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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[1] V. J. Ashby, H. C. Catron, L. L. Newkirk, and C. J. Taylor, Phys. Rev. **111**, 616 (1958).

[2] B. C. Diven, H. C. Martin, R. F. Taschek, and J. Terrell, Phys. Rev. **101**, 1012 (1956).

[3] D. J. Hughes, B. A. Magurno, and M. K. Brussel, *Neutron Cross Sections*, Brookhaven National Laboratory Report BNL-325 (U. S. Government Printing Office, Washington, D. C., 1960), 2nd ed., Suppl. No. 1 (erratum sheet).

The flux of neutrons incident on the (n,2n) target was measured by means of a small plastic scintillator. At each neutron energy this counter was calibrated with respect to a proton recoil telescope using the unswept beam of the cyclotron and then employed as the neutron monitor for pulsed beam operation. The absolute efficiency of the proton recoil telescope is known to better than 5%.[4] The ratio of the counting rate of the plastic scintillator to that of the telescope was observed to be constant for changes of a factor of at least 50 in beam level. This was interpreted to mean that bias shifts due to high counting rates in the plastic scintillator are not important at the counting rates that were used when calibrating the counter.

The threshold energies for the (n,2n) reaction in D and Be are 3.4 and 1.8 Mev, respectively; therefore it is necessary to know the energy spectra of the incident neutrons for energies greater than 1.8 Mev. The energy spectra of the neutrons produced by the cyclotron were measured by means of photographic emulsions and also by means of the proton recoil telescope. Figure 1 illustrates the distribution of neutron energies obtained with 7.9-Mev protons incident on the tritium gas target. Of the neutrons with energies greater than 1.8 Mev, approximately 80% are at the energy expected from the T(p,n)He^3 reaction. The remaining 20% have energies less than those from the T(p,n)He^3 reaction and are probably due to (p,n) reactions in the tantalum beam stopper of the gas target. The T(p,n)He^3 reaction was used as the neutron source for determining cross sections at 6.11, 6.55, 7.32, and 8.26 Mev, and the D(d,n)He^3 reaction used at 10.2 Mev. For the latter reaction, lower energy neutrons were produced by the $d+d$ breakup reaction and also by deuteron stripping reactions in the beam stopper. The number of D(d,n)He^3 neutrons was 44% of the number of lower energy neutrons whose energy was above 1.8 Mev.

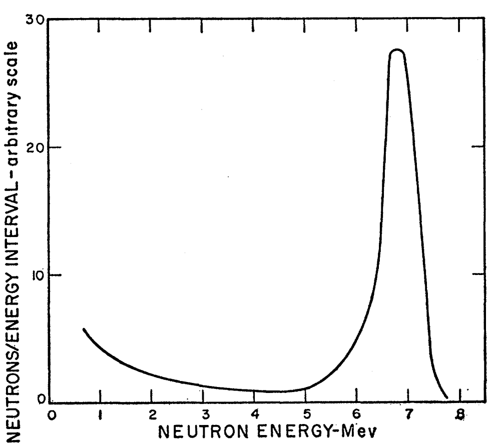

FIG. 1. Energy spectrum of neutrons produced by 7.9-Mev protons incident on the tritium target, as determined by nuclear emulsions. The peak contains the T(p,n)He^3 neutrons. The lower energy neutrons arise most probably from (p,n) reactions in the tantalum collimators and in the tantalum beam stopper of the target.

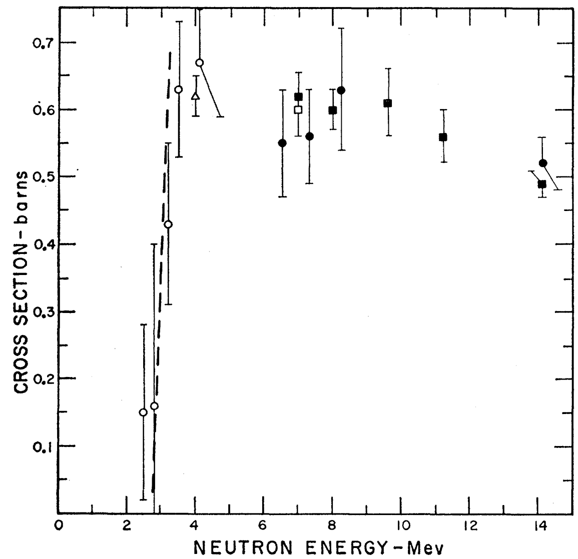

FIG. 2. The (n,2n) and nonelastic cross sections of Be, as a function of neutron energy. The solid circles represent the present data. The solid squares are from W. P. Ball, M. MacGregor, and R. Booth, Phys. Rev. **110**, 1392 (1958). The open circles are from J. Levin and L. Cranberg (private communication). The triangle is from Beyster *et al.*, Phys. Rev. **98** 1216 (1955), and the square is from Beyster *et al.*, Phys. Rev. **104**, 1319 (1956). The broken line represents the data of G. J. Fischer, Phys. Rev. **108**, 99 (1957).

DATA ANALYSIS

The data were analyzed by essentially the same method as that described by Ashby *et al.*[1] Corrections were made for the finite time resolution of the counting system, the air attenuation of the incident beam, and for the attenuation of the incident neutrons in traversing a thick target. The thick target correction includes an approximate calculation of the effect of neutrons which first scatter in the sample and subsequently produce an (n,2n) event. Corrections for target thickness increase the cross sections of beryllium by about 17% and those of deuterium by from 44% to 62%. The error introduced into the final cross sections due to this correction is believed to be less than 5%. The corrections for time resolution were about 10% for beryllium and varied from 40% to 80% for the dueterium data. An estimate of the uncertainty of this correction is obtained by measuring the (n,2n) cross section of CH_2. The incident neutron energies employed in these experiments are all less than the threshold for the (n,2n) reaction in carbon, so no (n,2n) events are expected from a CH_2 target. The single counting rates with a CH_2 target in place were approximately the same as those observed for the Be and CD_2 samples. The (n,2n) cross section measured for CH_2 was 0.006 ± 0.005 b; therefore, it is believed that the time resolution cor-

[4] M. D. Goldberg and J. M. Le Blanc, Phys. Rev. **122**, 164 (1961).

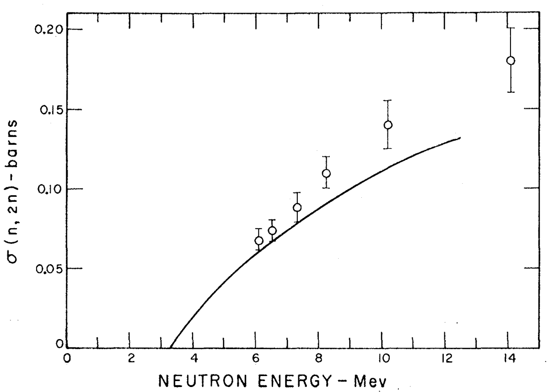

FIG. 3. The $(n,2n)$ cross section for deuterium as a function of neutron energy. The solid curve is the calculated cross section due to Frank and Gammel.[6]

rections were correctly applied. The air attenuation was about 7%.

The cross sections were also corrected for the low energy neutrons in the incident neutron beam. In making this correction it was necessary to assume an energy dependence for the $(n,2n)$ cross sections for D and Be. The energy dependence of the Be$(n,2n)$ cross section which was used to make this correction was obtained by subtracting the Be(n,α) cross section from the Be nonelastic cross section. The cross section for D was assumed to vary linearly from zero at threshold to 0.19 at 14 Mev. The neutron spectra were weighted by these cross sections and then integrated to give effective neutron fluxes for D and Be. The corrections for low energy neutrons increased the cross section by 20% and 5% for Be and D, respectively, for all energies except 10.2 Mev. At this energy, where the $D(d,n)He^3$ reaction was used as a neutron source, the correction was about 30% for deuterium. The corrections for the beryllium data at this energy were large; therefore, these data were used only to check the consistency of the correction which was applied to the deuterium data. The errors introduced in the final $(n,2n)$ cross sections by the low-energy neutron corrections are believed to be 5% or less.

TABLE I. Measured $(n,2n)$ cross sections of Be and D in barns.

Energy, Mev	Deuterium	Beryllium
6.11	0.067±0.007	
6.55	0.073±0.007	0.55±0.08
7.32	0.088±0.009	0.56±0.07
8.26	0.11±0.010	0.63±0.09
10.2	0.14±0.015	
14.1	0.18±0.02	0.52±0.04

RESULTS

The measured cross sections are listed in Table I. The values which were previously measured at 14-Mev incident neutron energy have been corrected to take account of the new value of $\bar{\nu}$.[3] Figure 2 shows the Be$(n,2n)$ and the previously measured nonelastic and $(n,2n)$ cross sections.[5] The deuterium data are shown in Fig. 3. The variation of the cross section with incident neutron energy is almost linear for energies less than 14 Mev. The calculations of this cross section by Frank and Gammel[6] are illustrated by the solid line in Fig. 3. This theory is seen to be in approximate agreement with the experimental data. The more detailed calculations of this cross section by Bransden and Burhop[7] give values much larger than the experimental values.

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[5] W. P. Ball, M. MacGregor, and R. Booth, Phys. Rev. **110**, 1392 (1958); J. S. Levin and L. Cranberg (private communication); Beyster *et al.*, Phys. Rev. **98**, 1216 (1955); **104**, 1319 (1956); G. J. Fischer, Phys. Rev. **108**, 99 (1957).

[6] R. M. Frank and J. L. Gammel, Phys. Rev. **93**, 463 (1954).

[7] B. H. Bransden and E. H. S. Burhop, Proc. Phys. Soc. (London) **A63**, 1337 (1950).