**Neutron Kerma Factors for H, C, N, O,
and Tissue in the Energy Range
of 20 to 70 MeV**

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in the Energy Range of 20 to 70 MeV*

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Abstract

Calculated kerma factors (kerma per unit fluence) in the energy range of 20 to 70 MeV based on nonelastic charged-particle-production cross-section data obtained from the intranuclear-cascade model of nuclear reactions are given for H, C, N, O, and tissue.

NEUTRON KERMA FACTORS FOR H, C, N, O, AND TISSUE
IN THE ENERGY RANGE OF 20 TO 70 MeV

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I. INTRODUCTION

At the present time, patient irradiation with fast neutrons is being conducted both in the United States and in Europe to determine the efficacy of these particles in cancer radiotherapy. The neutron beams being used for cancer radiotherapy often include substantial numbers of neutrons with energies > 20 MeV (LA73), (MANTA73),* and it is therefore desirable to have available data, e.g., kerma factors (kerma per unit fluence), that may be used to convert a fluence of these higher energy neutrons to absorbed dose in tissue. At present, neutron kerma factors are available in hydrogen for energies ≤ 100 MeV (Ba76), (Ca74) but are available in carbon, nitrogen, and oxygen only at energies ≤ 20 MeV (Ca74). In this paper, calculated neutron kerma factors for H, C, N, O, and tissue in the energy range of 20 to 70 MeV are presented. The available experimental data on charged-particle production from neutron interactions with C, N, and O nuclei at energies ≥ 20 MeV are very limited, and thus the results presented here are based almost entirely on theoretical cross-section data. Calculated results obtained with these cross-section data have previously been compared with a variety of experimental data and, in general, good agreement has been obtained (A174a), (A174b).

*Work is in progress at the Fermi National Accelerator Laboratory to conduct patient irradiation with a neutron beam that contains substantial numbers of neutrons at energies ~ 60 MeV (Aw76).

In section II the method of calculation is briefly discussed. In section III the results are presented and discussed. In particular in section III, the results are compared to those of (Ba76) for H and those of (Ca74) for H, C, N, and O at 20 MeV.

II. METHOD OF CALCULATION

All of the results presented here were obtained with the nucleon-meson transport code HETC (Ch72). This code and the manner in which the various physical processes are included in the code have been described in detail elsewhere (A174a), (A174b), (Ch72), (A170), so only a brief discussion will be given here. At the energies of interest in this paper, the code takes into account both elastic and nonelastic neutron-nucleus collisions. Elastic collisions with hydrogen are treated using the analytic fits to experimental data given by (Be63), and elastic collisions with nuclei other than hydrogen are treated using a combination of experimental and theoretical data which are on the 05R (Ir65) master cross-section tape. (This cross-section tape, together with the data used, is available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.) When a nonelastic collision occurs, the intranuclear-cascade code (Be63b), (Be71) is utilized to determine the type and energy of all particles emitted from the collision. The kerma factor, as calculated here, is obtained by adding the kinetic energies of all of the charged particles, including the recoiling residual nucleus, from a neutron-nucleus collision. The code HETC is capable of transporting the secondary particles produced by nuclear reactions, but this feature of the code was not utilized in obtaining the results presented here.

III. RESULTS AND DISCUSSION

In Fig. 1 the calculated kerma per unit fluence is given as a function of energy for H, C, N, O, and tissue. Also shown in the figure are the calculated results of (Ba76) for H and the calculated results of (Ca74) at 20 MeV for H, C, N, O, and tissue. The error bars on the calculated C and N data are statistical only and represent one standard deviation; i.e., these error bars represent the uncertainties in the calculated values due to the statistical nature of the calculation. These error bars do not, of course, indicate in any way the uncertainties in the calculated data due to cross-section uncertainties. Error bars are not shown for H, O, and tissue since for these elements the statistical errors are smaller than the plotted points.

All of the calculated results for H in Fig. 1 are in substantial agreement, as they should be, since the n-p differential-scattering cross section in the energy range considered here is quite well known. The kerma factor for C at 20 MeV as calculated here and that given in (Ca75) are in very good agreement, but for O, N, and tissue the values at 20 MeV as calculated here are lower than those given in (Ca74). The discrepancy in the tissue values at 20 MeV is smaller than that in the N and O values because of the large contribution of H to the tissue kerma. The (Ca74) calculations at 20 MeV are based insofar as possible on experimental cross-section data, while the calculations reported here are based to a very large extent on theoretical cross-section data. Thus the (Ca74) values at 20 MeV should be more reliable than those calculated here. The contribution to the kerma factors for N and O at 20 MeV from elastic scattering is not large and the differential elastic-scattering cross section is reasonably well known, so

Fig. 1. Kerma per unit fluence vs neutron energy for neutrons in H, C, N, O, and tissue.

it is the contribution to the kerma factors from nonelastic collisions that is primarily responsible for the discrepancies at 20 MeV shown in Fig. 1. Furthermore, the total nonelastic cross sections for N and O at 20 MeV obtained from the intranuclear-cascade model of (Be71) are in good agreement with the evaluated nuclear data given in the ENDF/B-IV (Oz73) files, so the discrepancies shown in Fig. 1 are due primarily to inadequacies in the differential charged-particle-production cross sections obtained from the intranuclear-cascade model at the lower energies. This is not unanticipated since many of the approximations used in deriving the intranuclear-cascade model become increasingly invalid as the energy decreases (Be63a), (Be63b), but, nevertheless, the model has often been used quite successfully (A174a), (A174b) at these lower energies because it is the only readily available source of particle-production cross-section data at energies ≥ 20 MeV. Since the intranuclear-cascade model becomes more reliable as the energy of the incident neutron increases, it is to be expected that for N, O, and tissue the calculated values of the kerma factors at 70 MeV are more reliable than are the calculated values at 20 MeV. Until better data become available, a best estimate of the lower limit on the kerma factors may be obtained by using the (Ca74) values at 20 MeV, the values calculated here at 70 MeV, and some form of interpolation between these data points to determine the kerma factors at intermediate energies between 20 and 70 MeV. A best estimate of the upper limit on the kerma factors may be obtained by renormalizing all of the values given here to the (Ca74) values at 20 MeV, i.e., by assuming that the calculated values at all energies ≥ 20 MeV are as much in error as those at 20 MeV.

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