Total Neutron Yields from Light Elements under Proton and Alpha Bombardment

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Total neutron production cross sections have been measured for targets of D, T, Li^7, Be^9, B^{11}, C^{13}, C^{14}, and F^{19} under proton bombardment and of Li^7, Be^9, B^{10}, and Si^{29} under alpha-particle bombardment. Energy ranges covered differ, but were contained between threshold and 5 Mev for protons and between threshold and 9 Mev for alphas. In several cases cross sections for the inverse reactions, (n,p) and (n,α), have been computed and compared, where available, with direct measurements.

INTRODUCTION

THE study of the locations and properties of nuclear energy levels in light nuclei by (p,n) and (α,n) reactions has been a fruitful field of investigation. In only a few cases, however, has the absolute cross section been determined. A knowledge of the absolute cross section should be valuable for several reasons. Resonance analysis can be considerably simplified and clarified if one knows the absolute cross section involved. An example of this is the 2.25-Mev resonance and the threshold-associated resonance in $Li^7(p,n)Be^7$.[1,2] A second reason for wanting to know absolute cross section is a utilitarian one, that of comparing the yields of different neutron-producing reactions not only in order to be able to choose an optimum neutron source, but also as an aid in choosing materials to be used in experiments, such as target backings which have very low neutron yields. A third reason is that cross sections for certain (n,p) and (n,α) reactions can be obtained only by studying the inverse reaction and then computing the direct reaction by means of the reciprocity theorem.[3] An example is $N^{13}(n,p)C^{13}$. Several reactions of this type provide critical parameters in theories of heavy-element buildup by stellar reactions[4] and in the problem of neutron-production mechanisms in supernovae. At the time when this work was initiated it was thought that a more quantitative comparison of some (p,n) and (α,n) reactions with their (measured) inverse reactions might be a sensitive test of the assumed validity of time-reversal invariance in strong interactions.[5]

EXPERIMENTAL

The neutron detector has been fully described elsewhere.[6] It consists of a five-foot diameter sphere of reactor-grade graphite with eight BF_3 counters embedded around its surface. A 4 in.×4 in. hole allows introduction of the target into the center of the sphere. The experimental arrangement and absolute efficiency calibration were essentially the same as reported earlier.[2] The proton and alpha-particle beams were obtained from the ORNL 5.5-Mv Van de Graaff accelerator.

Energy calibration was made assuming threshold energy for $Li^7(p,n)Be^7$ to be 1.8811 Mev.[7] The usual corrections[8] were made for energy losses associated with the gas targets. Particle energy was determined by proton resonance frequency, corrected for magnet saturation effects and relativistic mass.[9]

A daily check of relative counter efficiency and current integrator calibration showed variations of less than a few tenths of a percent. Proton or alpha current was collected in a four-foot Faraday cup when solid targets were used. Current collection for the case of the gas target measurements has been discussed previously.[10]

The determination of the absolute efficiency of the detector was discussed earlier.[6] More recent information, however, deserves mention here. It was pointed out in an earlier paper[2] that the detector efficiency "calibration" consisted of normalization to an Sb−Be source calibrated by the National Bureau of Standards. A preliminary independent determination of the efficiency of the sphere by measuring the thermal flux leakage out of the sphere indicated an efficiency some 8% higher than was indicated by the Sb−Be calibration. Since that report the "Ra−Be−II" second standard NBS source was obtained on loan in order to obtain a direct calibration. The result of this calibration was a sphere efficiency some $(4\pm2)\%$ lower than the value indicated by the earlier Sb−Be measurement. Also, a more careful analysis (including a solid angle factor that was unfortunately omitted in the earlier report) of the results of thermal leakage measurements indicated an efficiency factor some 13% lower than the preliminary value. The net result of these tests is that the local, independent calibration indicates a neutron yield of 1.21×10^6 n/sec for NBS, Ra−Be−II. The accuracy of this result is

[1] Newson, Williamson, Jones, Gibbons, and Marshak, Phys. Rev. **108**, 1294 (1957).
[2] R. L. Macklin and J. H. Gibbons, Phys. Rev. **109**, 105 (1958).
[3] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 336 ff.
[4] Burbidge, Burbidge, Fowler, and Hoyle, Revs. Modern Phys. **29**, 547 (1957).
[5] E. M. Henley and B. A. Jacobsohn, Phys. Rev. **108**, 502 (1957).
[6] R. L. Macklin, Nuclear Phys. **1**, 335 (1957).
[7] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).
[8] J. L. Fowler and J. E. Brolley, Revs. Modern Phys. **28**, 103 (1956).
[9] Kington, Bair, Cohn, and Willard, Phys. Rev. **99**, 1393 (1955).
[10] C. H. Johnson and H. E. Banta, Rev. Sci. Instr. **27**, 132 (1956).

TABLE I. Targets and target backings. The thicknesses of the boron targets, first measured by weight, were found by chemical analysis to contain much less boron than expected. Boron thickness by chemical analysis is given in parentheses. In other cases where chemical (Be, Si), mass spectrographic (D_2, T_2), or radioactivity (F^{19}) analyses were used, good agreement was obtained.

Target	Form	Isotopic purity (%)	Average total target thickness (μg/cm^2)	Backing
D	D_2	99.4	13.8	Pt
T	T_2; Zr−T	88.5	T_2: 47, 90; Zr−T: ~*150*	Pt
Li^7	Li; LiF	92.5	Li: 6.5, 40; LiF: 380	Pt; Al
Be^9	Metal	(100)	6, 70, 184	Pt
B^{10}	Metal	97.2	11 (1.6 B^{10})	Pt
B^{11}	Metal	89.1	12 (1.5 B^{11})	Pt
C^{13}	"Carbon"	61	24.8	Pt
C^{14}	"Carbon"	...	...	Pt
F^{19}	$U^{238}F_4$	(100)	120	Al
Si^{29}	SiO_2	70.8	43	Pt

still in some doubt because the neutron thermal diffusion length for the graphite has not yet been directly rechecked.[6] The NBS measurements yield 1.186×10^6 $\pm3\%$ n/sec. It is interesting to note in a recent communication[11] that this same source is within $(1\pm3)\%$ agreement with other "world standards." The close agreement found (for $\sim\frac{1}{2}$-Mev neutrons) is perhaps fortuitous in view of the graphite nonuniformity and anomalously long neutron pulse decay observed earlier.[6]

In the case of deuterium gas-target measurements, the neutron background was measured with the gas cell filled with helium. For the study of $T(p,n)He^3$, measurements were made as a function of tritium pressure. Blank target backings were used for the determination of solid target background. Corrections for the $D(p,p')p,n$ reaction ranged from 90% at 3.6 Mev to 15% at higher energies. Except for the first several points near threshold, background corrections for the remaining reactions were less than 10%.

TARGETS

Most reactions were studied using solid targets, vacuum-evaporated onto platinum backings. When possible, the thicknesses determined by weighing were checked by quantitative chemical analysis. With the exception of the boron targets satisfactory agreement was obtained between the two calibration techniques. In one case ($U^{238}F_4$) a third check was made, that of thickness determination by absolute alpha-particle counting. Lithium targets for absolute calibration purposes were prepared by using thick LiF targets since these are able to be weighed for thickness determination. The C^{13} target preparation has been described elsewhere.[12] The C^{14} target, prepared in a similar fashion to that of the C^{13} target, was obtained from Chalk River Laboratories. A summary of targets used is given in Table I.

Gas targets were used for studies involving deuterium and tritium. Separate target assemblies were, of course, used throughout the experiment for the two gases. The details of these targets and the associated uranium gas ovens have been fully described elsewhere.[10,13] The deuterium gas had been checked periodically and found to be 99+% pure. The tritium gas "purity," however, was found to be an elusive but significant source of error and uncertainty. It will be discussed in greater detail later.

RESULTS AND DISCUSSION

1. $D(p,p')p,n$

Barkas and White[14] first observed neutrons from the $p-D$ breakup at a bombarding energy of 5.1 Mev. Later studies of the sister reaction, $D(n,n')p,n$, by Poss *et al.*[15] and Allred *et al.*[16] considerably advanced knowledge of the interaction of protons and neutrons with deuterons. Henkel *et al.*,[17] and more recently Ferguson and Morrison,[18] have reported results for the absolute neutron yield at zero degrees. The measurement reported here is essentially the first absolute measurement of the *total* neutron yield as a function of proton energy. This is not only of interest in direct comparison with calculated results but also serves as normalization for angular distribution results.

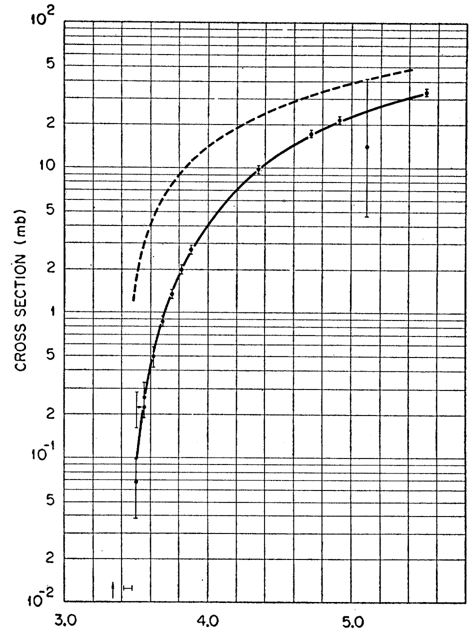

FIG. 1. $D(p,p')p,n$ cross section as a function of energy. The dashed line is from Frank and Gammel (reference 19) and the point at 5.1 Mev is from Barkas and White (reference 14).

[11] K. E. Larsson, J. Nuclear Energy **6**, 322 (1958).
[12] Bair, Kington, and Willard, Phys. Rev. **90**, 575 (1953).
[13] A. Galonsky and C. H. Johnson, Phys. Rev. **104**, 421 (1956).
[14] W. H. Barkas and M. G. White, Phys. Rev. **56**, 288 (1939).
[15] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
[16] Allred, Armstrong, and Rosen, Phys. Rev. **91**, 90 (1953).
[17] Henkel, Perry, and Smith, Phys. Rev. **99**, 1050 (1955).
[18] A. T. G. Ferguson and G. C. Morrison, Nuclear Phys. **5**, 41 (1958).

The results of the measurement are shown in Fig. 1. Background measured with the deuterium replaced by helium, was as high as 90% at 3.5 Mev. However, the error in the background correction was relatively small. Background corrections ranged downward from 90% to 15% at higher energies. For comparison the calculations of Frank and Gammel[19] are given in the figure. These calculations are, however, for the reaction $D(n,n')p,n$ and thus do not contain the Coulomb penetrability factors present in the case of $D(p,p')p,n$. The Coulomb correction is a product of two factors, one for the incoming proton wave and the second to account for the interaction of the two (free) protons in the outgoing channel. The first correction is not difficult to estimate but the second is sensitively dependent upon the relative velocity of the two protons in the center-of-mass system.[20] The effect of the first correction is to cause the calculated and experimental curve to essentially overlap at 5.5 Mev but diverge as one goes to lower energy, the calculated curve lying higher than the experimental curve. This is to be expected since the (neglected) Coulomb interaction in the exit channel is strongest at threshold. Thus we are in qualitative agreement with the predictions of Frank and Gammel.

Bransden and Burhop[21] published calculations prior to the work of Frank and Gammel in which they used a weak-interaction approximation. They were faced with bad divergences at high energies but their calculations should be valid in the energy region of our results. They calculated (without Coulomb corrections for the exit channel) a cross section of 30 mb at 5.1 Mev. This is in excellent agreement with our results, but the *slope* as well as curvature of their results appears to be in significant disagreement with the observed curve.

A linear extrapolation of the data of zero yield gives an incorrect (by $\sim$100 kev) value for the relatively well-known reaction threshold as determined by mass differences. Indeed, the yield curve must start up with a nearly zero slope.

2. $T(p,n)He^3$

There has not been entirely satisfactory agreement between the several earlier reported measurements of the absolute cross section for this reaction.[8,2] The true detailed shape of the neutron yield in this region is of considerable interest in attempts to fit the curve from either direct-interaction theory[22] or dispersion theory[3] since there appears to be some evidence[23,24] for the existence of an excited state in He^4 just below the neutron threshold. Finally, this reaction is important as a neutron source and accurate data on its yield are obviously needed. In an earlier paper[2] the results up to 2.4 Mev were presented and discussed. These measurements have been repeated and extended to 5 Mev.

Several checks were made on the accuracy of the results. The principal difficulty in an absolute measurement when using a gas cell is that of hydrogen contamination of the tritium. Of course, there is always the problem of tritium gas analysis for its isotopic abundance. For these reasons, two different gas samples were run on separate occasions. Good agreement was obtained between the two results. However, a later spectroscopic analysis of the second gas sample showed it to be different by some 30% from its "original" value.

This discrepancy, plus the lack of good agreement between various results for both $T(p,n)He^3$ and $He^3(n,p)T$ measurements, made mandatory a third measurement of the $T(p,n)He^3$ cross section. A new sample (500 atmos cm^3) of 99.9% purity tritium was obtained and transferred through an all-metal system into a new freshly prepared uranium oven.[10] After soldering onto the gas target assembly, the system was thoroughly leak-chased and pumped down to about 10^{-5} mm Hg. Then the uranium oven valve was opened into the pumping system and the uranium heated to 400°C to allow outgassing of He^3 as well as a small amount of tritium. After two preheating cycles, the system was sealed off from the diffusion pumps and the oven was heated to 440°C, the standard temperature for releasing tritium from the uranium. The entire gas target assembly as well as sample bottle *A* were filled to $\frac{1}{3}$ absolute atmosphere and left for 16 hours in order to condition the two (alcohol dried) neoprene "O" rings in the system as well as the walls of the vacuum housing.

After the "conditionlng" tritium was pumped off and discarded, sample bottle *A* was filled directly from the oven and sealed off. Then more tritium was evolved filling the gas target to $\frac{2}{3}$ atmosphere. The neutron yield was measured for this pressure and again for a target pressure of $\frac{1}{10}$ atmos. The reduction of pressure was done, not by allowing tritium to be soaked up by the uranium, but by opening a valve to evacuated sample bottle *B*. Thus the analysis of sample *B* should be that of the gas actually in the target. This process (neutron intensity measurement for two target pressures) was repeated once again, using sample bottle *C*. Finally, tritium was again evolved directly from the uranium oven into sample bottle *D*. This was essentially a repeat performance of the filling of sampling bottle *A* except that container *A* was a welded stainless steel can and container *D* was a glass container, located in a slightly different position than sample *A*. Analysis of sample *A* was performed at Savannah River and the remaining samples were analyzed at Los Alamos. Results of the gas analysis are summarized in Table II. It certainly appears that hydrogen contamination in the sampling and perhaps in the uranium oven was the principal source of

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[19] R. M. Frank and J. L. Gammel, Phys. Rev. **93**, 463 (1954).
[20] J. L. Gammel (private communication).
[21] B. H. Bransden and E. H. S. Burhop, Proc. Phys. Soc. (London) **A63**, 1337 (1950).
[22] W. Selove, Phys. Rev. **103**, 136 (1956).
[23] Bergman, Isakov, Popov, and Shapiro, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 9 (1957) [translation: Soviet Phys. JETP **6**, 6 (1958).]
[24] R. M. Frank and J. L. Gammel, Phys. Rev. **99**, 1406 (1955).

TABLE II. Results of mass spectrometric analysis of tritium gas samples, in atomic percent. These samples were taken at various stages of the $T(p,n)He^3$ cross-section measurement. The results indicate probable protium contamination by the uranium oven as well as unexpected difficulty in transferring and sampling tritium without introducing hydrogen contamination.

Sample Major constituent	Initial	*A* U-oven	*B* Target cell (a)	*C* Target cell (b)	*D* U-oven
Hydrogen	0.58	18.36	10.07	9.95	10.59
Deuterium	0.06	0.19	0.08	0.10	0.08
Tritium	99.24	80.50	88.25	88.73	87.46
Helium-3	···	0.62	1.57	1.21	1.21
Air	0.11	0.06	0.03	0.00	0.63
Tritium at sampling time	···	81.0	88.8	89.3	88.8

dilution of the tritium. The amount of dilution indicated is considerably greater than expected since the normal oven preparation techniques are thought to reduce the content of retained hydrogen in the oven to an insignificant amount.[10]

The two results for the absolute $T(p,n)He^3$ cross section for $E_p=2955$ kev gave 0.580 and 0.572 barn. Earlier studies of the reaction, which were made over a period of a year with both gas and Zr−T targets, have been normalized to the means of the values given above and are given in Fig. 2.

Because of the uncertainities in the gas purity, we must assign an error of ±10%. Although the values disagree with the earlier Los Alamos results (see Fig. 2), they are in agreement with recent integrated angular distributions.[25] The $He^3(n,p)T$ cross sections as calculated by reciprocity are shown in Fig. 3. The recent measurements at Harwell, shown for comparison, average 10% lower though one point of their ten overlaps ours.

3. $Li^7(p,n)Be^7$, Be^{7*}

The importance of this reaction as a neutron source is at least equal to that of $T(p,n)He^3$. Its rapid rise near threshold provides large quantities of low-energy neutrons. The yield near threshold and the resonance at 2.25 Mev have been discussed in an earlier paper.[2] For proton energies greater than 2.378 Mev the advent of a second neutron group due to $Li^7(p,n)Be^{7*}$ complicates attempts to fit the curve, since the total yield of this group is not separately known. It is clear, however, that the resonance seen in the $Li^7(p,\alpha)$ reaction[26] at about 3 Mev is at most barely evident (Fig. 4). Indeed it would be surprising to observe many neutrons from this alpha-emitting level. The suggestion of a broad peak centered about 3.2 Mev may be due to neutrons from $Li^7(p,n)Be^{7*}$.[27] The next maximum occurs at a bombarding energy of 5.0±0.05 Mev. Its width appears to be about 0.9 Mev and the peak cross section is about 140 millibarns. This restricts the possible resonance angular momentum to $J\geqslant 3$ if this maximum is due to a single

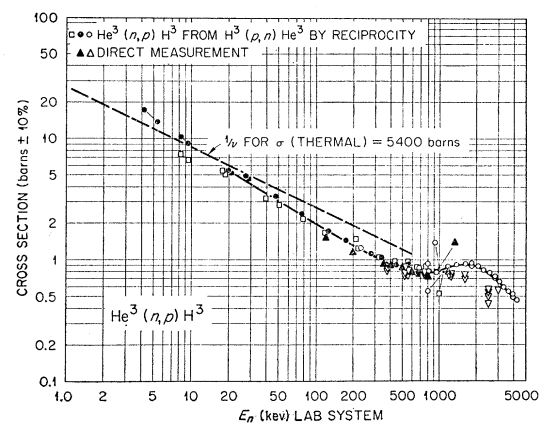

FIG. 3. $He^3(n,p)T$ cross section as a function of energy. The data reported here (circles and squares) were obtained by reciprocity from the $T(p,n)He^3$ data. The open and closed triangles are results of direct measurements given by J. H. Coon, Phys. Rev. **80**, 488 (1950) and Batchelor, Ave, and Skyrme, Rev. Sci. Instr. **26**, 1037 (1955), respectively.

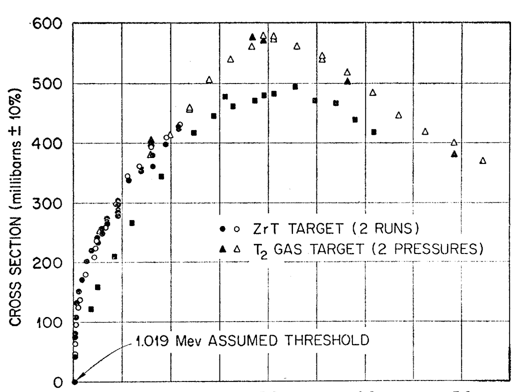

FIG. 2. $T(p,n)He^3$ cross section as a function of energy. The solid square data points are those given in *Charged Particles Cross Sections*, Los Alamos Scientific Laboratory Report LA-2014 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1957).

resonance. Bair *et al.*[28] reported a maximum at 4.89 Mev with a width of about 0.4 Mev, as determined from measurements of the zero-degree yield. It may be possible that the difference between the two results is due to the presence of multiple resonances, some with strong, forward-peaked angular distributions.

4. $Be^9(p,n)B^9$

The general features of the excitation curve are well known.[29–33] The cross section rises rapidly from thresh-

[25] Communicated by J. E. Perry, Jr., of Los Alamos.

[26] Heydenburg, Hudson, Inglis, and Whitehead, Phys. Rev. **74**, 405 (1948).

[27] Bevington, Mitchell, Rolland, Wilerzich, and Lewis (to be published).

[28] Bair, Willard, Snyder, Hahn, Kington, and Green, Phys. Rev. **85**, 946 (1952).

[29] W. J. Hushley, Phys. Rev. **67**, 34 (1945).

[30] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

[31] Hahn, Snyder, Willard, Bair, Klema, Kington, and Green, Phys. Rev. **85**, 934 (1952).

old (Fig. 5), leading to a peak at a bombarding energy of 2.563 Mev. Marion[33] reported the width of this resonance as 85 ± 10 kev, with a peak cross section of 100 mb if one includes the contribution of the underlying background. Our results, obtained with a 1-kev thick target (but normalized for cross-section determination with results using a thicker target at higher energy), indicate a width of 100 ± 10 kev (Fig. 6) with a peak cross section (again including the resonance background) of 160 mb. This resonance, it will be recalled, is actually an energy-degenerate doublet.[33]

The 2.563-Mev resonance is followed by what appears to be a broad maximum, peaked at a bombarding energy of about 3.5 Mev. This "resonance" is responsible for the neutron yield between threshold (2.059 Mev) and about 2.35 Mev. This presumably corresponds to the broad peak observed[33] in the 90° differential neutron yield near 3.2 Mev. The broad resonance is followed by a maximum between 4.5 and 5.0 Mev, due to two known[32] resonances reported at 4.7 and 4.9 Mev.

We have searched for evidence of the $Be^9(p,p'n)Be^8$ reaction between its threshold (~1.86 Mev) and the $Be^9(p,n)B^9$ threshold.[34] Using a 105-kev thick target the $(p,p'n)$ cross section does not exceed 1.0 microbarn for an average proton bombarding energy of 1.97 Mev.

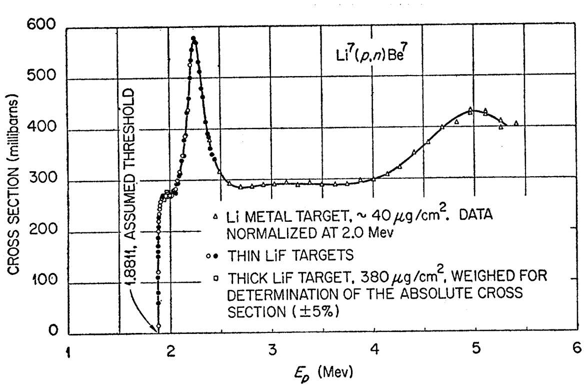

FIG. 4. $Li^7(p,n)Be^7,Be^{7*}$ cross section as a function of energy.

5. $B^{10}(p,n)C^{10}$

Ajzenberg and Franzen[35] observed neutrons from this reaction by means of photoplates at a bombarding energy 17 Mev. In their paper reporting measurements of energy levels in C^{10}, they refer to unpublished studies of $B^{10}(p,n)C^{10}$ and $B^{11}(p,n)C^{11}$ at a proton energy of 6 Mev where the yield of the two reactions differs by a factor of about 50. The total cross section for $B^{10}(p,n)C^{10}$, obtained in the present experiment, was $\leqslant 1.4$ mb at $E_p=5.35$ Mev and $\leqslant 2$ mb at $E_p=5.51$ Mev. Comparison of this result with the $B^{11}(p,n)C^{11}$ cross section (see below) indicates that the ratio of cross sections at 5.5 Mev is $\geqslant 45$, in good agreement with the earlier work. The cause of this large ratio in cross sections, pointed out by Ajzenberg and Franzen, is due to the large difference in ΔJ for the two reactions ($\Delta J=3$ for $B^{10}\rightarrow C^{10}$ and $\Delta J=0$ for $B^{11}\rightarrow C^{11}$). The source of the larger uncertainty in the results reported here is due to a large uncertainty in thickness of targets currently available.

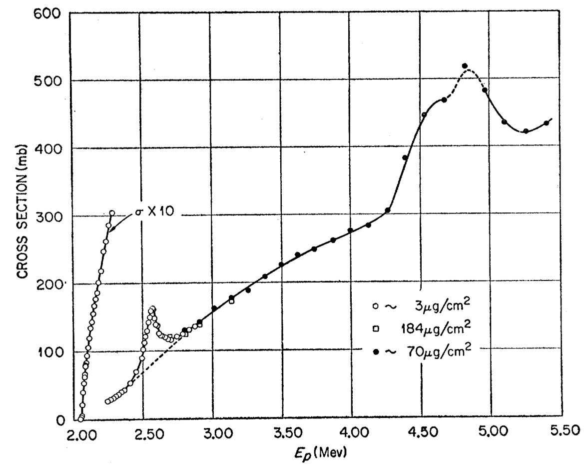

FIG. 5. $Be^9(p,n)B^9,B^{9*}$ cross section as a function of energy. The effects of such possible reactions as $Be^9(p,p')Be^8,n$ are also included here.

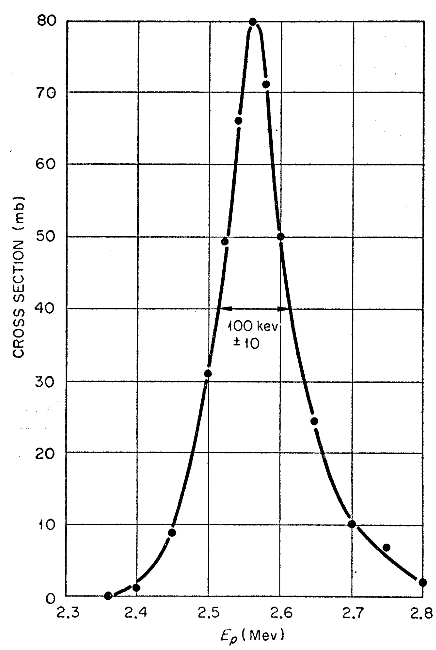

FIG. 6. A resonance in $Be^9(p,n)B^9,B^{9*}$. A smooth background (dashed line in Fig. 5) was subtracted from the total cross-section curve to obtain the one shown here.

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[32] Marion, Bonner, and Cook, Phys. Rev. **100**, 91 (1955).
[33] J. B. Marion, Phys. Rev. **103**, 713 (1956).
[34] Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **79**, 187 (1950).
[35] F. Ajzenberg and W. Franzen, Phys. Rev. **95**, 1531 (1954).

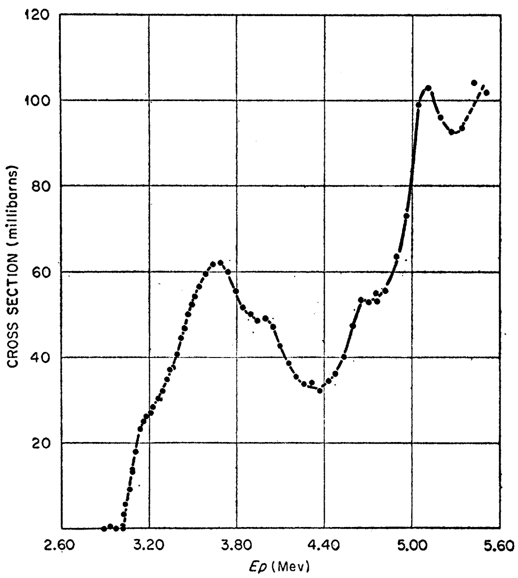

FIG. 7. $B^{11}(p,n)C^{11},C^{11*}$ cross section as a function of energy.

6. $B^{11}(p,n)C^{11}$, C^{11*}

Blaser *et al.*[36] observed resonances at 3.7, 5.18, and 5.87 Mev. Later, Bair *et al.*[37] reported resonances at 3.18, 3.63, 4.06, and 4.70 Mev. One difficulty in measuring reactions in which boron is the target material is the difficulty in obtaining pure, uniform targets. Although great care was taken in the preparation of these targets,[38] a comparison of micro-quantitative analysis of the boron deposition with determination of target thickness by weighing showed that most of the deposit formed in the evaporation process was due to the filament rather than the charge of boron. Boron cross sections reported here were, because of the difficulty in determining the average thickness of the target used, normalized at 4.5 Mev to the results of Blaser *et al.*,[36] who measured the total cross section for this reaction by activation. The results are given in Fig. 7. The resonance energies observed and the corresponding excitation energies in C^{12} are 3.18 (18.86), 3.67 (19.25), 4.70 (20.25), and 5.10 (20.49), where all energies are in Mev.

TABLE III. Resonances in $C^{13}(p,n)N^{13}$.

E_0 (Mev)	E_{ex} (N^{14})	Γ_n (kev)
3.77	11.04	110
3.98	11.20	25
4.14	11.38	50
4.51	11.73	140
4.74	11.94	
4.85	12.04	
5.03	12.21	

The observed resonances overlap strongly, making difficult the determination of level parameters. Comparison of our normalized total cross section with the 0–10° differential cross section at 3.46 Mev[37] indicates nearly isotropic neutron emission.

7. $C^{13}(p,n)N^{13}$, N^{13*}

This reaction has been studied by a number of investigators. Richards, Smith, and Browne[39] determined the laboratory threshold energy to be 3.236±0.003 Mev, and measurements have been reported[40] on the relative yield of neutrons. The same energy region of excitation in N^{14} has also been investigated with deuteron bombardments of C^{12}. Bair *et al.*[41] have made comparison between their (p,n) results and (d,p) results as to agreement in resonance energy and width. The results of our measurement are shown in Fig. 8. The behavior near threshold is indicative of a resonance below threshold. Such a level has been observed in $C^{12}(d,p)$ by Phillips.[42] This resonance would occur (if it were energetically possible) at 3.11 Mev. A summary of resonance energies observed, the corresponding excitation energy in N^{14}, and approximate widths is given in Table III.

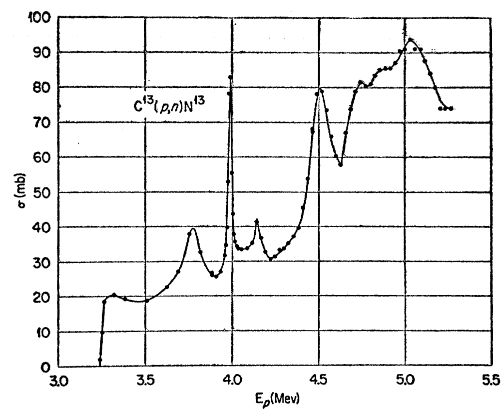

FIG. 8. $C^{13}(p,n)N^{13}$ cross section as a function of energy.

In agreement with Bair *et al.*,[41] the resonances expected from (d,p) results corresponding to $E_{ex}(N^{14})$ =11.26, 11.49, and 11.65 Mev were not observed. Of course the one at 11.49 Mev was not expected to be observed since its reported width is about 5 kev, but it is somewhat surprising that the other two levels are not seen in this measurement. The resonance reported by Bair *et al.* at a bombarding energy of 4.10 Mev was not observed. Further, their peak reported at 4.18 Mev appears at 4.14 Mev in the results reported here.

The cross sections for $C^{13}(p,n)N^{13}$ and its inverse,

[36] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 465 (1951).
[37] Bair, Kington, and Willard, Oak Ridge National Laboratory Progress Report, September, 1954 (unpublished).
[38] B. J. Massey (private communication).
[39] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[40] Adamson, Buechner, Preston, Goodman, and Van Patter, Phys. Rev. **80**, 985 (1950).
[41] Bair, Kington, and Willard, Phys. Rev. **90**, 575 (1953).
[42] G. C. Phillips, Phys. Rev. **80**, 164 (1950).

$N^{13}(n,p)C^{13}$, for kev neutrons are important quantities in calculations of heavy-element buildup in stars as well as calculations of the mechanism of neutron production in supernovae.[4] The (n,p) cross section can be obtained with ease by the reciprocity theorem from the (p,n) results.

Blaser *et al.*[36] reported measurements by activation of the absolute, total cross section for this reaction using a considerably thicker target. For comparison, they obtained a cross section of 50 mb at 4.2 Mev, and 140 mb at 4.9 Mev. These numbers are approximately 30% higher than the results reported here. Marion, Bonner, and Cook[32] reported a 0–10° differential cross section of 6.7 mb at $E_p=3.70$ Mev. A comparison of their result with the total cross section reported here indicates fairly strong forward peaking of the neutrons.

8. $C^{14}(p,n)N^{14}$

There are several previous measurements of the excitation function of this reaction[43,44] as well as comparisons of the reaction yield with that of its inverse, $N^{14}(n,p)C^{14}$.[45] Recently the reaction threshold was carefully remeasured and the excitation curve remeasured at zero degrees.[46] Sanders also measured resonance widths and absolute peak cross sections. The results reported in this paper are given in Fig. 9. In this particular case the absolute cross section was obtained by normalization to the results of Sanders for the peak cross section (315 mb) of the 1314-kev resonance. The value for the peak cross section of the 1314-kev resonance may also be obtained via the reciprocity theorem from the $N^{14}(n,p)C^{14}$ measurements of Johnson and Barschall.[45] Their value of 290 mb is in good agreement with the work of Sanders.

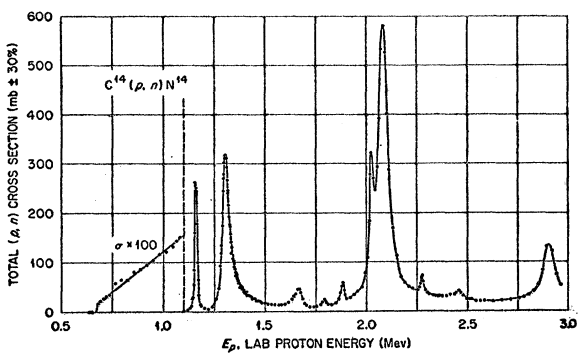

FIG. 9. $C^{14}(p,n)N^{14}$ cross section as a function of energy. The absolute cross-section determination in this case was found by normalization with earlier work at the peak of the 1314-kev resonance.

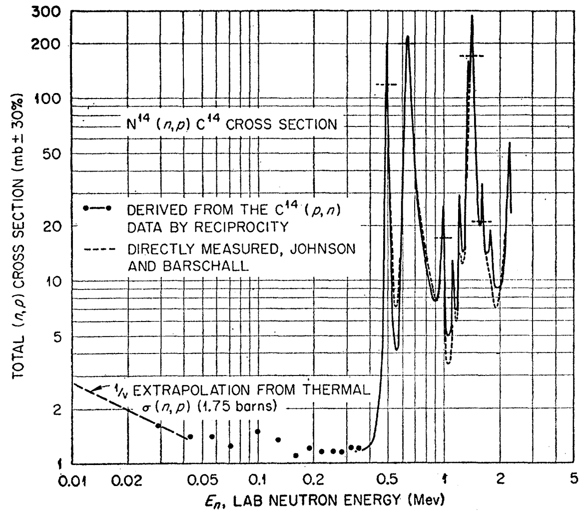

FIG. 10. $N^{14}(n,p)C^{14}$ cross section as a function of energy. The solid line is the cross section as derived by reciprocity from the $C^{14}(p,n)N^{14}$ results. For comparison the directly measured values of Johnson and Barschall are given as a dashed line.

This is the only case reported here in which the complete cross-section determination was not done at this laboratory. The uncertainty in absolute cross section, for a variety of reasons (described by Sanders), is about 30%. However, the *relative* error in the data from threshold to 1500 kev is only ±2%.

All resonances observed have been reported earlier. However, the asymmetry reported by Sanders[46] of the resonance at 1.16 Mev, which he attributed to target nonuniformity, is not observed, although definite asymmetry is observed in other resonances, especially the one at 1.31 Mev. Bartholomew *et al.*[44] have made the assignment of $J^\pi=\frac{1}{2}^-$ for the resonance at 1.61 Mev and $J^\pi=\frac{1}{2}^+$ (s-wave) for the resonance at 1.31 Mev as well as a broad one at 1.50 Mev, observed only in (p,γ)

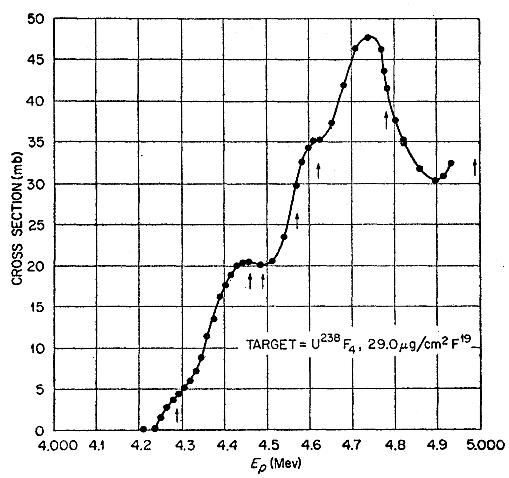

FIG. 11. $F^{19}(p,n)Ne^{19}$,Ne^{19*} cross section as a function of energy. The arrows correspond to peaks observed by Willard *et al.* (reference 48).

[43] Roseborough, McCue, Preston, and Goodman, Phys. Rev. **83**, 1133 (1951).
[44] Bartholomew, Brown, Gove, Litherland, and Paul, Can. J. Phys. **33**, 441 (1955).
[45] C. H. Johnson and H. H. Barschall, Phys. Rev. **80**, 818 (1950).
[46] M. Sanders, Phys. Rev. **104**, 1434 (1956).

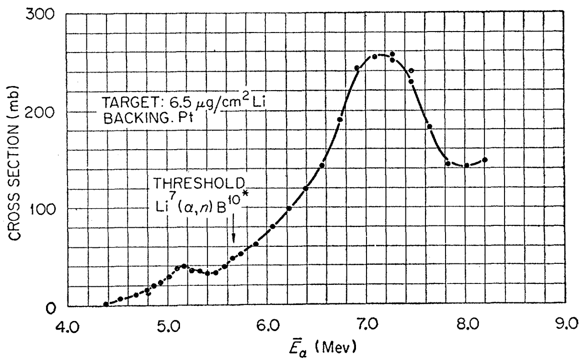

FIG. 12. $Li^7(\alpha,n)B^{10},B^{10*}$ cross section as a function of energy.

studies. Thus, if these assignments are correct, the asymmetry of the 1.31-Mev resonance may be due to interference between it and the broad, unresolved resonance at 1.50 Mev.

The cross section for $N^{14}(n,p)C^{14}$ has been computed using the (p,n) data and is presented as the solid line in Fig. 10. For comparison the directly measured results of Johnson and Barschall are given as a dotted line. There appears to be reasonably good agreement over the entire energy range studied.

Another object for the $C^{14}(p,n)$ measurement was the specific determination of the $N^{14}(n,p)C^{14}$ cross section for 55-kev neutrons. This quantity is of interest in recent studies of mechanisms for neutron production in supernovae.[4,47] It was found (see Fig. 10) that this number is 1.4 mb.

9. $F(p,n)Ne^{19}$

A detailed target yield measurement by Willard *et al.*[48] indicated eight resonances between threshold (4.235 Mev) and 5.0 Mev. Earlier, Blaser *et al.* measured, for a relatively thick target, the absolute (p,n) cross section by activation. The results reported here were also obtained with a relatively thick target. The target, $U^{238}F_4$, was chosen because of its good chemical stability and the fact that it had previously both been weighed and alpha-counted for two independent thickness determinations. The results are shown in Fig. 11. The measured laboratory reaction threshold, 4.235±0.005 Mev, is in excellent agreement with earlier work.[32,9] The measured total cross section reported here, however, is 80% higher than that reported by Blaser *et al.*[36]

10. $Li^7(\alpha,n)B^{10}$, B^{10*}

The reaction $B^{10}(n,\alpha)Li^7,Li^{7*}$ has, for many years, been used for neutron detection, especially in the energy range 0–500 kev. The cross section in the energy range 100–500 kev was, however, not well known until recently.[49] The partition between α-particle transitions to the ground state and first-excited state of Li^7 is well known for thermal neutrons and reasonably well known (and smoothly changing) for neutrons up to several Mev.[50,51] The reaction $Li^7(\alpha,n)B^{10}$ thus affords an opportunity to examine by reciprocity the ground-state transition component of $B^{10}(n,\alpha)Li^7$. Further, by use of such $B^{10}(n,\alpha)Li^7$ results one may separate the cross section for $Li^7(\alpha,n)B^{10*}$.

The most convenient chemical form for lithium targets is LiF because of stability. However the threshold Q-value for $F(\alpha,n)$ is appreciably lower than that of $Li^7(\alpha,n)$. Therefore a metallic lithium target was used. In this case calibration of the target thickness was accomplished by measuring the neutron yield under proton

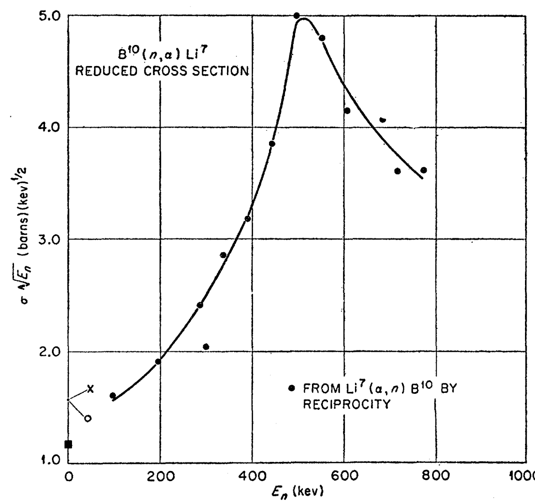

FIG. 13. $B^{10}(n,\alpha)Li^7$ "reduced" cross section as a function of energy derived by reciprocity from the $Li^7(\alpha,n)B^{10}$ results. For comparison the values obtained from the cross section $B^{10}(n,\alpha)Li^7,Li^{7*}$ for thermal neutrons, converted to $B^{10}(n,\alpha)Li^7$ cross section with the help of the known $(n,\alpha)/(n,\alpha\gamma)$ ratio, are shown at the extreme left of the figure. The open circle is due to Bichsel *et al.*,[50] the closed square to Hanna,[54] and the cross to Bujdoso.[55]

bombardment before switching the accelerator over to α particles. The absolute target thickness was obtained from the neutron yield through the relatively well-known $Li^7(p,n)$ cross section. Note that the target remained in vacuum throughout the two bombardments so that the average thickness remained essentially constant (6.5 μg/cm²).

The results are shown in Fig. 12. Because of the low slope of the yield near threshold, the value for the reaction threshold is not well determined from this measurement. The first resonance observed occurs at 5.15±0.07 Mev and is followed by a large peak at about 7.15 Mev. The slight "wobble" at 5.64 Mev, the threshold value for $Li^7(\alpha,n)B^{10*}$, may not be statistically significant. The

[47] A. G. W. Cameron (private communication).
[48] Willard, Bair, Kington, Hahn, Snyder, and Green, Phys. Rev. **85**, 849 (1952).
[49] H. Bichsel and T. W. Bonner, Phys. Rev. **108**, 1025 (1957).
[50] Bichsel, Hälg, Huber, and Stebler, Phys. Rev. **81**, 456 (1951).
[51] Petree, Johnson, and Miller, Phys. Rev. **83**, 1148 (1957).

peak at 5.15 Mev is in agreement with results of Bichsel and Bonner,[49] but we do not observe any significant peak in the neighborhood of 4.7 Mev as reported by those authors.

The data up to 5.64 Mev can be converted by means of the reciprocity theorem to cross section values for $B^{10}(n,\alpha)Li^7$. The result of such a transformation is given in Fig. 13 where we have included the values derived from $B^{10}(n,\alpha)Li^7,Li^{7*}$ measurements with thermal neutrons[52] combined with data[53–55] on the ratio $\sigma(n,\alpha)/\sigma(n,\alpha\gamma)$. From this point in the discussion we will consider this reaction from its inverse point of view, i.e., the $B^{10}(n,\alpha)Li^7$ reaction. Note that the ordinate in Fig. 13 is not cross section, but "reduced" cross section. The low slope of the curve for $0<E_n<100$ kev indicates that at least the ground-state transition component of the cross section of $B^{10}(n,\alpha)$ closely follows a "$1/v$" behavior up to about 100 kev. The departure of the (n,α) cross section from $1/v$ must be due in part to the resonance evident at $E_n=520$ kev.

The maximum observed by Bichsel and Bonner at $E_n=520$ kev in the reaction $B^{10}(n,\alpha)Li^7,Li^{7*}$ is fully accounted for by the resonance reported here for the channel $B^{10}(n,\alpha)Li^7$. Therefore it appears that the spin

TABLE IV. Possible spin and parity assignments to the resonance in B^{11} seen in the $Li^7(\alpha,n)$ reaction at an alpha bombarding energy of 5.15 Mev.

l_n	$J\pi$ (B^{11*})	l_α
0,2	$\frac{5}{2}+$	1,3
1	$\frac{3}{2}-$	0,2

and parity of the corresponding level in B^{11} is of such a value as to forbid transition to a final state $J^\pi=\frac{1}{2}-$ but allows transitions to $J^\pi=\frac{3}{2}-$. This immediately limits possible values of J^π for the intermediate state in B^{11}. If we restrict angular momenta to $l_n\leqslant 2$ and $l_\alpha\leqslant 3$, we obtain the possibilities given in Table IV.

Next we observe that the peak cross section is $\sigma_{max}\simeq 150$–200 mb, while the maximum possible cross section, which occurs when $\Gamma_n=\Gamma_\alpha=\Gamma/2$, is $\sigma_{max}{}^0=g\pi\lambda\!\!\!^{-2}=0.75$ barn where we have taken $g\simeq\frac{1}{2}$ because of the high ground-state spin (3^+) of B^{10}. Therefore we have condition $\Gamma_n\Gamma_\alpha/(\Gamma_n+\Gamma_\alpha)^2\approx 17$; hence Γ_α/Γ_n or $\Gamma_n/\Gamma_\alpha\approx 17$. If Γ_n were larger, we would expect observable neutron scattering. The B^{10} neutron total cross section shows no structure near 500 kev to within a few tenths of a barn; hence we conclude $\Gamma_n\cong 20$ kev and $\Gamma_\alpha\cong 300$ kev for this resonance. One may obtain an upper limit on l_n and l_α by comparison of the reduced partial widths, $\gamma_n{}^2$ and $\gamma_\alpha{}^2$, with the Wigner limit (single-particle width). We have, following Weisskopf's notation,

[52] W. W. Havens (unpublished).
[53] Bichsel, Hälg, Huber, and Stebler, Helv. Phys. Acta **25**, 119 (1952).
[54] G. C. Hanna, Phys. Rev. **80**, 530 (1950).
[55] E. Bujdoso, Nuclear Phys. **6**, 107 (1958).

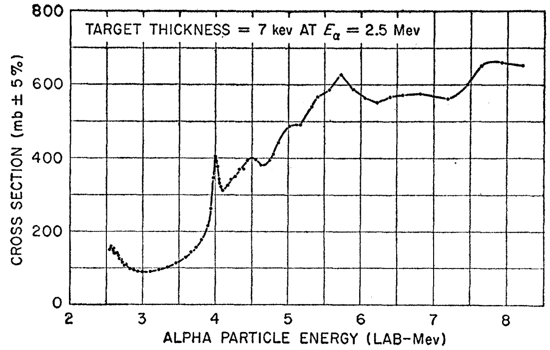

FIG. 14. $Be^9(\alpha,n)C^{12},C^{12*}$ cross section as a function of energy.

where reduced widths are expressed in energy units, $\Gamma=2kRP_l\gamma^2$, where R is the "interaction radius" and P the barrier factor. For neutrons P_l is the centrifugal barrier,[3] and for alphas P_l includes also the Coulomb barrier.[56] The assumed interaction radii for the two cases were 4.2×10^{-13} cm for neutrons and 4.7×10^{-13} cm for alphas. One finds that $l_n\geqslant 2$ gives a reduced neutron width that equals or exceeds the Wigner limit. The large value of E_α allows values of l_α of at least 3, so that no additional information is obtainable here, and we are left with a conclusion that the state in B^{11} is identified as $J^\pi=\frac{5}{2}+$ or $\frac{3}{2}-$ formed by s- or p-wave neutrons, respectively.

The threshold for $Li^7(\alpha,n)B^{10*}$ occurs at a bombarding energy of about 5.64 Mev. The presence of this second neutron group complicates any analysis of the resonance at $E_\alpha=7.15$ Mev. The corresponding resonance in $B^{10}(n,\alpha)$ at $E_n=1.9$ Mev has been discussed by Petree *et al.*[51] and may correspond to more than one level in B^{11}.

11. $Be^9(\alpha,n)C^{12}$, C^{12*}

This reaction has been carefully studied[57–59] up to 5-Mev bombarding energy. The work reported in this paper starts near the peak of the well-known resonance at 2.58 Mev and extends the yield measurement to a bombarding energy of 8.2 Mev. The results are shown in Fig. 14. Note that a thin target was used so that the observed smearing out of individual resonances at

TABLE V. Resonances in $Be^9(\alpha,n)C^{12}$.

E_0	Γ	E_{ex} (C^{13})
2.58	0.3	12.44
4.00	0.08	13.43
4.50	~0.5	13.78
5.0	~0.3	14.12
5.75	...	14.64
7.8	...	16.06

[56] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).
[57] Bennett, Roys, and Toppel, Phys. Rev. **93**, 924(A) (1954).
[58] R. E. Trumble, Phys. Rev. **94**, 748(A) (1954).
[59] Bonner, Kraus, Marion, and Schiffer, Phys. Rev. **102**, 1348 (1956).

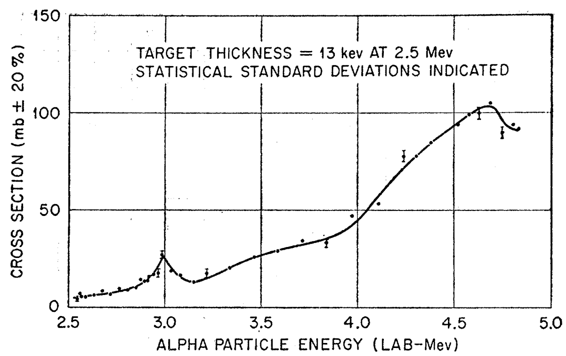

FIG. 15. $B^{10}(\alpha,n)N^{13},N^{13*}$ cross section as a function of energy.

higher energies is real, probably due to the increasing alpha width. The location of resonances is in good agreement within the range of overlap with the data of Bonner *et al.*[59] A summary of major observed resonance energies, widths, and the corresponding excitation energy in C^{13} is given in Table V.

The high (5.71-Mev) positive Q of this reaction nominally produces neutrons in the 6–10 Mev range, well into the energy range where the detection sensitivity of the graphite sphere begins to fall off.[6] However, a great majority of the emitted neutrons appear to lead, not to the C^{12} ground state, but to the level at 4.43 Mev.[60] Thus the true neutron energy range probably lies between 1.5 and 5 Mev, where the detection sensitivity is still fairly uniform.

12. $B^{10}(\alpha,n)N^{13}$, N^{13*}

Earlier studies of this reaction included work in the alpha energy range 1.0–2.3 Mev[61,62] and more recently, a survey of neutron and γ-rays from 2.0 to 5.4 Mev.[59] The first resonance observed above 2.5-Mev bombarding energy occurs at 2.98 Mev with a width of about 100 kev (Fig. 15). This is not in very good agreement with results of Bonner *et al.*,[59] who obtained $E_0=2.90$ kev, $\Gamma\sim200$ kev. Other results of resonance energy determinations for this level in N^{14} lie approximately midway between our value and the results of Bonner *et al.*

The next resonance evident occurs at $E_\alpha\simeq3.6$ and is several hundred kev broad. This is in good agreement with earlier work. Finally a broad maximum appears, peaked near 4.7 Mev. This maximum undoubtedly is composed of the several previously reported resonances.[59]

13. $Si^{29}(\alpha,n)S^{32}$, S^{32*}

Resonances in S^{33} in the region of excitation upward from 10 Mev have been previously observed in $S^{32}(n,n)$ and $S^{32}(n,\alpha)$ studies.[63–65] The results reported here (Fig. 16) show that the previously reported maxima are actually clusters of several levels in S^{33}. Indeed it is apparent that the results reported here were not obtained with resolution sufficient to separate all energy levels. Note the importance of the Coulomb barrier in this range of α-energy and atomic weight as evidenced by the rapidly rising cross section at higher alpha energies. The principal uncertainty in this measurement

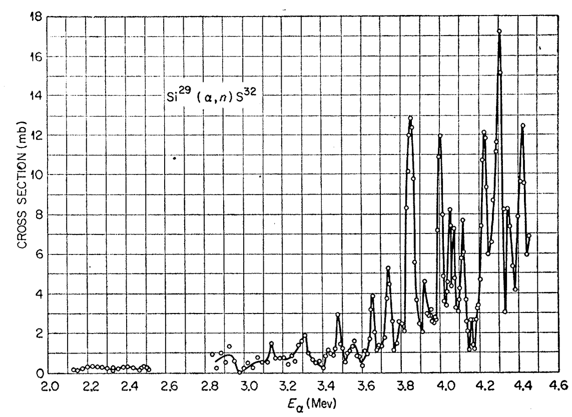

FIG. 16. $Si^{29}(\alpha,n)S^{32}$ cross section as a function of energy.

was, as usual, the target thickness. Comparison between target thickness by weight measurement agreed (to 6%) with a thickness determination by quantitative chemical analysis.

For alpha energies less than 4.3 Mev, all neutrons lead to the ground state of S^{32}; thus a direct total cross section comparison, by means of the reciprocity theorem, may be made with $S^{32}(n,\alpha)Si^{29}$ measurements.

[60] Guier, Bertini, and Roberts, Phys. Rev. **85**, 426 (1952).
[61] Shire, Wormald, Lindsay-Jones, Lunden, and Stanley, Phil. Mag. **44**, 1197 (1953).
[62] E. S. Shire and R. D. Edge, Phil. Mag. **46**, 640 (1955).
[63] *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 1955).
[64] R. Ricamo, Nuovo cimento 8, 383 (1951).
[65] T. Hürliman and P. Huber, Helv. Phys. Acta **28**, 33 (1955).