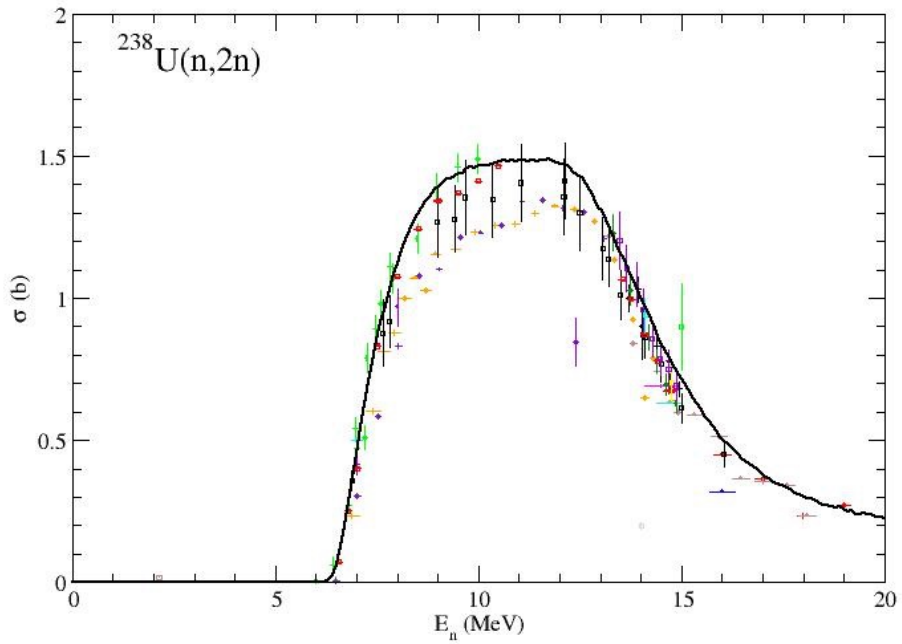


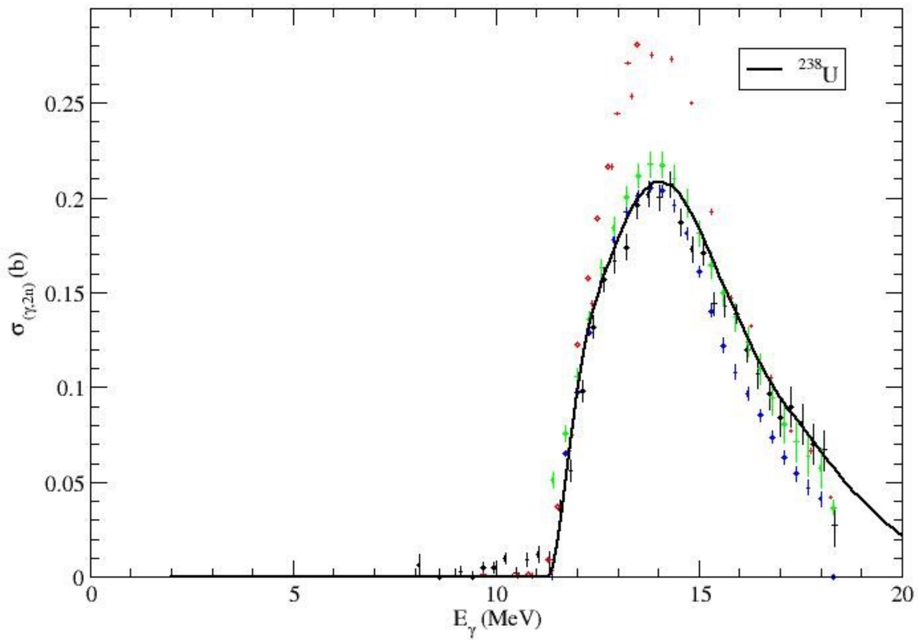


Fission parameters “fit” to (n,f) only, but derived from ^{238}U (n,f), ^{237}U (n,f), and ^{236}U (n,f) data

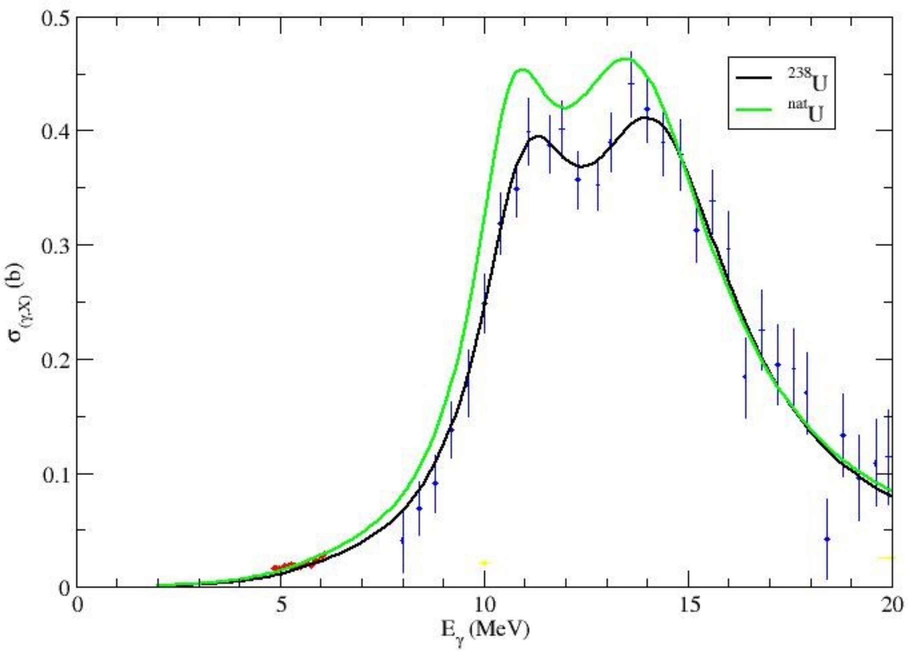
Consistency between (n,f) and (γ,f) to ~ 10-15%

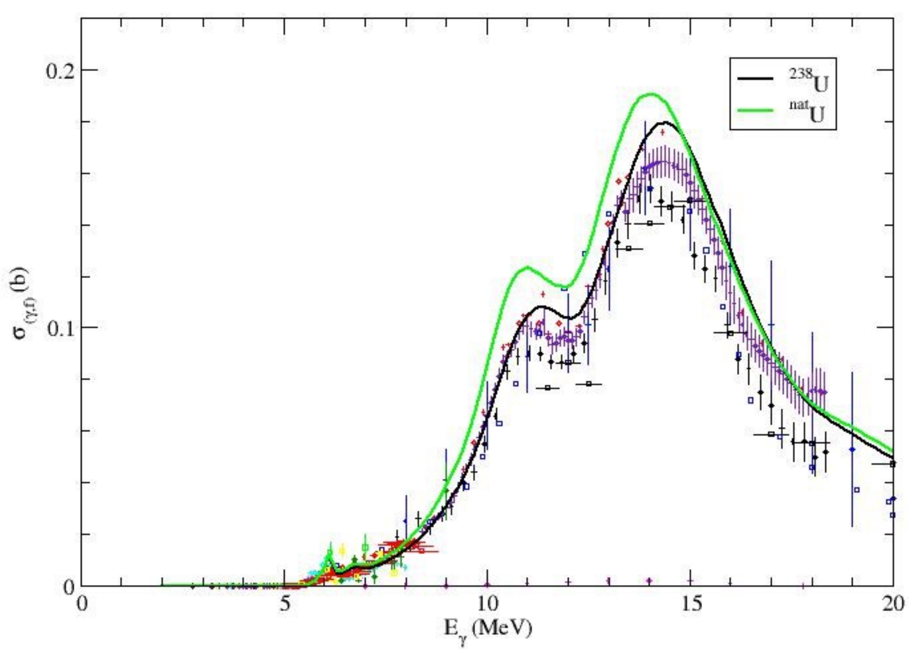
Modeling of nuclear reactions:
Modeling ^{238}U: n and γ-2n reactions





Modeling of nuclear reactions:
Role of the GDR absorption cross section

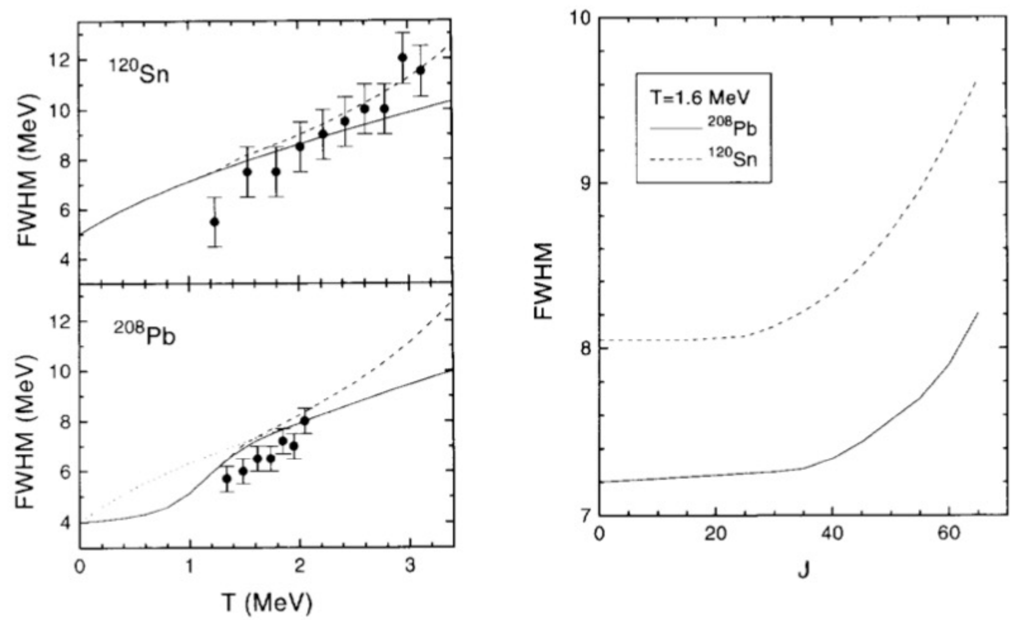




Uncertainties in σ_{GDR} limits ability to predict where there is no data

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);
Nucl. Phys. A **614**, 217 (1997)

GDR strength function broadens with excitation energy and J

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