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Gamma-Ray Production Cross Sections for 0.9 to 20 MeV Neutron Interactions with ^{10}B

R. L. Bywater, Jr.

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GAMMA-RAY PRODUCTION CROSS SECTIONS FOR 0.9 TO 20 MeV NEUTRON INTERACTIONS WITH ^{10}B

R. L. Bywater, Jr.*

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R. L. Bywater, Jr.

ABSTRACT

Gamma-ray spectral data previously obtained at the 20-meter station of the Oak Ridge Electron Linear Accelerator flight-path 8 were studied to determine cross sections for 0.9- to 20-MeV neutron interactions with ^{10}B. Data reduction techniques, including those for determination of incident neutron fluences as well as those to compensate for Doppler-broadened gamma-ray-detection responses, are given in some detail in this report.

1. INTRODUCTION

Boron-10, comprising approximately 20% of naturally-occurring boron, is well known for its large neutron-absorption cross section. This feature has led to its widespread use as accelerator and reactor shielding material. As prototype fusion reactors are being developed, it is apparent that there are large fluences of high-energy neutrons during their operation which must be attenuated. Designers of shielding make calculations of radiation attenuation through the shielding material. These calculations require cross-section data of the neutron-induced reactions in the material.

In view of their extensive use, there is a need for improved cross-section measurements of neutron-induced reactions in ^{10}B and a need for carrying these measurements out to neutron energies of 20 MeV. D. C. Larson and J. K. Dickens conducted a series of experiments using the Oak Ridge Electron Linear Accelerator (ORELA) at Oak Ridge National Laboratory (ORNL) to determine gamma-ray production cross sections of ^{10}B for the neutron energy range from 0.9 MeV to 20 MeV. The author of the present report was responsible for reduction of the data to cross section.

The reduction of the data is formulated as follows:

$$\sigma_\gamma = \frac{(Y/\epsilon)}{n_n n_s} \tag{1}$$

where

σ_γ	=	cross section for production of a gamma-ray having energy E_γ by neutrons having energies in a given energy bin (E_{low} to E_{high})
Y	=	yield (in counts) of the peak in spectral data corresponding to the gamma ray having energy E_γ
ϵ	=	efficiency of the recording gamma-ray detector for detection of the gamma ray having energy E_γ
n_n	=	number of neutrons (flux) in the energy bin (E_{low} to E_{high})
n_s	=	number of scatterers (number of atoms of ^{10}B)

Of the four basic parameters, Y, ϵ, n_n, n_s, my tasks included (1) deducing values of Y (for 10 different gamma rays and for 29 different gamma-ray spectra) and (2) deducing a distribution of neutron flux from which values of n_n could be obtained. Determinations of Y are discussed in detail in Sect. 2.1, and of the neutron flux in Sect. 2.2. The efficiencies of the detector, $\epsilon(E_\gamma)$, were determined using standard commercially-available sources. The sample was boron, enriched to 92.4% ^{10}B and had a mass of 48.91 grams.

Data acquisition utilized an SEL 810B computer system with a 0.5-Mword fixed-head disk for data storage. Data were then transferred to a VAX 11/785 system for off-line analysis. Flux measurements were made using an NE-110 plastic scintillator. The experimental layout for the flux measurements is shown in Fig. 1. For the ^{10}B measurements, the NE-110 detector was replaced with the sample and an intrinsic-Ge detector was placed at an angle of 125° with respect to the incident neutron direction (a schematic is shown in ref. 1).

2. DATA REDUCTION AND ANALYSIS

2.1 GAMMA-RAY YIELDS

The gamma-rays emanating from the sample during the neutron bombardment are a result of de-excitation of energy levels of the ^{10}B from inelastic collisions with the incident neutrons or of nuclear transmutations of neutrons with ^{10}B, in particular $^{10}B(n,\alpha)^7Li$ and $^{10}B(n,p)^{10}Be$. Normally, gamma-ray spectra are analyzed by using a peak identification code such as GRPGLI,[2] which locates gamma-ray peaks, determines their areas and uncertainties, computes the cross sections, and attempts to identify them. However, the present data present a problem to the GRPGLI code.

Because ^{10}B is a relatively light nuclide, when it is struck by a high-energy neutron it is given a substantial amount of kinetic energy. This motion of the residual ^{10}B ion often lasts longer than the lifetime of the excited state. Consequently, gamma decay occurs in flight, and there is a resultant broadening of the gamma-ray peaks in a spectrum. This phenomenon is known as Doppler broadening. The amount of this broadening is approximately expressed as[3]

$$R \sim E_\gamma \beta_{ion} F(t) \tag{2}$$

where

R	=	the contribution of Doppler broadening to the line width
E_γ	=	the energy of the emitted gamma ray
β_{ion}	=	the scalar velocity of the ion in units of c
$F(t)$	=	a function of the lifetime of the decaying energy level (may have values between 0 and 1, depending on the lifetime of the decaying level)

As an example, consider a 5-MeV neutron inelastically colliding with a stationary ^{10}B ion. Shortly thereafter the ^{10}B ion emits a 718-keV gamma ray, leaving approximately 4.3 MeV for kinetic energies of the neutron plus the recoiling ^{10}B ion. We know that the rest mass of the neutron is ~938 MeV and the rest mass of the ^{10}B ion is approximately ten times this, or ~9380 MeV. From relativity theory, the rest mass, m_o, is related to the mass, m, of the same body in motion by:

$$m = \gamma m_o \tag{3}$$

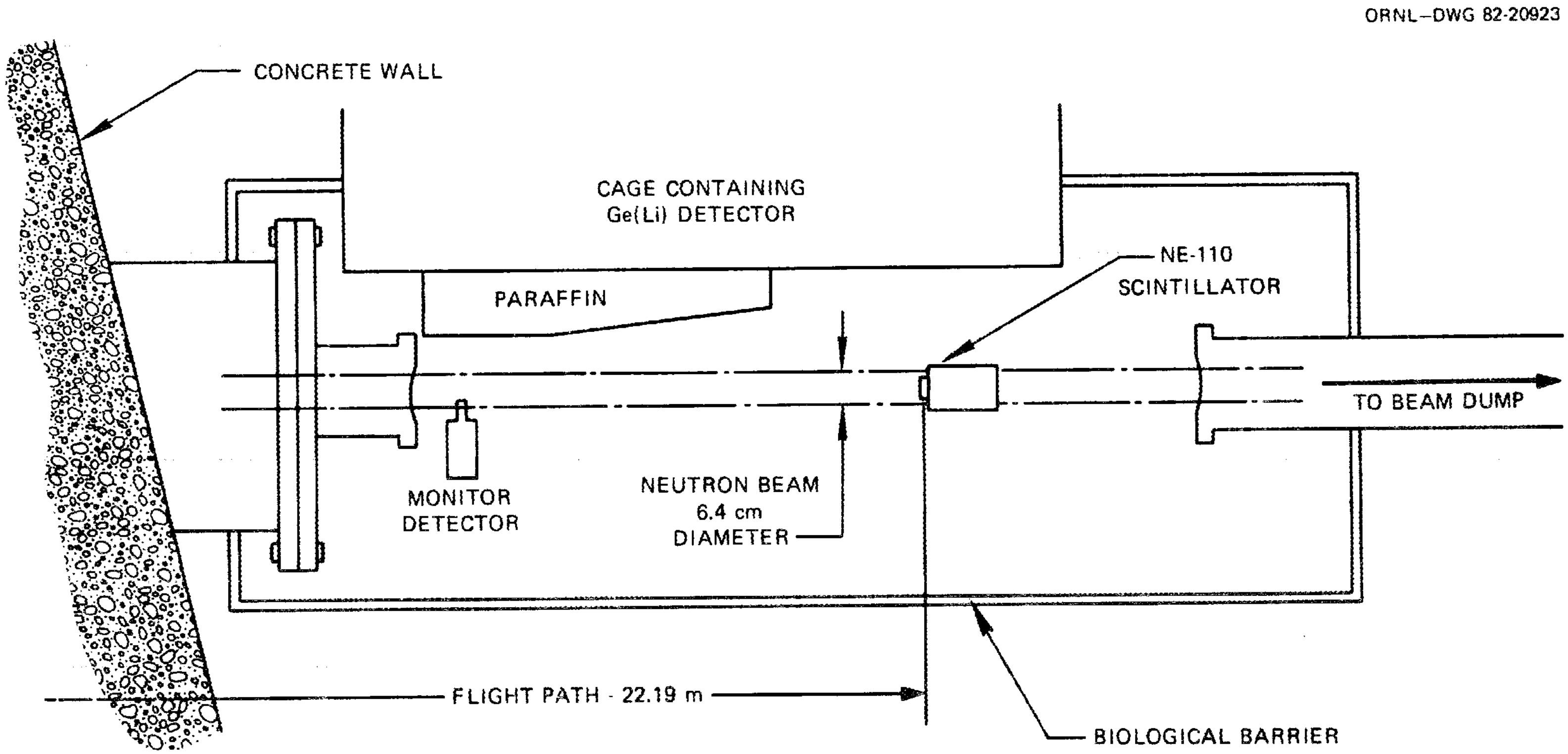

Fig. 1. Experimental arrangement for neutron flux measurements. The detector location is 22.19 m from the neutron-producing target (either Be or Ta) of the ORELA.

where

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} \tag{4}$$

and

$$\beta = v/c \quad . \tag{5}$$

Mass and energy are interchangeable quantities. This means that the moving mass may be expressed as the sum of the rest mass and the kinetic energy (KE) of the object. Thus:

$$\gamma = 1 + \frac{KE}{m_o} \quad .$$

In calculating $\gamma_{^{10}B}$ the ^{10}B ion has 1/10 of the remaining KE. Therefore, the ^{10}B ion will have 0.43 MeV of KE. So,

$$\gamma_{^{10}B} = 1 + \frac{0.43 \text{ MeV}}{9380 \text{ MeV}}$$

or

$$\gamma_{^{10}B} - 1 = 4.6\text{E}-5$$

leading to

$$\beta_{^{10}B} = 9.6\text{E}-3 \quad .$$

This is the scalar velocity of the recoiling ^{10}B ion in units of c. Now, if we place this value of β and the gamma-ray energy into the Doppler-broadening equation [Eq. (2) above], and assuming a value of $F(t) = 1.0$, we can determine what the maximum Doppler broadening of this particular peak should be:

$$R \sim 718 \text{ keV} \times 9.6\text{E}-3$$

or

$$R \sim 6.9 \text{ keV}$$

which may be compared to the gamma-ray detection resolution of ~2 keV for this energy gamma ray.

This broadening of the gamma-ray peaks cannot be handled correctly by the present GRPGLI package. Instead, the task of determining the gamma-ray yields was completed by the process of interactive peak stripping. To do this task, a segment of computer code was written that would allow a user to view a particular spectrum, narrow the field of view to a peak of interest, place endpoints on the peak, and calculate the peak's centroid, area, and the uncertainty of the area. This code was written on an IBM PC based on an existing BASIC program that would read a spectrum from a data file and display segments of it on the screen. The modified program with the peak analysis routine is listed in the Appendix.

The program, PLOTPACK, first reads in the whole gamma-ray spectrum and then allows the user to expand a segment of it on the PC monitor screen to identify individual peaks. Then, the user calls the peak analysis routine which asks for the desired peak endpoint channels. Upon input, the routine exhibits a line (designating the background radiation) between the points, computes the slope of this line, and starts a loop summing the background radiation over the channels within the peak. Also within this loop, the total area and the first moment are summed over the peak interval. When the loop is completed, the centroid, the net peak area, and the uncertainty in the area are computed and displayed on the PC screen. If the user is satisfied with these results, they can be saved in an output file for later reference.

This technique was used to analyze the 29 ^{10}B spectra obtained at the ORELA facility with incident neutron energies ranging from 0.08 MeV to 42 MeV. Each spectrum was searched for any of the ^{10}B (and ^{11}B) gamma rays listed in the decay diagrams for these isotopes.[4] As could be expected, some peaks were more difficult to analyze than others. The reasons for this difficulty included factors such as the energy of the gamma ray itself, the proximity of background peaks to the peak in question, and the Doppler broadening of the peaks.

Examples of peaks that were relatively easy to analyze are shown in Fig. 2a for E_γ = 718.4 keV and in Fig. 2c for E_γ = 2154.3 keV. Figure 2b shows a more difficult situation where the 1021.7-keV peak is very close to an unwanted background peak. The endpoints must be chosen to minimize as much as possible any contribution from the background peak. In this case, the area of the 1021.7-keV peak was underestimated. To account for this underestimation, an estimate had to be made to determine where the actual background line would be if the other peak was not there. Then an estimate was made to determine what this extra area was, and it was added to the computer-generated area. This extra area is shown as the dashed triangle in the figure. Figure 2c shows one of the more moderately difficult situations which happened quite frequently. In this case, the 2124.8-keV ^{11}B peak is unusually wide and there is a fluctuation in the surrounding background which made it necessary to try several sets of endpoints.

The best spectra for peak analysis were those in the low-middle neutron energy range with energies from 3.8 MeV to 7.4 MeV. The gamma-ray peaks were generally isolated and narrow, neither too broad nor too small to be easily analyzed. All peak calculations were stored in output files corresponding to each spectrum. An example of an output file is shown in Fig. 3. These data were later used to correct the GRPGLI output, as discussed in Sect. 2.3.

2.2 NEUTRON FLUX DETERMINATION

The neutron fluence was determined as follows:

1. Measurements with equipment as shown in Fig. 1 for both the NE-110 and the monitor detectors.
2. Preparation and plotting of the measured data.
3. Determination of the NE-110 efficiencies using the Monte Carlo computer routine O5S.[5]
4. Determination of the monitor efficiencies.

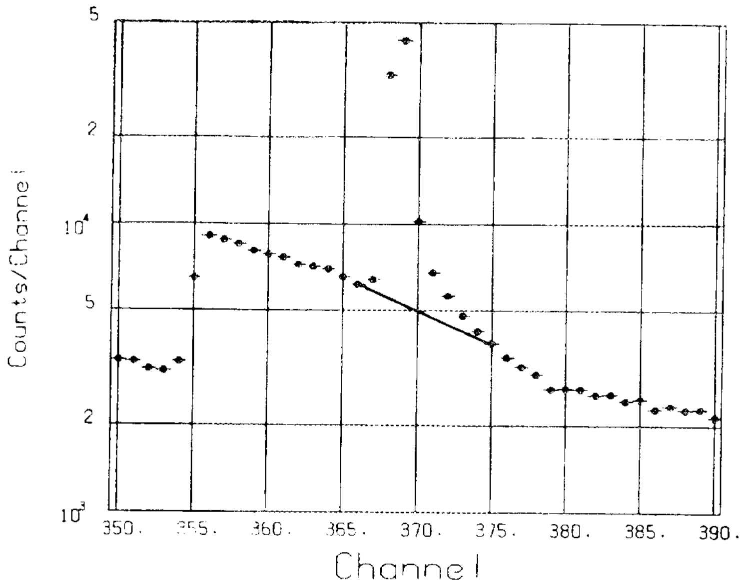

Fig. 2a. Portion of a spectrum showing the 718.4-keV ^{10}B gamma-ray peak. The solid line represents the computer-drawn background line used in the peak area calculations. For this spectrum the incident neutron energy ranged from 1.69 MeV to 2.35 MeV. The spectral dispersion is about 2 keV/channel.

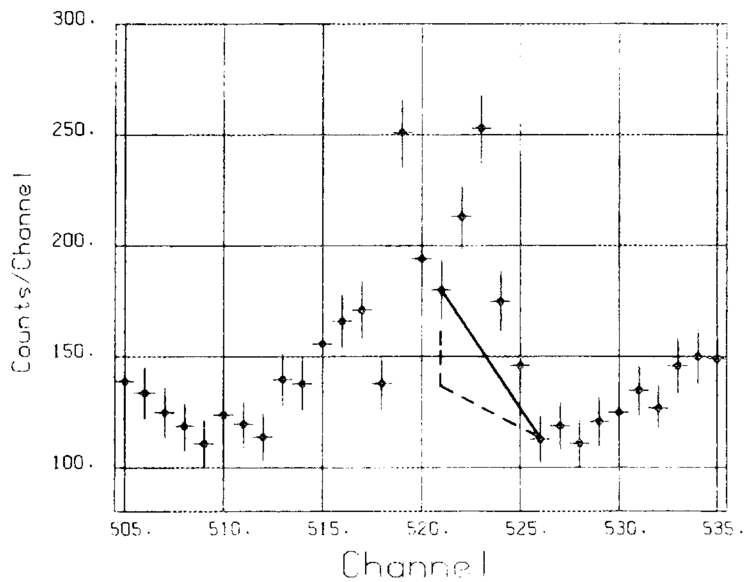

Fig. 2b. Portion of a spectrum showing the 1021.7-keV ^{10}B gamma-ray peak on the right side of an unwanted aluminum background peak at 1016 keV. The computer-generated background line results in an underestimation of the peak area. The estimated compensation area is denoted by the dashed triangle. To correct for the underestimation, approximately 80 counts were added to the computed area. For this spectrum the incident neutron energy ranged from 11.95 MeV to 13.8 MeV.

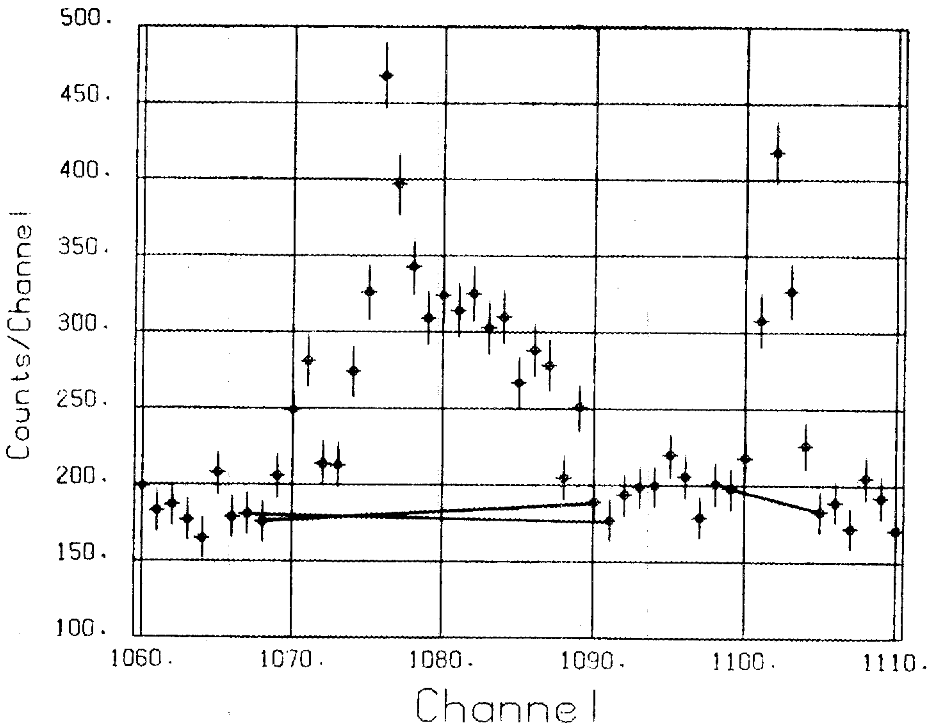

Fig. 2c. Portion of a spectrum showing the 2124.8-keV ^{11}B and 2154.3-keV ^{10}B gamma-ray peaks. Note that the 2124.8-keV peak is quite broad and that it is more difficult to determine where to place the endpoints on it. For this spectrum the incident neutron energy ranged from 4.70 MeV to 5.63 MeV.

```
pcplot\10b.s27        outbs27a.dat
      &
   centroid         net area        delta area
   734.7316        1400.5000          89.0140
  1082.5220         316.0000          47.5395
  1102.1390         257.5000          35.8678
```

Fig. 3. Example of a spectrum output data file. In this case the file is called outbs27a.dat, corresponding to the spectrum labeled 10b.s27. Data shown for each peak are the centroid of the peak, the net area, and the uncertainty in the area. The peak at channel "734.7316" corresponds to E_γ = 1435.9 keV (in ^{10}B), the peak at channel "1082.522" corresponds to E_γ = 2124.8 keV (in ^{11}B), and the peak at channel "1102.139" corresponds to E_γ = 2154.3 keV (in ^{10}B).

The flux data that were received for my project had already been divided into energy bins, based on time-of-flight parameters. For each energy bin there was a proton-recoil spectrum of 4096 channels. The value of light units for each spectrum also was computed. This term corresponds to the light produced by scattered protons whose energy was that of the incident neutrons. In a spectrum, it is defined as corresponding to the channel of half-height of the upper edge of the distribution.[6] Plots were made of each of the spectra, and the channels of maximum proton energy were determined.

As the plots were made, it was noted that the higher neutron-energy bins were not being represented as they should be. The channels of half-pulse height and the values of light units were deviating from their expected linear relationship for neutron energies greater than 3.8 MeV. These spectra had to be "stretched" so that the point described by plotting the channel of half-pulse height versus light units would show a linear relationship. This "stretching" was accomplished with the program RESPEC. New plots were made of the stretched spectra, and they were then ready for comparison to the Monte Carlo calculations.

The Monte Carlo calculations were made using the code O5S for the same energy bins as measured experimentally. Plots were made of each of these calculated spectra, and generally they fit well to the stretched data spectra. The ratio of the data spectra to the O5S spectra for each energy bin was calculated by the program COMPARE which integrated the two spectra between two input channels and computed the ratio between the two sums. This ratio was used to determine the corrected neutron yield for each energy bin. Dividing the corrected yield by the width of the neutron energy bin provided the neutron flux for each bin in neutrons/MeV. The calculated flux distribution for a beryllium neutron-producing target is shown in Fig. 4. Also, shown for comparison is the flux distribution for a tantalum neutron-producing target that had been deduced earlier. The tantalum flux was used for the ^{10}B gamma-ray measurement.

Uncertainties in the flux calculations were obtained by quadratically combining the uncertainties in the fitting of the O5S spectra to the data spectra, the ratio of the data-to-O5S integrals, and the O5S code itself. The uncertainty in the fitting procedures varied with neutron energy. The greatest uncertainties were in the low and high neutron-energy bins where they were between 10% and 20%. In the middle-range bins, the uncertainty was typically less than 5%. The uncertainty in the ratio of the integrals was typically less than 1%. The uncertainty in the O5S calculations was evaluated to be 1.3%.

The final step was to determine the efficiency of the small monitor detector. Yields for the monitor detector over the same energy bins as the NE-110 flux detector were compared to the corrected yields of the flux detector for each energy bin and the efficiencies were calculated. Uncertainties in the calculations for the monitor detector were obtained by quadratically combining the uncertainties in the neutron flux and the yield of the monitor detector. The uncertainties in the yields of the monitor detector were less than 1%. The results of the flux determinations and monitor detector efficiency calculations for the Be-block flux are presented in Table 1.

2.3 DETERMINATION OF CROSS SECTIONS

With the four basic parameters Y, ϵ, n_n, and n_s, of σ_γ evaluated, it was possible to make the individual cross-section calculations. Much of the work was accomplished by the program GRPGLI. When the parameters ϵ, n_n, n_s, neutron bin energies, and energy to channel calibrations were input, the program would search the ^{10}B spectra for gamma-ray peaks, determine their areas, compute the absolute cross sections, and attempt to identify the sources of the peaks by comparisons with a table of nuclide level-decay data.

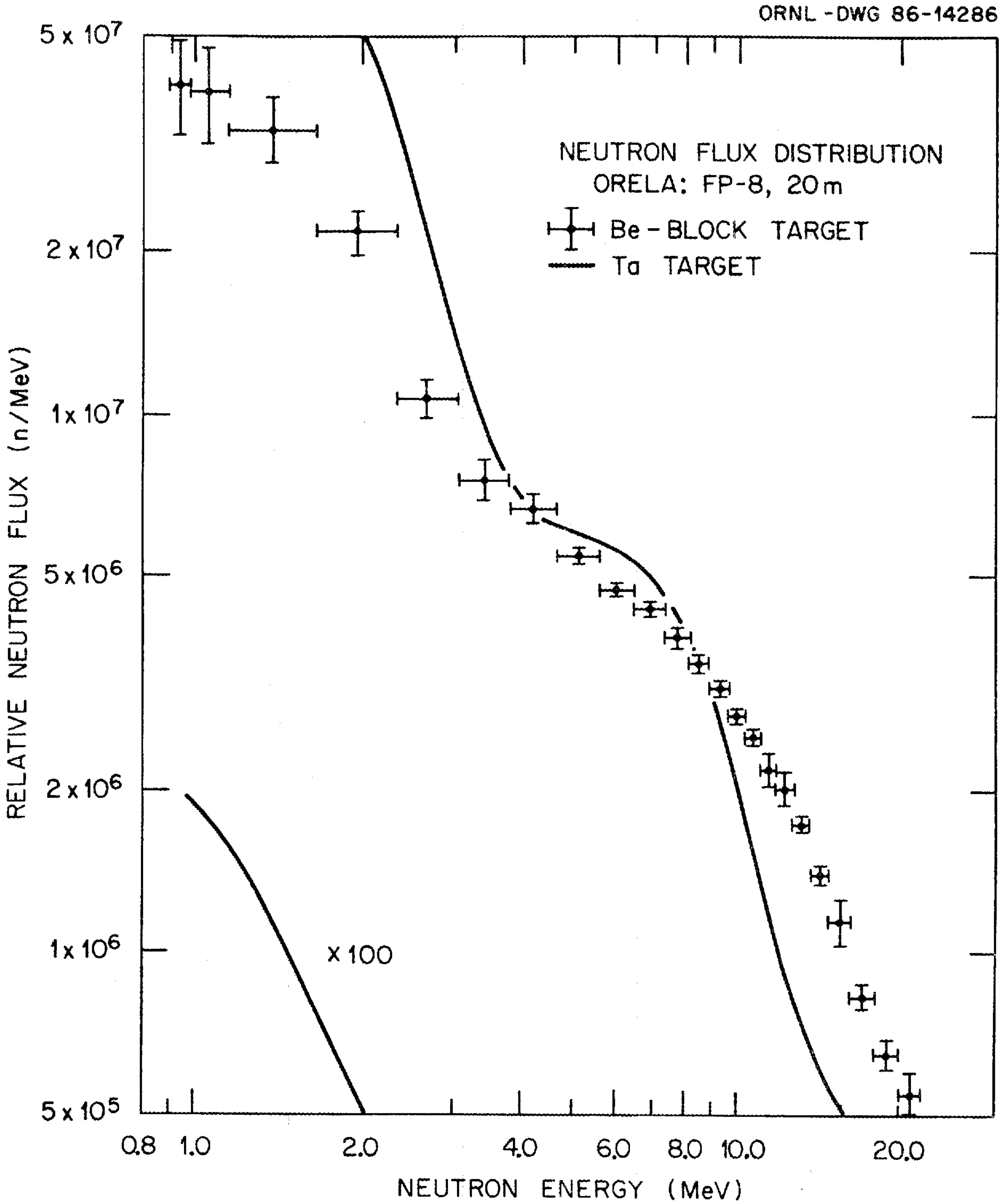

Fig. 4. Measured beam flux at the sample position due to neutron production using the Be-block target compared with similar data obtained using a Ta target.

Table 1. Results of beam flux and monitor efficiency calculations

Neutron energy bin (MeV)	Neutron flux (n/MeV)	Monitor detector efficiency (%)
0.91-0.98	4.07E7 ± 8.23E6	0.31 ± 0.06
0.98-1.15	3.97E7 ± 7.98E6	0.45 ± 0.09
1.15-1.68	3.37E7 ± 5.09E6	1.06 ± 0.16
1.68-2.35	2.17E7 ± 2.11E6	1.64 ± 0.16
2.35-3.05	1.06E7 ± 7.29E5	1.79 ± 0.12
3.05-3.81	7.60E6 ± 5.95E5	1.79 ± 0.14
3.81-4.68	6.69E6 ± 4.09E5	1.64 ± 0.10
4.68-5.60	5.47E6 ± 1.48E5	1.50 ± 0.04
5.60-6.48	4.71E6 ± 1.04E5	1.37 ± 0.03
6.48-7.39	4.32E6 ± 1.09E5	1.22 ± 0.03
7.39-8.15	3.83E6 ± 1.63E5	1.14 ± 0.05
8.15-8.89	3.42E6 ± 8.48E4	1.05 ± 0.03
8.89-9.74	3.08E6 ± 7.39E4	0.96 ± 0.03
9.74-10.38	2.75E6 ± 6.60E4	0.90 ± 0.02
10.38-11.08	2.51E6 ± 5.88E4	0.85 ± 0.02
11.08-11.85	2.19E6 ± 1.53E5	0.80 ± 0.06
11.85-12.71	2.01E6 ± 1.38E5	0.77 ± 0.05
12.71-13.66	1.72E6 ± 4.13E4	0.74 ± 0.02
13.66-14.73	1.41E6 ± 6.47E4	0.74 ± 0.04
14.73-16.25	1.14E6 ± 1.24E5	0.74 ± 0.08
16.25-18.01	8.26E5 ± 4.28E4	0.82 ± 0.04
18.01-20.08	6.48E5 ± 4.62E4	0.78 ± 0.06
20.08-22.00	5.45E5 ± 5.50E4	0.74 ± 0.08

However, as was discussed earlier, many of the peaks in a ^{10}B spectrum are broadened due to Doppler broadening. When the GRPGLI code finds one of these broadened peaks, it assumes that there are two or more narrow peaks there and computes a cross-section value for each one. As a result, the computed cross sections are too small.

To correct for the underestimation of cross sections, the computed cross section of each gamma ray was multiplied by a correction factor. This factor was equal to the ratio of the yield of a particular gamma ray as determined by interactive peak stripping to the yield of the same gamma ray as determined by GRPGLI. This ratio was also multiplied by the computed uncertainty of the cross section to determine the actual uncertainty of the cross section.

A correction factor has also been included to account for the gamma-ray attenuation within the sample itself.[7] Corrections that have not been included, and tend to be difficult to make, are the attenuation of neutrons within the source (which result in a reduction of gamma rays) and the multiple-scattering of neutrons in the sample (which result in an increase of gamma rays). Typically, these effects tend to cancel, resulting in an overall estimated effect of less than 5%. The absolute measured cross sections and uncertainties for ten gamma rays, including the ^{10}B(n,α)^{7}Li and ^{10}B(n,p)^{10}Be reactions, are presented in Table 2.

Table 2. **Absolute measured cross sections (in mb) for production of gamma rays following neutron interactions with ^{10}B**

E_n (MeV)	Gamma-ray energy (KeV) 414.1	718.3	1021.7	1432.8	1435.9	2154.3	2868.7	3587.1	477.6	3368
0.91–0.98									175.4 ± 120	
0.98–1.16		4.6 ± 1.7							145.9 ± 53.2	
1.16–1.69		7.5 ± 1.0							100.5 ± 15.3	
1.69–2.36		37.3 ± 4.8							105.5 ± 11.0	
2.36–3.07	1.3 ± 0.6	36.0 ± 3.9	2.1 ± 0.3		1.4 ± 0.3	0.3 ± 0.1			74.0 ± 6.5	
3.07–3.83	6.1 ± 0.6	35.7 ± 2.6	6.2 ± 0.5		4.3 ± 0.6	1.1 ± 0.2			56.1 ± 4.1	
3.83–4.70	11.1 ± 1.4	71.1 ± 4.0	14.2 ± 1.0	1.2 ± 0.3	7.2 ± 0.5	2.3 ± 0.4	8.5 ± 1.0		81.3 ± 5.0	3.4 ± 1.2
4.70–5.63	11.9 ± 0.9	68.7 ± 4.1	13.3 ± 0.8	2.0 ± 0.4	7.0 ± 0.5	3.4 ± 0.5	16.3 ± 1.8	2.33 ± 0.8	38.9 ± 2.5	10.1 ± 2.0
5.63–6.53	12.5 ± 1.4	64.3 ± 4.0	13.2 ± 0.9	3.2 ± 0.6	7.7 ± 0.6	2.6 ± 0.6	24.5 ± 3.4		29.6 ± 2.5	10.8 ± 2.5
6.53–7.44	12.4 ± 1.4	67.4 ± 3.9	12.6 ± 0.9	2.5 ± 0.6	9.0 ± 0.8	4.7 ± 0.7	28.6 ± 4.1		24.2 ± 2.5	
7.44–8.21	12.0 ± 1.5	53.6 ± 3.5	11.5 ± 0.9	1.6 ± 0.4	7.2 ± 0.7	2.2 ± 0.6	14.6 ± 4.0		18.5 ± 2.5	
8.21–8.96	8.8 ± 1.0	46.8 ± 3.3	8.0 ± 0.7		3.9 ± 0.6	1.6 ± 0.5			14.1 ± 2.4	
8.96–9.82	6.9 ± 1.0	39.3 ± 2.6	12.7 ± 1.2		4.8 ± 0.5	2.6 ± 0.7			16.1 ± 2.7	
9.82–10.46	6.6 ± 1.0	34.6 ± 2.7	12.3 ± 1.5		3.5 ± 0.5				12.5 ± 3.4	
10.46–11.17	6.6 ± 1.1	31.0 ± 2.4	6.1 ± 1.1		3.2 ± 0.9				16.0 ± 3.2	
11.17–11.95	5.3 ± 1.0	30.2 ± 2.5	5.8 ± 0.9		3.9 ± 0.7				10.7 ± 2.9	
11.95–13.79	4.3 ± 0.6	25.1 ± 1.3	4.9 ± 0.9		3.4 ± 0.4				11.8 ± 2.5	
13.79–14.87	4.1 ± 0.9	26.0 ± 2.0	3.8 ± 2.0		3.1 ± 1.4				7.6 ± 2.4	
14.87–20.31	3.7 ± 0.6	18.4 ± 1.5	2.6 ± 0.5						13.6 ± 2.3	

3. SUMMARY AND CONCLUSION

The objective of this project was to determine gamma-ray production cross sections for neutron interactions with ^{10}B. In all, 104 cross sections were calculated for a total of ten gamma rays produced by interactions with neutrons whose energies ranged from 0.9 MeV to 20 MeV.

In 1970, Nellis, Tucker, and Morgan[8] published results of a similar measurement for E_n between 50 keV and 5 MeV and at 14.8 MeV. A comparison of their results with the present results indicates that the present results are, on the average, 25% smaller. However, the present data agree quite well with earlier $^{10}B(n,\alpha)^7Li$ alpha-particle measurements of Davis, Gabbard, Bonner, and Bass.[9] Although as mentioned above, not all corrections have been made to the present data, it seems unlikely that such can account for the difference between the present data and those of Nellis, et al.

Raw data for this experiment were available for neutron energies up to 40 MeV. Monte Carlo calculations to determine neutron fluences, n_n, however, were not determined for $E_n > 22$ MeV. It would be interesting to obtain this information and to deduce cross sections to 40 MeV and what the results are at these higher energies.

ACKNOWLEDGEMENTS

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APPENDIX: Listing of PLOTPACK, an IBM-PC BASIC program to read and display spectral data and to define and integrate peaks.

```
10 REM PLOTPACK...Revised 7/86 by Russell Bywater
20 REM The purpose of this program is to read and display a gamma-ray
30 REM spectrum from a data file on the screen and allow the user to
40 REM integrate peaks
50 REM
60 REM
70 REM High resolution graphics required
80 SCREEN 2
90 REM
100 REM
110 REM Open input data file from sub-directory
120 INPUT "Which sample data file would you like to examine ";X$
130 FILESPEC$="pcplot\"+X$
140 OPEN FILESPEC$ FOR INPUT AS #1
150 NGRP=8
160 NLINES=6
170 GOSUB 230
180 STOP
190 REM
200 REM
210 REM Open output file where peak calculations are placed
220 REM and write heading
230 INPUT "What would you like to name the output file ";Z$
240 DATASPEC$="pcplot\"+Z$
250 OPEN DATASPEC$ FOR OUTPUT AS #2
260 PRINT #2,FILESPEC$;"     ";Z$
270 PRINT #2,USING"#####";NGRP
280 PRINT #2 ,"   centroid     net area      delta area "
290 FOR I=1 TO NLINES
300   INPUT #1,A$
310   PRINT A$
320 NEXT I
330 REM
340 REM
350 REM Start data input routine
360 GOSUB 2650
370 REM
380 REM
390 REM initial setup of data
400 YM=0: NCHAN=512*NGRP
410 FOR I=2 TO NCHAN
420   IF YM<DAT(I) THEN YM=DAT(I)
430 NEXT I
440 YZ=0!: YP=100!
450 IF YM<YP THEN GOTO 500
460 YS=LOG(YM)/2.3025
470 IYS=INT(YS) +1
480 YP=10!^IYS
490 IF YM<.3*YP  THEN YP=.3*YP
500 XZ=0
```

```
510 REM
520 REM
530 REM Begin plotting routine
540 GOSUB 620
550 KEY ON
560 CLOSE #1: CLOSE #2
570 STOP
580 RETURN
590 REM
600 REM
610 REM initial conditions for first plot
620 KEY OFF
630 IAXIS=0:IAYIS=0
640 XADD=200: XQ=50: XR=55
650 YADD=YP-YZ:YDEL=YADD/8!
660 REM
670 REM
680 REM Display plot labels
690 CLS: FOR I=1 TO 1000: NEXT I
700 LOCATE 25,1: PRINT"1zeroch 2num-ch 3y-min 4y-max 5lin-y 6log-y"
710 LOCATE 25,45:PRINT"7save 8centroid 10exit"
720 LOCATE 23,5:PRINT "y-min=";YZ:XP=XZ+XADD
730 LOCATE 2,17
740 PRINT XZ;" < - - - - - -   Channel   - - - - - - > ";XP;" Ymax= ";YP
750 REM
760 REM
770 REM plot x-y box and vertical lines
780 YP=YP+YDEL
790 WINDOW (XZ-XR,YZ-YDEL) - (XP,YP)
800 YP=YP-YDEL
810 LINE (XZ,YZ)-(XP,YP),,B
820 XN=XZ/XQ
830 IX=INT(XN)
840 DIX=XQ*(IX+1)
850 FOR X=DIX TO XP STEP XQ
860   LINE (X,YZ) - (X,YP),,,&HAAAA
870 NEXT X
880 REM
890 REM
900 REM Test for log plot
910 IF IAYIS=0 THEN GOSUB 2010
920 IF IAYIS=1 THEN GOSUB 2180
930 GOSUB 1730
940 REM
950 REM
```

```
960 REM waiting for function command
970 ON KEY(10) GOSUB 1160
980   KEY(10) ON
990 ON KEY(1) GOSUB 1210
1000   KEY(1) ON
1010 ON KEY(2) GOSUB 1260
1020   KEY(2) ON
1030 ON KEY(3) GOSUB 1410
1040   KEY(3) ON
1050 ON KEY(4) GOSUB 1470
1060   KEY(4) ON
1070 ON KEY(5) GOSUB 1620
1080   KEY(5) ON
1090 ON KEY(6) GOSUB 1670
1100   KEY(6) ON
1110 ON KEY(7) GOSUB 1550
1120   KEY(7) ON
1130 ON KEY(8) GOSUB 2410
1140   KEY(8) ON
1150 GOTO 970
1160 GOTO 550
1170 RETURN
1180 REM
1190 REM
1200 REM reset x0
1210 INPUT "New Starting Channel = ";XZ
1220 GOTO 690
1230 REM
1240 REM
1250 REM reset # of channels plotted, 500 max
1260 INPUT "number of channels =";XADD
1270 IF XADD<0 THEN GOTO 1260
1280 XQ=1
1290 IF XADD>6 THEN XQ=2
1300 IF XADD>15 THEN XQ=5
1310 IF XADD>33 THEN XQ=10
1320 IF XADD>66 THEN XQ=20
1330 IF XADD>150 THEN XQ=50
1340 IF XADD>330 THEN XQ=100
1350 IF XADD>500 THEN XADD=500
1360 XR=.275*XADD
1370 GOTO 690
1380 REM
1390 REM
1400 REM reset ymin
1410 INPUT "New Y-min =";YZ
1420 IF IAYIS=1 THEN GOTO 1510
1430 GOTO 1480
1440 REM
1450 REM
```

```
1460 REM reset ymax
1470 INPUT "New Y-max =";YP
1480 IF YP>YZ THEN GOTO 650
1490 PRINT "Error at input. Given y-min and y-max are";YZ;YP
1500 GOTO 970
1510 IF YZ<1 THEN GOTO 1490
1520 GOTO 1480
1530 REM
1540 REM
1550 REM save info in output file
1560 PRINT #2,USING"######.####    ";CENTR,AREAN,AREAU
1570 PRINT "data saved in ";Z$
1580 RETURN
1590 REM
1600 REM
1610 REM reset linear plot
1620 IAYIS=0
1630 GOTO 690
1640 REM
1650 REM
1660 REM reset ylog plot
1670 IAYIS=1
1680 IF YZ<1 THEN YZ=1
1690 GOTO 690
1700 REM
1710 REM
1720 REM Plot data points on screen and uncertainty in Y
1730 IF XZ>NCHAN THEN GOTO 1970
1740 XC=XP
1750 IF XC>NCHAN THEN XC=NCHAN
1760 FOR X=XZ TO XC
1770     YD=DAT(X)
1780     IF YD<YZZ THEN GOTO 1850
1790     IF YD>YP THEN GOTO 1850
1800     X1=X-.5
1810     X2=X+.5
1820     IF IAYIS=0 THEN Y=YD
1830     IF IAYIS=1 THEN Y=YZZ+SLOPE*(LOG(YD)-YLO)
1840     LINE (X1,Y)-(X2,Y)
1850     YLL=YD-SQR(YD)
1860     IF YLL>YP THEN GOTO 1960
1870     IF YLL<YZZ THEN YLL=YZZ
1880     IF IAYIS=0 THEN YL=YLL
1890     IF IAYIS=1 THEN YL=YZZ+SLOPE*(LOG(YLL)-YLO)
1900     YUU=YD+SQR(YD)
1910     IF YUU<YZZ THEN GOTO 1960
1920     IF YUU>YP THEN YUU=YP
1930     IF IAYIS=0 THEN YU=YUU
1940     IF IAYIS=1 THEN YU=YZZ+SLOPE*(LOG(YUU)-YLO)
1950     LINE (X,YL)-(X,YU)
1960 NEXT X
1970 RETURN
```

```
1980 REM
1990 REM
2000 REM draw horiz lines for linear plot
2010 YY=.43429*LOG(YADD/3.2)
2020 IYY=INT(YY)
2030 YQ=10!^IYY
2040 IF YADD>6.5*YQ  THEN YQ=2!*YQ
2050 IF YADD>7.5*YQ  THEN YQ=2.5*YQ
2060 IF YQ<1!        THEN YQ=1!
2070 YN=YZ/YQ
2080 IYN=INT(YN)
2090 DIY=YQ*(IYN+1)
2100 FOR Y=DIY TO YP  STEP YQ
2110     LINE (XZ,Y)-(XP,Y),,,1285
2120 NEXT Y
2130 YZZ=YZ
2140 RETURN
2150 REM
2160 REM
2170 REM draw horiz lines for ylog plot
2180 YZZ=YZ
2190 IF YZZ<1 THEN YZZ=1
2200 YLO=LOG(YZZ)
2210 SLOPE=YADD/(LOG(YP)-YLO)
2220 FOR I=1 TO 6
2230     YTEN=10!^I
2240     IF YTEN<YZZ THEN GOTO 2360
2250     FOR J=2 TO 8 STEP 2
2260         YL=J
2270         YLN=.1*YTEN*YL
2280         IF YLN<YZZ THEN GOTO 2320
2290         IF YLN>YP THEN GOTO 2370
2300         Y=YZZ+SLOPE*(LOG(YLN)-YLO)
2310         LINE (XZ,Y)-(XP,Y),,,1285
2320     NEXT J
2330     IF YTEN>YP THEN GOTO 2370
2340     Y=YZZ+SLOPE*(LOG(YTEN)-YLO)
2350     LINE (XZ,Y)-(XP,Y)
2360 NEXT I
2370 RETURN
2380 REM
2390 REM
```

```
2400 REM peak stripping and analysis written by R L Bywater 7/86
2410 INPUT"first peak channel = ";I
2420 INPUT "last peak channel = ";J
2430 YDI=DAT(I):YDJ=DAT(J)
2440 AREAT=0:AREAB=0:AREAN=0:AREAU=0:CENTR=0:FMOMENT=0
2450 IF IAYIS=0 GOTO 2490
2460 YI=YZZ+SLOPE*(LOG(YDI)-YLO)
2470 YJ=YZZ+SLOPE*(LOG(YDJ)-YLO)
2480 GOTO 2500
2490 YI=YDI:YJ=YDJ
2500 LINE(I,YI)-(J,YJ)
2510 M=(YDJ-YDI)/(J-I)
2520 FOR C=I TO J
2530     AREAT=AREAT+DAT(C)
2540     YB=(C-I)*M+YDI
2550     AREAB=AREAB+YB
2560     FMOMENT=FMOMENT+C*(DAT(C)-YB)
2570 NEXT C
2580 AREAN=AREAT-AREAB
2590 AREAU=SQR(AREAT+AREAB)
2600 CENTR=FMOMENT/AREAN
2610 PRINT CENTR,AREAN,AREAU
2620 RETURN
2630 REM
2640 REM input data routine
2650 DIM D(9), CHAN(1024), DAT(8192)
2660 L=1
2670 M=1
2680 FOR N=1 TO NGRP
2690     FOR J=1 TO 64
2700         FOR K=1 TO 9
2710             INPUT #1, D(K)
2720             ON ERROR GOTO 2860
2730         NEXT K
2740         CHAN(M)=D(1)
2750         FOR K=2 TO 9
2760             DAT(L)=D(K)
2770             L=L+1
2780         NEXT K
2790         M=M+1
2800     NEXT J
2810 NEXT N
2820 NCHAN=NGRP*512: NGG=NCHAN-1
2830 FOR I=1 TO NGG
2840     DAT(I)=DAT(I+1)
2850 NEXT I
2860 RETURN
```

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