TOTAL GIANT RESONANCE PHOTONUCLEAR CROSS SECTIONS FOR LIGHT NUCLEI:

A DATABASE FOR THE FLUKA MONTE CARLO TRANSPORT CODE

A Fassò*, A. Ferrari†, P.R. Sala†

* SLAC, Radiation Physics Department, ms 48, P.O. Box 4349, Stanford CA 94309, USA
†INFN, Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy

Abstract

The use of Monte Carlo programs to design electron accelerator shielding is limited by the lack of suitable photonuclear total cross section data in the energy region below 30 MeV. This is especially important for light nuclei, in which the total and the (γ,n) cross sections differ considerably from each other and cannot be easily parameterized. An attempt has been made to compile a database as complete as possible for nuclei with $Z \leq 29$, using all available information. The data will be included in the FLUKA data library, extending the code capability to simulate photonuclear reactions at any energy and in as many nuclei as possible.

1 Introduction

Up to recent times, Monte Carlo programs have played a very different role in the shielding design of electron and proton machines. While existing transport codes can be applied to study all aspects of proton accelerator shielding, only a more limited range of problems connected with electron machines (target calculations, thin shields, gas bremsstrahlung, synchrotron radiation) has been handled by Monte Carlo so far, at least in a single stage. This is because traditional electron-photon transport codes do not simulate photonuclear reactions, which are the source of the dominant radiation component behind thick shields. Bulk shielding assessment is thus mainly based on empirical source terms and attenuation lengths, sometimes inserted into computer programs [1]. However, such programs and analytical formulae are generally applicable only to very simplified geometries and to a maximum of two or three target and shielding materials.

More complex situations are either treated in a simplified, conservative way, or require the coupling of two Monte Carlo codes. An electron-photon transport code is first needed to score energy and possibly position dependent photon fluence in a region of space; then the fluence so obtained is folded with experimental photoneutron cross sections to produce a source for a neutron transport code [2, 3, 4]. This technique however, in addition of being rather cumbersome, lacks the spatial, angular and energy resolution of a full Monte Carlo simulation, since a lot of information is lost in the process of converting a scored photon fluence into a neutron source.

A transport code capable to simulate not only the electromagnetic interactions of photons and electrons, but also photonuclear reactions, would find interesting applications not only in shielding but also in dosimetry. The unwanted dose to the patient due to photoneutrons produced both in the structure of medical accelerators and in the tissue of the body, which has been investigated by several authors using the multistage technique described above [5, 6, 7], could be assessed with better accuracy. In addition, such a code could help to predict induced activity in structural components of electron accelerators and background neutron radiation in physics experiments [8].

2 Monte Carlo

2.1 Existing and past implementations of photonuclear reactions

Photonuclear interactions have actually already been implemented in a more or less comprehensive manner in a few Monte Carlo transport codes. The first has been probably PICA, written by Gabriel and originally based on the Levinger quasi-deuteron model coupled with the Bertini intranuclear cascade-evaporation model [9]. The present version includes also single pion production and according to the author [10] has been extended to the energy region below 30 MeV using the photoneutron cross sections reported in the first edition of the so-called "Berman's Atlas" [11]. It is not clear from [10] if the code can handle any nucleus, including those not reported by Berman, and if photonuclear reactions other than (γ,n) are implemented below 30 MeV.

Barashenkov [12] described a similar code based on his intranuclear cascade model, covering the energy range 50 MeV-1.3 GeV and nuclei with A$\geq$27. However, that code doesn't seem to have been used outside the USSR.

Other implementations of photonuclear reactions (limited to photoneutron reactions) have been reported by Alsmiller and Moran [13, 14] and by Hansen et al. [15]. The cross sections used were those reported in Berman's Atlas. Morioka and Kadotani [16] have announced a version of the SANDYL code including photonuclear processes. None of such codes seems to be in use at present time.

A more recent program is DINREG by Degtyarenko [17], based on a high energy multifragmentation model of M. Kossov. The author claims in [17] that this code has empirically been extended to apply to the "region of lower nuclear excitations", but gives neither further detail about the actual lower limit, nor information about the cross sections used.

The implementation of photoneutron production in MCNP4A has been recently announced [18], but it is limited to just four nuclides having a very low photoneutron threshold energy, and the cross section is calculated analytically in an approximate way.

2.2 FLUKA

The work presented here is connected with the attempt to extend the capability of the FLUKA code to simulate in detail photonuclear reactions at any energy and in any nuclide. The photonuclear module of FLUKA, which was already presented at the 8th International Conference on Radiation Shielding in Arlington [19], has been successfully benchmarked for photon energies larger than 30 MeV. The cross sections used by the code are calculated analytically in the quasi-deuteron energy range, and are tabulated from published experimental data for energies around the Δ resonance and above. The interaction is simulated via the PEANUT intranuclear cascade-preequilibrium-evaporation code [20] below about 700 MeV, and according to the Vector Meson Dominance model above.

FLUKA can handle in principle also photonuclear reactions in the energy region of the Giant Dipole Resonance (GDR), although not quite with the same accuracy as those in the quasi-deuteron region. Several physical models have been developed to describe the collective nuclear excitation which is typical of photon energies between about 8 and 30 MeV, but to our knowledge none of them has been successful enough to suggest a practical application, and in any case no Monte Carlo event generator has yet been reported. However, while there is no simple way to predict the excitation function, the nuclear de-excitation is very similar to that of a typical compound nucleus. Therefore, the interaction cross section must be read from tables or parameterized, but the energy dissipation in the nucleus can be treated by the PEANUT preequilibrium-evaporation module.

In the first version presented in Arlington, all cross sections were parameterized according to a formula proposed by Dietrich and Berman [21], and that was sufficient to reproduce fairly accurately the experimental thick target data by Barber and George [22]. However, that formula does not apply to light nuclei and refers anyway to photoneutron reactions, while the probability of interaction is described by the total photoabsorption cross section. For heavy nuclei the values of the two cross sections are sufficiently close to justify such an approximation, but in low-Z nuclei the emission of charged particles can be very important, and in some cases the total cross section can be much larger that the photoneutron one.

Many elements contained in the concrete used for shielding, and all the important constituents of tissue have a low atomic number: therefore the capability of FLUKA to simulate most cases of practical interest would be greatly diminished unless total photoabsorption cross sections for light nuclei be made available in a way or another.

3 Available data

As a first step it has been found necessary to search the literature for any published experimental cross sections: total if possible, but also (γ,n), (γ,p), etc., with the hope to be able to reconstruct the total cross section as a sum of the partial ones. However, this is not an easy task, since published data on photonuclear reactions are sparse, often inconsistent, incomplete and affected by large errors (especially those found in the older literature). As an example, in Fig. 1 is reported the total photoabsorption cross section of ^{32}S reported by three different authors [23, 24, 25]. Discrepancies of the same order are not uncommon among data published before 1970. Old measurements are also often badly documented: for instance it is not always clear whether the reported data refer to (γ,1n) + (γ,2n) (cross section for photoneutron interaction with emission of any number of neutrons), or to (γ,1n) + 2(γ,2n) (neutron yield cross section). Inconsistent notation has been used (and is still being used) by different authors: $\sigma(\gamma, n)$, $\sigma(\gamma, Tn)$, $\sigma(\gamma, Sn)$, $\sigma(\gamma, sn)$, $\sigma(\gamma, xn)$, $\sigma(\gamma, n_t)$ are given nonuniform and often overlapping meanings. No data is ever reported in numerical form, but always as graphical plots (often of very poor quality).

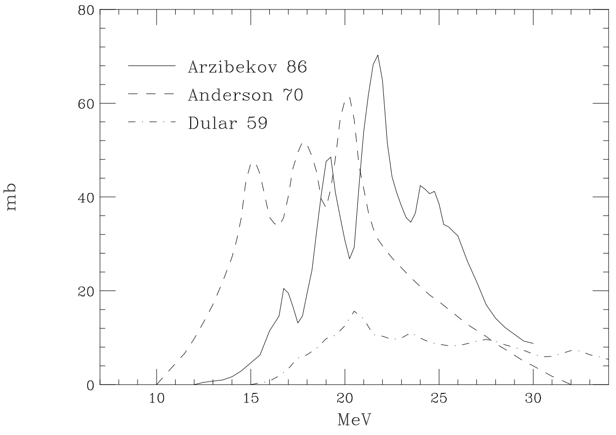

Figure 1: σ_{tot} of ^{32}S as reported in [23, 24, 25]

3.1 Reviews and bibliographies

Several published reviews have been of great help when preparing the present database. First of all the new edition of the well known “Berman's Atlas” [21]. The data reported in the Atlas have the great advantage of being available on request in numerical form and are all of good quality, the authors having excluded any measurements not performed with monoenergetic photon beams. Indeed, old data obtained by unfolding measurements made with bremsstrahlung radiation present often large errors and spurious fluctuations in the excitation curve. However, modern statistical techniques presently allow to limit unwanted correlations, and many photoneutron cross sections not reported in the Atlas have been found equally interesting, in particular those measured by the Melbourne and by the Moscow groups. Useful compilations of earlier measurements can be found in a report of Lund University [45] (up to 1972) and in the Abstract Sheets of the National Bureau of Standards (up to 1982) [46]. A more recent compilation, containing also some evaluations, is that of Blokhin and Nasyrova [47], based on the EXFOR data library. We have had knowledge of this document only recently, therefore it has not been used for the present work.

There are also useful bibliographical reviews such as those of IAEA [48] and of JAERI [49], but many interesting data cited there were published in local journals or internal reports that are difficult to find.

No attempt seems to have been done so far to publish a comprehensive collection of evaluated data, such as the celebrated BNL-325 for the neutron cross sections.

3.2 Total cross sections

Total photoabsorption cross sections have been measured with good accuracy only for a limited number of nuclei, either of natural isotopic composition or single nuclides: the main sources for the present compilation have been the papers of Ahrens et al. [26, 27], Bezić et al. [28, 29], and McNeill [30]. Some examples are shown in Fig. 2, 3, 4.

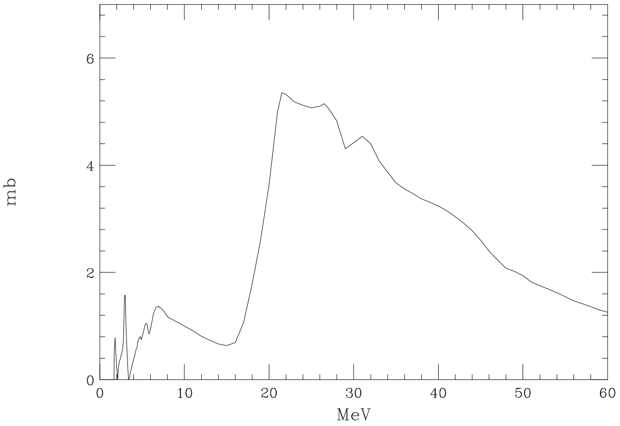

Figure 2: Total photoabsorption cross section of ^{9}Be ([26] completed at the lowest energies with data of [31, 32, 33, 34]

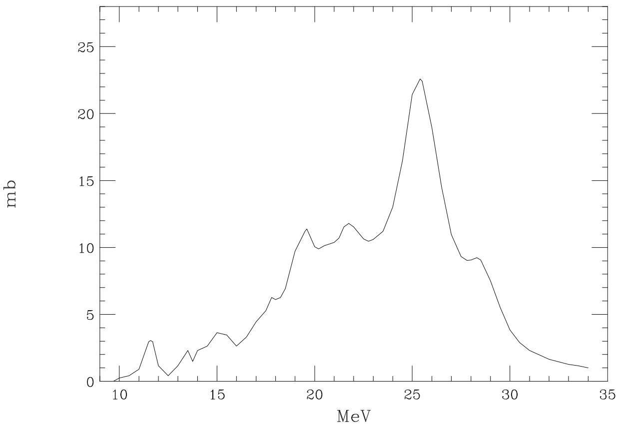

Figure 3: Total photoabsorption cross section of ^{15}N, from McNeill et al. [30]

3.3 Summing partial cross sections

Other useful data, not measured directly, but reconstructed as sums of experimental partial cross sections, have been found in [25, 35, 36, 37, 38, 39]. An example is shown in Fig. 5.

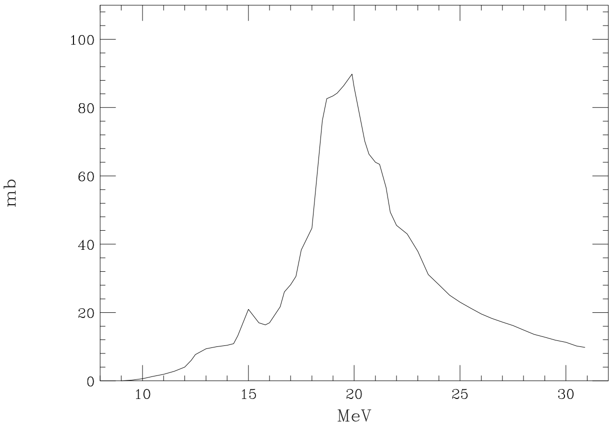

Figure 4: Total photoabsorption cross section of ^{nat}Ca, from [28]

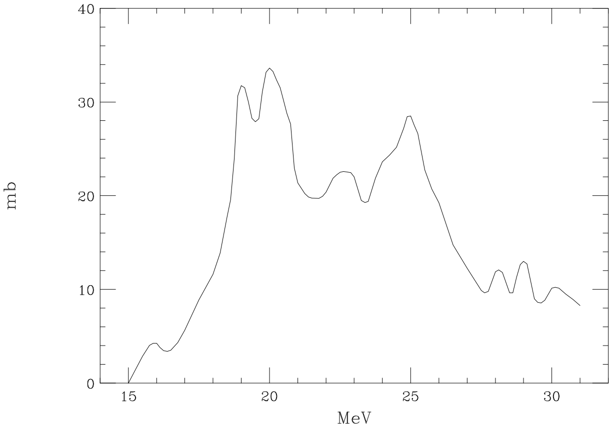

Figure 5: Total photoabsorption cross section of ^{24}Mg, evaluated by Irgashev et al. [35] summing published partial cross sections

In particular, a very accurate evaluation of total cross sections of ^{12}C, ^{14}N and ^{16}O has been published by Fuller [40]. As an example, in Fig. 6 is reported the total cross section of ^{16}O measured by Ahrens et al. [26] and corrected by Fuller especially at the lowest energies.

On the other hand, it has not been possible so far, except in the single case of ^{4}He (See Fig. 7 and 8), to collect sufficient data to perform the same kind of reconstruction on further nuclides. There are several reasons why summing partial cross sections has turned out more difficult than expected. In very light nuclei several channels are available

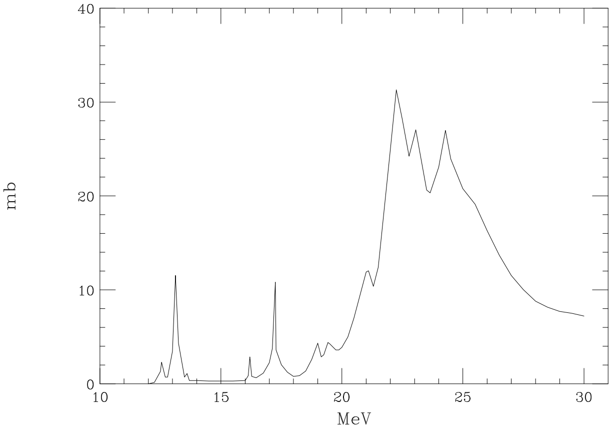

Figure 6: Total photoabsorption cross section of ^{16}O, measured by Ahrens et al. [26], and modified by Fuller [40]

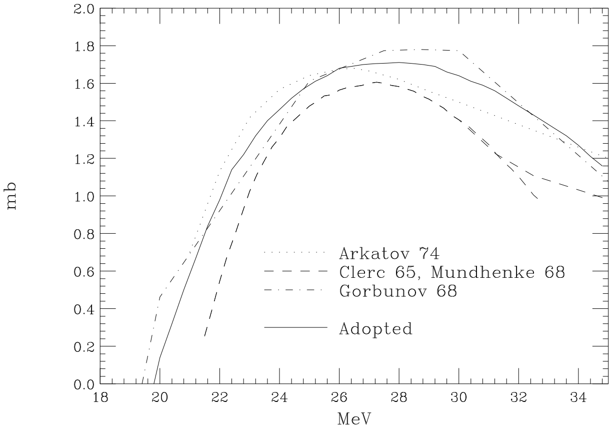

Figure 7: $\sigma_{\gamma,p}$ of ^{4}He from different authors [41, 42, 43, 44] and adopted curve

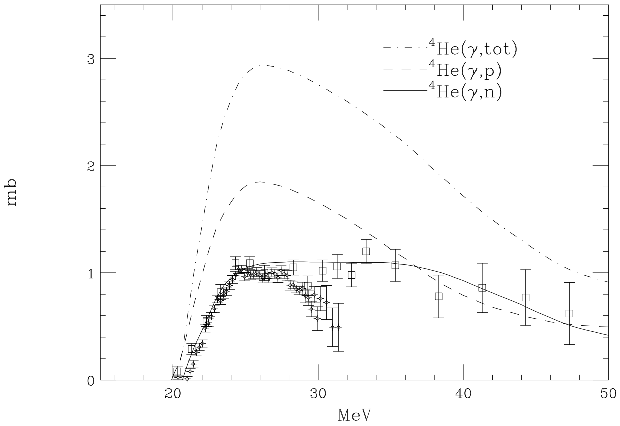

Figure 8: σ_{tot} of ^{4}He obtained by summing $\sigma_{\gamma,n}$ and $\sigma_{\gamma,p}$

for emission of charged particles without accompanying neutron: (γ,p), (γ,α), (γ,d), (γ,t), etc., and it is difficult to find reliable information about all of them for the same nuclide. In addition, the instruments used to detect charged particles have a detection threshold which is difficult to account for. Finally, detection usually takes place at only one or two fixed angles but the angular distribution is generally not uniform.

3.4 Sum or difference of isotopes

While in several cases the cross section of a natural mixture of nuclides has been obtained by summing those of the various components, the reverse has also occurred: in Fig. 9 is shown the cross section of ^{28}Si derived by substraction of that of ^{29}Si and ^{30}Si, measured by McNeill et al. [30] from that of natural silicium, measured by Bezić et al. [28].

4 Renormalizing γ, n data with PEANUT

In order to evaluate the total cross section of nuclei for which only γ,n cross sections are available, the PEANUT code was run standalone providing the relative frequency of inelastic events with and without emission of neutrons. The total cross section was obtained multiplying the photoneutron cross sections by the ratio $\frac{N}{N_n}$, where N is the total number of simulated events, and N_n is the number events in which at least one neutron was emitted. A similar scheme was used to correct γ, Tn cross sections (neutron yields). An example is given in Fig. 10, where the experimental γ,n data by Veyssière et al. [50] (as reported in in Berman's Atlas) are presented together with the calculated total cross section.

To give an idea of the accuracy which can be attained with this method, the total cross section calculated with PEANUT from photoneutron data from Saclay and Livermore, reported by Dietrich and Berman [21], is compared in Fig. 11 with that measured by Ahrens et al. [26].

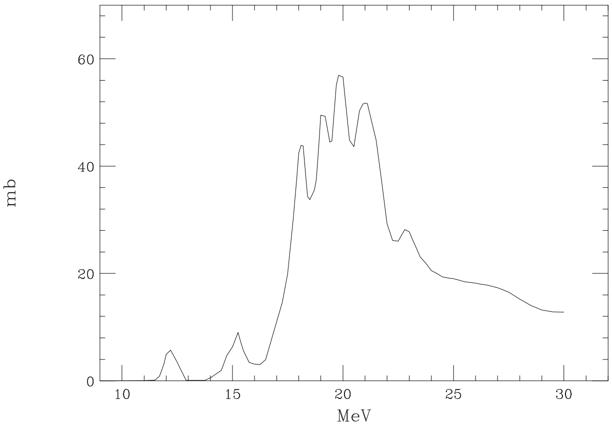

Figure 9: Total photoabsorption cross section of ^{28}Si, obtained by substraction of ^{29}Si and ^{30}Si from ^{nat}Si

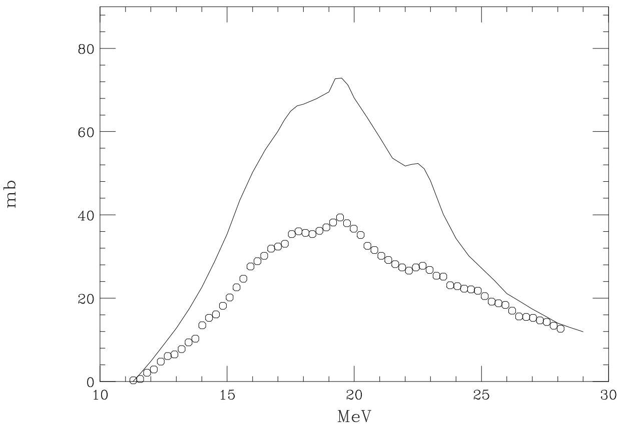

Figure 10: Total photoabsorption cross section of ^{45}Sc, obtained by correcting experimental photoneutron cross sections with PEANUT calculated factors. Symbols: experimental points; solid curve: evaluated total cross section

As it can be seen, the agreement is not equally good over the whole energy range, but deviations of that order can be acceptable in those cases where no direct measurement is available. As already shown, discrepancies of the same order occur frequently among the oldest experimental data.

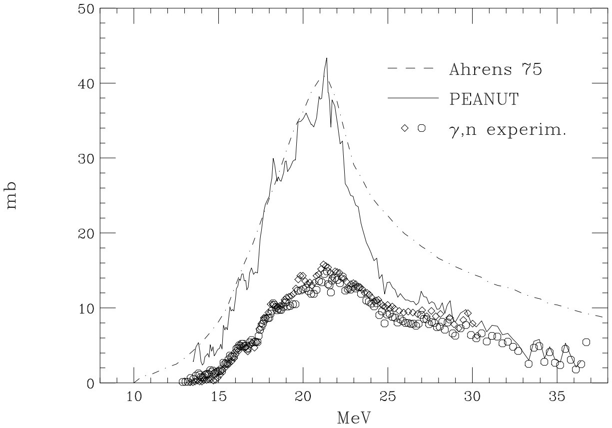

Figure 11: Total photoabsorption cross section of ^{27}Al, obtained by correcting experimental photoneutron cross sections with PEANUT. Symbols: experimental points; solid curve: σ_{tot} calculated by PEANUT; dashed curve: measured by Ahrens et al. [26]

More comparisons of this kind will be made in the near future to identify possible systematic differences. It must also be stressed that this technique can be applied successfully only when the ratio $\sigma(\gamma, tot)/\sigma(\gamma, n)$ is not too large. For neutron-poor nuclei such as ^{54}Fe and ^{58}Ni, and also close to neutron emission threshold in nuclei with low threshold for charged particle emission, that ratio can become very large and even small uncertainties can be amplified into unphysical cross section values (see Fig. 12).

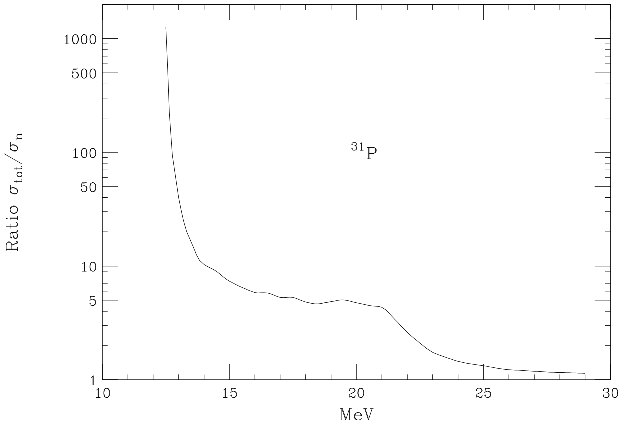

Figure 12: Ratio total/photoneutron cross section calculated by PEANUT for ^{31}P

5 Available and missing nuclides

At present time, the status of the FLUKA photonuclear cross section database is the following:

Measured Total Cross Section : ^{3}H, ^{3}He, ^{7}Li, ^{nat}Li, ^{9}Be, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{19}F, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{27}Al, ^{29}Si, ^{30}Si, ^{nat}Si, ^{32}S, ^{nat}Ca

Published evaluation : ^{34}S

γ,n + γ, p : ^{4}He

Sum of components : ^{nat}He, ^{nat}B, ^{nat}C, ^{nat}N, ^{nat}O, ^{nat}Mg

Difference : ^{6}Li, ^{28}Si, ^{35}Cl

Measured γ,n renormalized by PEANUT : ^{10}B, ^{11}B, ^{nat}Cl, ^{40}Ar, ^{nat}K, ^{42}Ca, ^{45}Sc, ^{48}Ti, ^{50}Ti, ^{51}V, ^{nat}Cr, ^{55}Mn, ^{nat}Fe, ^{59}Co, ^{60}Ni, ^{nat}Cu, ^{63}Cu, ^{65}Cu

Theoretical γ,n renormalized by PEANUT : ^{37}Cl

γ,n available, but not renormalizable : ^{nat}Ne, ^{31}P, ^{46}Ti, ^{58}Ni, ^{54}Fe

Nothing available : ^{20}Ne, ^{21}Ne, ^{22}Ne, ^{nat}S, ^{33}S, ^{36}S, ^{36}Ar, ^{38}Ar, ^{36}K, ^{38}K, ^{40}K, ^{43}Ca, ^{44}Ca, ^{46}Ca, ^{48}Ca, ^{nat}Ti, ^{50}V, ^{nat}V, ^{50}Cr, ^{52}Cr, ^{53}Cr, ^{54}Cr, ^{56}Fe, ^{57}Fe, ^{58}Fe, ^{nat}Ni, ^{61}Ni, ^{62}Ni, ^{64}Ni

As it can be seen, there are reasonable data for 47 nuclei, but there are still about 30 for which no data whatsoever has yet been found. Many of them are of relatively low importance in most practical shielding and dosimetry problems, and for others the data about natural composition are normally sufficient. A few however, like nickel and titanium, are important structural materials. The goal of this work was to set up a database as complete as possible, but it is possible to envisage in a first stage a situation similar to that of neutrons, for which calculations are possible only if the material of interest is available in the cross section library.

As an alternative, there is however some hope that a total cross section excitation curve can be "guessed" even for those nuclides for which no data have been found. At any given photon energy, the total cross section can be represented as a simple function of the quantity NZ/A, as shown in Fig. 13.

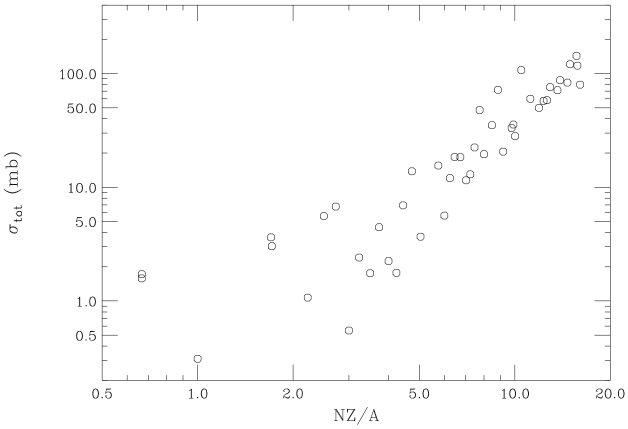

Figure 13: Total photoabsorption cross section at 17 MeV vs. NZ/A

The slope varies with energy, and between 22 and 30 MeV the function is not a simple power law but reaches a constant value at about NZ/A = 5 (Fig. 14).

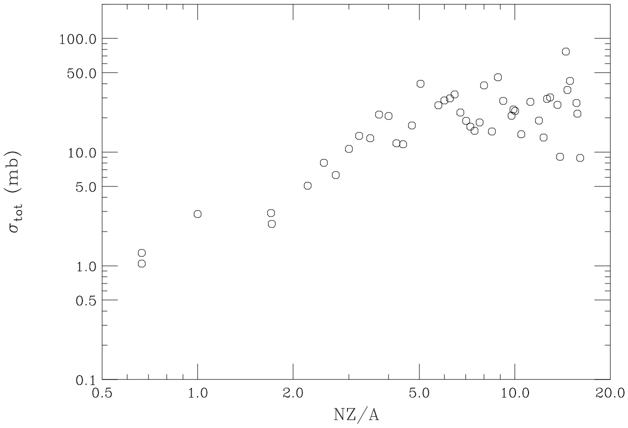

Figure 14: Total photoabsorption cross section at 25 MeV vs. NZ/A

There is more data scattering at the two ends of the 9–35 MeV energy range, but that affects only the tails of the excitation curve and should not be important for most applications.

6 Future work

The present status of the database allows it to be implemented immediately in FLUKA. However, it is still possible to add a few refinements. The shape of the excitation curves can be improved near threshold using detailed information about thresholds for each partial channel and about Coulomb barriers. The Thomas-Reiche-Kuhn (TRK) sum rule can be used to spot anomalies either in the experimental data or in the renormalization: an example is shown in Fig. 15, where an abnormally high value for ^{42}Ca was identified. That cross section, obtained by renormalizing photoneutron data of [51] using PEANUT, will be further renormalized so as to bring down the integral of the excitation curve over the interval 0 to 35 MeV to a value equal to one-half of 60 NZ/A. (The TRK rule predicts twice that value but only if the integral is calculated up to the photopion threshold).

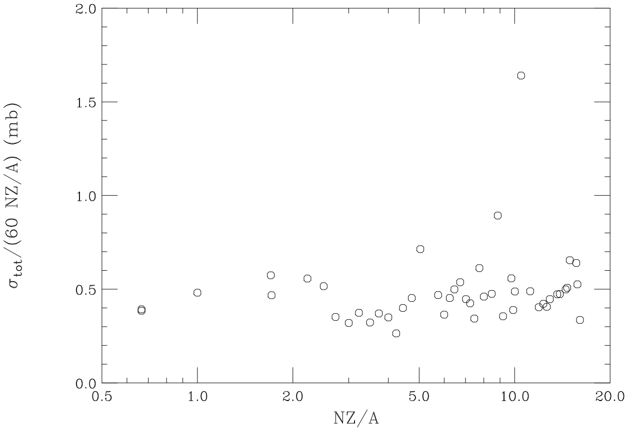

Figure 15: Integral $\int \sigma_{tot}(E)\,dE$ divided by 60 NZ/A, vs. NZ/A; the anomalous value at NZ/A = 10.5 is that of ^{42}Ca

It would be interesting also to extend the comparison of data from different sources: for the time being this has been done only in a few cases in order to obtain as soon as possible the most complete library. In general, for example, preference has been given to measurements reported by Dietrich and Berman (when available) because a better consistency among data could be expected, but a good evaluation should take all the existing experiments into account.

The compilation work will continue also for heavier nuclei, but with less emphasis on total versus photonuclear cross sections.

Finally, hopefully this attempt will encourage other groups and possibly some professional nuclear data evaluators to join our effort to create a photonuclear cross section library in numerical form.

References

[1] W.R. Nelson, T.M. Jenkins, "The SHIELD11 Computer Program", SLAC Radiation Physics Note RP-97-1 (1997)

[2] A. Fassò, M. Pelliccioni, "Evaluation of Radiation Skyshine from the Main Rings of the DAΦNE Project", Frascati Internal Report LNF–92/111 (IR) (1992)

[3] H. Nakashima et al., "Accelerator shielding benchmark experiment analyses", Proc. SATIF–2 Geneva 12-13 Oct. 1995, OECD-NEA Paris 1996, p. 115

[4] J.C. Liu, W.R. Nelson, K.R. Kase, X.S. Mao, Rad. Prot. Dosim. 70, 49 (1997)

[5] S. Agosteo, A. Foglio Para, F. Gerardi, M. Silari, A. Torresini, G. Tosi, Phys. Med. Biol. 38, 1509 (1993)

[6] C. Manfredotti, U. Nastasi, W. Ornato, A. Zanini, Rad. Prot. Dosim. 44, 457 (1992)

[7] X.S. Mao, K.R. Kase, J.C. Liu, W.R. Nelson, J.H. Kleck, S. Johnsen, Health Phys. 72, 524 (1997)

[8] A. Fassò, S. Rokni, V. Vylet, "Radiation Studies for a High Energy Free Electron Laser", Presented at SARE–3, KEK 5-9 May 1997

[9] T.A. Gabriel et al., "PICA, An Intranuclear Cascade Calculation for High Energy Photon-Induced Nuclear Reactions", ORNL–4687 (1971)

[10] P.K. Job, T.A. Gabriel, "The Photoneutron Yield Predictions by PICA and Comparison with the Measurements", Proc. SATIF–2 Geneva 12-13 Oct. 1995, p. 93

[11] B.L. Berman, "Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons", UCRL 78482 (1976)

[12] V.S. Barashenkov et al., Nucl. Phys. A231, 462 (1974)

[13] R.G. Alsmiller, jr., H.S. Moran, Nucl. Instr. Meth. 48, 109 (1967)

[14] R.G. Alsmiller, jr., H.S. Moran, Nucl. Instr. Meth. 51, 339 (1967)

[15] E.C. Hansen, C.S. Bartoletti, P.B. Daitch, J. Appl. Phys. 46, 1109 (1975)

[16] S. Morioka, H. Kadotani, "A Monte Carlo Simulation of electron-photon cascades including photonuclear processes, presented Int. Conf. on Nuclear Data for Science and Technology, Mito (Japan), May 30-June 3, 1988 Century Research Center Corporation Rep. CRC–ET0188.4 (1988)

[17] P. Degtyarenko, "Applications of the Photonuclear Fragmentation Model to Radiation Protection Problems", Proc. SATIF–2 Geneva 12-13 Oct. 1995, p. 67

[18] F.X. Gallmeier, "Photoneutron Production in MCNP4A", Proc. 1996 ANS Topical Meeting, No. Falmouth, Mass., Apr. 21-25 1996, p. 780

[19] A. Fassò, A. Ferrari, P.R. Sala, "Designing Electron Accelerator Shielding with FLUKA", Proc. 8th Int. Conf. on Radiation Shielding, Apr. 24-28 1994, Arlington, Texas, p. 643

[20] A. Fassò, A. Ferrari, J. Ranft, P.R. Sala, "FLUKA: Performances and Applications in the Intermediate Energy Range", Proc. SATIF–1 Arlington (Texas) 28-29 Apr. 1994, p. 287

[21] S.D. Dietrich, B.L. Berman, At. Data Nucl. Data Tables 38, 199 (1988)

[22] W.C. Barber, W.D. George, Phys. Rev. 116, 1551 (1959)

[23] J. Dular et al., Nucl. Phys. 14, 131 (1959)

[24] D.W. Anderson et al., Nucl. Phys. A 156, 74 (1970)

[25] U.R. Arzibekov et al., Sov. J. Nucl. Phys. 44, 727 (1986)

[26] J. Ahrens et al., Nucl. Phys. A251, 479 (1975)

[27] J. Ahrens et al., "Total Absorption Cross-Sections, Particularly Above 30 MeV", Proc. Int. Conf. on Photonuclear Reactions and Applications, Asilomar (California), Vol. 1, 1974, p. 23

[28] N. Bezić et al., Nucl. Phys. A117, 124 (1968)

[29] N. Bezić et al., Nucl. Phys. A128, 426 (1969)

[30] K.G. McNeill et al., Phys. Rev. C47, 1108 (1989)

[31] J.H. Gibbons et al., Phys. Rev. 114, 1319 (1959)

[32] W. John and J.M. Prosser, Phys. Rev. 127, 231 (1962)

[33] B.L. Berman et al., Phys. Rev. 163, 958 (1967)

[34] R.J. Hughes et al., Nucl. Phys. A238, 189 (1975)

[35] K.M. Irgashev et al., Nucl. Phys. A483, 109 (1988)

[36] B.S. Ishkanov et al., Sov. J. Nucl. Phys. 33, 303 (1981)

[37] B.S. Ishkanov et al., Phys. At. Nucl. 60, 319 (1997)

[38] Y.I. Assafiri, M.N. Thompson, Nucl. Phys. A460, 455 (1986)

[39] D. Ehhalt et al., Z. Phys. 187, 210 (1965)

[40] E.G. Fuller, Phys. Rep. 127, 185 (1985)

[41] Yu.M. Arkatov et al., Sov. J. Nucl. Phys. 19, 598 (1974)

[42] H.G. Clerc et al., Phys. Lett. 18, 316 (1965)

[43] R. Mundhenke et al., Z. Phys. 216, 232 (1968)

[44] A.N. Gorbunov, M. Spiridonov, Sov. Phys. JETP 6, 16 (1958)

[45] B. Bülow, B. Forkman, "Photonuclear cross sections", LUNP 7208 (1972)

[46] E.G. Fuller, H. Gerstenberg, "Photonuclear Data – Abstract sheets, 1955-1982", NBSIR 83–2742

[47] A.I. Blokhin, S.M. Nasyrova, "Plots of the Experimental and Evaluated Photoneutron Cross-Sections", IAEA INDC(CCP)–337 (1991)

[48] V.A. Varlamov, M.E. Stepanov, V.V. Sapunenko, "Photonuclear Data Index 1986–1990", IAEA INDC(CCP)–348 (1992)

[49] T. Asami, T. Nakagawa, "Bibliographic Index to Photonuclear Reaction Data (1955–1992)", JAERI–M 93–195 (1993)

[50] A. Veyssière et al., Nucl. Phys. A227, 513 (1974)

[51] Y.I. Assafiri et al., Nucl. Phys. A357, 429 (1981)