Nuclear Data for Science and Technology(1988 MITO), 213- 215,

$^{10,11}B(n, x\gamma)$ REACTIONS FOR INCIDENT NEUTRON ENERGIES BETWEEN 0.1 AND 25 MeV

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Abstract: Measurements have been made of gamma-ray production due to neutron interactions with samples of boron for incident neutron energies between 0.1 and 25 MeV. For ^{11}B a 54-g sample of naturally-occurring boron in the shape of a solid cylinder was used. For ^{10}B, samples enriched to 95% in the ^{10}B isotope were used. One sample, about 49 g, was used to obtain γ-ray data following inelastic scattering; the other sample, of about 15 g, was used to delineate the production of the 478-keV gamma ray following the $^{10}B(n,\alpha\gamma)^7Li$ reaction for E_n between 0.1 and 4 MeV. The Oak Ridge Electron Linear Accelerator (ORELA), a white source, was used to provide the incident neutrons. Data were obtained using a high-purity intrinsic-germanium photon detector positioned at 125 deg with respect to the incident neutron beam. Because the peak shapes in the raw data were substantially broadened by Doppler motion, peak yields were determined with graphic-interactive methods. Except for the 478-keV gamma ray for $E_n < 1$ MeV, the γ-ray production cross sections are all small, the largest being < 200 mb.

(Boron, ^{10}B, ^{11}B, neutron-induced reactions, gamma-ray production)

Introduction

The material elemental boron has at various times been suggested for use in proposed fusion reaction designs,[1] for example, as a component of the reflector and moderator systems, or for use in the shielding region. Among the requests for nuclear data for boron[2,3] the gamma-ray production cross sections as a function of neutron energy are given priority I status. In this report we present results from $(n, x\gamma)$ measurements recently completed for neutron interactions with samples of boron for incident neutron energies between 0.1 and 25 MeV.

Experimental Details

The experimental system for $(n, x\gamma)$ measurements has been reported in some detail in previous reports;[4,5] salient features pertaining to the measurements with the boron samples are, however, presented in this section. Briefly, 5-to-15 ns bursts of neutrons were created by the Oak Ridge Electron Linear Accelerator (ORELA), and after traversing a 22-m flight path, struck a boron sample. Gamma rays created by neutron interactions in the sample were detected by a heavily shielded intrinsic-Ge detector placed 0.4 m from the sample. Electronic time-of-flight techniques were used to determine the energy of the neutron responsible for the interaction in the sample. The flux of neutrons vs neutron energy was determined in a separate experiment.

The raw data from the detector analysis system were accumulated in a three-dimensional array, namely yield vs gamma-ray energy vs neutron time of flight. A total of 74 gamma-ray pulse-height spectra, each of 4096 channels, and having a gamma-ray energy dispersion of ~2 keV/channel, were obtained. Because of the small cross sections for the reactions of interest it was necessary to use rather coarse binning in neutron energy to ensure sufficient counts for off-line analysis in a given pulse-height spectrum.

Three samples were studied in this experiment: (a) a sample of boron having a "natural" isotopic composition; the sample was 54 g of metallic boron in powder form enclosed in a 9 g CH_2 bottle 1.8-cm radius by 5.8-cm height; (b) a sample of boron isotopically enriched to ~95% in the ^{10}B isotope enclosed in a similar bottle; and (c) a second sample of the enriched material enclosed in a thin-walled Al container of ~0.5 g having a radius of 0.48 cm and ~10-cm height. The neutron beam was collimated to ~7 cm in diameter, so the ends of the Al-contained sample were not in the beam. The ^{10}B enriched sample was also in powder form and the chemical form was given to us as metallic. A preliminary report on a more recent chemical analysis indicated that the sample contained ≈5% carbon apparently as a graphite and not in stoichiometric equilibrium with the boron. We have requested a more accurate determination prior to final determination of production cross sections.

Data reduction initially utilized the FORTRAN data-reduction code GRPGLI.[6] However, it was necessary to extract most of the peak areas interactively, and for this purpose a BASIC program[7] was 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[8] and (b) corrections due to neutron multiple scattering. For the Al-contained sample these latter corrections were small, < 3% for most of the gamma-ray production cross sections determined with this sample. But for the two larger samples the corrections were not always small, ranging as large as 20%. These corrections were determined using Monte Carlo techniques in which the values of cross sections for various neutron-induced reactions were taken from ENDF/B-V evaluations.[9]

Results

For the samples enriched in the isotope ^{10}B, data reduction included extracting cross sections for (a) $(n, n'\gamma)$ gamma-ray energies of 414, 718, 1021, 2154, 2868, and 3587 keV; (b) $(n, \alpha\gamma)$ for the 478-keV gamma ray in ^7Li; and (c) $(n, p\gamma)$ for the 3368-keV gamma ray in ^{10}Be. Data were obtained for the 478-keV gamma ray for incident neutron energies as low as 0.1 MeV partly to ensure an understanding of our absolute normalization and partly to compare with several earlier measurements[10-13] designed to determine this cross section with sufficient accuracy to be used as a standard. Our data agree with other experimental[10-13] cross sections for $E_n < 0.125$ MeV, but after a careful analysis of our uncertainties we found them to range between 5 and 8%, rather too large for "standard" purposes. In this regard, our absolute values were determined entirely from our experimental program and not by normalization of our data to some other "accepted" values.

Excitation functions for three gamma rays following inelastic scattering of neutrons by ^{10}B are shown in Figures 1-3. Figure 1 exhibits the excitation function for the 718-keV gamma ray for incident neutron energies

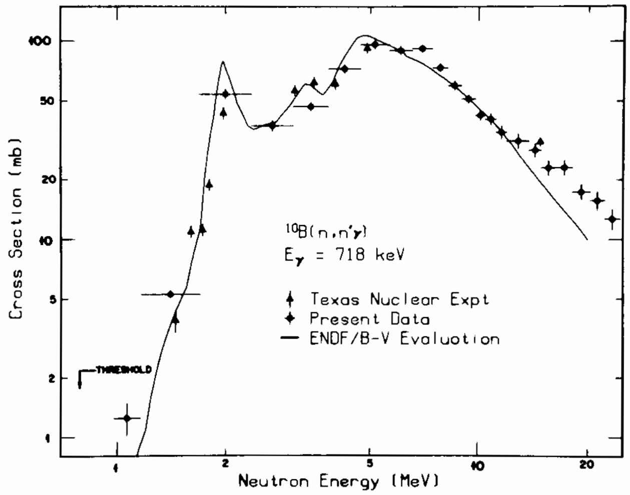

Figure 1. Gamma-ray production for the 718-keV gamma ray following decay of the first-excited state in ^{10}B. The data labelled "Texas Nuclear" are given in ref. 13, and the evaluation is given in ref. 9.

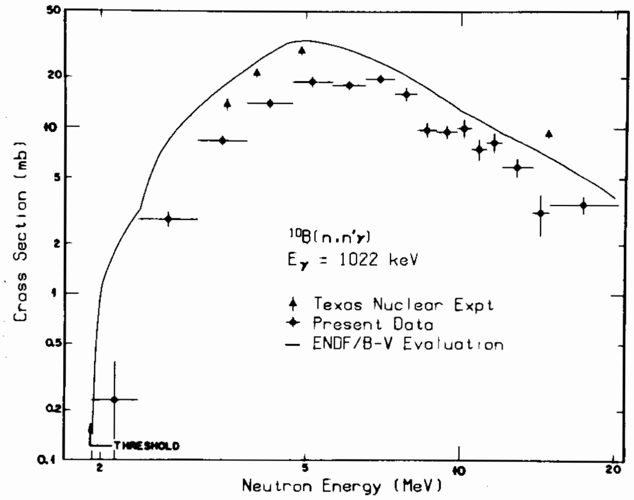

Figure 2. Gamma-ray production for the 1022-keV gamma ray following decay of the second-excited state at E_x = 1740 keV in ^{10}B. The data labelled "Texas Nuclear" are given in ref. 13, and the evaluation is given in ref. 9.

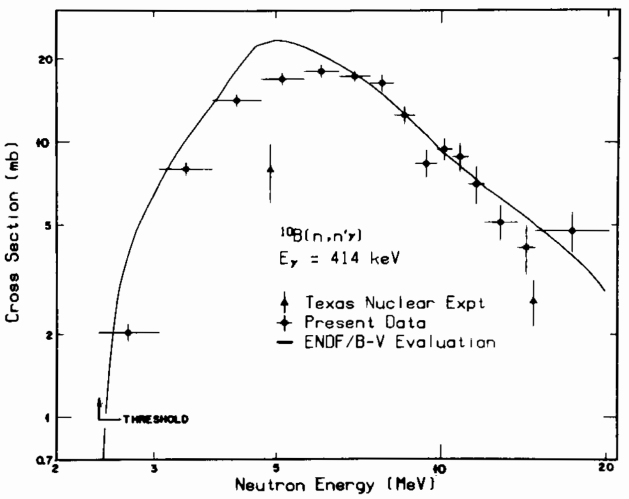

Figure 3. Gamma-ray production for the 414-keV gamma ray following decay of the third-excited state at E_x = 2154 keV in ^{10}B. The data labelled "Texas Nuclear" are given in ref. 13, and the evaluation is given in ref. 9.

between threshold and 25 MeV compared with earlier data by Nellis et al.[13] and with the excitation function deduced from the current ENDF/B-V evaluation.[9] Our data suggest that this quite small excitation function near threshold is somewhat larger than that deduced from the evaluation; however, rather strikingly good agreement is observed in the mid-range for E_n between about 4 and 12 MeV. For $E_n > 12$ MeV, the present data are larger than the evaluation and more consistent with the earlier Nellis measurement[13] at 14 MeV. As exhibited in Figure 2, our data for the weakly-excited 1021-keV gamma ray are smaller than the Nellis data[13] and the curve deduced from the evaluation. This gamma ray comes from decay of the second-excited state in ^{10}B, a $J^\pi = 0^+$ state, and the present data may be interpreted as indicating that the cross sections for direct neutron excitation of this state are very small. One experimental note with regard to data reduction for this gamma ray — the peak is not Doppler broadened and so was resolved from the observed (and ubiquitous) 1014-keV gamma ray from neutron interactions with Al. In Figure 3 is shown the excitation function determined from the present experiment compared with two data points from Nellis[13] and an excitation function determined from the evaluation for the 414-keV gamma ray, which results from decay of the third excited state in ^{10}B. The comparison with the evaluation is similar to that shown in Figure 1.

For the sample of boron having "natural" concentrations of ^{10}B and ^{11}B, data were reduced for (a) $(n,n'\gamma)$ reactions having gamma-ray energies of 2125, 4445, 5020, 6743, 6793, and 7286 keV, and (b) the tertiary reaction $(n,n\alpha\gamma)$ for the 478-keV gamma ray from decay of the first-excited state in ^{7}Li. In addition the 478-keV and 718-keV gamma rays following neutron interactions with the ^{10}B in the sample were studied. For the isotopic composition we used the value of 80.2% recommended by Lederer et al.[14] (out of a range of measured isotopic compositions ranging between 79 and 82% depending upon the source of the boron). Comparing the excitation function for the 718-keV gamma ray determined from this sample with that obtained for the isotopic sample (as shown in Figure 1) indicates a difference in absolute normalization between the two data sets of ~8%. This difference may be related to the above-discussed question of the chemical composition of the enriched sample, or it may be that our particular "natural" sample is slightly more enriched in ^{11}B than 80.2%. Our experimental excitation function for the 2125-keV gamma ray, which is due to decay of the first-excited state in ^{11}B, is shown in Figure 4. Included is the excitation of this state as given in the current (albeit quite old) evaluation for E_n up to 6.4 MeV. Also shown are some recent (n,n') data by Glendinning et al.[15] for E_n between 7 and 14 MeV. Shown in Figure 5 are our data for the multibody reaction $^{11}B(n,n'\alpha\gamma)^7Li$ reaction, leaving the ^{7}Li in its first-excited state. (The experimental production cross sections for this gamma ray were corrected for the $^{10}B(n,\alpha\gamma)$ cross sections as deduced from the measurements with the ^{10}B enriched sample.)

Concluding Remarks

The present experiment has provided a comprehensive set of gamma-ray production measurements for neutron interactions with isotopes of boron, particularly for the usually difficult incident neutron energy range between about 6 and 14 MeV. All of the needed corrections have been applied to the data, and all that is needed is a careful determination of the exact chemical compositions of these samples to finalize these data. One important deduction is that for incident neutron energies of the present measurement the gamma-ray production cross sections are small

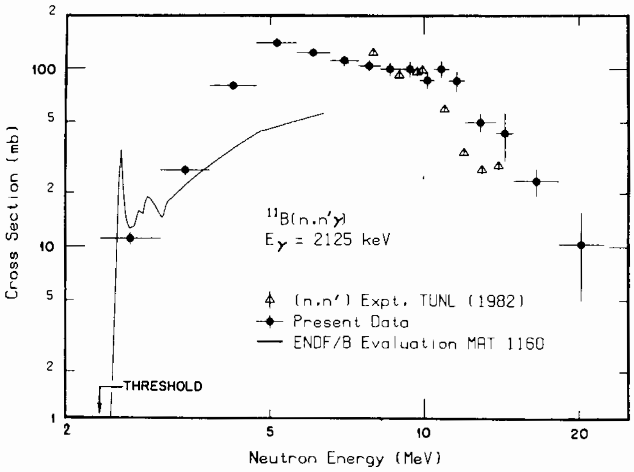

Figure 4. Gamma-ray production for the 2125-keV gamma ray following decay of the first-excited state in ^{11}B. The data labelled "TUNL" are given in ref. 15, and the evaluation is given in ref. 9.

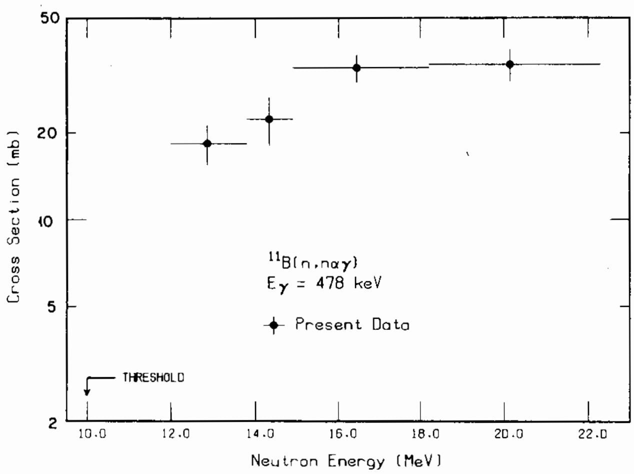

Figure 5. Gamma-ray production for the 478-keV gamma ray following decay of the first-excited state in ^{7}Li, attributed to the ^{11}B$(n,n\alpha)^{7}$Li reaction.

compared to the elastic-scattering cross sections.[9,15] However, because the gamma-ray energies, at least for neutron interactions with ^{11}B, are comparatively large (up to 7 MeV), gamma-ray heating may be important in any configuration containing boron that is exposed to fusion reactor neutrons.

Acknowledgements

We express our appreciation to T. A. Lewis and the ORELA staff for excellent machine operation and to J. H. Todd for assistance with the electronics. This research was sponsored by the Office of Energy Research, Nuclear Physics, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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