Title: NUCLEAR DATA FOR RADIOTHERAPY: PRESENTATION
OF A NEW ICRU REPORT AND IAEA INITIATIVES

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Nuclear Data For Radiotherapy: Presentation of a New ICRU Report and IAEA Initiatives

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An ICRU report entitled "Nuclear Data for Neutron and Proton Radiotherapy and for Radiation Protection" is in preparation. The present paper presents an overview of this report, along with examples of some of the results obtained for evaluated nuclear cross sections and kerma coefficients. These cross sections are evaluated using a combination of measured data and the GNASH nuclear model code for elements of importance for biological, dosimetric, beam modification and shielding purposes. In the case of hydrogen both R-matrix and phase-shift scattering theories are used. In the report neutron cross sections and kerma coefficients will be presented up to 100 MeV and proton cross sections up to 250 MeV.

An IAEA Consultants' Meeting was also convened to examine the "Status of Nuclear Data needed for Radiation Therapy and Existing Data Development Activities in Member States". Recommendations were made regarding future endeavours.

Key words: Neutron therapy, Proton therapy, Radiation protection, Nuclear data

An International Commission on Radiation Units and Measurements (ICRU) report which will describe nuclear data that are needed in fast neutron and proton radiotherapy studies and for radiation protection is in preparation. Neutron cross sections and kerma coefficients will be presented up to 100 MeV and proton cross sections up to 250 MeV. Potential uses of these data include their implementation in radiation transport and treatment planning computer codes to optimize dose delivery to the treatment volume; studies of the impact of nuclear reactions on the relative biological effectiveness of neutron and proton therapy beams; determination of radiation shielding requirements; and use of kerma coefficients to determine absorbed dose for a given neutron energy distribution, and to convert the absorbed dose, measured with a dosimeter of a given material composition, to absorbed dose in tissue.

The nuclear cross sections are evaluated using a combination of measured data and GNASH [32] nuclear model calculations. The report will review measurements that have determined cross sections and kerma coefficients, but since there are only a limited number of experimental data sets for biologically-important target elements, theoretical predictions are needed to supplement these data. Numerous benchmark comparisons will be presented that compare the model predictions with measured data to validate the calculations of energy- and angle-dependent emission spectra, as well as total, non-elastic, and elastic scattering cross sections. For hydrogen, an evaluation is described that uses both R-matrix and phase-shift scattering theories to represent neutron-proton reaction data. Kerma coefficients are derived from the evaluated neutron cross sections and presented for individual elements as well as for ICRU muscle, A-150 tissue-equivalent plastic and other substances.

The current state of knowledge on neutron and proton sources will be described, with a particular emphasis on sources at energies used in therapy. This is important because calculations of radiation transport and absorbed dose for a therapy beam require an accurate understanding of the source characteristics. Both thick-target and monoenergetic neutron sources will be discussed as the latter are used for calibrations and for the determination of fundamental data.

The evaluated cross sections and kerma coefficients will be tabulated in the report for neutron- and proton-induced reactions on H, C, N, O, Al, Si, P, Ca, Fe, Cu, W, and Pb. Most detailed information will be provided for the most important elements, with less information for the others. However, complete tabulations on a fine incident-energy grid will be provided for all target elements as electronic files on an accompanying compact disc (CD). The CD will also contain the same cross section evaluations in the Evaluated Nuclear Data File (ENDF) format which are useful for implementation in radiation transport calculations.

Evaluation Methods

The evaluated nuclear cross sections and kerma coefficients which will be presented in the report were determined by nuclear model calculations using the GNASH code [32] and were benchmarked to available measurements [8, 9, 10]. The GNASH nuclear model code applies theories for compound nucleus, pre-equilibrium and direct reaction mechanisms. Optical model calculations serve to determine total, non elastic and elastic scattering cross sections. Making use of experimental data is particularly important for the analysis of the interaction of neutrons and protons with biologically-important elements, since an accurate theoretical description is generally difficult because of the non-statistical properties of light nuclei (caused by their widely-spaced nuclear levels). However, while there have been some useful recent measurements which have expanded the experimental database, the experimental information above 15 MeV is still relatively sparse, and for this reason nuclear theories and models provide a valuable tool for supplementing the measured data. Additionally, a nuclear-model computer code can generate the large amount of information specifying a reaction (cross sections for the secondary reaction products at all out going energies and angles) in a manner which conserves energy, angular momentum, parity, and unitarity (flux conservation).

There are a number of previous studies which aimed at determining neutron cross sections above 20 MeV for biologically-important elements, using nuclear model calculations. The most important of these are the calculations of Brenner and Prael [3],

and Dimbylow [12], both of which show extensive comparisons of their results with experimental data. The present work represents an advance over these earlier approaches principally in two ways: (1) it makes use of recent improvements in nuclear model calculations and optimizes them for describing nuclear reactions in the 0-250 MeV energy region; and (2) new experimental information, which has become available since the earlier studies, is used extensively to guide the calculations. Perhaps the most important measurements of non elastic processes are the neutron cross section measurements by Benck et al. [2], Haight et al. [14], Nauchi et al. [22], Slypen et al. [27, 28] and Subramanian et al., [29, 30] and the proton cross section measurements by Bertrand and Peelle [2], Cowley [11], Förtsch et al. [13] and Meier et al. [18, 19].

Results and Comparisons with Measurements

The ICRU report in preparation will provide extensive comparisons between the evaluated nuclear data and measured cross sections. In this paper we provide two illustrative examples taken from these comparisons: one particularly relevant to neutron therapy studies (neutron-induced emission spectra for oxygen); and one particularly relevant to proton therapy studies (proton-induced total nonelastic cross sections up to 250 MeV). In neutron therapy, calculations of energy deposition, and secondary neutron, photon, and charged particle production, depend critically on the accuracy of the nuclear reaction cross sections. Figure 1 shows the calculated proton, deuteron, and alpha-particle angle-integrated emission spectra for 27, 40 and 60 MeV neutrons incident on oxygen. Experimental data are shown from Benck et al. [2] and Subramanian et al. [29, 30], and the agreement is seen to be good. Calculations by Brenner and Prael [5], shown as a dashed line, are also shown for comparison. An accurate description of such microscopic reaction cross sections is important in radiation transport simulations of radiation therapy since oxygen is the most abundant tissue element (by mass), and a significant fraction of the energy deposited by neutrons in tissue is due to light secondary charged particles produced in neutron nonelastic interactions.

In proton therapy, protons lose energy mainly through electromagnetic interactions with atomic electrons, and because of the relatively small mass of the electron the protons lose only a small fraction of their energy and are only deflected by small angles in each interaction. The probability of nuclear reactions occurring increases with proton energy, but is still relatively small in the therapeutic energy range. However, these reactions in general remove primary protons from the beam and result in the production of secondary particles such as neutrons, gammas, protons, light ions and heavier recoil nuclei which can be emitted at large angles to the incident proton beam thus reducing the energy deposition along the beam path. The relative energy deposition of the neutron-induced heavier secondary charged particles is highest at, or just beyond, the maximum range of the primary proton beam [16]. Their contribution to the integral absorbed dose is small, but their enhanced biological effect can complicate dosimetric, biological and clinical phenomena. Particles emitted out of the beam can also result in small, but undesirable absorbed doses to a patient outside the target. Figure 2 shows the evaluated total nonelastic cross sections for protons on C, O, Fe and Pb up to 300 MeV compared with experimental data [6]. The evaluated results are based on optical model calculations, but small modifications to the calculated results were made to improve agreement with measurements. Carbon and oxygen are two of the most important tissue elements; iron and lead are present in accelerator collimators, shielding, and beam modifiers.

Kerma coefficients are derived from the evaluated microscopic neutron cross sections. The ICRU report presents comparisons between these kerma coefficients and experimental kerma coefficient data, obtained from both integral measurements of the ionization due to the secondary charged particles and from cross section measurements. Results are shown for both individual elements, and for mixtures and compounds, and the agreements are found to be good in most cases. An example is shown in Figure 3 for A-150 tissue-equivalent plastic. Results from a previous compilation [7] are also shown for comparison.

A particularly important quantity in neutron therapy is the kerma ratio for ICRU-muscle

to A150 plastic, since this can be used to relate A150 plastic ionization chamber measurements to those in muscle. By convoluting this quantity with the neutron therapy source fluence spectra, and averaging the results for the National Accelerator Centre, Fermi National Accelerator Laboratory, and a p(66)/Be neutron fluence spectrum assumed by Awschalom et al. [1] a value of 0.94 is obtained. This is in good agreement with the recommendation of 0.95 in both the international neutron dosimetry protocol [21] and in ICRU Report 45 [15]. A direct measurement of this ratio (using microdosimetric techniques) in the National Accelerator Centre's p(66)/Be beams gave 0.92 ± 0.02 [4].

IAEA Initiatives

The International Atomic Energy Agency (IAEA) convened a Consultants' Meeting to discuss the "Status of Nuclear Data for Radiation Therapy and Existing Data Development Activities in Member States". The meeting was held to review the current activities in member states and to determine the future role of the IAEA in this field.

In addition to the ICRU Report Committee "Nuclear Data for Fast Neutron and Proton Radiotherapy and for Radiation Protection", the details of which are described above, the Consultants took cognisance of the other groups which are presently active in related fields. These included the following IAEA Co-Ordinated Research Programs:

- Nuclear Data Needed for Neutron Therapy (completed, report in press)
- Applications of Heavy Charged Particles in Cancer Radiotherapy
- Compilation and Evaluation of Photonuclear Data
- Charged Particle Cross Section Database for Medical Radioisotope Production

The Consultants resolved that as far as possible there should be no overlap with the activities of other groups. It was therefore recommended that relevant information and nuclear data on the following topics, which are not presently being considered by these groups, be gathered and that the situation be assessed towards the end of 1998:

Accelerator-based neutron capture therapy (physical aspects)

- Heavy-ion (^{12}C and heavier) radiation therapy
- Therapeutic radionuclides
- Activation cross sections of tissue and shielding elements by particle therapy beams

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Figure Captions

- Figure 1. Evaluated angle-integrated emission spectra for $n+^{16}\text{O}$ from GNASH [32] model calculations (full line), compared with experimental data and Brenner and Prael's calculations [5] (dashed lines) for 25, 40 and 60 MeV. Triangles represent the data of Benck et al. [2], circles the data of Subramanian et al. [30] and crosses the re-determination of Subramanian's data at 60 MeV by Chadwick et al. [8].
- Figure 2. Evaluated total nonelastic cross sections for protons incident on C, O, Fe and Pb compared with measurements [6].
- Figure 3. Total kerma coefficient for A-150 tissue-equivalent plastic, k_0 , as a function of the energy of incident neutrons, E_n . The evaluated data (full line) are compared with an earlier evaluation (dashed line) by Caswell et al. [7] and with data (symbols) measured by Menzel et al. [20], McDonald and Cummings [17], Pihet et al. [23], Schrewe et al. [24, 25], Schuhmacher et al. [26] and Wu and Milavickas [31].