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Title: Neutron, Proton, and Photonuclear Cross Sections for Radiation Therapy and Radiation Protection

Author(s): M. B. Chadwick, T-2

Submitted to: For Proceedings of the "International Meeting on Computational Methods in Track Structure Simulation in Physical and Biological Sciences, Theory and Applications"
September 10-13, 1998
Harwell Laboratory, Oxford, U.K.

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Neutron, Proton, and Photonuclear Cross Sections for Radiation Therapy and Radiation Protection

M.B. Chadwick*

¹*University of California, Theoretical Division,
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
(September 4, 1998)*

Abstract

We review recent work at Los Alamos to evaluate neutron, proton, and photonuclear cross sections up to 150 MeV (to 250 MeV for protons), based on experimental data and nuclear model calculations. These data are represented in the ENDF format and can be used in computer codes to simulate radiation transport. They permit calculations of absorbed dose in the body from therapy beams, and through use of kerma coefficients allow absorbed dose to be estimated for a given neutron energy distribution. For radiation protection, these data can be used to determine shielding requirements in accelerator environments, and to calculate neutron, proton, γ -ray, and radionuclide production. Illustrative comparisons of the evaluated cross section and kerma coefficient data with measurements are given.

This research is supported by the Department of Energy under contract W-7405-ENG-36.

*Address: MS B243, Los Alamos National Laboratory, Los Alamos, NM 87545, USA;
Telephone 505 667 9877; Fax 505 667 9671; email mbchadwick@lanl.gov

I. INTRODUCTION

There has been an interest in recent years to develop accurate nuclear cross section data for incident energies up to 150–250 MeV, for use in radiation transport codes [1,2]. These data can be used to calculate energy deposition and radiation transport for neutron, proton, and photon radiotherapy beams, in order to optimize dose delivery to the treatment volume. They can also be used for radiation protection considerations, to quantify shielding requirements and to estimate induced radioactivity. In addition to these medical applications, high-energy cross section data are needed for the design of new accelerator-driven technologies to transmute radioactive waste [3], produce spallation neutrons for material science studies, and produce tritium [4].

This paper describes evaluated nuclear cross section data for H, C, N, O, Al, Si, P, Ca, Fe, Cu, W, Hg and Pb, collectively known as the LA150 Library [1], that have been developed in support of the above applications. The neutron and proton data, along with extensive discussions of methods used in their evaluation and their role in medical applications, are described in detail in a new International Commission on Radiation Units and Measurements (ICRU) report that will be published in 1999 [5]. The present paper provides a summary of this work, along with a description of new work on the evaluation of photonuclear data needed for characterizing photoneutron production in accelerator collimators, beam modifiers, and targets.

For neutron kerma coefficients, the present work can be viewed as an update on the work of Caswell, Coyne, and Randolph [6], which provided tabulations of total kerma coefficients up to 30 MeV. A comprehensive description of our calculated kerma coefficients up to 150 MeV for elements and mixtures/compounds important in dosimetry is given in Ref. [7].

In parallel to work on the evaluation of nuclear cross sections, Monte Carlo radiation transport codes are under development to utilize these data. At Los Alamos National Laboratory, the new MCNPX code [8] merges the MCNP and LAHET radiation transport codes and uses the evaluated LA150 cross sections for nuclear events below 150 MeV (and the intranuclear cascade model at higher energies). At Lawrence Livermore National Laboratory, the PEREGRINE code is being developed specifically for radiotherapy simulations [9]. These data have also been used in Monte Carlo studies of clinical proton dosimetry by Medin and Andreo [10].

Section II describe the methods used to evaluate the cross section and kerma coefficient data. Section III provides a summary of the results obtained for neutron, proton, and photon projectiles, and conclusions and future work are given in Sec. IV.

II. EVALUATION METHODS

The methods used to evaluate neutron-, proton-, and photon-induced cross sections use a combination of measured cross section data and nuclear model calculations with the GNASH code, and have been described in detail in Refs. [5,11,12]. Below 20 MeV for neutrons, no new cross section evaluations were performed; rather, we made use of evaluated data in the ENDF/B-VI library which is maintained at the Brookhaven National Laboratory National Nuclear Data Center (NNDC) [13].

Measured particle emission spectra were used to adjust input parameters in the nuclear reaction model calculations (*e.g.*, level densities, preequilibrium decay rates), within the range of their uncertainties, to optimize agreement with the experimental data. As statistical assumptions break down for light nuclei, important biologically, measured data served to guide the model calculations and improve the resulting information. However, the experimental information above 15 MeV is still relatively sparse, and for this reason nuclear theories and models are essential to supplement the measured data.

A. Experimental data

Measured cross section data are archived at the Brookhaven NNDC [13], and in the following, a selection of these data on biologically-important elements are described.

For neutrons, measurements of the total, elastic, and total non-elastic cross sections, such as the high-precision total cross section data of Finlay *et al.* [14] and Dietrich *et al.* [15] are important for the evaluations described here. Experimental data, such as those described in Ref. [16] have provided differential and total elastic scattering cross sections for biologically-important nuclei that are used to determine optical potentials for optical model analyses. We also made use of neutron total non-elastic cross section measurements compiled by the NNDC [13]. Charged-particle production spectra have been particularly important for guiding and testing the calculations, principally the measurements from the University of California at Davis [17,18], Los Alamos [19], Louvain-la-Neuve [20–22] and Tohoku University [23].

For protons, measurements of secondary particle emission spectra from Oak Ridge National Laboratory [24], the University of Maryland [25,26], Los Alamos [27,28], and the National Accelerator Center (Faure) [29], have played a significant role in the evaluations. The total nonelastic cross sections were obtained from the compilation by Carlson [30], and from optical model calculations.

Photonuclear experimental data compiled by Dietrich and Berman [31] were important for determining the photoabsorption cross sections, and for testing the calculation's accuracy in predicting photoneutron production. Very little emission spectra data exist from monochromatic photon projectiles, and so the model calculations are particularly important here.

B. Nuclear model calculations

The Los Alamos GNASH code [32] was used to calculate nuclear reaction cross sections for non-elastic processes. This code treats a nuclear reaction as proceeding through an initial preequilibrium phase, from which high-energy ejectiles can be emitted, followed by a process of sequential particle emission from decaying compound nuclei, until the final residual nucleus attains its ground state via gamma-ray emission. The Hauser-Feshbach theory is used to calculate emission from the compound nucleus, with a full conservation of spin and parity. Production cross sections and emission spectra of secondary light particles, γ -rays, and recoil nuclides are obtained from the calculations.

The total, elastic, and total non-elastic cross sections, as well as the inelastic scattering cross sections to low-lying nuclear states, were determined through optical model analyses.

These nuclear reaction theories were used for calculations on all target nuclei except hydrogen. An accurate representation of neutron-proton scattering is particularly important since such reactions provide the dominant contribution to the kerma coefficient in tissue and in tissue-equivalent plastics up to approximately 60–70 MeV. Neutron-proton scattering utilized a recommendation of the Nuclear Energy Agency [33] – adopting the ENDF/B-VI hydrogen cross sections up to 26 MeV, which is based on an R-matrix scattering analysis [34], with the phase-shift VL40 solution of Arndt [35] at higher energies. This recommendation was also adopted by White *et al.* [36].

III. RESULTS

A. Neutron cross sections and kerma coefficients

The evaluations include descriptions of the total, elastic, and non-elastic reactions, and energy- and angle-dependent emission spectra for the non-elastic reactions. From these cross section data, kerma coefficients are derived using the product of the production cross sections and average kinetic energies of each type of secondary charged particle. Above 20 MeV, this procedure is unambiguous since our new evaluations are complete. But below 20 MeV, where the ENDF/B-VI data is frequently incomplete in its representation of charged-particle reactions (since the principal use originally was for neutron-photon transport), the kerma coefficients were calculated by energy balance using the NJOY code [37].

An example of the evaluated charged particle emission spectra, integrated over all angles, is shown in Fig. 1 for neutrons on carbon. Spectra are shown for protons (left column), deuterons (middle column), and alpha particles (right column), since these particles are the dominant contributors to the kerma. Incident energies of 27 MeV (1st row), 40 MeV (2nd row), 60 MeV (third row), and 70 MeV (fourth row) are shown. The solid line shows the evaluated result [12] from GNASH model calculations transformed into the laboratory frame of reference; the dashed line shows the results from Brenner and Prael's calculations [38]. It is evident that the evaluated result is in good agreement with the experimental data [17,19–21], with the exception of the 70 MeV proton production where the calculation underpredicts the measurement. Additional comparisons with experimental cross section data for other elements are given in Refs. [11,12,1]. The generally-good agreement is particularly important for accurate calculations of kerma coefficients, and of absorbed dose when these data are used by a transport code.

For neutron interactions with tissue, water, and tissue mimicking plastic and gas, carbon and oxygen are the most important elements besides hydrogen. The evaluated kerma coefficients, derived from the cross section data, are compared with measurements in Fig. 2 for carbon and oxygen. The experimental data were obtained from both direct measurement of the ionization produced by the charged particles, and by measurement of the charged-particle production cross sections (supplemented by theoretical predictions for data at unmeasured energies and angles). The evaluations are consistent with the measurements, though the spread in the experimental data is large. We estimate the following uncertainties in the kerma coefficients: For carbon, 5% below 10 MeV, and 10% from 10–150 MeV; For oxygen,

5% below 10 MeV, 15-20% from 10-150 MeV. For hydrogen, no figure comparing the kerma coefficient data is provided since the neutron-proton scattering cross sections are known to very high precision, and therefore the H kerma coefficient is known to 1-2 % accuracy. Comparisons of kerma coefficient data for other elements and A150 plastic, and the kerma ratios for carbon to oxygen and ICRU-muscle to A-150 plastic, are given in Refs. [5,7].

B. Proton cross sections

In proton therapy, protons lose energy mainly through electromagnetic interactions with atomic electrons. The probability of nuclear collisions occurring increases with incident energy. An important aspect to proton nuclear reactions in proton therapy is that primary protons are removed from the therapy beam, and result in the production of secondary neutrons, protons, gamma-rays, and other particles at angles away from the direction of the incident beam. This affects the energy deposition along the beam path, and leads to undesirable absorbed doses to a patient outside the target volume. An understanding of proton nuclear interactions is also important for radiation protection, since they lead to secondary radiation from the accelerator components that may need to be shielded.

Examples of the evaluated total nonelastic cross section for incident protons on C, O, Fe, and Pb are shown in Fig. 3, compared with experimental data from Carlson's compilation [30]. At the highest energies, these cross sections are comparable to the geometrical cross section area of the nucleus. At lower energies, the increase in the cross section is due to interference effects in the scattering and is predicted by the optical model. The threshold at the lowest energies occurs when there are no inelastic scattering channels available (below the first excited nuclear state).

Evaluated proton and alpha particle emission spectra, integrated over all angles, are compared with measurements in Fig. 4 for carbon and oxygen targets. Figure 5 shows the double-differential (*i.e.* angle- and energy-dependent) neutron emission spectra for 250 MeV protons on lead. The experimental data of Meier *et al.* [28] represent one of the very-few measurements of neutron production in this energy range. Agreement of calculation and experiment is good, though deviations are evident in the 20-30 MeV emission energy range.

C. Photonuclear cross sections

Recently we have begun a program to evaluate photonuclear cross sections to 150 MeV for a range of materials important in accelerator components, bremsstrahlung and spallation targets, and shielding. Until now, such data have not been available in the ENDF/B-VI data library, nor have radiation transport codes such as MCNP [39] and MCNPX [8] been able to use photonuclear data in a fully-coupled manner. Work is underway at Los Alamos to extend the MCNP and MCNPX transport codes to include photonuclear reactions. This will facilitate quantitative estimates of photoneutron production in accelerator environments [40] and thus allow more accurate determinations of shielding requirements. Indeed, a calculation of the importance of photoneutron production in a bremsstrahlung tungsten target for an electron linac indicated a significant effect [40].

Photoneutron production is also important, albeit at a smaller level than in neutron- and proton-induced reactions, in certain accelerator driven systems where a proton beam incident on a spallation target produces neutrons. The high gamma-ray fluences within these systems extending to energies above the neutron separation energy (typically 7-8 MeV for medium-heavy nuclei) can lead to photoneutron production. Additionally, a heavy water moderator is used in many of these designs, and photoneutron production from deuterium can be significant owing to the very small 2.2 MeV threshold energy.

The GNASH code has been developed to include photonuclear processes, using a giant dipole resonance mechanism below 20-30 MeV, and a quasideuteron mechanism at higher energies [32]. Fast particle emission can occur from the early stages of the reaction, followed by equilibrium decay from the compound nucleus. The calculations can be tested against experimental data, where they exist, for $(\gamma,1n)$, $(\gamma,2n)$, and $(\gamma,3n)$ cross sections as well as the total photoneutron production cross section (γ,xn) . Very little experimental data exists on the energy-dependence of the emission spectra, and thus the code's ability to calculate these spectra is important.

To date, cross sections have been evaluated for isotopes of Fe, W, and Pb. Additional isotopes will be studied in the coming year that are important in accelerator applications and shielding. An example of the evaluated total photoneutron production cross section compared with data, for lead, is shown in Fig. 6. The importance of the giant dipole resonance leading to a large photoneutron cross section near 12-13 MeV is evident.

IV. CONCLUSIONS

Cross sections for neutron, proton, and photon induced nuclear reactions have been evaluated for a range of high priority materials for medical applications and for accelerator-driven technologies. These data facilitate detailed computations of radiation transport, energy deposition, neutron production, induced radioactivity, and radiation damage.

Whilst these evaluated data have been shown to be in good agreement with experimental microscopic cross sections, further tests of the data are needed. In particular, comparison of radiation transport code predictions against integral "benchmark" experiments such as neutron transmission through macroscopic slabs of material, and thick-target neutron production from proton beams, are needed to further validate the data. Such comparisons may result in future modifications and improvements to the cross section data. The cross section data are available on the internet at: <http://t2.lanl.gov/data/he.html>; they will also be available on the compact disc accompanying the ICRU report [5].

V. ACKNOWLEDGMENTS

I gratefully acknowledge useful discussions with my collaborators at Los Alamos: P.G. Young, S. Chiba, G.M. Hale, H.G. Hughes, A.J. Koning, R.C. Little, R.E. MacFarlane, R.E. Prael, L.S. Waters; and my collaborators on the ICRU report committee: H.H. Barschall, R.S. Caswell, L.J. Cox, P.M. DeLuca, G.M. Hale, D.T.L. Jones, J.P. Meulders, J.V. Siebers, H. Schuhmacher, A. Wambersie.

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FIGURES

FIG. 1. Angle-integrated emission spectra of protons, deuterons, and alpha particles, from $n+^{12}\text{C}$ reactions. GNASH nuclear model calculations (full line) are compared with experimental data and with Brenner and Prael's calculations (dashed lines for 25, 40, and 60 MeV). Circles represent the data of Subramanian *et al.* [17], and triangles the data of Slypen *et al.* [20,21].

FIG. 2. Evaluated neutron kerma coefficient compared with measurements for carbon and oxygen, up to 150 MeV. Citations to the measured data can be found in Refs. [11,12].

FIG. 3. Evaluated proton nonelastic cross section compared with measurements [30] for C, O, Fe, and Pb.

FIG. 4. Evaluated proton and alpha particle emission spectra, integrated over all angles, compared with measurements [24] for C and O. In the case of alpha-particle emission from oxygen, the neutron-induced data from Subramanian *et al.* [18] are shown for comparison.

FIG. 5. Evaluated double-differential neutron emission spectra for 250 MeV protons on Pb compared with measurements [28].

FIG. 6. Evaluated photoneutron production cross section for ^{208}Pb compared with measurements (for citations to measurements, see Ref. [31]).

Fig 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6