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Isotopic Cross Sections for Production of Gamma Rays Created by Neutron Interactions with ^{11}B for E_n Between 2 and 22 MeV: Tabulated Data

D. C. Larson and J. K. Dickens

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D. C. Larson and J. K. Dickens[‡]

[‡]Joint Institute for Heavy Ion Research
College of Arts and Sciences
Department of Physics and Astronomy
The University of Tennessee
Knoxville, TN 37996

TABLE OF CONTENTS

LIST OF TABLES

ABSTRACT

Inelastic and nonelastic neutron interactions with [11]B have been studied for incident neutron energies between 2 and 22 MeV. Neutrons from the Oak Ridge Electron Linear Accelerator (ORELA) impinged a sample of natural boron. Gamma rays resulting from neutron interactions were detected using a well-calibrated intrinsic-Ge detection system. Data reduction included compensation for Doppler broadening of the observed peaks and corrections due to incident neutron attenuation, effects due to multiple scattering of neutrons, and sample attenuation of the outgoing gamma rays. Cross sections for gamma rays having energies (in keV) of 2124, 4445, 4741, 5020, 6434, 6743+6793 (combined), and 7286 following inelastic scattering, of 478 keV from the [11]B(n,nαγ)[7]Li reaction, and of 718 keV from the [11]B(n,2nγ)[10]B reaction as functions of incident neutron energy are presented in tabular form.

1.0 INTRODUCTION

As part of a now-terminated program to measure and report[1-5] photon-production cross sections for neutron interactions with elements for applications to fusion-power technology, isotopic photon-production cross sections are reported for neutron interactions with ^{11}B. At the time these measurements were made, the gamma-ray production cross sections as a function of incident neutron energy were given priority 1 status in the national and world request lists.[6] A preliminary report on the results of the experiment was presented.[3] Since then, a computer program was developed to predict multiple-scattering effects important to this and other similar experiments with much greater accuracy than had been available earlier. The final deduced cross sections are documented in this report.

2.0 EXPERIMENTAL DETAILS

The general experimental system for (n,xγ) measurements at the ORELA has been documented in some detail in previous reports.[1,7] The major specific item pertinent to the present experiment is that rather coarse binning in incident neutron energy was required because of the small cross sections for the reactions of interest; a total of 17 neutron-energy bins covering the range 1.69 $\leq E_n \leq$ 22.2 MeV were adopted. For each bin, a gamma-ray spectrum of 4096 channels, having a gamma-ray energy dispersion of ~2 keV, was obtained.

The sample studied was 54 g of metallic boron in powder form enclosed in a 9-g CH_2 bottle of 1.8-cm radius by 5.8-cm height. Data reduction initially used the FORTRAN program GRPGLI;[8] however, because the program could not adequately handle the peaks in the spectrum which were substantially Doppler broadened, most of the peak areas were extracted interactively using a BASIC program[9] written for the IBM PC-AT. In addition, following the data reduction by GRPGLI it was necessary to determine (a) gamma-ray absorption by the sample[10] and (b) corrections due to neutron attenuation and multiple scattering in the sample. These latter corrections were not always small, as large as $\approx$ 10%. These corrections were determined using Monte Carlo techniques in which the values of cross sections for various neutron-induced reactions were taken from the ENDF/B-VI evaluation[11] for ^{11}B.

The method of obtaining the absolute normalization has been to insert into the incident neutron beam a small scintillator mounted on a photomultiplier tube, and then to scale the total number of events recorded by this scintillator during a measurement. The calibration of this scintillator was accomplished by placing a neutron detector (NE-110 mounted on a photomultiplier) in place of the sample and run the accelerator at very low power. The relative flux was determined as a function of incident neutron energy by time-of-flight. The absolute efficiency of the detector at the sample position was determined by calculated pulse-height distributions using a Monte Carlo code (for example, the SCINFUL code[12]) which were compared with experimental pulse-height distributions to obtain the integrated detection efficiency of the specific detector configuration including the electronic bias setting. This detection efficiency determination relies primarily on the n+H cross section, so that our overall normalization relied indirectly on the n+H cross section. A

detailed example of the method is given in ref. 13; the overall uncertainty assigned to this method has been ± 10%.

Recently a new measurement of the 478-keV gamma from $^{10}B(n,\alpha\gamma)^7Li$ for neutron energies up to 4 MeV has been reported.[14] This reaction gamma-ray is also observed in the present measurement, since elemental boron is 20% in the isotope ^{10}B. Isotopic cross sections for the production of the 478-keV gamma were extracted from the experimental data; these are compared in Table 1 with the data of Schrack et al.[14]

Table 1. Comparison of present experimental isotopic cross sections for the $^{10}B(n,\alpha\gamma)^7Li$ reaction, $E_\gamma = 478$ keV, with values deduced from measurements of Schrack et al.

| Neutron Energy Bin (MeV) | Cross Section (mb) | | Ratio E/S |
	Present Experiment	Schrack et al.[a]	
1.69-2.35	142.5 ± 7.7	125.4 ± 3.0	1.136 ± 0.067
2.35-3.07	87.9 ± 6.4	88.7 ± 2.9	0.991 ± 0.078
3.07-3.83	71.5 ± 4.7	68.4 ± 3.8	1.045 ± 0.078

a. Ref. 14.

Additional corrections were made to the initially extracted photon yields. The largest correction was to the data for the 4.445-MeV gamma ray due to the contribution from the inelastic scattering of neutrons by ^{12}C in the polyethylene bottle. This contribution was deduced by obtaining a separate measurement with an empty bottle as the sample. Contributions from n+H scattering from the hydrogen in the thin front face of the bottle were estimated to be negligible; kinematics eliminated any contributions from the sides and back of the bottle from this source. More than half of the bottle mass was in the top and bottom; here, also, kinematics of n+H scattering eliminated nearly all of the potential contributions from this source for the data of interest. A second correction was needed: the data for the 2.124-MeV gamma ray was corrected for a minor contribution in the background due to neutron interactions with the lead shielding surrounding the detector. For high-energy neutrons, peaks representing gamma rays of 478 and 718 keV from multibody n + ^{11}B breakup reactions were observed. These yields were corrected for contributions from n + ^{10}B reactions leading to the same gamma rays; the estimates for the latter were taken from earlier preliminary data reduction for n + ^{10}B reactions;[9] uncertainties assigned to these yields include uncertainties in the estimated data for the n + ^{10}B reactions.

3.0 RESULTS

The results of the data reduction, normalized to the neutron flux determination as discussed above, and also normalized to the isotopic composition of the boron sample, are presented in Table 2. The uncertainties in Table 2 are dominated by statistical (counting) uncertainties; most of the peaks in the raw data were Doppler broadened and were superimposed on a comparatively large background.

The final data were not renormalized following the comparisons exhibited in Table 1; rather these comparisons were taken to validate the overall method of data reduction.

4.0 FINAL REMARKS

The importance of the monitor cross section for the $^{10}B(n,\alpha_1 \gamma)^7Li$ cross section spurred follow-on experiments to the measurements reported by Schrack, et al.[14] Preliminary results have been reported (ref. 15); the authors conclude that the results of the newer experiment[15] implies that the absolute values quoted in ref. 14 could be high by 5%. If further experiments verify this conclusion regarding a renormalization of the data in ref. 14, then after a renormalization of the persent $^{10}B(n,\alpha, \gamma)$ data the comparisons exhibited in Table 1 would be less satisfactory than shown in that Table.

ACKNOWLEDGMENTS

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Table 2. Absolute Isotopic Production Cross Sections and Relative Uncertainties[a] (mb) for Neutron Interactions with ^{11}B.

Neutron Energy Bin (MeV)	Gamma-ray Energy (keV)								
	478[b]	718[c]	2125[d]	4445[d]	4739[e]	5020[d]	6434[f]	6743+6792[d]	7286[d]
2.35 - 3.07			10.3± 0.9						
3.07 - 3.83			23.5± 1.9						
3.83 - 4.70			75.5± 4.3						
4.70 - 5.63			137.6± 6.9	49.7± 9.2[g]					
5.63 - 6.53			120.9± 6.3	76.0± 8.5		34.3± 2.4			
6.53 - 7.44			106.4± 6.8	116.5±12.0		58.2± 4.7			
7.44 - 8.21			100.2± 6.3	134 ±15		65.6± 4.7		16.0± 4.3	
8.21 - 8.96			97.4± 7.6	118 ±16		63.6± 5.6		24.6± 6.0	19.4±3.9
8.96 - 9.82			96.8± 9.2	125 ±16		49.1± 6.1		51 ±11	23.3±5.8
9.82 - 10.5			83.7± 8.0	150 ±17				43 ±13	30.7±7.4[h]
10.5 - 11.2			97.8± 9.8	94 ±19	16.4± 5.5			22 ±11	28 ±7[h]
11.2 - 12.0			83.6± 9.8	114 ±18	9.4± 4.8			18.7± 6.2	23 ±8[h]
9.82 - 12.0						36.7± 4.2	9.3± 2.3		
12.0 - 13.8	14.7± 2.5		49.5± 5.8	80 ±13		23.3± 8.3			
13.8 - 14.9	21.5± 4.2		41.6±12.7	111 ±18		10.7± 6.9			
14.9 - 18.2	31.3± 3.6	3.4± 2.0	22.3± 3.9	67 ±12					
18.2 - 22.3	33.3± 4.3	10.2± 2.0	9.4± 5.3	25 ± 8					

Footnotes To The Table:
  a. Tabulated uncertainties do not include the uncertainty in absolute normalization which is estimated as ±8% (see text).
  b. For the ^{11}B(n,nαγ) reaction, corrected for the estimated ^{10}B(n,αγ) contribution.
  c. For the ^{11}B(n,2nγ) reaction, corrected for the estimated ^{10}B(n,n'γ) contribution.
  d. Ground-state transition(s).
  e. Transition between 9185- and 4445-keV excited states.
  f. Transition between 8560- and 2125-keV excited states.
  g. For incident neutron energy bin 4.85-5.63 MeV.
  h. May be a doublet.

12

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