Neutron Total Cross Sections of Be, B^{10}, B, C, and O†

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Total cross sections of Be, B^{10}, B, C, and O have been measured for neutrons of energies between 3.4 and 16 Mev. Neutrons of energy spreads between 15 and 40 kev were produced by bombarding tritium targets with protons or deuterium targets with deuterons, the charged particles being accelerated in a tandem electrostatic accelerator. Sharp peaks in the total cross sections of B^{11}, C, and O yielded information about energy levels in B^{12}, C^{13}, and O^{17}. None of the total cross sections of the five nuclei investigated showed sharp peaks above energies corresponding to an excitation energy of the order of 12 Mev of the respective compound nucleus. The transition from sharp structure to a slowly varying cross section occurs quite abruptly, except for the compound nucleus B^{11} which is excited to almost 12 Mev even for slow neutrons.

I. INTRODUCTION

MEASUREMENTS of the energy dependence of neutron cross sections[1] in the range from 1 to 30 Mev have employed the reactions $T(p,n)$, $D(d,n)$, and $T(d,n)$ as neutron sources. A few experiments have used (α,n) reactions[2] and neutrons from reactors.[3] The (α,n) reactions have the disadvantage of rapid variations of yield with energy, while the continuous spectrum of neutrons from reactors introduces experimental complications.

The source of charged particles for producing the reactions has in most experiments been an electrostatic accelerator. If only the $T(p,n)$, $D(d,n)$, and $T(d,n)$ reactions are used with conventional electrostatic accelerators, there are neutron energies around 10 Mev which cannot be conveniently reached.[4] While neutrons of energies above 12 Mev can be obtained from the $T(d,n)$ reaction, it is difficult to achieve as good energy resolution in this range as at lower energies. With the availability of the tandem accelerators[5] it is possible to reach neutron energies as high as 16 Mev with the $D(d,n)$ reaction and thus perform measurements in the neutron energy range in which experiments with good energy resolution had previously been difficult.

Details of the energy dependence of cross sections in the Mev region are expected to be of interest in the light nuclei. As a first application of the new accelerator as a neutron source of variable energy, the total cross sections of Be, B^{10}, B, C, and O were measured. This choice of elements was based on previous studies[6] which had shown sharp resonance structure at energies of the order of 1 Mev, but still wide enough level separation so that resonances at higher energies would not become unobservable because of overlap.

The total cross sections of these elements had previously been measured up to an energy of 3.3 Mev at this laboratory using the $Li(p,n)$[7] and the $T(p,n)$[6] reactions as neutron sources, with neutrons from $C^{13}+\alpha$ between 4.4 and 5.6 Mev,[2] and with neutrons from $Be^9+\alpha$ between 7.6 and 8.6 Mev.[2] In all these measurements the energy spread of the neutrons was of the order of 25 kev. Except for measurements covering only short energy regions most other measurements above 4 Mev have used energy spreads of 100 kev and more. It appeared worthwhile to remeasure the entire range from 3.4 to 16 Mev. In this way a survey of resonances could be carried out with uniform techniques. At the same time, it was desired to test the usefulness of the new accelerator as a source of neutrons of variable energy and small energy spread. Difficulties were anticipated because of high neutron and gamma-ray backgrounds produced by the charged particles of energies of the order of 10 Mev striking nuclei other than the hydrogen isotopes in the target.

II. EXPERIMENTAL

Source

The tandem accelerator produces protons and deuterons of energies up to 13 Mev. With the $T(p,n)$ reaction it is therefore possible to obtain neutrons of energies up to about 12 Mev, with the $D(d,n)$ reaction up to about 16 Mev, and with the $T(d,n)$ reaction up to 30 Mev.

The energy spread of neutrons emitted in a given direction will be governed primarily by straggling and energy losses in the target, which was in the present experiments larger than the energy spread of the incident charged particle beam. Since the energy spread of the neutrons increases with increasing target thickness, the choice of resolving power has to be based on considerations of neutron intensity, taking into account sources of neutron background. Straggling and energy losses are, at a given energy, greater for deuterons than for protons, and they are greater at the lower bombarding

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[1] D. W. Miller in *Fast Neutron Physics* (Interscience Publishers, Inc., New York), Part II, Chap. V.A (to be published).
[2] R. L. Becker and H. H. Barschall, Phys. Rev. **102**, 1384 (1956).
[3] N. Nereson and S. E. Darden, Phys. Rev. **89**, 775 (1953).
[4] J. E. Brolley and J. L. Fowler, *Fast Neutron Physics* (Interscience Publishers, Inc., New York, 1960), Part I, Chap. I.C.
[5] J. L. Danforth, Can. Electronic Engr. **2**, 18 (1958).
[6] C. K. Bockelman, D. W. Miller, R. K. Adair, and H. H. Barschall, Phys. Rev. **84**, 69 (1951).
[7] C. K. Bockelman, Phys. Rev. **80**, 1011 (1950).

energies. Consequently, for the lower neutron energies the $T(p,n)$ reaction enables one to obtain better intensity for a given neutron energy spread. In addition, at the higher energies the forward yield of neutrons from $T(p,n)$ becomes smaller than that from the $D(d,n)$ reaction.[4] For producing neutrons of a given intensity and energy spread, the $D(d,n)$ reaction becomes more favorable at the higher energies. In the present experiments the $T(p,n)$ reaction was used for neutron energies up to about 7 Mev for measurements on Be, C, and O and to about 9.5 Mev for B^{10} and B; the $D(d,n)$ reaction was used above these energies. Because of straggling of low-energy deuterons, the $D(d,n)$ reaction is advantageous compared to the $T(d,n)$ reaction at the neutron energies which can be obtained with both reactions.

Deuterium and tritium targets can be used either in solid form by absorption in Zr or as gas targets. At the higher bombarding energies the Zr produces a large background compared to the intensity of the desired neutrons, while at the lower energies there is an appreciable amount of straggling in the foil which separates the gas from the vacuum system of the accelerator. In the present experiments Zr-T targets were used at the lower neutron energies when the smallest energy spread was desired; otherwise deuterium or tritium gas targets into which the charged particles entered through a 1.3-μ thick Ni foil were used. The charged particles were stopped in a pure Au backing. The neutron energy spreads resulting from these targets varied between 15 and 20 kev up to 7 Mev neutron energy, and between 40 and 50 kev above 7 Mev, for the measurements on Be, C, and O. For B and B^{10} the energy spread was between 30 and 40 kev up to 9.5 Mev, and above this energy it varied from 40 to 50 kev. Sharp peaks observed in the cross section of B were studied further with a Zr-T target of 15 kev thickness.

For charged particles with energies as high as 13 Mev, consideration had to be given to the collimation and focusing of the beam in order to prevent large backgrounds. For the Zr-T target, which was 2 cm in diameter, the proton beam was focused by a magnetic lens composed of two crossed quadrupole magnets. The size of the beam spot was observed on a retractable quartz plate. For the smaller gas target a 0.3-cm diam Ta diaphragm was used to collimate the beam. To minimize the number of background neutrons produced by this collimation, the diaphragm current was metered and minimized with the magnetic lens.

Detector

Neutrons were detected with a stilbene scintillator, 2 cm in diameter and 2.5 cm long, which served as a biased proton recoil detector. On the basis of observations of the proton-recoil spectrum the discriminator bias was set so that only monoergic neutrons were detected, while the lower energy neutrons from deuteron breakup were eliminated and the number of recoils from neutrons originating in the target backing and at the collimating apertures was greatly reduced.

Since at high bombarding energies many gamma rays are emitted from the target, it was necessary to discriminate against recoil electron pulses produced by these gamma rays. This was accomplished by taking advantage of the difference in pulse shape between electron- and proton-induced scintillations in stilbene.[8] The gamma-ray discrimination circuit used in this experiment was designed by H. W. Lefevre of this laboratory. Care was taken to prevent overlap of the pulses which results in a counting rate loss in the discrimination circuit. This is especially important at the high energies where the number of gamma rays and background neutrons is very large. With the deuterium gas target the beam current had to be limited to about 0.3 μa at the lower deuteron energies and to about 0.02 μa at the highest energies in order to avoid counting losses. For the Zr-T targets the current was limited to about 2 μa in order to prevent outgassing of tritium.

Procedure

The total cross sections were measured by a transmission experiment in good geometry with the detector placed 40 cm from the neutron source. In this geometry the neutron energy spread as a result of the finite angle subtended by the detector was less than 5 kev for the $T(p,n)$ reaction and less than 10 kev for the $D(d,n)$ reaction. The samples were placed halfway between the detector and the source.

At each energy enough counts were taken to keep the statistical errors in the cross section below 3%.

Neutrons scattered in the sample into small forward angles are detected as if no interaction had occurred. The transmissions were corrected for these inscattered neutrons assuming that the small-angle scattering can be calculated from diffraction theory for a black nucleus.[9] This diffraction theory yields for the 0° differential scattering cross section values not far from those measured for 14-Mev neutrons.[10] Since the inscattering correction was less than 3% in all cases, the approximation should not introduce an appreciable error.

The effect of neutrons not coming directly from the source was determined by interposing between the target and the detector a 32-cm long Cu shadow cone which had a transmission of less than 0.1%. The effect of neutrons which are not produced by the source reaction was measured by replacing the Zr-T target with a Zr-H target or by filling the gas target with He. Although the neutron intensities from the blank targets reached values as high as 10% at the highest deuteron

[8] F. D. Brooks, *Progress in Nuclear Physics* (Butterworths-Springer, London, 1956), Vol. 5, p. 252.

[9] B. T. Feld, H. Feshbach, M. L. Goldberger, H. Goldstein, and V. F. Weisskopf, Atomic Energy Commission Report NYO-636, January 31, 1951 (unpublished).

[10] J. H. Coon, R. W. Davis, H. E. Felthauser, and D. B. Nicodemus, Phys. Rev. **111**, 250 (1958).

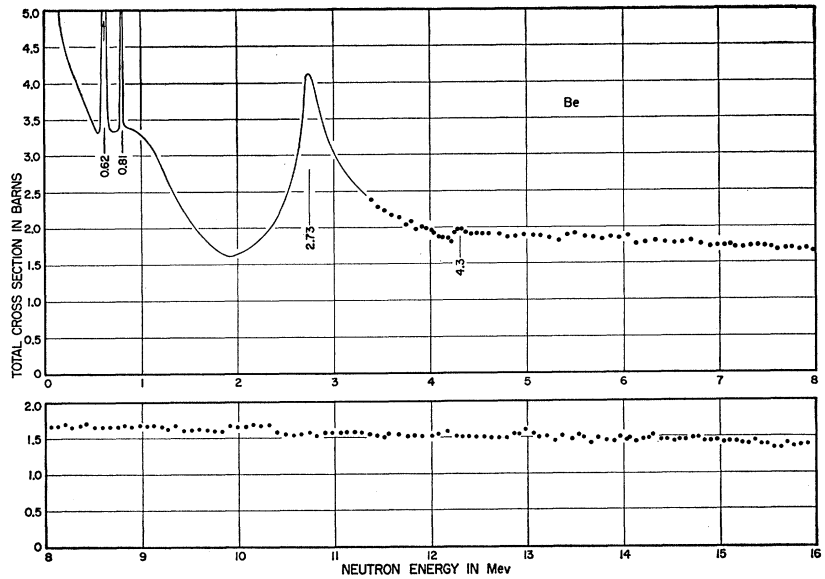

FIG. 1. The total neutron cross section of Be. The curve up to 3.4 Mev represents measurements from references 6 and 7. Each dot is an average of three data points below 7 Mev and of two data points above this energy. Statistical errors are less than 3%. The neutron energy spread is about 20 kev up to 7 Mev and above this energy about 45 kev.

energies, the transmission of the samples for these neutrons did not differ substantially from that for the source neutrons, so that the correction to the transmission for these neutrons was always less than 2%. The total correction for both types of backgrounds was always less than 3% of the cross section.

Samples

Cylindrical samples, 2.5 cm in diameter, were used in the transmission measurements. The lengths of the samples were chosen to give about 50% transmission.

The Be sample consisted of cast metal; that of C was made of graphite.

The samples referred to as "B^{10}" contained boron powder enriched in B^{10}(94% B^{10}); the samples referred to as "B" were made of elemental boron powder of the normal isotopic composition (81% B^{11}). The former contained, according to the analysis supplied by the Oak Ridge National Laboratory, one percent B^{11} and 5% impurities of uncertain composition, mostly O. In calculating cross sections it was assumed that the enriched sample contained only B^{10}. This introduces an uncertainty in the B^{10} cross section because of the uncertainty of the number of B^{10} atoms in the samples, although the O cross section is not very different from that of B^{10}.

Cross sections of O were determined by comparing the transmission of a sample of BeO powder with that of a sample of metallic Be containing the same number of Be atoms per unit area.

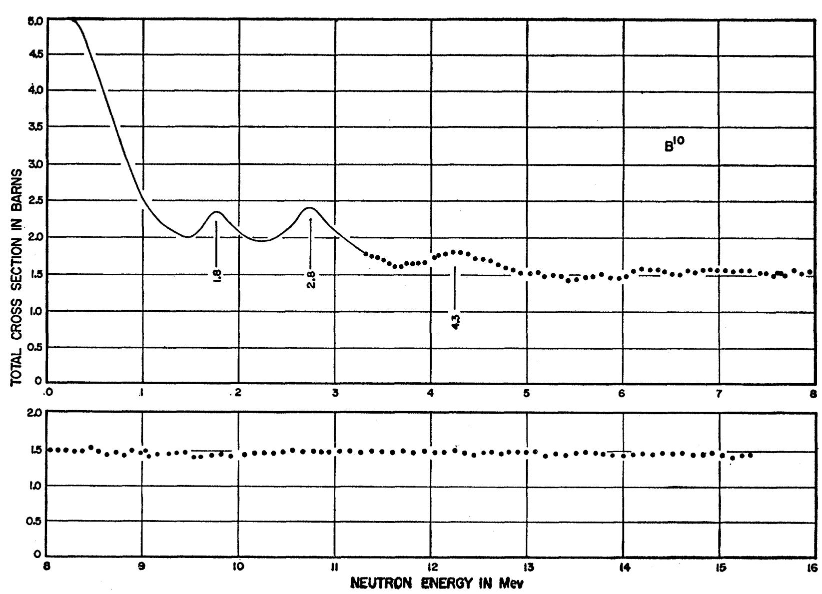

FIG. 2. The total cross section of B^{10}. The curve up to 3.4 Mev represents measurements from references 6 and 7. Each dot is an average of two data points. Statistical errors are less than 3%. The neutron energy spread is about 30 kev up to 9.5 Mev and above this energy about 45 kev.

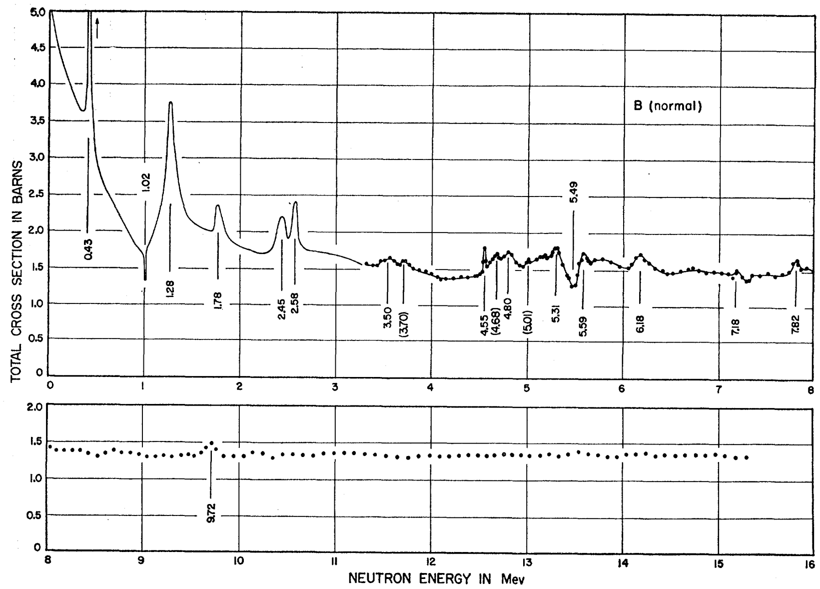

FIG. 3. The total cross section of normal B. The curve up to 3.4 Mev represents measurements from references 6, 7, and 12. Except at the sharp peaks where all the measurements are shown, each dot is an average of two data points. Statistical errors are less than 3%. The neutron energy spread is about 30 kev up to 9.5 Mev and above this energy about 45 kev.

III. EXPERIMENTAL RESULTS

The total cross sections plotted as a function of neutron energy in the laboratory system are shown in Figs. 1–5. Previous measurements[6,7] carried out at this laboratory are represented by the solid curve at low energies, and the present measurements start with the solid circles at 3.4 Mev. In Fig. 3 the minimum around 1 Mev is drawn through the data of Imhof *et al.*[11]

In order to display the complete cross-section dependence on energy of a nucleus in one figure without overlap of points, not all the measurements are presented. Data were taken at intervals of the target thickness; however, in energy regions in which the cross section varied slowly, averages of three points are presented in Figs. 1, 4, and 5 up to 7 Mev. In Figs. 2 and 3 and above 7 Mev in Figs. 1, 4, and 5 the points shown are averages of two data points. As a consequence, the energy spread of the neutrons was actually less than the energy separation of the points shown in Figs. 1 to 5 except in the sharp peaks in Figs. 3, 4, and 5. In order to show the rapid variations with energy of the O cross section all the measured cross sections are shown in Fig. 6 on an expanded energy scale. In this figure the energy spread is equal to or greater than the spacing of the points.

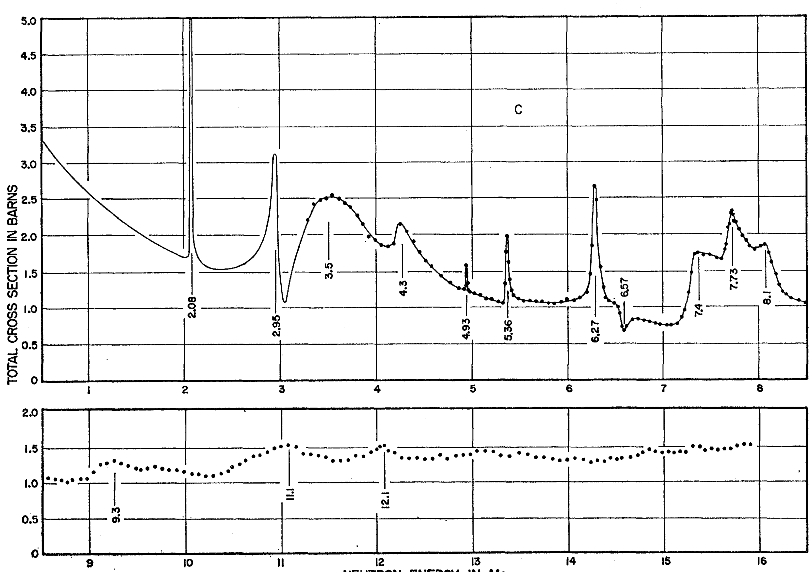

FIG. 4. The total cross section of C. The curve up to 3.4 Mev represents measurements from references 6 and 7. Except at the sharp peaks where all the measurements are shown, each dot is an average of three data points below 7 Mev and of two data points above this energy. Statistical errors are less than 3%. The neutron energy spread is about 20 kev up to 7 Mev and above this energy about 45 kev.

[11] W. L. Imhof, R. G. Johnson, F. J. Vaughn, and M. Walt, Bull. Am. Phys. Soc. 5, 245 (1960).

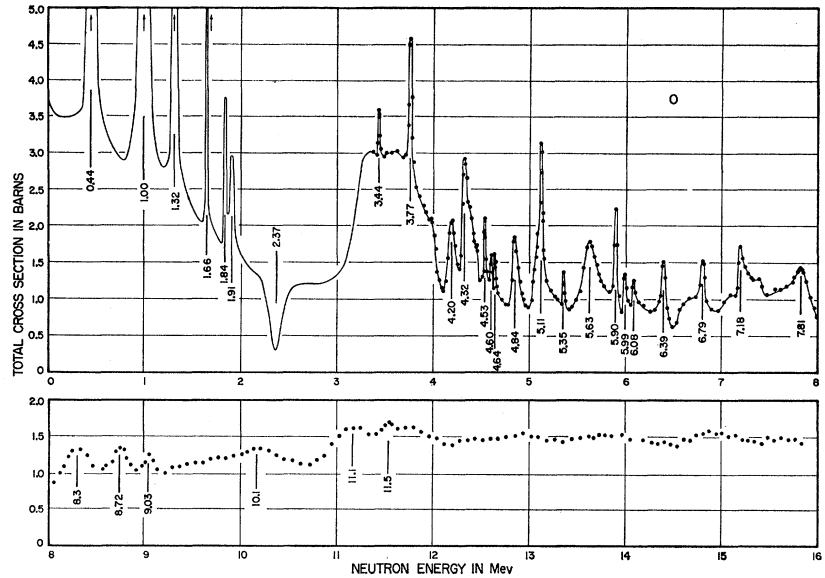

FIG. 5. The total cross section of O. The curve up to 3.4 Mev represents measurements from references 6 and 7. Except at the sharp peaks where all the measurements are shown, each dot is an average of three data points below 7 Mev and of two data points above this energy. Statistical errors are less than 3%. The neutron energy spread is about 20 kev up to 7 Mev and above this energy about 45 kev.

The neutron energy calculations are based on the tabulation of Fowler and Brolley.[12]

Statistical errors are less than the size of the points shown except at the sharp peaks. At the peaks an additional uncertainty is introduced because of the uncertainty in energy which is of the order of 10 kev. Uncertainties caused by the corrections and by impurities or nonuniformities of the samples are believed to be smaller than the statistical uncertainties except in the case of B^{10} for which the uncertainty in the sample composition is larger than the statistical uncertainty.

Neutron energies at which well-defined peaks in the cross section occur are given below each peak, energies at which sharp minima occur are indicated above the minima.

IV. COMPARISON WITH PREVIOUS MEASUREMENTS

For all the nuclei the present results agree with previous measurements[6] at this laboratory between 3.3 and 3.4 Mev where the two measurements overlap. Comparisons with other previous measurements show differences which are primarily caused by the different energy resolutions used in the different experiments.

Most of the previous measurements between 3.5 and 13 Mev neutron energy were done with neutrons from the $D(d,n)$ reaction with energy spreads between 50 and 100 kev. This applies to the measurements performed at Los Alamos,[13] those of Bondelid *et al.*,[14] the measurement on O carried out by Walton *et al.*,[15] the experiments by Ricamo and Zünti[16] in which a D_2O ice target was used, and the measurements of Bratenahl *et al.*[17] which were carried out at about 2-Mev intervals using deuterons from a cyclotron. The older measurements of Freier *et al.*[18] used $D(d,n)$ neutrons with energy spreads between 100–400 kev.

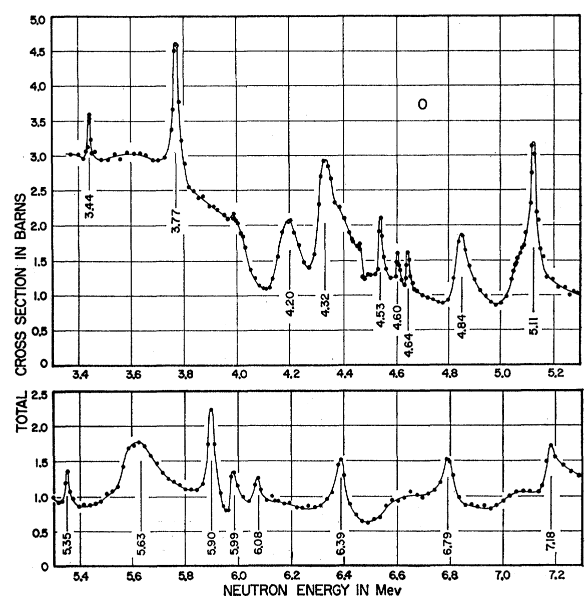

FIG. 6. The total cross section of O. Each dot represents one data point. Statistical errors are less than 3%. The neutron energy spread varied between 15 and 20 kev.

[12] J. L. Fowler and J. E. Brolley, Revs. Modern Phys. **28**, 103 (1956).

[13] *Neutron Cross Sections*, compiled by D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1958), 2nd ed.

[14] R. O. Bondelid, K. L. Dunning, and F. L. Talbott, Phys. Rev. **105**, 193 (1957).

[15] R. B. Walton, J. D. Clement, and F. Boreli, Phys. Rev. **107**, 1065 (1957).

[16] R. Ricamo and W. Zünti, Helv. Phys. Acta **24**, 419 (1951).

[17] A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. **110**, 927 (1958).

[18] G. Freier, M. Fulk, E. E. Lampi, and J. H. Williams, Phys. Rev. **78**, 508 (1950).

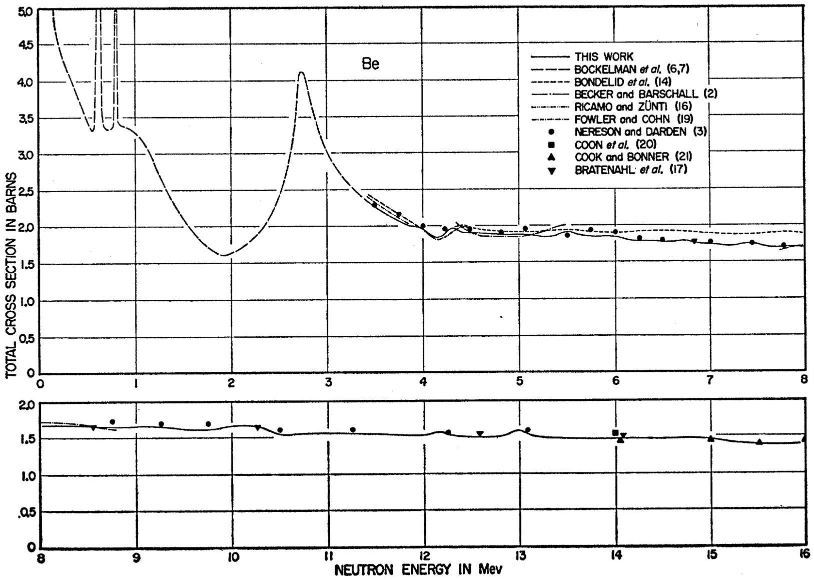

FIG. 7. The total neutron cross section of Be is compared with previous measurements from the indicated references.

Fowler and Cohn[19] measured the Be cross section up to 4.6 Mev with $T(p,n)$ neutrons which had about 25-kev energy spread. Their results agree with the present results and show also a small anomaly at 4.3 Mev.

Above 14 Mev neutrons from the reaction $T(d,n)$ were used by Coon *et al.*[20] and by Cook and Bonner.[21] For Be, C, and O the energy range from 3 to 12 Mev was studied by Nereson and Darden[3] with neutrons from a reactor which had a broad energy spread of about 10%. These measurements agree well with the present results if the latter are averaged over resonances.

Measurements between 4.4 and 5.6 Mev carried out with neutrons from $C^{13}(\alpha,n)$ earlier at this laboratory[2] agree well with the present results except for B^{10} where the sample compositions may have differed. Measurements between 7.6 and 8.6 Mev using neutrons from $Be(\alpha,n)$[2] show some disagreements at the peaks in the C and O cross sections. Because of the experimental difficulties in using $Be(\alpha,n)$ neutrons it is believed that the present measurements are more reliable.

Most recently Tsukada and Fuse[22] measured the cross sections of C and O with $D(d,n)$ neutrons in the energy range from 3.4 to 5.1 Mev with energy spreads which

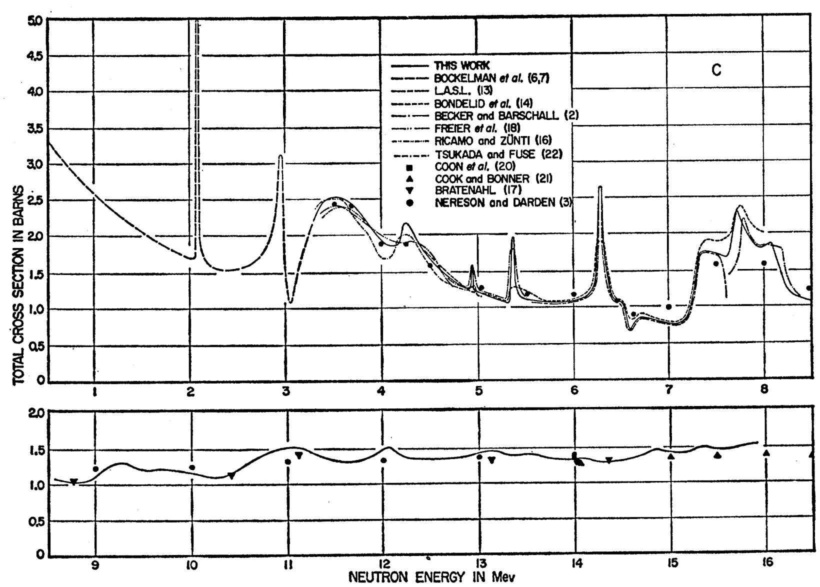

FIG. 8. The total cross section of C is compared with previous measurements from the indicated references.

[19] J. L. Fowler and H. O. Cohn, Bull. Am. Phys. Soc. **4**, 385 (1959).
[20] J. H. Coon, E. R. Graves, and H. H. Barschall, Phys. Rev. **88**, 562 (1952).
[21] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 651 (1954).
[22] K. Tsukada and T. Fuse, J. Phys. Soc. Japan **15**, No. 11, 1994 (1960).

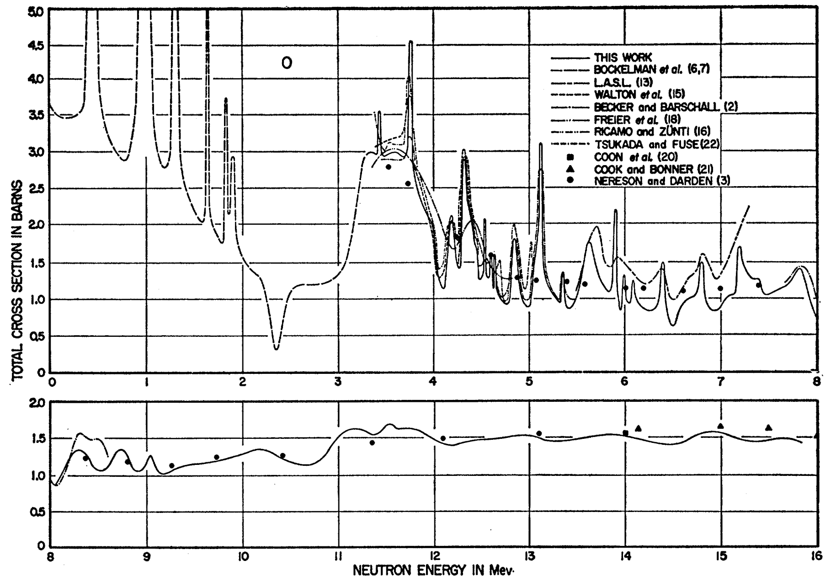

FIG. 9. The total cross section of O is compared with previous measurements from the indicated references.

were estimated by the authors to be between 10 and 50 kev. These measurements agree well with the present results except at the sharp resonances which appear to be better resolved in the present measurements. This difference may be due to an underestimate of the straggling in the Ni foil through which the deuterons entered the gas target.

The present measurements on Be, C, and O are compared with previous measurements in Figs. 7, 8, and 9. In Fig. 9 some of the data from references 2 and 22 are not shown near 4.6 Mev because the curves overlapped. While the results from reference 2 agree with the present measurements in this energy region, the studies reported in reference 22 do not show as much structure as the present results.

Because relatively few measurements have been carried out above 3.5 Mev on B^{10} and B no comparison curves are presented. Measurements on B^{10} and B have been carried out with (α,n) neutrons at this laboratory,[2] and there are some unpublished measurements from Los Alamos.[13] For B, additional measurements are available at 14 Mev[21] and above [20] for D+T neutrons.

V. ENERGY LEVELS IN THE COMPOUND NUCLEI

The peaks in the measured total cross sections can be interpreted in terms of energy levels in the compound nucleus. If the target nucleus has spin I and the compound state has an angular momentum J, the maximum variation in the total cross section $\Delta\sigma$ that can be caused by an isolated level is given by

$$\Delta\sigma = 2\pi\lambda\!\!\!^{-2}(2J+1)/(2I+1),$$

where $\lambda\!\!\!^{-}$ is the reduced wavelength of the incident neutron in the c.m. system. This maximum variation occurs if elastic scattering of the neutrons is the only type of interaction which occurs. The only case in the present measurements in which this condition would be expected to hold is the interaction of neutrons below 4.8 Mev with C^{12}.

In the interaction of neutrons with O^{16} the only process which competes with elastic scattering of neutrons below 6.4 Mev is the $O^{16}(n,\alpha)$ reaction. In this case the maximum variation in cross section is given by

$$\Delta\sigma = 2\pi\lambda\!\!\!^{-2}(2J+1)\Gamma_n/(\Gamma_n+\Gamma_\alpha),$$

where Γ_n and Γ_α are the neutron and α-particle widths of the compound state. From studies of the $C^{13}(\alpha,n)$ reaction[15] information about Γ_n/Γ_α is available.

In the other nuclei, and in C and O at higher energies, the competition from inelastic scattering will reduce the maximum variation. Since the widths of levels for inelastic scattering were not known, it is then possible to deduce from the observed $\Delta\sigma$ only minimum values of J.

In the interpretation of resonances at lower energy it is frequently possible to obtain information about the orbital angular momentum of the neutrons forming a given compound state by calculating the reduced width of the state. At the neutron energies used in the present experiments the penetrability of the centrifugal barrier varies more slowly with orbital angular momentum. In addition, calculated reduced widths are much smaller than the Wigner limit. As a consequence, little information about the angular momenta of the neutrons forming the compound states could be obtained from calculations of reduced widths.

In order to compare the measured and calculated values of $\Delta\sigma$ it is necessary to take into account the finite resolving power used in the experiments. For the case in which the distribution in energy of the neutrons can be represented by a Gaussian, Feld *et al.*[9] have

TABLE I. Energy levels in B^{12} (*present results*).

E_n (Mev)	E_{ex} (Mev)	$\Gamma_{c.m.}$ (kev)	J
3.5	6.6	140	≥ 1
(3.70)	(6.75)	65	≥ 0
4.55	7.53	≤ 14	≥ 4
(4.68)	(7.65)	45	≥ 1
4.80	7.76	90	≥ 1
(5.01)	(7.95)	27	≥ 1
{5.31	8.22	65	≥ 2
{5.49	8.39	110	
{5.59	8.48	75	≥ 2
6.18	9.02	120	≥ 2
7.18	9.94	100	≥ 1
7.82	10.52	65	≥ 3
9.72	12.26	120	≥ 3

calculated the decrease of $\Delta\sigma$ caused by an energy spread of half-width δ in terms of Γ/δ.

The cross section of Be shows only one anomaly in the energy range studied. This occurs at a neutron energy of 4.3 Mev corresponding to an excitation energy of Be^{10} of 10.7 Mev. The observed variation in cross section of 0.2 b may be interpreted as caused by a state of $J \geq 1$ in Be^{10}. Two levels in Be^{10} have been observed in the $Li^7(t,n)Be^9$ reaction at excitation energies of 17.83 and 18.43 Mev.[23] These energies correspond to neutron energies of 12.2 and 12.9 Mev. Near these neutron energies the observed cross section shows a small increase, but it is not clearly outside statistics.

The B^{10} cross section shows no sharp structure. It exhibits a broad maximum, 500 kev wide, at 4.3-Mev neutron energy. This resonance occurs at an excitation energy of 15.3 Mev in the B^{11} compound nucleus, and has a variation in cross section which implies a minimum J of $\frac{5}{2}$. Two other small maxima about the size of the statistical uncertainty are suggested by the data at 5.8 and 6.2 Mev corresponding to excitation energies of 16.7 and 17.1 Mev. Previous results involving B^{11} have shown levels at approximately the same three energies and an additional level at 17.5 Mev.[24] In the present work no indication of a level was observed near this energy.

In Tables I, II, and III the experimental results on energy levels in B^{12}, C^{13}, and O^{17}, respectively, are summarized. The first column gives neutron energies at which peaks in the total cross sections were observed in the present experiment. In the second column the corresponding excitation energies of the compound nuclei are listed. The third column presents the widths of the peaks in the c.m. system. The fourth column lists values of J deduced from $\Delta\sigma$. For B^{12} there are no previously observed levels in the energy region measured. For C^{13} and O^{17} the excitation energies of previously observed compound nucleus levels taken from the compilation by Ajzenberg-Selove and Lauritsen[24] and from results obtained at Rice University[25,26] are presented in the fifth column. Only those levels are given which occur in the energy range covered by the present measurements. The last two columns of Tables II and III give the width, angular momentum, and parity of these levels from the same references.

The energy level parameters for B^{12} presented in Table I were calculated from the data on normal boron taking into account the B^{10} content of the samples. Inelastic scattering is energetically possible in the energy range covered; thus only minimum J values can be deduced from the observed resonances. Because Γ is less than δ for the 4.55-Mev resonance, the level width is less than or equal to the measured 14 kev. Near 5.5 Mev two small maxima separated by a large minimum were observed which may be caused by two or three levels in B^{12}. The energies of both the two peaks and the dip are listed. The levels shown in parentheses correspond to peaks which are only slightly larger than the statistical uncertainty.

In Table II the experimental results on energy levels in C^{13} are summarized. The 4.93-Mev resonance was narrower than the energy spread of the neutrons so that only an upper limit of the width could be given. The structure occurring near 6.5 Mev may be caused by more than one level. The positions of both the maxima and the minimum are given in Table II even though the cross-section measurement does not enable one to conclude definitely that there is more than one level involved. Between 7.2 and 8.2 Mev the measurements show a structure which is undoubtedly caused by several resonances. Since the position and width of the levels responsible for this structure could not be deduced

TABLE II. Energy levels in C^{13}.

Present results				Previous work		
E_n (Mev)	E_{ex} (Mev)	$\Gamma_{c.m.}$ (kev)	J	E_{ex} (Mev)	Γ (kev)	J^π
3.5	8.2	700	$\frac{3}{2}$	8.33	1000	$\frac{3}{2}^+$
4.3	8.9	220	$\frac{1}{2}$	8.82		
4.93	9.50	≤ 10	$\geq \frac{1}{2}$	9.50		
5.36	9.90	30	$\geq \frac{3}{2}$	9.90		
6.27	10.74	65	$\geq \frac{7}{2}$	10.76		
{6.5	10.9			10.94		
{6.57	11.01			11.02	50	$(\frac{1}{2}^+)$
{6.7	11.1			11.08	sharp	
(7.4)	11.8	(250)	$(\geq \frac{5}{2})$	11.87	200	$(\frac{7}{2}^-)$
7.73	12.08	(200)	$(\geq \frac{7}{2})$	12.16	200	
(8.1)	12.4	(150)	$(\geq \frac{1}{2})$	12.44	140	$(\frac{1}{2}^-)$
				12.81		
				13.41	50	
9.3	13.5	370	$(\geq \frac{1}{2})$	13.54	500	
				13.77	280	
				14.1	210	
				14.64		
11.1	15.2	450	$(\geq \frac{3}{2})$			
12.1	16.1	230	$(\geq \frac{1}{2})$	16.1		

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uniquely from the measurements, the widths of the peaks and the calculated values of J are given in parentheses. As mentioned previously, only lower limits for J can be given above 4.8-Mev neutron energy. There is also some doubt whether any of the three broad peaks occurring above 9 Mev are caused by single levels. For this reason the J values for these peaks are given in parentheses.

Table III summarizes the experimental results on energy levels in O^{17}. Five levels were observed with $\Gamma<\delta$. With the exception of the five narrow levels, J values were deduced for levels up to 6.44 Mev with the aid of Γ_n/Γ_α information.[4] Above this energy only minimum J values can be assigned. The O cross section structures occurring above 10 Mev may be caused by broad overlapping levels; thus corresponding minimum J values are given in parentheses. The broad peak centered around 3.6 Mev is also listed in parentheses in Table III since it is not at all clear that it is caused by a single level. Small anomalies occurring at 3.98- and 4.45-Mev neutron energy are barely outside the statistical uncertainty and are likewise listed in parentheses.

TABLE III. Energy levels in O^{17}.

Present results				Previous work		
E_n (Mev)	E_{ex} (Mev)	$\Gamma_{c.m.}$ (kev)	J	E_{ex} (Mev)	Γ(kev)	J^π
3.44	7.39	≤ 8	$\geq\frac{5}{2}$	7.37	≤ 2	$\frac{5}{2}$
				7.56	≤ 4	$\geq\frac{7}{2}$
3.77	7.70	25	$\frac{5}{2}$	7.67	22	$\geq\frac{5}{2}$
(3.6)	(7.6)	600	$(\frac{3}{2})$	7.72	750	$(\frac{3}{2}^-)$
(3.98)	(7.90)			7.94	90	$\frac{1}{2}$
4.20	8.10	80	$\frac{3}{2}$	8.07	75	$\frac{3}{2}$
4.32	8.22	60	$\frac{3}{2}$	8.20	60	$\frac{3}{2}$
				8.27		
(4.45)	(8.34)			8.34	≤ 5	$\frac{1}{2}$
4.53	8.41	≤ 10	$\geq\frac{5}{2}$	8.39	8	$\frac{5}{2}$
4.60	8.48	≤ 11	$\geq\frac{3}{2}$	8.46	9	$\frac{7}{2}$
4.64	8.52	≤ 13	$\geq\frac{3}{2}$	8.49	≤ 6	$(\frac{3}{2})$
4.84	8.70	55	$\frac{3}{2}$	8.70	70	$\frac{3}{2}$
				8.89	110	$\frac{3}{2}$
5.11	8.96	28	$\frac{7}{2}$	8.96	30	$\frac{7}{2}$
				9.06		
				9.15	≤ 6	
5.35	9.18	≤ 17	$\geq\frac{3}{2}$	9.20	≤ 4	$\frac{5}{2}$
5.63	9.45	140	$\geq\frac{3}{2}$	9.50	11	$\frac{7}{2}$
5.90	9.70	28	$\geq\frac{5}{2}$	9.73	19	$\frac{7}{2}$
5.99	9.79	28	$\geq\frac{3}{2}$	9.78	55	
6.08	9.87	25	$\geq\frac{1}{2}$	9.89	12	9/2
				9.98	150	$(\frac{5}{2},\frac{7}{2})$
6.39	10.16	38	$\geq\frac{3}{2}$	10.21	50	
				10.34		
6.79	10.54	40	$\geq\frac{3}{2}$	10.57		
				10.80		
7.18	10.91	70	$\geq\frac{3}{2}$	10.95		
				11.11		
				11.28		
7.81	11.50	190	$\geq\frac{3}{2}$	11.55		
				11.88		
8.3	12.0	270	$\geq\frac{3}{2}$	12.00		
				12.25		
8.72	12.36	130	$\geq\frac{1}{2}$	12.45		
9.03	12.65	95	$\geq\frac{1}{2}$	12.71		
10.1	13.7	400	$(\geq\frac{1}{2})$			
11.1	14.6	340	$(\geq\frac{3}{2})$			
11.5	14.8	180	$(\geq\frac{1}{2})$			
				15.2		
				15.8		

TABLE IV. Energies above which no sharp structure was observed.

Compound nucleus	Neutron energy (Mev)	Excitation energy of compound nucleus (Mev)
Beryllium (10)	4.5	11
Boron (11)	<0	<11
Boron (12)	10	12
Carbon (13)	8	12
Oxygen (17)	9	12

VI. DISCUSSION

In measurements of total cross sections resonances may be missed for several reasons: the variation of the cross section at the resonance may be smaller than the statistical uncertainty, the width may be narrow compared to the energy spread of the neutrons, or the level density may be so high that the resonances form a continuum.

For compound states of given angular momentum the variation of cross section $\Delta\sigma$ is inversely proportional to the neutron energy E and to $2I+1$. In the present measurements the statistical accuracy limits observable values of $\Delta\sigma$ to about 0.1 b. If one calculates $\Delta\sigma$ for $\Gamma=\Gamma_n$ and for target nuclei with spin $I=0$, one finds that even for the lowest possible value of J, which is $\frac{1}{2}$, $\Delta\sigma$ reaches 0.1 b only at $E=30$ Mev. This means that all resonances in C and O for which $\Gamma_n/\Gamma>\frac{1}{2}$ should have a large enough $\Delta\sigma$ to be observable in the present experiments.

For target nuclei of spin $\frac{3}{2}$, i.e., Be^9 and B^{11}, all resonances with $J=0$ would have been missed above 4 Mev, and with $J=1$ above 12 Mev. For B^{10} with $I=3$, the energies at which resonances would have been missed are: 4 Mev for $J=\frac{1}{2}$, 9 Mev for $J=\frac{3}{2}$, 14 Mev for $J=\frac{5}{2}$. In all cases small values of Γ_n/Γ would also make the levels unobservable.

The second reason for missing levels is that they are narrow compared to the neutron energy spread, i.e., that $\Gamma\ll\delta$. Whether a resonance with a given Γ is observable, depends also on $\Delta\sigma$. One might expect that the widths of resonances will increase with neutron energy. Since, on the other hand, $\Delta\sigma$ decreases with E, the fraction of narrow levels missed may not depend strongly on neutron energy.

At the energy above which the $D(d,n)$ reaction was used in the present experiments, δ increases by about a factor of two. To investigate the effect of the source reaction on observed resonances, some energy regions in which resonances occurred in C and O were measured with both source reactions. The same structure was observed in both cases.

From what is known about the spacing of energy levels in the light nuclei it is not to be expected that the level density in the regions studied in the present experiment would be high enough to form a continuum.

The most striking feature of the results shown in Figs. 1, 3, 4, and 5 is the occurrence of sharp peaks at the lower energies and the absence of sharp peaks at higher energies. While one would expect that an increasing number of resonances would be missed as the neutron energy is increased, the abrupt change in character of the energy dependence of the cross section was unexpected.

The transition from sharp peaks to smooth dependence on energy occurs for the different nuclei studied at the neutron energies shown in the second column of Table IV. The fact that this transition occurs at such different energies makes it unlikely that it is an instrumental effect, such as a decrease of resolving power with energy.

The excitation energies of the compound nucleus corresponding to the neutron energies given in the second column are listed in the third column of Table IV. It may be seen that these excitation energies vary much less than the neutron energies given in the second column. The reason for the abrupt transition in the character of the total cross sections is not apparent at this time.

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Deuterium and Beryllium $(n,2n)$ Cross Sections Between 6 and 10 Mev*

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The $(n,2n)$ cross sections of deuterium and beryllium have been measured for incident neutron energies in the range from 6 to 10 Mev using a large liquid scintillator. The cross sections in barns obtained for deuterium were 0.067 ± 0.007 at 6.11 Mev, 0.073 ± 0.007 at 6.55 Mev, 0.088 ± 0.009 at 7.32 Mev, 0.11 ± 0.010 at 8.26 Mev, and 0.14 ± 0.015 at 10.2 Mev. The beryllium cross sections were 0.55 ± 0.08 at 6.55 Mev, 0.56 ± 0.07 at 7.32 Mev, and 0.63 ± 0.09 at 8.26 Mev.

INTRODUCTION

The $(n,2n)$ cross sections of deuterium and beryllium have been measured for incident neutron energies in the range from 6 to 10 Mev. Neutrons were produced by the $T(p,n)He^3$ and the $D(d,n)He^3$ reactions at the Livermore variable-energy cyclotron. The $(n,2n)$ events were identified by the detection of both of the emitted neutrons in a large liquid scintillator.

EXPERIMENTAL METHOD

The external beam of the cyclotron was periodically deflected onto the gas target by an external sweeping system so as to produce burst of neutrons with a time duration of 1 μsec and a repetition rate of 2 kc/sec. These neutrons were collimated by means of a tapered hole in a concrete wall 5 ft. thick and then passed through a cylindrical hole in the center of a 240-gal cadmium-loaded liquid scintillator. Deuterium (CD_2) or beryllium targets were placed so as to intercept the neutron beam at the center of the scintillator. The scintillator, associated electronics, and their application to $(n,2n)$ cross section measurements have been previously described by Ashby *et al.*[1]

An $(n,2n)$ event in the target material will, in general, give rise to two counts in the liquid scintillator. These counts are separated in time because the neutrons are moderated before their capture in the cadmium. The scintillator used in these experiments captured more than 90% of the neutrons within 25 μsec. Thus the counting electronics were gated on for 25 μsec by a pulse which was delayed by 2 μsec from the neutron burst. When n pulses occur during any 25 μsec detection interval, this event is defined as having a multiplicity of n. A counting circuit containing a beam switching tube determines the multiplicity of each event for values of n from one through six.

The neutron detection efficiency of the scintillator was determined by placing a Cf^{252} or Cm^{244} fission counter in the center of the scintillator and measuring the average number of pulses per spontaneous fission event. The efficiency of the counter is then given by the ratio of this number to $\bar{\nu}$, the average number of neutrons per fission for these nuclei. The values of $\bar{\nu}$ that were used are 3.80 for Cf^{252} and 2.75 for Cm^{244}. These values were obtained by renormalizing the values of Diven *et al.*[2] to a value of $\bar{\nu}$ for U^{235} at thermal energy of 2.43.[3]

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