Available Photonuclear Reaction Data and Libraries, and Evaluation Method

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Major Photonuclear Data Libraries

- IAEA photonuclear data library released in 1999
  - IAEA Coordinated Research Project, chaired by M.B. Chadwick
  - 164 isotopes evaluated based largely on model calculations (GNASH and others)
- ENDF photonuclear data library adopted IAEA1999 with some upgrades
- JENDL photonuclear data libraries
  - older evaluations by ALICE-F, and upgraded by CCONNE

- IAEA 2019
  - New IAEA CRP, including both the photon strength function and photonuclear data library
  - 219 isotopes, extended photon energy of 200 MeV
  - Nuclear Data Sheets 163, 109 (2020)
IAEA Photonuclear Data Library 2019

- New experimental data provided by NewSUBARU, Laser Compton Scattering Facility by Utsunomiya
- Evaluation of existing experimental data by Varlamov
  - Neutron-counting experiments, \((g,1n)\), \((g,2n)\) etc, sometimes show cross-talk between different reaction channels
  - They were “corrected” by CPNRM, and data in EXFOR marked as “evaluated”
- Evaluated data produced by several institutes with different HF codes
  - Cho (KAERI) uses TALYS
  - Filipescu et al. (IFIN-HH), EMPIRE
  - Iwamoto (JAEA), CCONÉ
  - Xu et al. (CIAE), GLUNF for light elements, MEND-G for medium to heavy
  - Kawano (LANL) didn’t produce actual files but performed calculations with CoH₃
Available Experimental Data

- **Bremsstrahlung**
  - continuous energy spectrum requires unfolding
  - quasi mono-energetic photons by tagging - U. Illinois

- **Positron annihilation produces quasi mono-energetic photons**
  - Saclay and LLNL

Data are available in EXPOR, but need some interpretation

- **Laser Compton scattering - NewSUBARU**

- **HIgS (TUNL), ELI (EU)**
Typical Evaluation Method, Light Element

- R-matrix analysis very limited (no evaluation in IAEA2019)
- Hybrid method
  - Photo-absorption cross section taken from experimental data
  - Hauser-Feshbach statistical decay calculation

Typical Evaluation Method, Light Element

(a) $^9\text{Be}(\gamma, \text{abs})$  
(b) $^9\text{Be}(\gamma, n2\alpha)$
Evaluation Method, Medium to Heavy Nuclei

- Full Hauser-Feshbach model calculation
  - Photo-absorption = Giant Dipole Resonance + Quasi-Deuteron model
    - GDR parameterized by Lorentzian
      \[ \sigma_{GDR} = \sigma_R \frac{E_\gamma^2 \Gamma_R^2}{(E_R^2 - E_\gamma^2)^2 + E_\gamma^2 \Gamma_R^2} \]
    - QD photo-absorption by Levinger, Chadwick, at higher energies
      \[ \sigma_{QD} = L \frac{NZ}{A} \sigma_d P_b \]

\[ \text{Cross Section [mb]} \]
\[ \text{Photon Energy [MeV]} \]

(a) $^{139}\text{La(}\gamma,1\text{nX)}$

(b) $^{139}\text{La(}\gamma,2\text{nX)}$

(c) $^{139}\text{La(}\gamma,3\text{nX)}$
Evaluation Method, Actinide

- All actinide evaluations in IAEA2019 evaluated by Iwamoto with CCONE
- Photo-fission calculated with Hauser-Feshbach
- or taken from neutron-induced library

(b) $^{239}\text{Pu}(\gamma,f)$

(c) $^{239}\text{Pu}(\gamma,\text{xn})$
Data Compilation and Representation

- Two approaches to store all the calculated results in an evaluated file
  - **Inclusive**: Total absorption cross section given in MF3 MT5 (3), then production of residual nuclei and/or emitted particles given in MF6
  - **Exclusive**: Cross sections for each channel given in MF3
- There are 6 different data representation given in IAEA2019 (IAEA-NDS-0232)

![Graphs showing cross section and multiplicity](image)

- Cross section [mb] vs. Photon Energy [MeV]
- Multiplicity vs. Incident photon energy [MeV]

**7Li**

This is not the issue, but often causes problems when compared with experimental data.
Data Processing Issue

- NJOY problem reported in IAEA-NDS-0232
  - Angular distribution of secondary particles not correctly handled
  - This was probably caused by the data format in IAEA1999
    - Evaluation performed with the GNASH code
    - Pre-equilibrium angular distributions given by Kalbach’s systematics
    - NJOY implicitly assumes Kalbach’s parameters are given,
    - while new evaluations give the Legendre coefficients
  - Already fixed by W. Haek (LANL), and updated NJOY available
Need More Development in Theories

- R-matrix analysis, if possible, including photon channels

- Better GDR parameters predicted by nuclear structure theories, such as QRPA or FAM, when experimental data are unavailable (Sasaki, arXiv:2202.13214)

- High energy photon reactions still uncertain
  - Pre-equilibrium process for photon-induced reaction still uncertain
    - angular distributions by mimicking neutron-induced reaction
  - Quasi-deuteron cross section parameterized by Chadwick adopted all the codes
    - photo-absorption cross sections identical at higher energies

- Evaluated experimental data include model calculation
  - Correction factor depends on the model employed
  - This may cause some uncertainties if evaluation performed based on the corrected data
Missing Photo-Fission Gamma Production

- Prompt fission neutron spectrum given, However, MF6/MT5 for ZAP = 0 includes channels other than fission only
  - Fission gamma multiplicities should be ~ 7
- LANL model, published in PRC by Lovell et al., is able to produce the fission gamma-rays, at least up to 20 MeV

A.E. Lovell, PRC 103, 014615 (2021)

H. Makii, PRC 100, 044610 (2019)
Concluding Remarks

- IAEA 2019 is the most updated photonuclear data library
  - International effort, evaluated by multiple institutes
  - Model-calculation-based evaluations, which include NewSUBARU data
  - GDR parameters compiled by Plujko et al. tabulated in the report

- Deficiencies in theoretical modeling
  - R-matrix for light elements
  - Pre-equilibrium process for photon-induced reactions
  - Angular distributions for secondary neutrons, protons, etc.
  - Photo-fission needs more work, both theory development and experimental data
    - prompt and delayed neutron energy spectra and multiplicities
    - prompt fission gamma