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The Frequency of Occurrence of Various Nuclear Reactions When Fast Neutrons ($\lesssim$50 MeV) Pass Through Tissue-Equivalent Material

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THE FREQUENCY OF OCCURRENCE OF VARIOUS NUCLEAR REACTIONS WHEN FAST NEUTRONS ($\leqslant$ 50 MeV) PASS THROUGH TISSUE-EQUIVALENT MATERIAL*

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Abstract

Calculated results are presented for the frequency with which various partial nuclear-reaction cross sections are utilized when fast neutrons ($\leq$ 50 MeV) are transported through a tissue-equivalent phantom to obtain an indication of which cross sections are of most importance for radiotherapy applications and are therefore in need of experimental verification.

I. INTRODUCTION

When fast neutrons (≤ 50 MeV) such as those that are presently being used in cancer radiotherapy pass through tissue, a large variety of nuclear reactions occur, and radiations with high linear energy transfer (LET) are produced. In a previous paper,[1] hereinafter referred to as 1, calculated results were presented of the physical and biological effects that occur when several different neutron spectra are incident on a tissue-equivalent phantom, and it was shown that the calculated absorbed-dose results are in good agreement with experimental measurements. Much of the nuclear cross-section data used in obtaining the results presented in 1 were based on theoretical considerations because experimental data are not generally available. The amount of cross-section data needed to obtain the results given in 1 is very large, and much of it is not likely to be available experimentally for a long time. However, not all of the data needed are likely to be of equal "importance" in producing the results of interest in radiotherapy, and it is, therefore, of interest to know which nuclear-reaction cross sections contribute significantly to the results presented in 1.

In this paper, data are presented on the frequency as a function of energy with which the various partial nuclear-reaction cross sections were used in obtaining the results presented in 1 for an incident neutron spectrum produced by 67-MeV ^{1}H on a thick Li target.* The major uncertainties in the cross sections are associated with nonelastic nuclear reactions which occur at the higher energies, and, therefore, data are presented here for only

*Results similar to those presented in Section III have also been obtained for the other incident neutron spectra considered in 1, i.e., for the neutron spectra produced by 35- and 50-MeV ^{2}H on Be.[2] These additional results are not, however, substantially different from those given in Section III.

neutron energies > 10 MeV. It must be emphasized that the frequency of occurrence of a partial nuclear-reaction cross section in the transport calculations is only an approximate estimate of the "importance" of the cross section since biological effects are also very dependent on such things as the type and energy distribution of the emitted particles which are not explicitly considered here. Nevertheless, the information presented here should serve at least as an indication of those cross sections which are most in need of experimental verification for radiotherapy applications.

II. CALCULATIONAL DETAILS

The transport code HETC,[3] which was used to obtain the data given in 1, contains, in part, theoretical cross-section models that are employed to generate the differential cross-section data as a function of energy needed as the transport calculations are carried out, and explicit information on the frequency with which various partial cross sections in various energy ranges are used during the transport calculations is not usually obtained. To obtain the results presented here, the code has been modified slightly to provide this information. The results supplement those given in 1 but do not in any way change them. In particular, the source spectrum and geometry considered here are the same as those used in Section IV of 1, and the composition of tissue-equivalent material is the same as that used in 1.

The nuclear cross-section data and nuclear models utilized in HETC, and the manner in which they are used, have been described in detail previously,[4-11] so only a brief discussion will be given here. For neutron energies > 15 MeV, the neutron-hydrogen elastic differential cross-section data are taken from the analytic fits to experimental data as given by Bertini,[4] and the differential cross-section data for the elastic collisions of neutrons with elements other than hydrogen are taken from experimental data and optical-model calculations.* For neutron-nucleus nonelastic collisions at energies > 15 MeV, all differential particle-production cross sections are obtained from the intranuclear-cascade-evaporation model of nuclear reactions as formulated by Bertini and Guthrie.[4-9] It is the inclusion of this nuclear cross-section model in HETC that gives the code the capability of transporting the higher energy (≳ 15 MeV) neutrons through matter. At neutron energies < 15 MeV, differential elastic cross-section data and total nonelastic cross-section data are taken from ENDF/B[13] and DNA[14] data files.† When a nonelastic nuclear collision occurs at energies of < 15 MeV, the evaporation code of Guthrie[9] is used to determine the differential particle-production cross sections. The use of an evaporation model in this manner is undesirable since it does not allow the use of all of the evaluated data in the ENDF/B[13] and DNA[14] libraries, particularly the detailed data on gamma-ray production. In the next section, calculated results are presented on the frequency with which the various partial cross sections are utilized as a function of energy when neutrons produced by 67-MeV ^{1}H on a thick Li target are transported through a tissue-equivalent phantom.

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*These data are contained on the master cross-section tape for use in the 05R Monte Carlo code.[12] The data, together with references to the sources of the data, are available from the Radiation Shielding Information Center of the Oak Ridge National Laboratory.

†The results in 1 were obtained with MAT. Nos. 4148 for H, 1165 for C, 4133 for N, and 4134 for O.

III. RESULTS AND DISCUSSION

All of the results presented here have been averaged over the tissue-equivalent phantom, that is, no spatial information is presented, and, therefore, the collisions which are discussed may occur anywhere within the phantom. In considering the results, it should be remembered that an individual neutron may undergo a variety of collisions in the course of being transported through the phantom.

In Table I the total number of collisions in various energy intervals (> 10 MeV) per source neutron is given. Note that 5-MeV intervals are used between 10 and 30 MeV and 10-MeV intervals are used between 30 and 60 MeV. The higher energy interval does not extend above 66 MeV because there are no incident neutrons above this energy. Also shown in the table are the fraction of the total number of collisions in a given energy interval which are elastic and the fraction of the total number of collisions in a given energy interval which are nonelastic. The fractional values in Table I and throughout the remainder of the paper may be converted to absolute numbers by using the total number of collisions per source neutron in a given energy interval that is given in Table I. The various fractional values do not always sum exactly to unity as they should because of roundoff. All of the results presented here were carried out using Monte Carlo techniques and are, therefore, subject to statistical fluctuations. In all of the tables, the numbers in parentheses represent one standard deviation expressed in percent. From Table I it may be seen that at all energies considered approximately 75% of the collisions are elastic and approximately 25% of the collisions are nonelastic.

In Table II the frequency of occurrence of elastic and nonelastic collisions with the individual elements in the tissue-equivalent phantom is

Table I. Number of Total, Elastic, and Nonelastic Collisions when Neutrons from 67-MeV ^{1}H on Li are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)							
	10-15	15-20	20-25	25-30	30-40	40-50	50-60	60-66
Total number of collisions in a given energy range per source neutron	.23(1)[a]	.19(3)	.16(3)	.14(2)	.25(4)	.22(3)	.18(3)	.09(4)
Fraction of the collisions in a given energy interval which are elastic	.76(1)	.77(1)	.77(1)	.76(1)	.76(1)	.75(1)	.74(1)	.69(2)
Fraction of the collisions in a given energy interval which are nonelastic	.24(4)	.23(4)	.23(3)	.24(4)	.24(3)	.25(3)	.26(2)	.31(5)

a. The numbers in parentheses represent one standard deviation expressed in percent.

Table II. Frequency of Occurrence of Elastic and Nonelastic Collisions with Individual Elements when Neutrons from 67-MeV ^{1}H on Li are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)							
	10-15	15-20	20-25	25-30	30-40	40-50	50-60	60-66
Fraction of the elastic collisions in a given energy range which are with H	.57(2)[a]	.52(2)	.43(4)	.39(3)	.34(3)	.29(5)	.27(4)	.21(5)
Fraction of the elastic collisions in a given energy range which are with C	.07(12)	.11(5)	.13(8)	.13(7)	.11(6)	.13(6)	.13(5)	.14(8)
Fraction of the elastic collisions in a given energy range which are with N	.01(14)	.02(16)	.02(18)	.03(19)	.03(11)	.02(14)	.03(15)	.03(16)
Fraction of the elastic collisions in a given energy range which are with O	.35(3)	.35(3)	.42(4)	.45(3)	.52(2)	.56(2)	.57(1)	.62(2)
Fraction of the nonelastic collisions in a given energy range which are with C	.12(13)	.17(8)	.20(11)	.17(11)	.20(8)	.18(6)	.20(9)	.19(10)
Fraction of the nonelastic collisions in a given energy range which are with N	.06(15)	.05(17)	.03(27)	.03(31)	.04(17)	.04(15)	.05(20)	.04(17)
Fraction of the nonelastic collisions in a given energy range which are with O	.82(3)	.78(2)	.77(3)	.80(3)	.76(2)	.78(2)	.75(2)	.76(3)

a. The numbers in parentheses represent one standard deviation expressed in percent.

given. The results in the table are dependent both on the magnitude of the cross sections and on the number density of the individual elements in the phantom.* At all energies considered, the large majority of the elastic collisions are with hydrogen and oxygen, but there is a nonnegligible number of elastic collisions with carbon. At the lowest energies considered, elastic collisions with hydrogen predominate over those with oxygen, but at the highest energies considered, elastic collisions with oxygen predominate over those with hydrogen. At all energies considered, a major fraction of the nonelastic collisions are with oxygen, but there is a substantial fraction of the nonelastic collisions which are with carbon. The fraction of both elastic and nonelastic collisions with nitrogen is small because of the small amount of nitrogen in the phantom.

In Table III the frequency of occurrence of various types of nonelastic collisions in various energy ranges is given. In the table, inelastic collisions, i.e., collisions in which the nucleon number and atomic number of the target nucleus are the same before and after the collision, are denoted by (n,n). It is also to be understood that with all other reaction types considered, gamma rays may or may not be emitted from the reactions. In the table, results are given explicitly in a given energy range for only those reaction types which have a statistical error of < 25%. Also shown in the table is the fraction of all nonelastic collisions due to all reaction types with statistical errors > 25%.

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*The number densities used in the calculations were 6.6×10^{22} atoms/cm^3 H, 8.2×10^{21} atoms/cm^3 of C, 1.6×10^{21} atoms/cm^3 of N, and 3.0×10^{22} atoms/cm^3 of O.

Table III. Frequency of Occurrence of Various Types of Nonelastic Collisions when Neutrons from 67-MeV ^{1}H on Li are Transported through a Tissue-Equivalent Phantom

Element	Reaction Type	Fraction of the Nonelastic Collisions which are of a Given Type[a]							
		Energy Interval (MeV)							
		10-15	15-20	20-25	25-30	30-40	40-50	50-60	60-66
C	n,n[b]	.12(13)[c]	.04(23)	.04(25)		.02(23)			
	n,np		.05(18)		.06(22)	.06(16)	.04(16)	.05(18)	.04(19)
	n,2np					.04(23)	.03(18)	.02(20)	
	n,n3α		.08(12)	.08(13)	.06(19)	.05(16)	.02(25)	.03(21)	
	n,2npα							.03(24)	
N	n,n[b]	.06(15)							
O	n,n[b]	.78(3)	.25(8)	.17(13)	.11(15)	.10(11)	.07(15)	.07(24)	
	n,2n				.05(17)	.04(14)	.05(17)	.05(18)	.04(23)
	n,np		.30(8)	.32(8)	.33(6)	.23(9)	.23(6)	.20(8)	.20(10)
	n,nα		.16(10)	.16(7)	.15(13)	.08(13)	.07(15)	.04(14)	
	n,2np			.05(22)	.14(11)	.23(7)	.23(6)	.17(14)	.16(12)
	n,2n2p						.06(17)	.10(13)	
	n,3n2p							.02(24)	
All nonelastic reaction types in a given energy range which have a statistical error > 25%		.04(27)	.12(12)	.17(11)	.11(15)	.15(12)	.21(6)	.21(8)	.55(4)

a. Only those reactions in a given energy range which have a statistical error < 25% are considered explicitly.

b. Includes all inelastic collisions, i.e., all nonelastic collisions in which the nucleon number and atomic number of the target nucleus are the same before and after the collision.

c. The numbers in parentheses represent one standard deviation expressed in percent.

At energies < 15 MeV, essentially all nonelastic collisions that occur in the calculations are inelastic. As the energy increases, the types of reactions that occur become more numerous. At energies > 15 MeV, no single reaction is of overwhelming importance, but at various energies there are appreciable contributions from the (n,n), (n,np), (n,nα), and (n,2np) reactions in oxygen. Also, it is worth noting that at the higher energies an appreciable fraction of the nonelastic collisions is due to those reaction types which have a statistical error of < 25%.

In considering the results, it must be remembered that only the frequence of occurrence of the various cross sections in the transport calculations has been considered, and this is only a very approximate estimate of the "importance" of the cross section when fast neutrons are used in cancer radiotherapy.

APPENDIX

In this appendix, results analogous to those presented in the body of the paper are given for neutron spectra produced by 35- and 50-MeV ^{2}H on thick beryllium targets. The spectra used are shown in Ref. 1. The conclusions that may be drawn from the results presented in this appendix are not substantially different from those that may be drawn from the results presented in Section III.

Table I.A. Number of Total, Elastic, and Nonelastic Collisions when Neutrons from 35-MeV ^{2}H on Be are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)				
	10-15	15-20	20-25	25-30	30-40
Total number of collisions in a given energy interval per source neutron	.48(2)[a]	.38(2)	.16(3)	.06(4)	.02(11)
Fraction of the collisions in a given energy interval which are elastic	.76(1)	.76(1)	.77(1)	.77(2)	.81(4)
Fraction of the collisions in a given energy interval which are nonelastic	.24(2)	.24(3)	.23(4)	.23(6)	.19(16)

a. The numbers in parentheses represent one standard deviation expressed in percent.

Table II.A. Frequency of Occurrence of Elastic and Nonelastic Collisions with Individual Elements when Neutrons from 35-MeV ^{2}H on Be are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)				
	10-15	15-20	20-25	25-30	30-40
Fraction of the elastic collisions in a given energy range which are with H	.56(1)[a]	.53(2)	.41(3)	.38(5)	.37(11)
Fraction of the elastic collisions in a given energy range which are with C	.09(6)	.10(6)	.13(8)	.13(10)	.12(13)
Fraction of the elastic collisions in a given energy range which are with N	.01(18)	.02(12)	.03(16)	.03(27)	.02(47)
Fraction of the elastic collisions in a given energy range which are with O	.34(2)	.35(3)	.44(3)	.45(4)	.49(7)
Fraction of the nonelastic collisions in a given energy range which are with C	.09(8)	.20(7)	.16(11)	.19(19)	.17(37)
Fraction of the nonelastic collisions in a given energy range which are with N	.05(14)	.04(15)	.03(27)	.02(38)	.00(100)
Fraction of the nonelastic collisions in a given energy range which are with O	.86(1)	.76(2)	.81(2)	.79(5)	.83(8)

a. The numbers in parentheses represent one standard deviation expressed in percent.

Table III.A. Frequency of Occurrence of Various Types of Nonelastic Collisions when Neutrons from 35-MeV ^2H on Be are Transported through a Tissue-Equivalent Phantom

Element	Reaction Type	Fraction of the Nonelastic Collisions which are of a Given Type[a]				
		Energy Interval (MeV)				
		10-15	15-20	20-25	25-30	30-40
C	n,n[b]	.08(9)[c]	.06(18)	.04(19)		
	n,np		.06(10)	.04(24)		
	n,n3α		.06(19)		.06(24)	
N	n,n[b]	.04(16)				
	n,np		.02(21)			
O	n,n[b]	.79(1)	.25(6)	.17(12)		
	n,p		.01(18)			
	n,α		.02(21)			
	n,2n	.07(16)	.02(16)			
	n,np		.26(6)	.39(5)	.32(13)	
	n,nα		.18(8)	.16(13)	.18(20)	
	n,2np			.04(21)	.15(24)	
All nonelastic reaction types in a given energy range which have a statistical error > 25%		.01(38)	.05(13)	.15(13)	.28(16)	1.00(0)

a. Only those reactions in a given energy range which have a statistical error < 25% are considered explicitly.

b. Includes all inelastic collisions, i.e., all nonelastic collisions in which the nucleon number and atomic number of the target nucleus are the same before and after the collision.

c. The numbers in parentheses represent one standard deviation expressed in percent.

Table IV.A. Number of Total, Elastic, and Nonelastic Collisions when Neutrons from 50-MeV ^2H on Be are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)					
	10-15	15-20	20-25	25-30	30-40	40-50
Total number of collisions in a given energy interval per source neutron	.37(2)[a]	.39(2)	.33(2)	.14(4)	.08(4)	.01(15)
Fraction of the collisions in a given energy interval which are elastic	.75(1)	.77(1)	.78(1)	.77(2)	.77(2)	.77(5)
Fraction of the collisions in a given energy interval which are nonelastic	.25(2)	.23(3)	.22(2)	.23(6)	.23(6)	.23(18)

a. The numbers in parentheses represent one standard deviation expressed in percent.

Table V.A. Frequency of Occurrence of Elastic and Nonelastic Collisions with Individual Elements when Neutrons from 50-MeV ^{2}H on Be are Transported through a Tissue-Equivalent Phantom

	Energy Interval (MeV)					
	10-15	15-20	20-25	25-30	30-40	40-50
Fraction of the elastic collisions in a given energy range which are with H	.56(1)[a]	.52(2)	.43(2)	.40(3)	.36(5)	.33(22)
Fraction of the elastic collisions in a given energy range which are with C	.07(8)	.11(4)	.12(4)	.12(10)	.12(9)	.08(38)
Fraction of the elastic collisions in a given energy range which are with N	.01(18)	.02(13)	.02(12)	.03(19)	.02(26)	.01(100)
Fraction of the elastic collisions in a given energy range which are with O	.35(2)	.35(2)	.43(2)	.46(3)	.50(3)	.58(12)
Fraction of the nonelastic collisions in a given energy range which are with C	.10(8)	.21(6)	.18(8)	.17(11)	.20(15)	.14(32)
Fraction of the nonelastic collisions in a given energy range which are with N	.06(12)	.03(16)	.03(24)	.06(18)	.02(46)	.04(61)
Fraction of the nonelastic collisions in a given energy range which are with O	.84(1)	.76(2)	.79(2)	.77(3)	.77(4)	.81(10)

a. The numbers in parentheses represent one standard deviation expressed in percent.

Table VI.A. Frequency of Occurrence of Various Types of Nonelastic Collisions when Neutrons from 50-MeV ^{2}H on Be are Transported through a Tissue-Equivalent Phantom

Element	Reaction Type	Fraction of the Nonelastic Collisions which are of a Given Type[a]					
		Energy Interval (MeV)					
		10-15	15-20	20-25	25-30	30-40	40-50
C	n,n[b]	.10(8)[c]	.07(15)	.02(25)			
	n,np		.07(9)	.06(16)	.07(19)		
	n,n3α		.06(13)	.07(17)			
N	n,n[b]	.06(12)	.02(22)				
	n,np				.04(24)		
O	n,n[b]	.79(1)	.22(4)	.13(6)	.11(17)	.08(22)	
	n,α	.06(13)	.01(24)				
	n,2n		.03(21)	.04(20)	.06(23)		
	n,np		.28(5)	.36(5)	.33(8)	.25(8)	
	n,nα		.19(6)	.17(10)	.13(12)	.08(22)	
	n,2np		.01(25)	.07(11)	.12(14)	.23(15)	
All nonelastic reaction types in a given energy range which have a statistical error > 25%		.00(71)	.05(14)	.09(12)	.14(15)	.36(8)	1.00(7)

a. Only those reactions in a given energy range which have a statistical error < 25% are considered explicitly.

b. Includes all inelastic collisions, i.e., all nonelastic collisions in which the nucleon number and atomic number of the target nucleus are the same before and after the collision.

c. The numbers in parentheses represent one standard deviation expressed in percent.

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