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Comparison of Photoneutron Yields in Tungsten Calculated by MCNPX Using Different Photonuclear Cross-Section Data for Typical Radiation Therapy Energies

Bryan Bednarz, Bin Han & X. George Xu

COMPARISON OF PHOTONEUTRON YIELDS IN TUNGSTEN CALCULATED BY MCNPX USING DIFFERENT PHOTONUCLEAR CROSS-SECTION DATA FOR TYPICAL RADIATION THERAPY ENERGIES

RADIATION BIOLOGY AND MEDICINE

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BRYAN BEDNARZ, BIN HAN, and X. GEORGE XU*
Nuclear Engineering and Engineering Physics
Rensselaer Polytechnic Institute, Troy, New York 12180

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During radiation therapy treatments, neutron contamination can be a source of unwanted radiation dose to the patient and medical personnel. Accurate cross-section data is needed to characterize the neutron contamination in medical accelerators using Monte Carlo methods. In this study, a comparison of the photoneutron yields using the default LA150U and the Chinese Nuclear Data Center (CNDC) photonuclear cross sections was performed. Thick tungsten plates, each of 0.125-cm thickness (one-third radiation length), were directly irradiated by an electron beam in MCNPX. In order to match typical radiation therapy energy ranges, the energy distribution of the electron beam was modeled as a Gaussian distribution with a mean energy of 18.3 MeV and a 3% full-width at half-maximum. The photoneutron yield using the LA150U is consistently ~12 to 17% higher than those from the CNDC data for each target thickness. The average photoneutron energy difference between the two cross-section libraries ranged from 3 to 42%. No major differences were seen between relative neutron fluences per solid angle for the two cross-section libraries. The discrepancies between the datasets provided above can be attributed to the oversimplification of using the default LA150U ^{184}W cross section for all other naturally occurring isotopes of tungsten. Therefore, the lack of cross-section data in the LA150U library is a definite concern when using MCNPX to determine secondary neutron production in a medical accelerator room since a majority of contamination neutrons are produced in tungsten components.

I. INTRODUCTION

External beam radiation treatment uses linear electron accelerators operated in energies up to 18 MeV. Secondary neutrons can be produced through photonuclear interactions within the head of the accelerator and the patient body. Such neutron contamination can be a source of unwanted radiation dose to the patient and medical personnel during radiation therapy treatments. Neutrons are of particular concern due to their high quality factor or ability to damage DNA through elastic collisions in human tissue. Some have warned that the secondary dose from neutron contamination during radiation therapy could increase the risks of latent effects in patients and ultimately weaken the efficacy of the treatment.[1] Furthermore, new modalities such as intensity modulated radiation therapy and tomotherapy require longer beam-on times, thus prolonging the patient exposure to neutron contamination from high-energy treatment beams.[1]

Several studies have focused on estimating the neutron dose during radiation therapy treatments. These studies have used measurements, Monte Carlo simulations, or both. Direct measurements of neutron fluence and spectra in a medical accelerator room require complex measurement techniques and can often be time

*E-mail: xug2@rpi.edu

consuming and labor intensive. Monte Carlo methods, on the other hand, have become an alternative method since they are quicker, more flexible, and less rigorous than taking measurements. To characterize the neutron contamination in medical accelerators using Monte Carlo methods, accurate cross-section data is needed. The Monte Carlo Neutral Particle Extended (MCNPX) code[2] has been the code of choice for these types of simulations because of its superior neutron transport capabilities and its ability to handle photonuclear interactions.

Currently, MCNPX Version 2.5.0 has limited photonuclear libraries. The LA150U is the only photonuclear library supported by the most recent release of MCNPX (Ref. 2). Since the majority of neutrons is produced in accelerator components made of tungsten,[3] it is interesting to investigate potential discrepancies due to the limited cross-section data in LA150U that accounts for only one out of the five naturally occurring isotopes of tungsten. One possible approach to circumvent this limitation is to implement external cross-section libraries into MCNPX simulations. For example, the International Atomic Energy Agency (IAEA) has recently provided a complete compilation and evaluation of photonuclear data taken from several different international research institutes.[4] The IAEA database has cross-section libraries that include data for all isotopes of tungsten.

In this work, we compare the photoneutron production in tungsten slabs in energies relevant to the photon radiation treatment using the MCNPX default LA150U library and the Chinese Nuclear Data Center (CNDC) library that is part of the IAEA recommended photonuclear cross-section database.

II. METHODS AND MATERIALS

A series of tungsten plates, each 0.125-cm thick, was directly irradiated by an electron beam in the MCNPX code, which follows similar techniques used in previous studies.[5,6] In order to match typical radiation therapy energy ranges, the energy distribution of the electron beam was modeled as a Gaussian distribution with a mean energy of 18.3 MeV and a 3% full-width at half-maximum (FWHM). The electron beam had a Gaussian spatial spread of 1-mm FWHM. The tungsten plates were given a nominal density of 18.0 g/cm^3. Detailed physics models were used for electrons, photons, and neutrons in all simulations. The ITS electron indexing method was implemented, which picks the cross-section data consistent with the energy binning.

To reduce computation time, the cutoff energies for electrons and photons were set to 5 MeV. This energy seemed appropriate since it is below the photonuclear threshold for all isotopes of tungsten and high enough to avoid unnecessary transport of secondary electrons in the problem geometry. No other variance reduction techniques were used in the simulations.

Two different sets of photonuclear cross-section libraries were compared in this work: the default LA150U library and the CNDC library from the IAEA database. Since the LA150U library had only cross-section data for ^{184}W, the mix-and-match feature in MCNPX was utilized to use this data for all other isotopes of tungsten. The CNDC library contained cross-section data for all naturally occurring isotopes of tungsten (^{180}W, ^{182}W, ^{183}W, ^{184}W, and ^{186}W); therefore, no cross-section substitution was necessary. The CNDC (γ, n) cross sections along with the ^{184}W LA150U (γ, n) cross section are plotted in Fig. 1.

Comparisons were made between the yields, average neutron energy, and angular distribution of the neutrons emanating from the tungsten plates for each of the cross-section libraries. The neutron yields and average neutron energies for each tungsten isotope are calculated implicitly in MCNPX and can be found in Table 140 of the output.[2] The angular distribution of the neutrons was calculated using point and ring detector tallies (F5:n). These detectors estimate the neutron fluence by calculating the probability that after every source or collision event the neutron will transport to the detector. All points and rings were placed at a radius of 300 cm from the upstream surface of the target and the measurement angle with respect to the central axis of the electron beam. The tally results were then multiplied by the square of the source-to-detector distance to normalize the results per steradian (sr^{-1}). Thus, the final result gives the neutron yield as the number of neutrons that exit the target into a given solid angle per incident electron.

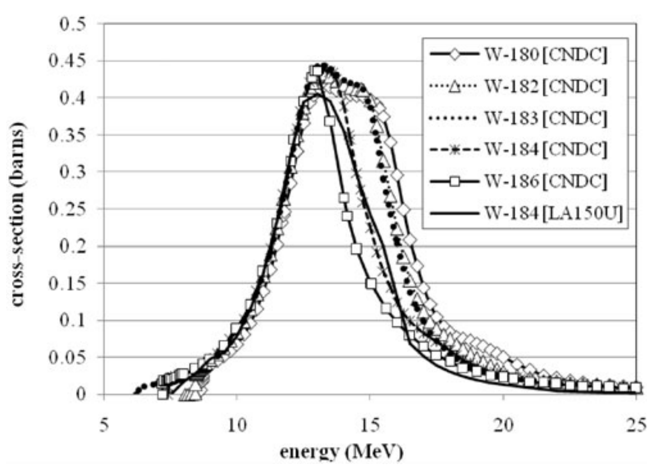

Fig. 1. CNDC and LA150U (γ, n) cross-section data for tungsten.

III. RESULTS AND DISCUSSION

The ratio of the photoneutron yield using the LA150U and CNDC libraries versus target thickness is provided in Fig. 2 for comparison. The yield using the LA150U is consistently ~12 to 17% higher for each target thickness. The ratio of the average photoneutron energy using the two different libraries versus target thickness is provided in Fig. 3. The average energy difference between the two cross-section libraries ranged from 3 to 42%, with the average energy using the LA150U cross sections always exceeding the average energy using the CNDC cross section. The ratio of neutron fluence per solid angle (relative to the central axis fluence) between the two cross-section libraries is provided in Fig. 4 as a function of measurement angle with respect to the central axis. No major differences were seen between the two cross-section libraries.

The discrepancies between the data sets provided above can be attributed to the oversimplification of using the default LA150U ^{184}W cross section for all other naturally occurring isotopes of tungsten. There are four important features that characterize the giant dipole resonance (GDR) region of the photonuclear cross section. These features include the photonuclear threshold energy (E_{th}), the center energy (E_m), the peak cross section (σ_{max}), and the width of the resonance peak (Γ). The differences between the center energy E_m vary only slightly between isotopes of similar atomic numbers. In contrast, however, the peak cross section σ_{max} increases with nucleon number. The threshold energy E_{th} and the width Γ exhibit very irregular behavior with strong oscillations as a function of nucleon number. This behavior is attributed to the deformation of the nuclei seen in heavy isotopes. If the shape of the nucleus is not spherical—but rather elongated (prolate or oblate)—the GDR is a superposition of two resonance curves.[7] This type of curve is irregularly shaped with a larger total width. These differences, which strongly influenced the photoneutron yields provided in this study, can be seen in Fig. 1.

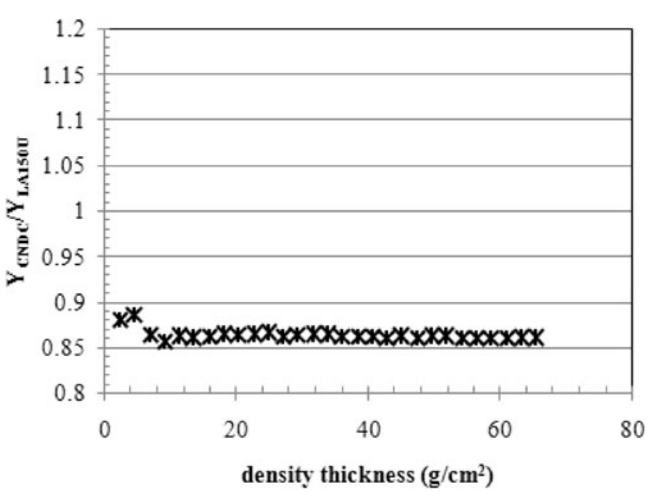

Fig. 2. Ratio of photoneutron yields as a function of target thickness between simulations using the CNDC and the LA150U cross-section libraries.

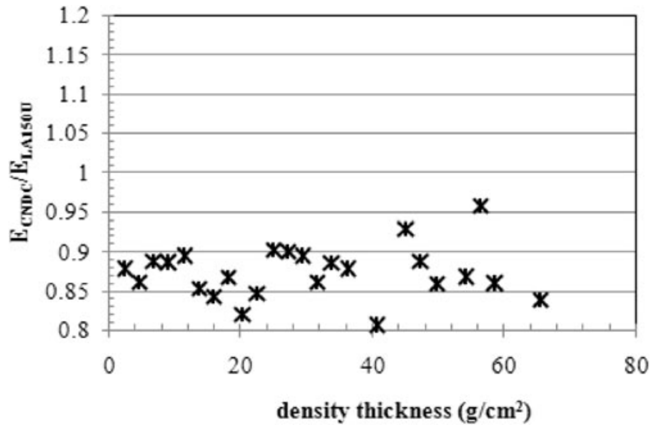

Fig. 3. Ratio of average neutron energies as a function of density thickness between simulations using the CNDC and the LA150U cross-section libraries.

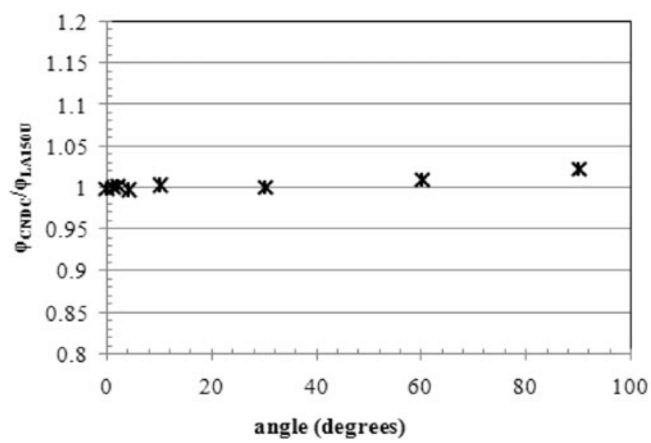

Fig. 4. Ratio of the relative neutron fluence per solid angle between simulations using the CNDC and the LA150U cross-section libraries.

IV. CONCLUSIONS

The photoneutron yields from tungsten plates irradiated with an electron beam similar to that seen in medical accelerators were compared using two different cross-section libraries. Simulations using the LA150U library with cross-section data for only one isotope of tungsten provided higher yields and average neutron energies as a function of thickness compared to simulations using the CNDC library depending on the target thickness. No major differences were seen between the relative neutron fluence per solid angle using the two different cross-section libraries.

The incomplete cross-section data for tungsten isotopes in the LA150U library is a definite concern when using MCNPX to determine neutron doses in a medical accelerator room since a majority of contamination neutrons are produced in tungsten components. We recommend that the user take these shortcomings into consideration when using the default LA150U cross-section libraries.

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