REVIEW OF PHOTONUCLEAR CROSS SECTIONS

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We provide an overview of recent efforts to create extensive library of photonuclear cross sections. An international project under the auspices of the IAEA produced the library of photonuclear cross sections for 164 isotopes (43 elements), mostly up to 140 MeV. This useful initial work served as the basis for the first US photonuclear cross-section library that is part of the new US Evaluated Nuclear Data File for nuclear science and technology, ENDF/B-VII.0, released in December 2006. We also briefly discuss future needs and challenges. Among them are measurements with tagged photons, strengthening of compilation, more extensive validation, and the need of better data for detection of explosives and active interrogation of special nuclear materials.

I. INTRODUCTION

Photons, commonly produced as bremsstrahlung radiation by electron accelerators, are of interest for a number of applications. These include radiation shielding, calculations of absorbed dose in the human body in radiotherapy, physics and technology of fission and fusion reactors, interrogation technologies to identify special nuclear materials, transmutation technologies and astrophysical nucleosynthesis.

In the past, the availability of photonuclear cross-section data was scattered and very limited. The first systematic effort to make the data available was carried out by the Photonuclear Data Center of the US National Bureau of Standards that compiled large amount of data produced during 1955-1982. These data were published in the form of abstracts and tables by NIST in 1983-1986 (Ref. 1). Very useful and popular was Berman’s atlas of photo-neutron cross sections published first in 1975 and then, with Dietrich, in 1988 (Refs. 2 and 3). In the past, considerable experimental activities were carried out at LLNL Livermore (USA), CEA Saclay (France) and also at Moscow State University (Russia). Compilation effort to include photonuclear data into the experimental cross-section library, EXFOR was started by MSU Moscow in 1980-ies, but only about 20% of data have been compiled so far.

Systematic efforts to create evaluated photonuclear cross section library were initiated only later, in 1990-ies. These projects are discussed in more detail in the present paper. Then, we will also briefly mention photonuclear data needs and future challenges.

II. PHOTONUCLEAR CROSS SECTIONS

Three extensive photonuclear evaluation efforts were duly completed and these are subject to our review. The first was an extensive IAEA international project completed in 2000, followed by much smaller Japanese effort completed after numerous delays in 2004. The most recent was the US effort that produced the first US evaluated photonuclear data library in 2006.

All these libraries in general extend up to 140-150 MeV energy, the pion threshold, and provide photonuclear cross section data, energy spectra and angular distribution of emitted particles that are needed for radiation transport calculations.

II.A. IAEA Photonuclear Data Library

The IAEA Coordinated Research Project, CRP, on photonuclear data for applications was conducted in the period of 1996-1999. The project was chaired by M. B. Chadwick (LANL), its scientific secretary was P. Oblozinsky (then IAEA, since March 2000 at BNL) and its participants included A. I. Blokhin (IPPE Obninsk, Russia), T. Fukahori (JAERI, Japan), YongOuk Lee and Y. Han (both KAERI, Korea), M. N. Martins (University of Sao Paulo, Brazil), S. Mughabghab (BNL), V. V. Varlamov (MSU Moscow, Russia) and B. Yu and J. Zhang (both CIAE Beijing, China).

The IAEA project produced the photonuclear data library, formally made available in 2000, and described in an extensive technical document.[4] The IAEA library covers large amount of isotopes of practical interest. Among them are structural, shielding and bremsstrahlung target materials, biological, fissionable and other materials. The library includes data for 164 isotopes (materials) which belong to 43 elements. These are

- structural, shielding and bremsstrahlung target materials: Be, Al, Si, Ti, V, Cr, Fe, Co, Ni, Cu, Zn, Zr, Mo, Sn, Ta, W, Pb,
- biological materials: C, N, O, Na, S, P, Cl, Ca,
- fissionable materials: Th, U, Np, Pu, and
- other materials: H, K, Ge, Sr, Nb, Pd, Ag, Cd, Sb, Te, I, Cs, Sm, Tb.

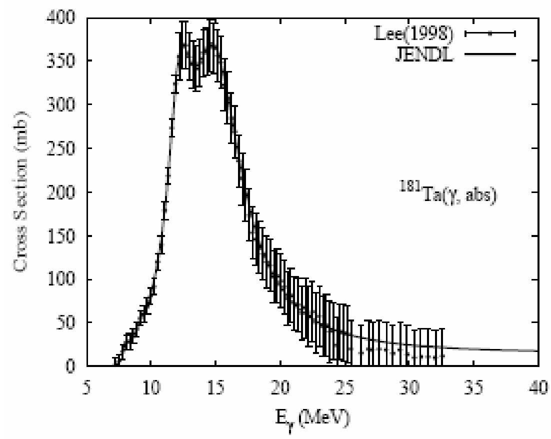

Fig.1. Photo-absorption cross-section on ^{181}Ta compared with the experimental data at low energies.

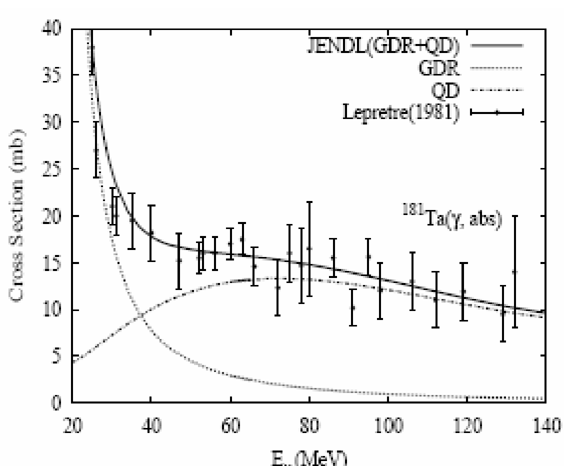

Fig.2. Photo-absorption cross-section on ^{181}Ta compared with the experimental data. The Giant Dipole Resonance (GDR) model dominates at low energies, while the Quasi-Deuteron (QD) model dominates above ~40 MeV.

The evaluation methodology was based on the recent advances included in the nuclear reaction model code GNASH by Chadwick, LANL, described in more detail in Ref. 5. The code GNASH incorporated two models for photo-absorption, the giant dipole resonance model at low energies, and the quasi-deuteron model[6] that dominates the high energy region starting from about 30-40 MeV. In addition, particle emission was properly modeled to handle preequilibrium photonuclear reactions and recently developed formalism for angular distribution in photonuclear reactions was implemented.

As an example, photo-absorption cross sections on ^{181}Ta, one of the few cases where data are available over extended range of incident photon energies, are shown in Figs.1 and 2.

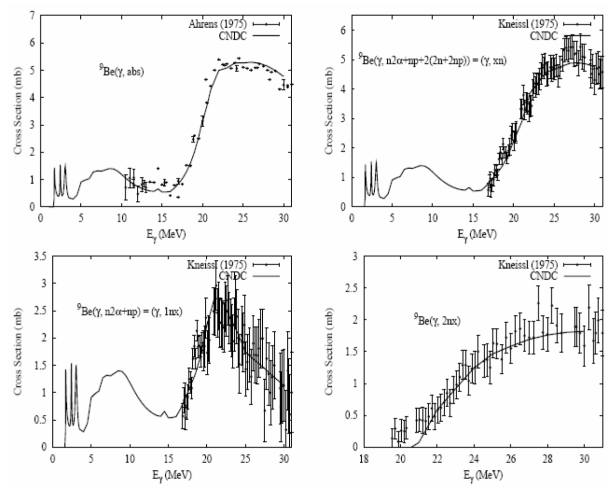

Fig.3. Photonuclear reactions on ^{9}Be: Shown clockwise from top left are photo-absorption, (γ, nx), (γ, 2nx) and (γ,1nx) cross sections. The experimental values are compared with the evaluations.

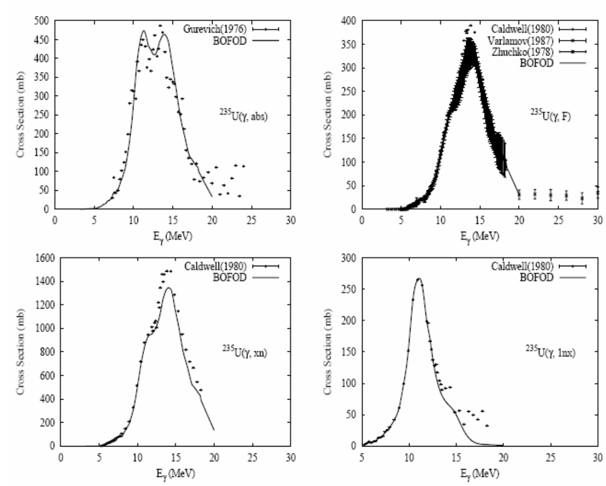

Fig.4. Photonuclear reactions on ^{235}U: Shown clockwise from top left are photo-absorption, fission, (γ,1nx) and (γ, nx) cross sections. The experimental values are compared with the evaluations.

For light nuclei and actinides specific approaches were used. In the case of light nuclei the evaluations were driven by experimental data with a limited addition provided by the theory. An example is shown in Fig. 3 illustrating the case of ^{9}Be which is of particular interest due to very low threshold energy (evaluated by the China Nuclear Data Center, CNDC). Photo-fission evaluations were based on the statistical model incorporated in the code developed by A. Blokhin, IPPE Obninsk in Russia. As an example, evaluations of photonuclear reactions including photo-fission on ^{235}U are shown in Fig.4 (evaluated for the Russian photonuclear library, BOFOD).

II.B. Japanese Photonuclear Data Library

The Japanese photonuclear data library was released in 2004 as a part of the broader JENDL-3.3 library, Ref. 7. The project was motivated by data needs for shielding design of high-energy accelerators and high-energy gamma-ray therapy (Ref. 8). The amount of photonuclear data included in this library is considerably smaller than in the IAEA photonuclear library. The Japanese library includes data for 37 elements (68 isotopes) up to 140 MeV of incident photons. Although much smaller than the IAEA library, the Japanese photonuclear library contains data for 7 elements not covered by the IAEA photonuclear project:

- He, Li, B, F, P, Hg and Gd.

The JENDL evaluation methodology was based on the statistical nuclear reaction modeling and thus similar to that used in the IAEA project. The physics was very much the same and incorporated in the codes MCPHOTO and ALICE-F that were used in evaluations. It should be noted, though, that more detailed description of photo-absorption was adopted. In particular for light nuclei fairly detailed resonance description was used for photo-absorption rather than the smooth giant dipole resonance model description. Also experimental data were analyzed more extensively.

II.C. US Photonuclear Data Library

The US photonuclear data effort was concentrated at Los Alamos. First, LANL reviewed and checked all files included in the IAEA library by using the processing code NJOY. Formatting errors and other deficiencies were identified and corrected. Second, some files were replaced with better or more complete evaluations performed at LANL. Among them are new evaluations on deuteron (^{2}H) and on several important actinides (^{235,238}U, ^{237}Np, ^{239,240}Pu and ^{241}Am), see Ref. 9 for more detailed account.

Photonuclear cross sections and spectra have been evaluated by LANL through use of both measured data and nuclear model calculations. The use of nuclear reaction theory facilitates the evaluation of the energy-spectra of the emitted particles. This is important since there are only a limited number of measurements for mono-energetic incident photons containing this information. Thus, in addition to reaction cross sections the US library contains secondary energy and angle spectra and it is suitable for use in radiation transport calculations. New actinide evaluations include also the average number of neutrons per fission (nubar), both prompt and delayed, of interest for active interrogation of special nuclear materials using small electron accelerators.

The US photonuclear data library was released in December 2006 as a part of the new general purpose library ENDF/B-VII.0 (Ref. 9). The photonuclear library includes evaluations for 163 materials (isotopes) covering 42 elements that extend mostly up to 140-150 MeV energy, the pion threshold, though a few extend just up to 20-30 MeV.

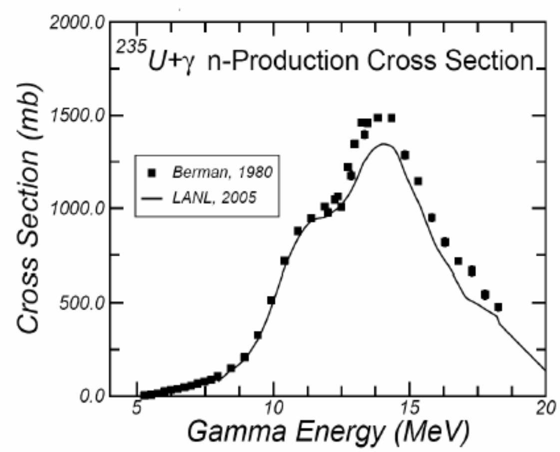

Fig.5. Neutron production cross sections for ^{235}U bombarded with photons up to 20 MeV. The LANL evaluation is compared with the experimental data.

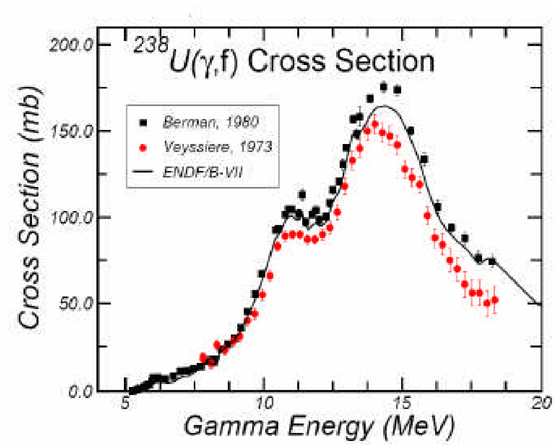

Fig.6. Photo-fission cross sections for ^{238}U bombarded with photons up to 20 MeV. The ENDF/B-VII evaluation by LANL is compared with the experimental data.

II.C.1. New Evaluations

Several examples of new evaluations of actinides performed at LANL by Chadwick et al. (for summary see Ref. 9), often in collaboration with CEA Saclay, are shown on Figs. 5-8 for incident photons up to 20 MeV. Fig.5 shows photo-neutron production cross sections for ^{235}U, and Fig.6 illustrates photo-fission on ^{238}U. Fig.7 deals with prompt nubars for ^{235}U, and Fig.8 illustrates delayed nubars for ^{239}Pu.

It should be noted that small, yet important, extension was made by BNL-LANL to meet data request for resonance absorption of 9.172 MeV photons on ^{14}N. These data are of interest for development of gamma resonance technologies to identify explosives.

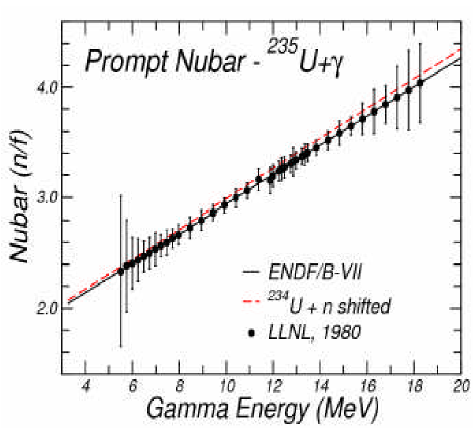

Fig.7. Average number of prompt neutrons emitted per fission (prompt nubar) from ^{235}U bombarded with photons up to 20 MeV.

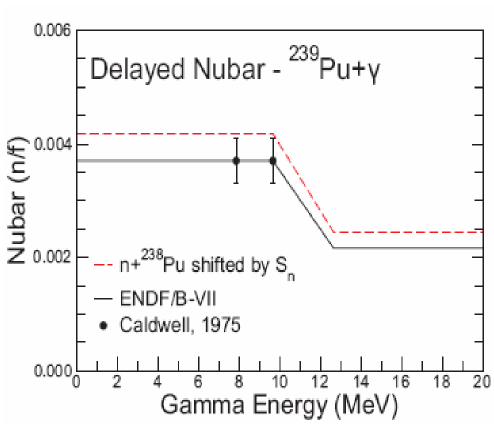

Fig.8. Average number of delayed neutrons emitted per fission (nubar) from ^{239}Pu bombarded with photons up to 20 MeV.

We note that there are similarities between neutron multiplicities (nubars) obtained from neutron-induced reactions and those from photonuclear reactions. A neutron-induced reaction on the target A-1, shifted by the neutron separation energy, should give approximately the same nubar as photonuclear reaction on target A. This can be seen in both Fig.7 and Fig.8.

II.C.2. Integral Validation

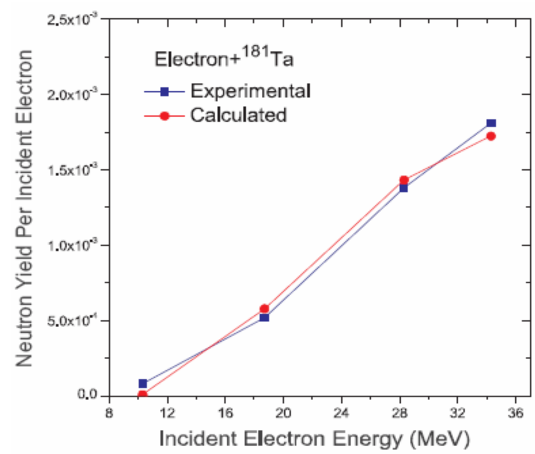

Fig.9. Neutron yield per incident electron on ^{181}Ta target as a function of the electron energy.

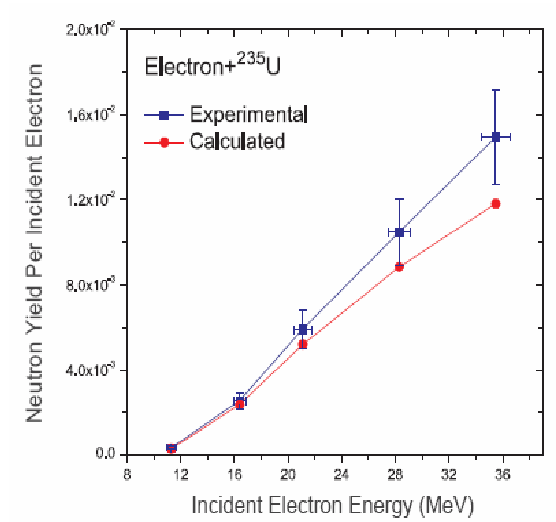

Fig.10. Neutron yield per incident electron on a 0.982 cm ^{235}U target as a function of the electron energy.

The US library was subject to integral validation for a limited number of cases. LANL used experimental data obtained by Barber and George[10] using a well-characterized electron source. In these experiments electrons were converted on a thick target to produce bremsstrahlung radiation, this was followed by neutrons produced from photonuclear reactions and finally neutron yields were measured.

Examples of neutron yields are shown in Figs. 9 and 10 where comparison between the calculated and experimental yields is made. This analysis was performed by Morgan White et al. (Ref. 11). A good performance can be seen for ^{181}Ta. In general, though, a more typical is the case of ^{235}U. Fig. 10 shows that the initial good agreement up to about 22 MeV is gradually replaced by differences that grow up to 20-30% at higher energies. These discrepancies need to be better understood since neutron yield is influenced by both photonuclear cross sections and also by electron to photon conversion, though it is likely that the major contribution comes from large uncertainties in neutron multiplicity.

III. FUTURE NEEDS AND CHALLENGES

We provide only a brief discussion of future needs and challenges in the area of photonuclear cross sections.

From the experience of all evaluation projects mentioned in the present review it is clear that better experimental data are needed. Modern techniques allow avoiding problematic unfolding procedures and rely on fairly clean tagged bremsstrahlung photon data where the incident photon energy is well defined.

In addition to the need for better measurements, we note that although a considerable amount of data were measured in the past, as much as ~80% of them have not been compiled to CSISRS/EXFOR database of experimental cross-section data. This represents a problem for evaluators who often rely on computerized databases that considerably facilitate modern evaluation process.

Another lesson from the evaluation projects is that more extensive validation should be done. Final judgment on the quality of evaluated data comes from the validation against integral experiments. Thus, the IAEA data have been released in 2000 without any validation. Also, as clearly seen in the case of the US photonuclear project, only limited validation was done so far. Once deficiencies are identified one should proceed with improved evaluation. These deficiencies were already identified for several actinides at electron energies above ~20 MeV.

A comment should be made on recent interest in the development and testing of technologies for security applications where photonuclear data are needed for simulation calculations. Among them is detection of explosives via the gamma resonance technology. Another one is active interrogation to identify special nuclear materials (SNM). As already indicated in the present review, better neutron multiplicities (nubars) are needed. Of special importance are delayed nubars as they provide a clear signature that the fission process took place and hence SNM must have been detected.

IV. CONCLUSIONS

Since 2000, three evaluated photonuclear cross-section libraries were completed and made available to users. First, the IAEA was released in 2000. This was followed by a much smaller, yet very useful, photonuclear data library incorporated into JENDL-3.3 library and made available in 2004. Still more recently, in December 2006, the first US photonuclear cross-section library was released, as a part of the new ENDF/B-VII.0 library. Altogether, the three evaluated photonuclear cross-section libraries provide photonuclear data for almost 200 materials (isotopes) that correspond to 50 chemical elements, mostly up to 140-150 MeV.

The photonuclear data community faces several challenges. There is a need for measurements with tagged photons, where the incident photon energy is well defined. It would be most useful to intensify photonuclear data compilation to preserve the data for future use in a form of the computerized database. Validation of evaluated photonuclear data libraries should be done more extensively. Several specific photonuclear data needs are related to security applications, such as identification of explosives and active interrogation of special nuclear materials.

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