# Photonuclear Reactions in FLUKA: Cross Sections and Interaction Models

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**Abstract.** Photonuclear reactions, implemented in FLUKA about ten years ago, have opened the way to a more accurate design of electron accelerator shielding. Since then, they have been introduced also in other codes: but the FLUKA design, covering all nuclei over the whole energy range, remains still unique. The FLUKA scheme is based on several physical models corresponding to different energy ranges but partially overlapping to ensure continuity. All models are smoothly integrated in the FLUKA hadronic event generator. Here we will mainly focus on the FLUKA Giant Resonance total cross-section database, which has been derived from experimental data or from existing evaluations for 190 nuclides. For all other nuclei, excitation functions are obtained from parameterizations or by interpolation. Many partial cross sections, not used explicitly in FLUKA, have also been evaluated in order to ensure consistency of the total cross sections entered into the database. The FLUKA implementation of photonuclear reactions has been successfully benchmarked with activation and neutron spectrometry experiments, and is being widely used to design shielding and to predict radiation damage.

## INTRODUCTION

FLUKA was the first Monte Carlo particle transport code where photonuclear interactions were implemented over the whole energy range (MeV to TeV) [1], resulting in a program capable to simulate in an integrated way not only electromagnetic and hadronic cascades, but also the two-way coupling between them. For the first time calculation techniques that had already been used since many years only at proton machines could be applied also to the shielding design of electron accelerators.

To model photonuclear interactions, two basic ingredients were needed: a total energy-dependent cross section (interaction probability), and a set of nuclear interaction models (event generators). The design goal was to cover all existing stable nuclei.

## CROSS SECTION EVALUATION

### The First Phase

The existing FLUKA event generators (evaporation, Fermi break-up, preequilibrium, Generalized Intranuclear Cascade, Dual Parton Model) were easily adapted to work with a photon projectile. A Vector Meson Dominance model was added to describe photon interactions at the highest energies. Total cross sections were calculated using the Levinger Quasi-Deuteron (QD) model, or parameterized as a function of atomic and mass number. The interaction models have been described in [1].

On the other hand, at the time of the first implementation (1994), photonuclear cross-section data in Giant Dipole Resonance (GDR) energy range were scarce, especially total ones. Therefore it was necessary to set up a differentiated approach depending on the information available for each nuclide. In a first phase, $(\gamma,n)$ cross sections were accepted, when available, as a substitute for total cross sections of heavy nuclei, and a parameterized Lorentz curve was assumed as a default when no data were available at all.

However, this approach was not satisfactory for light nuclei, important in shielding and dosimetry. A systematic search of the literature was started [2] in order to compile a library of GDR total cross sections covering at least most light nuclei. All available experimental and theoretical information was used. In some cases total cross sections were approximated by the sum of $(\gamma,n)$, $(\gamma,p)$ and other known partial cross sections. All cross sections were extrapolated to zero at threshold and forced to join smoothly the QD cross-section curve at the upper end of the GDR range. Various consistency checks were done, such as that the $\sigma(\gamma,n)$ value should at all energies be $\leq$ the corresponding $\sigma(\gamma,tot)$ value, and that the measured cross section of a naturally occurring element, when available, should match the weighted sum of the cross sections of the single isotopes.

CP769, *International Conference on Nuclear Data for Science and Technology,*
edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou

## New Evaluated Data

The first phase of cross-section compilation and evaluation took several years, and was extended also to heavier nuclides. In the meantime, general interest in photonuclear reactions had increased, and such reactions began to be introduced also into other programs [4, 5]. In recent years, various groups of professional evaluators have provided a large number of photonuclear cross-section data sets. In particular, the IAEA Photonuclear Data Library [3] contains recommended evaluated photonuclear data for 164 isotopes, and other evaluated data from various laboratories. Also, many experimental data that had been difficult to access have become available via the EXFOR database.

Therefore it was decided to profit from this new situation to update and complete the FLUKA library. However, although the number of evaluated entries in the library has increased substantially, the evaluations that had already been done were not much affected. An example is shown in Fig. 1 where the old $^{4}$He cross section, obtained as the sum of $^{4}$He(γ,n)+(γ,p)+(γ,d)+(γ,2p2n) is compared with the present adopted curve based on direct measurements of the total cross section. In addition,

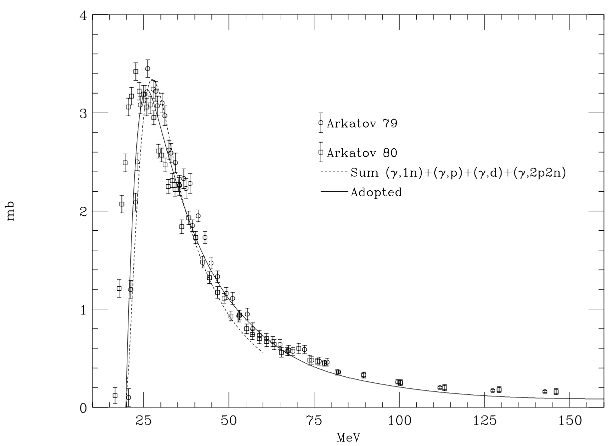


**FIGURE 1.** $^{4}$He(γ,tot).

when different data sets were available for the same nuclide, a choice was made based on a comparison with experimental data and on the usual consistency checks. This choice did not always coincide with the IAEA recommendations.

An illustration of the criteria used is seen in Figs. 2 and 3. The evaluations of the $^{238}$U total cross section by JENDL and BOFOD (the latter recommended by IAEA) were corrected in order to reproduce the available experimental results of $\sigma_{tot}(^{nat}\mathrm{U})$ [9].

The behavior near threshold, often neglected in many evaluated data sets, was accurately checked, in particular where fission contributed to the total cross section. An example can be seen in the same $^{238}$U cross-section

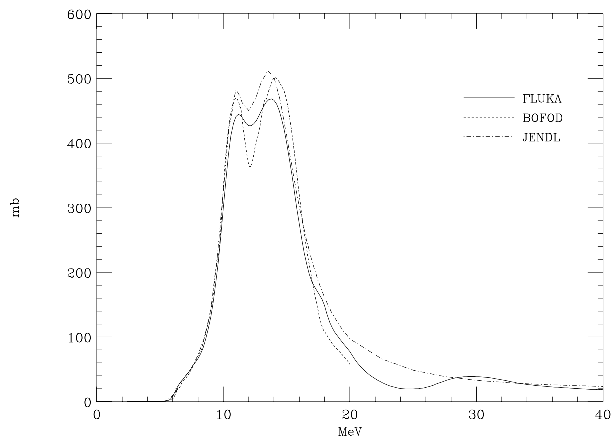


**FIGURE 2.** Comparison of adopted $\sigma_{tot}^{GDR}(^{238}\mathrm{U})$ with JENDL and BOFOD evaluations.

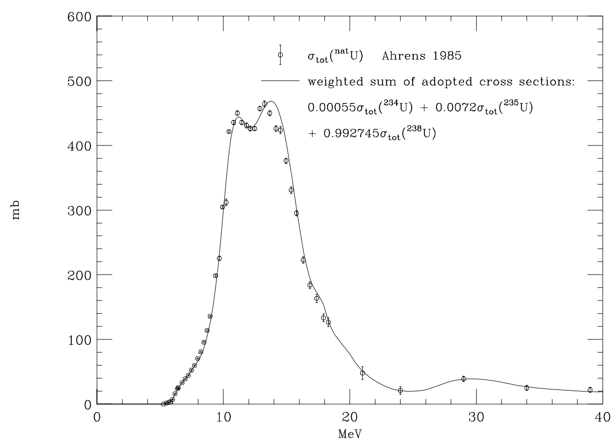


**FIGURE 3.** Experimental data for $^{nat}$U [9] compared with the weighted sum of adopted cross sections of the U naturally occurring isotopes.

curve, plotted in logarithmic scale (Fig. 4). An example of modifications due to consistency checks is shown in Figs. 5 and 6: the adopted cross section has been obtained as a reasonably weighted average of the existing evaluations, but experimental partial cross sections have been taken into account. Another type of consistency check, already seen in Figs. 2 and 3, uses available experimental cross sections of a natural element to constrain the cross section of a single isotope. Another example is shown for $^{88}$Sr in Figs. 7 and 8. A special case is that of $^{12}$C, $^{14}$N and $^{16}$O, three nuclei of great importance in dosimetry and environmental radiation protection for which the total cross section has been directly measured [6, 7]. For these nuclides, very elaborate corrections have been made by Fuller [8], which apparently have not been taken into account in the existing evaluations (Fig. 9).

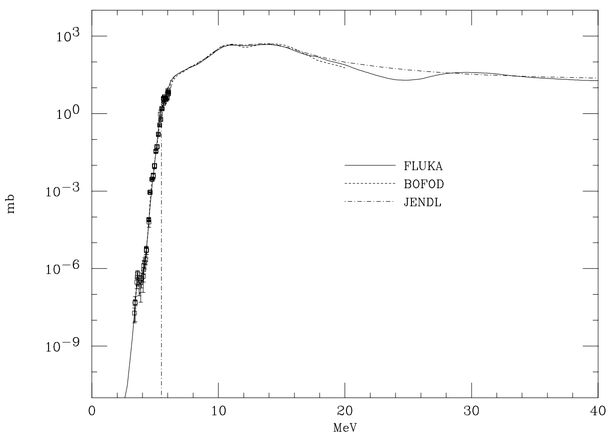


**FIGURE 4.** $\sigma_{tot}^{GDR}(^{238}U)$ in log scale, showing the low-energy threshold for photofission.

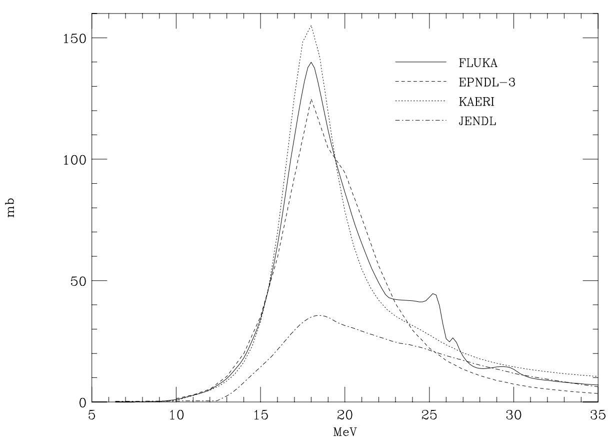


**FIGURE 5.** $\sigma_{tot}(^{58}Ni)$ compared with other evaluations. Note the adjustment to ensure it is not smaller than either $\sigma(\gamma,n)$ or $\sigma(\gamma,p)$ (Fig. 6).

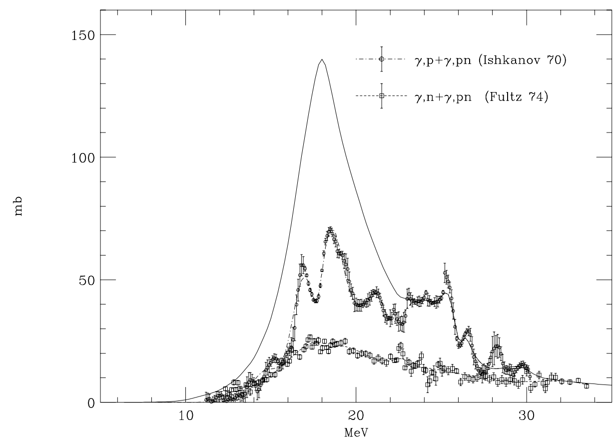


**FIGURE 6.** $\sigma_{tot}(^{58}Ni)$, $\sigma(\gamma,n)$ [14] and $\sigma(\gamma,p)$ [15].

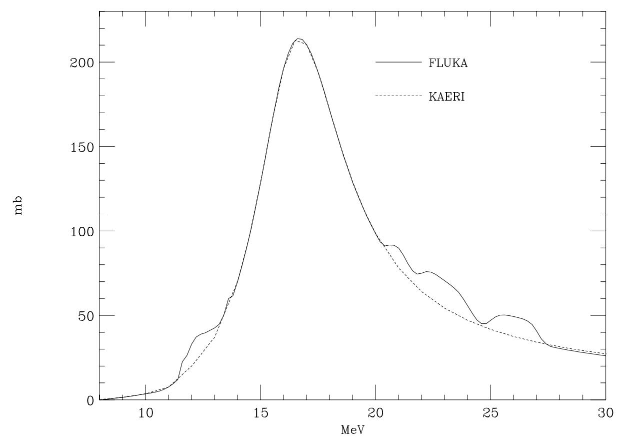


**FIGURE 7.** $\sigma_{tot}(^{88}Sr)$ compared with the KAERI evaluation. Note the adjustment to ensure it is compatible with $^{nat}Sr(\gamma,n)$ (Fig. 8).

The present library contains total cross-section data for 190 nuclides (see Fig. 12). All stable nuclides with $Z < 31$ are present, with the exception of $^{50}V$. It is to be noted that isotopes such as $^{13}C$, $^{15}N$, $^{17}O$ and $^{18}O$ have not been disregarded (unlike done in other codes): although rare, their contribution to neutron production can be important, due to their low photoneutron threshold. Figs. 10 and 11 show how FLUKA cross sections, derived from a same publication, appear to be in very different agreement with KAERI evaluations.

## The Library Structure

The GDR cross-section library has been designed to provide maximum computing efficiency when used in FLUKA. Since the GDR energy range covers only about one decade (≈6 to 60 MeV), the format chosen has not been a standard one such as ENDF, but a simple linear 0.2 MeV mesh. This structure presents two advantages: a very fast look-up without array search, and no need to store an array of energies. The only data needed are: an energy threshold (rounded to the closest 0.2 MeV) and the number N of data points, followed by N cross-section values (total cross section minus the QD component).

## ACKNOWLEDGMENTS

Part of this work was supported by the Department of Energy under contract DE-AC02-76SF00515.

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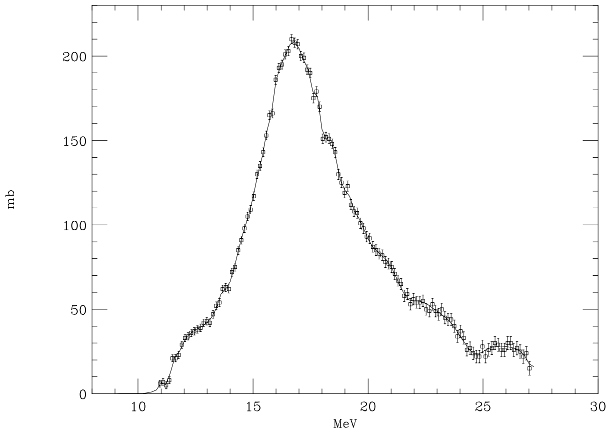


**FIGURE 8.** $^{nat}$Sr(γ,n) [16].

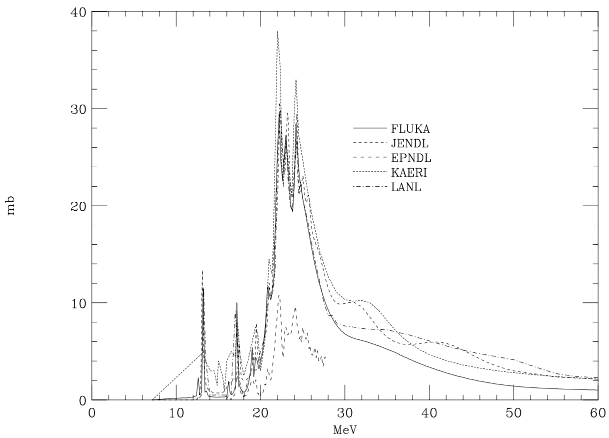


**FIGURE 9.** $\sigma_{tot}$ ($^{16}$O) according to [6] (corrected by [8]), compared with evaluated data.


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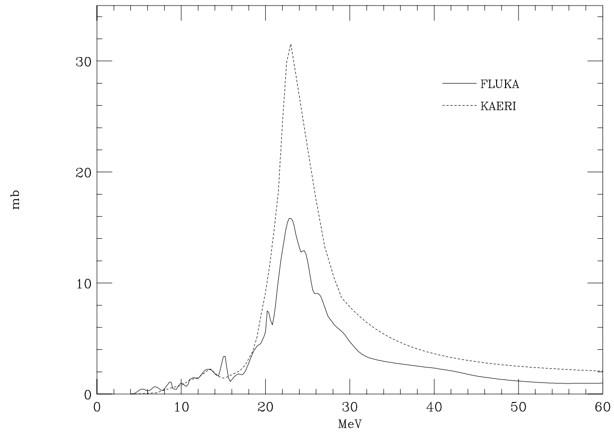


**FIGURE 10.** $\sigma_{tot}$ ($^{17}$O) according to [10], compared with KAERI evaluated data.

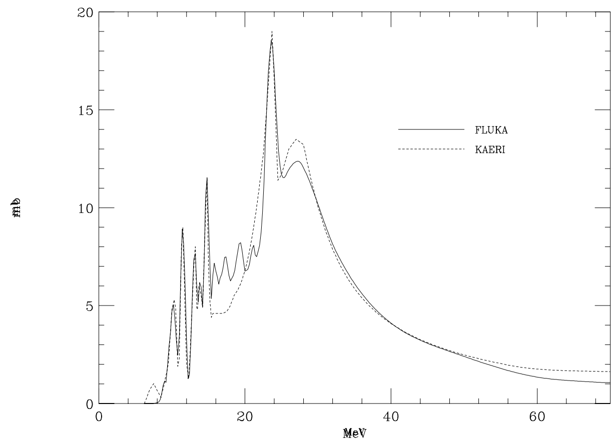


**FIGURE 11.** $\sigma_{tot}$ ($^{18}$O) according to [10], compared with KAERI evaluated data.

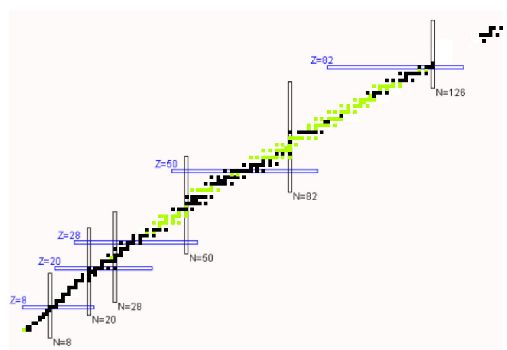


**FIGURE 12.** The 190 nuclides of the FLUKA GDR total cross-section library (black squares). The grey squares indicate the stable nuclides not included in the library.