native pairing. On this basis, we conclude that there is no Hermitian Hamiltonian which seems equally applicable to β^- and β^+ processes and at the same time satisfies Stech and Jensen's isotropy postulate.

Konopinski and Mahmoud[5] have constructed a consistent account of the interactions between fermions, in which the concept of "particle" as opposed to "antiparticle" plays a leading role. They treat negatrons, positive mu mesons and nucleons as "particles," as do Stech and Jensen. However, it seems that the arguments of Konopinski and Mahmoud remain valid, especially insofar as forbidden processes are concerned, if one lets the "particles" be positrons, negative mumesons and nucleons.

We would also note that Peaslee[2] has shown that when the invariants are constructed by associating the particles in the customary way (S, T, etc), the Hamiltonian $S-T+P$ is an eigenvector of the operator which interchanges neutron and neutrino wave functions, but that for neutron-positron exchange the interaction must be $S+T+P$. Again, there is no Hermitian Hamiltonian which allows interchange in both orders of pairing.

ACKNOWLEDGMENTS

We wish to acknowledge correspondence with Professor Jensen and Dr. Stech.

[5] E. J. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953).

PHYSICAL REVIEW VOLUME 102, NUMBER 5 JUNE 1, 1956

Neutrons and Gamma Rays from the Alpha-Particle Bombardment of Be^9, B^{10}, B^{11}, C^{13}, and O^{18}†

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(Received February 20, 1956)

Excitation curves at 0° and 90° were studied for neutrons and γ rays produced in bombardment of thin targets of Be^9, B^{10}, B^{11}, C^{13}, and O^{18} by α particles with energies of from 1.8 to 5.3 Mev. Resonances were observed in the $Be^9(\alpha,n)C^{12}$ reaction at bombarding energies of 1.9, 2.3, 2.6, 3.98, 4.4, and 5.0 Mev. The $C^{13}(\alpha,n)O^{16}$ reaction showed resonances at 2.09, 2.25, 2.42, 2.605, 2.69, 2.775, 2.825, 3.09, 3.33, 3.42, 3.67, 3.73, 4.125, 4.42, 4.50, 4.63, 4.75, and 5.05 Mev. The $B^{10}(\alpha,n)N^{13}$ excitation curve has resonances at 2.16, 2.25, 2.90, 4.53, 4.85, and 5.36 Mev, while the γ-ray yield from the $B^{10}(\alpha,p\gamma)C^{13}$ reaction showed all these as well as resonances at 3.6 and 3.95 Mev. The $B^{11}(\alpha,n)C^{13}$ reaction has resonances at bombarding energies of 2.06, 2.60, 2.93, 2.97, 3.23, 3.54, 3.72, 3.92, 4.25, 4.34, and 5.00 Mev. The $O^{18}(\alpha,n)Ne^{21}$ reaction was studied with a thicker target (90–130 kev). Resonances in the neutron yield were resolved at 2.21, 2.47, 2.57, 2.72, 2.94, 3.24, 3.63, 3.91, 4.12, 4.22, 4.33, 4.52, and 4.82 Mev. Cross sections and widths of the resonances in the various reactions were determined.

INTRODUCTION

EXCITATION curves of reactions from α-particle bombardment of the light elements have recently been studied extensively[1] at energies up to 2.5 to 3 Mev with an energy resolution of from 10 to 100 kev. Earlier experimental work[2] in this field was carried out using natural α emitters with limited resolution and intensity. Recent alterations in the Rice Institute Van de Graaff accelerator have made it possible to obtain a singly charged alpha-particle beam up to 5.5 Mev in energy with currents of up to 5 microamperes in the target area. Excitation curves on several light elements were run for α-particle induced reactions, studying only neutrons and γ rays as reaction products. The object of the experiments was to observe resonances in these reactions in order to find the energies of the excited states of the compound nuclei involved. Another purpose of the experiments was to obtain cross sections for the reactions as an aid in understanding the mechanism of disintegrations produced by α particles.

EXPERIMENTAL PROCEDURES

The modifications of the Van de Graaff generator consisted of installing a leak in the high-voltage terminal permitting helium to flow into the rf ion source at the required rate of a few ml per hour. To keep the neutron background to a minimum, all measurements were conducted twenty feet from the analyzing magnet over a deep pit covered with a $\frac{1}{4}$-inch aluminum floor.

The neutron detector used was a modified long-counter with a paraffin moderator 5 inches in diameter and 5 inches long surrounding a BF_3 counter which was

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[1] Bennett, Roys, and Toppel, Phys. Rev. **82**, 20 (1951); **93**, 924(A) (1954). F. L. Talbott and N. P. Heydenburg, Phys. Rev. **90**, 186 (1953); R. E. Trumble, Phys. Rev. **94**, 748(A) (1954); E. S. Shire and R. D. Edge, Phil. Mag. **46**, 640 (1955); Walton, Becker, Clement, and Zucker, Phys. Rev. **99**, 1649(A) (1955); F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[2] I. Halpern, Phys. Rev. **76**, 248 (1949); R. L. Walker, Phys. Rev. **76**, 244 (1949).

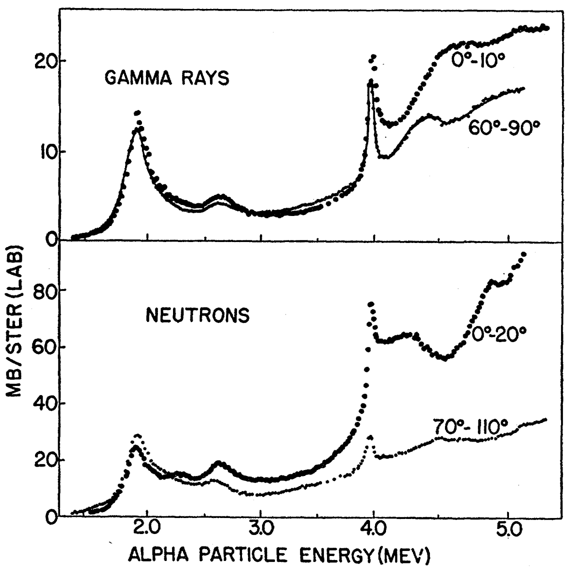

FIG. 1. Neutron and γ-ray yields from the α-particle bombardment of a Be^9 target. The target was about 10 kev thick to 2-Mev alphas. Statistical errors are less than or equal to the diameter of the points.

1 inch in diameter and extended to the front surface of the paraffin. This smaller and more compact counter was used in place of a long-counter so that considerable angular resolution could be obtained with the counter in a position such that its paraffin face was only 5 inches from the target. Under such geometrical conditions the background counts were small in comparison to the counts from thin targets of the elements that were investigated. The modified long counter does not have an exactly flat response, independent of neutron energy; its efficiency for counting 4-Mev neutrons is only 60% as great as for 1-Mev neutrons. Neutron cross sections were obtained by using weighed targets and comparing the yield to that from a Ra-Be source calibrated by the National Bureau of Standards. The cross sections measured in this way are accurate for neutron energies that approximate that of the Ra-Be source, but may introduce uncertainties as great as 50% in some of the reactions which were studied. In order to check the thin-target cross-section measurements, an alternative method was used with thick targets where the difference in yield was obtained between two points on the excitation curve. When this was equated to the area under the corresponding portion of the differential excitation curve, a cross section was obtained. This latter method used the stopping power in the various target materials for 2-Mev α particles, a quantity which is known only to an accuracy of about 10%; however, this uncertainty was usually as small as that of the mass of evaporated materials on the thin targets.

A 1 in.×1 in. NaI crystal mounted on a DuMont 6292 photomultiplier tube was used for the γ-ray detector. Gamma-ray cross sections were obtained by using the yield of 4.4-Mev γ rays from a standardized RaD-Be source assuming 0.6 γ rays per neutron.[3] This is thought to be accurate to about 10%. Direct calculation of the efficiency of the NaI counters for 4.4-Mev γ radiation gave results which would give cross sections that are 15% larger. The detector efficiencies were corrected where the γ-ray energy was different from that used for calibration.

Bombarding energies were determined by measuring the magnetic field in the analyzing magnet with a Li^7-moment detector. The $Li^7(\alpha,n)$ threshold, which was calculated from mass values to occur at 4.385 ± 0.005 Mev, was used for calibration at the higher energies and the $Li^7(p,n)$ threshold for molecular hydrogen at lower energies. Energies below 4.5 Mev are believed to be accurate to 15 kev. Above this energy bombarding energies are known to approximately 30 kev. More rapid accumulation of carbon on the targets was obtained with α-particle bombardment than with protons or deuterons; errors in absolute energy determinations as great as 40 kev were observed with targets that had only been bombarded for about 10 hours.

$Be^9(\alpha,n)C^{12}$, $Q=5.71$ Mev

The excitation curve for this reaction is shown in Fig. 1. The neutron curve includes the total neutron yield, while the γ rays are almost entirely due to the 4.4-Mev state in C^{12}. It is estimated that at most 10% of the γ-ray yield could be caused by neutrons in the NaI crystal.

As is to be expected, all the resonances found for 4.4-Mev γ rays also appear in the neutron yield since they are due to neutrons leaving C^{12} in its 4.43-Mev first excited state. Not all the neutron resonances, however, show up as peaks on the γ-ray excitation curve. The information on the resonances is summarized in Table I. The neutron resonances at 1.9, 2.3, and 2.6 Mev agree with those found by Trumble,[1] who studied the neutron yield up to 3.5-Mev bombarding energy, except for the state he reports at 3.4 Mev. No peak was

TABLE I. Resonances in the reactions $Be^9(\alpha,n)C^{12}$ and $Be^9(\alpha,n\gamma)C^{12}$.

		Differential cross sections, mb/sterad (laboratory coordinates)				Excitation energy in C^{13}	
E_α (Mev)	Resonance widths (kev)	Neutrons 0°–20°	Neutrons 70°–110°	Gammas 0°–10°	Gammas 60°–90°	Present work (Mev)	Other reactions (Mev)
1.9	200	25	29	14	12	11.97[a]	11.92[b]
2.3	~200	15	14			12.25[a]	12.17[b,c]
2.6	~200	20	12	4.7	4.0	12.46[a]	
3.98	60	79	29	20	18	13.41	
4.4	~400	60	27	18	14	13.7[a]	
5.0	~300	87	30	23	17	14.1[a]	

[a] Uncorrected for effects of Coulomb barrier penetration.
[b] H. Hall and T. W. Bonner, Bull. Am. Phys. Soc. Sec. II 1, 96 (1956).
[c] Becker, Perkins, and Barschall, Phys. Rev. 99, 1649(A) (1955).

[3] D. E. Diller and M. F. Crouch, Phys. Rev. 93, 362(A) (1954).

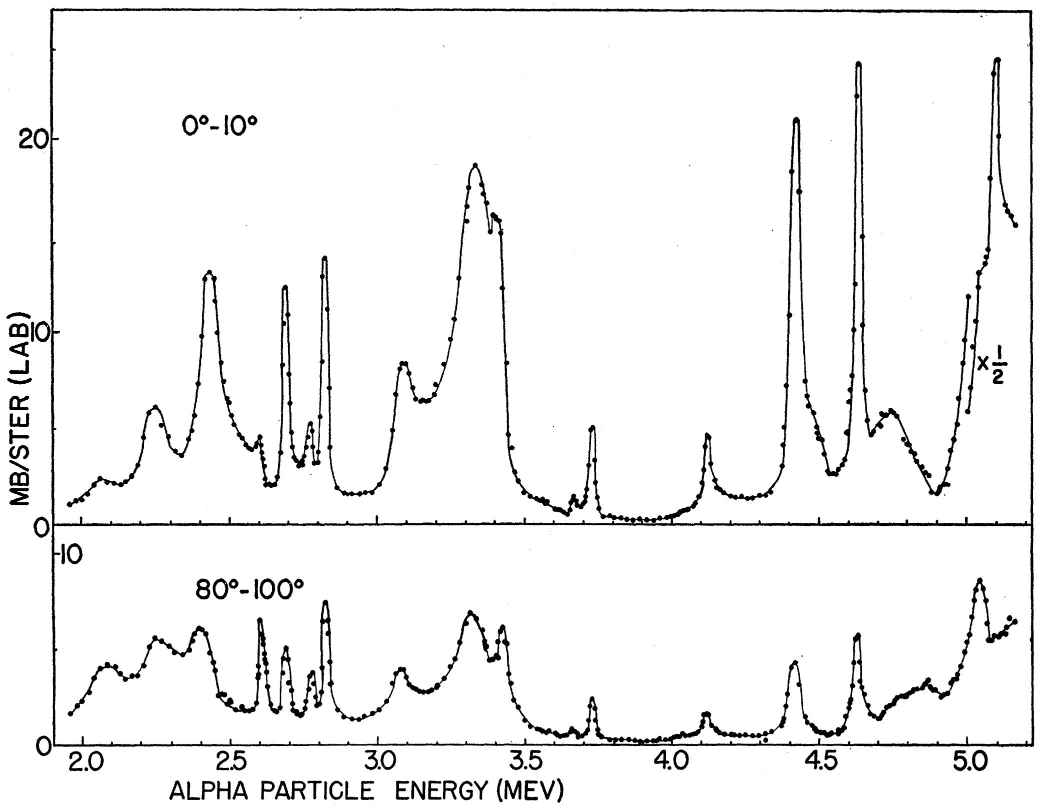

FIG. 2. Neutron yields from the α-particle bombardment of a 67% enriched C^{13} target. The target was about 20 kev thick to 3-Mev α particles. Since several of the resonances are narrower than 20 kev, the differential cross-section scale does not always indicate the true differential cross sections.

found in this experiment corresponding to a resonance at that energy. The previously reported[2] broad rise at 4.4 Mev was resolved as due partly to the narrow resonance at 3.98 Mev and to two or more broad resonances. The resonances at 1.9 and 2.3 Mev give energies of excited states in C^{13} which are 50 to 80 kev higher than the states found in C^{13} by neutron scattering in C^{12}. With such wide levels in the compound nucleus the effects of the Coulomb barrier penetration on the α particles would tend to displace the peaks to higher energies. The cross section calibration was made at the 1.9-Mev resonance using both weighed evaporated Be targets on 0.002 in. aluminum foil and a thick Be target. A stopping power of 1.40 Mev/mg/cm² was used for 1.9-Mev alphas in Be^9. The excitation curve was made using a target which was 5–10 kev thick depending on the bombarding energy. It is estimated that the neutron cross sections are accurate to about 25% while the γ-ray cross sections are probably known to 40%. All cross sections, angles, and energies are given in the laboratory system.

The differential cross section for neutron emission is in good agreement with the total cross-section measurements of Halpern,[2] who obtained a cross section of 0.40 barn at 5.3 Mev and 0.13 barn at 1.9 Mev.

$C^{13}(\alpha,n)O^{16}$, $Q=2.20$ Mev

The excitation curve for this reaction is given in Fig. 2. For most of the excitation curve, only the neutron group that leaves O^{16} in its ground state can be observed. No γ radiation was observed from this reaction that could be attributed to anything but neutron effects in the NaI crystal. The threshold for the 6.06-Mev state in O^{16} was observed at a bombarding energy of 5.05 Mev, as is shown by the sharp rise in the 0° neutron yield with no corresponding rise in the 90° yield. All the resonances observed are listed in Table II. The excitation curves were obtained with a target that was 20 kev thick for 3.0-Mev α particles and several of the resonances had an experimental width which was approximately this amount, indicating a true width which was narrower than 20 kev. For those resonances which were narrower than the target thickness, an approximate value of the width was obtained from measuring the energy interval for the rise on the leading edge of the resonances. Cross sections were calculated by assuming the resonances to have the widths listed in Table II, and using 20 kev for the target thickness. The actual measurement of the cross sections was made with a weighed C^{13} foil from which the yield of the 4.42-Mev resonance was measured.

This counting rate was compared to that from the calibrated Ra-Be source. With the exception of some of the lower resonances, for which interference effects appear to be strong, all the resonances were observed to be more intense in the forward direction than at 90°. Similarly, interference can account for the energy difference in some of the peaks, as observed at the two angles. These were at 2.43, 3.425, and 4.7 Mev at 0° and 2.40, 3.405, and 4.77 Mev at 90°. It seems remarkable, in view of the results obtained from the other isotopes studied, that the nonresonant yield between 3.5 and 4.0 Mev was virtually zero.

The lower levels observed are in good agreement with other work[1] on the same reaction. Some information in this region of excitation of O^{17} is known from the neutron scattering experiments with O^{16}; however, as can be seen from the levels listed above 9 Mev in Table II, many levels were not observed in the neutron scattering experiments because of the limited energy resolution.

$B^{10}(\alpha,n)N^{13}$, $Q=1.07$ Mev and $B^{10}(\alpha,p\gamma)C^{13}$, $Q=4.07$ Mev

Resonances in the neutron yield and γ-ray yield obtained with a 96% B^{10} target are shown in Fig. 3. The neutron yield can be due to neutrons leaving N^{13} in its ground state or first excited state at 2.37 Mev, and above 3.4 Mev bombarding energy in the second and third states. The NaI counter was biased in such a manner that it would efficiently detect the 3.68- and 3.86-Mev γ ray from C^{13}. Because of the limited resolution of a scintillation detector, it is impossible to state what fraction of the γ-ray yield shown could be assigned to the 3.51-Mev γ ray from N^{13}, which has a threshold at an α-particle energy of 3.42 Mev. It is clear, however, from the cross sections that at least at the lower energies the γ-ray yield is almost entirely due to the $(\alpha,p\gamma)$ reaction.

TABLE II. Resonances in the reaction $C^{13}(\alpha,n)O^{16}$.

E_α (Mev)	Resonance width (kev)	Differential cross sections, mb/sterad (laboratory coordinates) Neutrons 0°–10°	Neutrons 80°–100°	Excitation energy in O^{17} (Mev)	Excitation energy from other work (Mev)
2.09	100	2.7	4.6	7.94	
2.25	100	6.7	6.2	8.065	8.06[a]
2.42	80	14	6.8	8.20	8.21[a]
2.605	⩽6	⩾12	⩾15	8.335	8.3,[b,c] 8.35[a]
2.69	10	24	10	8.40	8.41,[a] 8.38[a]
2.775	10	10	7.5	8.465	8.47,[a] 8.46[a]
2.825	⩽7	⩾36	⩾20	8.50	8.51,[a] 8.5[b]
3.09	90	9.1	4.3	8.70	8.70,[a] 8.7[b]
3.33	150	20	7.6	8.89	8.91,[a] 8.87[a]
3.42	30	17	7.4	8.95	8.96,[a] 9.0[b]
3.67	⩽8	⩾3.5	⩾2.1	9.15	
3.73	⩽5	⩾17	⩾8	9.2	
4.125	15	7.4	2.8	9.50	9.5[b]
4.42	25	28	5.7	9.725	9.7[b]
4.50	70	6		9.78	
4.63	15	38	9.1	9.885	
4.75	200	6.8	3.5	9.97	
5.05	65	30	9.5	10.20	10.2[b]

[a] Resonances in the $C^{13}(\alpha,n)O^{16}$ reaction, Walton, Becker, Clement, and Zucker, reference 1; R. E. Trumble, reference 1.
[b] Data on scattering of neutrons in O^{16} (Los Alamos) given by D. J. Hughes and J. Harvey, Brookhaven National Laboratory Report BNL 325, 1955 (unpublished).
[c] Freier, Fulk, Lampi, and Williams, Phys. Rev. **78**, 508 (1950); Baldinger, Huber, and Proctor, Helv. Phys. Acta **25**, 142 (1952).

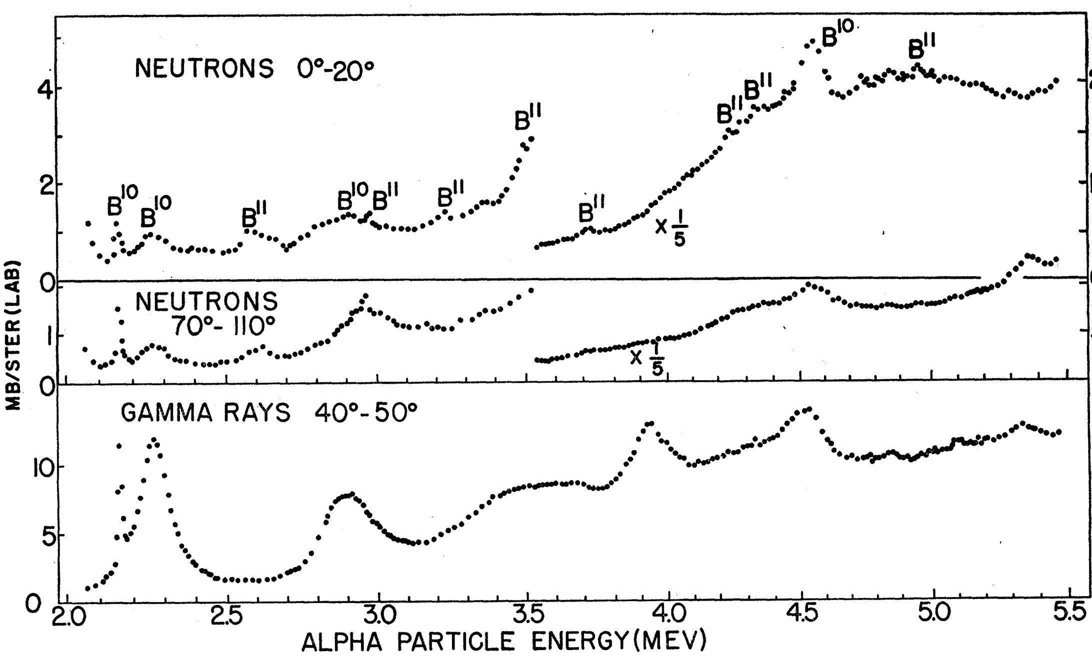

FIG. 3. Neutron and γ-ray yields from the α-particle bombardment of a 96% enriched B^{10} target. The target was about 10 kev thick to 2-Mev alphas. The resonances in the neutron yield assigned to B^{10} and to B^{11} are indicated.

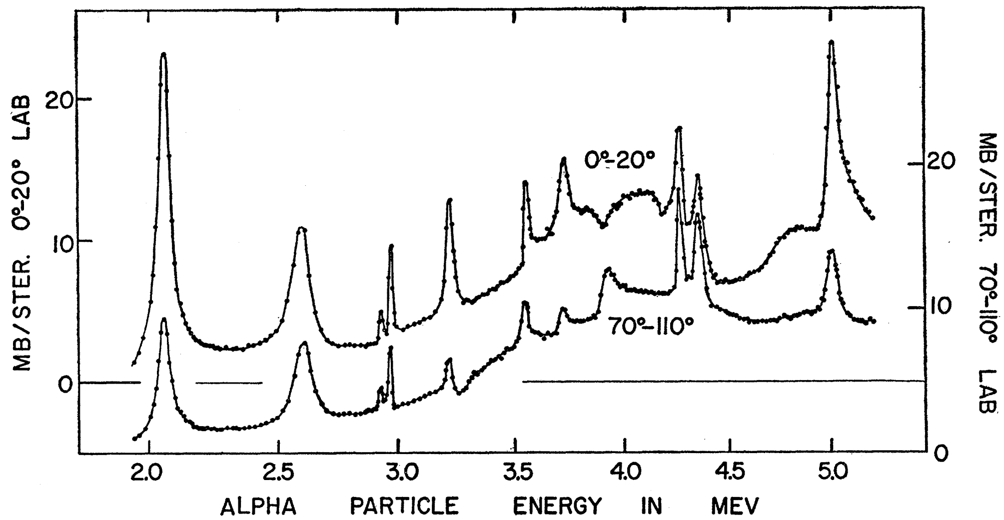

FIG. 4. Neutron yields from the α-particle bombardment of B^{11}. The target was 15-kev thick to 2-Mev α particles.

At energies above 4.5 Mev there is a prominent resonance on two of the curves at 5.35 Mev and a weaker resonance on all three curves at 4.85 Mev. There is some indication of several other weak resonances in this region which have not been listed in Table III. The resonances at bombarding energies of 2.16, 2.26, and 2.90 Mev have been previously reported.[1] Some of the peaks observed correspond to resonances observed in the $C^{12}(d,p)C^{13}$ reactions, where the compound nucleus is also N^{14}. The characteristic feature of the neutron yield is a very low cross section, compared to the other elements studied, up to approximately 3.4 Mev. Between 3.4 and 4.5 Mev the neutron yield at 90° shows an increase of a factor of 6. This large increase is probably due to a stronger competition between the (α,n) reaction to the $(\alpha,p\gamma)$ reaction at energies where the N^{13} may be left in its second and third excited states. These states have spins of $3/2^-$ and $5/2^+$ and are mirror states of the levels in C^{13} at 3.68 and 3.86 Mev, which give rise to the γ rays which have an intensity about 10 times as great as the neutrons at bombarding energies below 3 Mev. Such a change in yield would be expected from levels in the compound nucleus with $J \geq 2$, since B^{10} has an angular momentum of 3 and the ground state and first excited states of N^{13} are $1/2^-$.

TABLE III. Resonances in the reactions $B^{10}(\alpha,n)N^{13}$ and $B^{10}(\alpha,p\gamma)C^{13}$.

E_α (Mev)	Resonance widths (kev)	Differential cross sections, mb/sterad (laboratory coordinates) Neutrons 0°–20°	Neutrons 70°–110°	Gammas 40°–50°	Excitation energy in N^{14} (Mev)	Excitation energy from other work (Mev)
2.16	30	0.9	1.2	12	13.16	13.16,[a] 13.17[b]
2.26	200	0.6	0.5	12	13.23	13.24[a,c]
2.90	200	1.1	1.2	8.0	13.68	13.72,[a] 13.70[b]
3.6	400			8.7	14.18	14.2[b]
3.94	~200			13	14.43	14.4[b]
4.53	~200	24	9.8	14	14.85	14.84[b]
4.85	~ 50	21	7.6	11	15.08	15.09[b]
5.36	~100		13	13	15.44	

[a] F. L. Talbott and N. P. Heydenburg, reference 1.
[b] Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956).
[c] E. S. Shire and R. D. Edge, reference 1.

Both the neutron and the γ-ray cross sections were determined from the weighed evaporated B targets which were 96% B^{10}; an additional check was obtained by comparing the cross section of B^{10} to that of B^{11} from the relative intensities of the B^{10} and B^{11} resonances as observed with the 96% B^{10} targets. The target used in the excitation curve was thin compared to all the resonances observed.

$B^{11}(\alpha,n)N^{14}$, $Q=0.15$ Mev

An evaporated normal boron target which was about 15 kev thick for 2-Mev α particles was used to investigate the yield of neutrons from B^{11}. Neutrons were observed at 0°–20° and at 70°–110°, and γ radiation at 85°–95°. The results for neutrons are shown in Fig. 4. The NaI crystal which was used as a γ detector was biased so that it would count γ radiation of 2.31 Mev from the first excited state of N^{14} as well as the 3.09-, 3.68-, and 3.86-Mev γ radiation from C^{13*}. The resulting yield of γ radiation showed the same resonances as that obtained from a B^{10} target with the exception of a resonance at 5.00 Mev which was the only one which could be attributed to B^{11}. These results indicate that the yield of γ radiation from the reaction $B^{10}(\alpha,p\gamma)C^{13}$ is much greater than from the reaction $B^{11}(\alpha,n\gamma)N^{14}$ except at the 5.00-Mev resonance. From the data of Fig. 4, the widths and differential cross sections of nine resonances were determined and are given in Table IV. Two of the resonances at 2.93 and 2.97 Mev were as narrow as the target thickness and so were investigated with a target that was approximately 4 kev thick. The results, which are given in Fig. 5, indicate that the resonance at 2.93 Mev is narrower than 3 kev and that the higher resonance has a width of 7 kev. In addition to the sharp resonances there is a rise in the continuum between resonances in the region from 2 Mev to 4 Mev. This slow rise may be due to one or more wide resonances or to a continuum. The resonance at 3.92 Mev has a normal resonance shape at 70°–110° but appears as an antiresonance at 0°–20° due to interference effects with the continuum. Below 3.5 Mev the contribution to the total yield of neutrons from B^{10} is negligible. Above this energy the yield of neutrons from B^{10} rises rapidly and at the 4.53-Mev resonance in B^{10} amounts to 36% of the yield at 0°–20° and 17% at 70°–110°. The yield of neutrons from B^{10} has been subtracted from the experimental data so that the curves of Fig. 4 give the true cross section for B^{11}.

Experiments of Trumble[1] above 2 Mev indicated resonances at 2.09, 2.63, 3.00, and 3.26 Mev and experiments by Shire and Edge[1] showed the resonance at 2.05 Mev. The doublet at 2.93 and 2.97 Mev was not resolved in the earlier experiment. The same excited state in the compound nucleus N^{15} at 12.49 Mev has also been observed in the elastic scattering of neutrons from N^{14}.[4] A number of the higher excited states of N^{15} have also been observed in neutron scattering experiments[4] but the resolution in the experiments was not sufficient to clearly resolve all the levels that were found in the present experiments.

The differential cross section for neutron emission from $B^{11}+\alpha$ has not been previously reported. The total cross section experiments of Walker[2] with a polonium source give a value of 0.17 b at 4 Mev and 0.22 b at 5.0 Mev, which amounts to 13.5 and 17.4 mb/sterad, respectively, if spread uniformly in all directions. These values are in rough agreement with the 70°–110° cross sections obtained in the present experiment.

TABLE IV. Data on the resonances in the reaction $B^{11}(\alpha,n)N^{14}$

α-particle energy in Mev	Resonance widths (kev)	Differential cross sections, mb/sterad (laboratory coordinates) Neutrons 0°–20°	Neutrons 70°–110°	Excitation energy in N^{15} (Mev)	Excitation energy in N^{15} from other work	Angular momentum and parity
2.06	59	23	9.4	12.50	12.49[a,b]	5/2+ [a]
2.60	90	11	7.8	12.90	12.93[a]	3/2− [a]
2.93	<3	>8.9	>8.2	13.14		
2.97	~7	17.7	13.7	13.17		
3.23	25	13	6.6	13.36		
3.54	20	14	11	13.59	13.64[c]	
3.72	40	16	10	13.72		
3.92	70	11	13	13.87	13.83[c]	
4.25	~10	18	18	14.11		
4.34	35	14	17	14.18	14.20[c]	
5.00	72	24	14	14.66		

[a] J. L. Fowler and C. H. Johnson, reference 4.
[b] E. S. Shire and R. D. Edge, reference 1.
[c] D. J. Hughes and J. Harvey, see footnote b of Table II.

[4] J. L. Fowler and C. H. Johnson, Phys. Rev. **98**, 734 (1955); D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL 325, 1955 (unpublished).

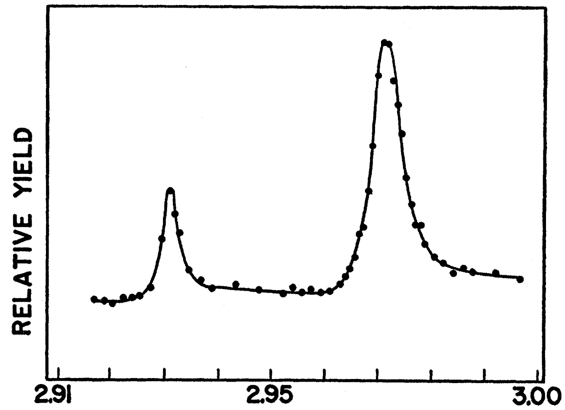

FIG. 5. Neutron yields from the α-particle bombardment of B^{11} near the narrow resonances at 2.93 and 2.97 Mev. The target thickness was approximately 3 kev.

$O^{18}(\alpha,n)Ne^{21}$, $Q=-0.70$ Mev

O^{18} enriched to 40% isotopic concentration was kindly provided by Professor A. O. C. Nier. The targets were prepared by heating a tungsten disk in an induction heater with a sample of the enriched oxygen. A surface layer of the target was thus transformed into tungsten oxide with the approximate composition of W_2O_3. The targets which were prepared primarily for use with protons and deuterons were rather thick for α-particle experiments, being about 90 kev thick for 5-Mev α particles. The excitation curve for neutrons at 0°–30° is shown in Fig. 6. A number of resonances are shown by the curve and undoubtedly others are present but are not resolved because of the relatively thick target.

Cross sections were obtained by estimating the amount of oxygen in the target from the yield obtained in measuring the $O^{16}(d,n)$ threshold.[5] Knowing the

TABLE V. Resonances in the reaction $O^{18}(\alpha,n)Ne^{21}$. The values of E_α have been corrected for target thickness.

E_α (Mev)	Resonance widths (kev)	Differential cross sections, mb/sterad[a] (laboratory coordinates) 0°–30°	Excitation energy of Ne^{22} (Mev)
2.21	30	0.3	11.47
2.47	<15	0.9	11.68
2.56	25	2.3	11.75
2.72	<15	2.6	11.89
2.94	~40	5.2	12.07
3.24	~70	9.2	12.31
3.63	~200	16	12.63
3.91	~40	13	12.86
4.12	~40	16	13.03
4.22	~40	29	13.11
4.33	~100	42	13.20
4.52	~70	27	13.35
4.82	~40	31	13.60

[a] Cross sections are averages over the target thickness which varies from 90 kev at the highest energies to 130 kev at the lowest energies.

[5] Harlow, Marion, Chapman, and Bonner, Phys. Rev. **101**, 214 (1956).

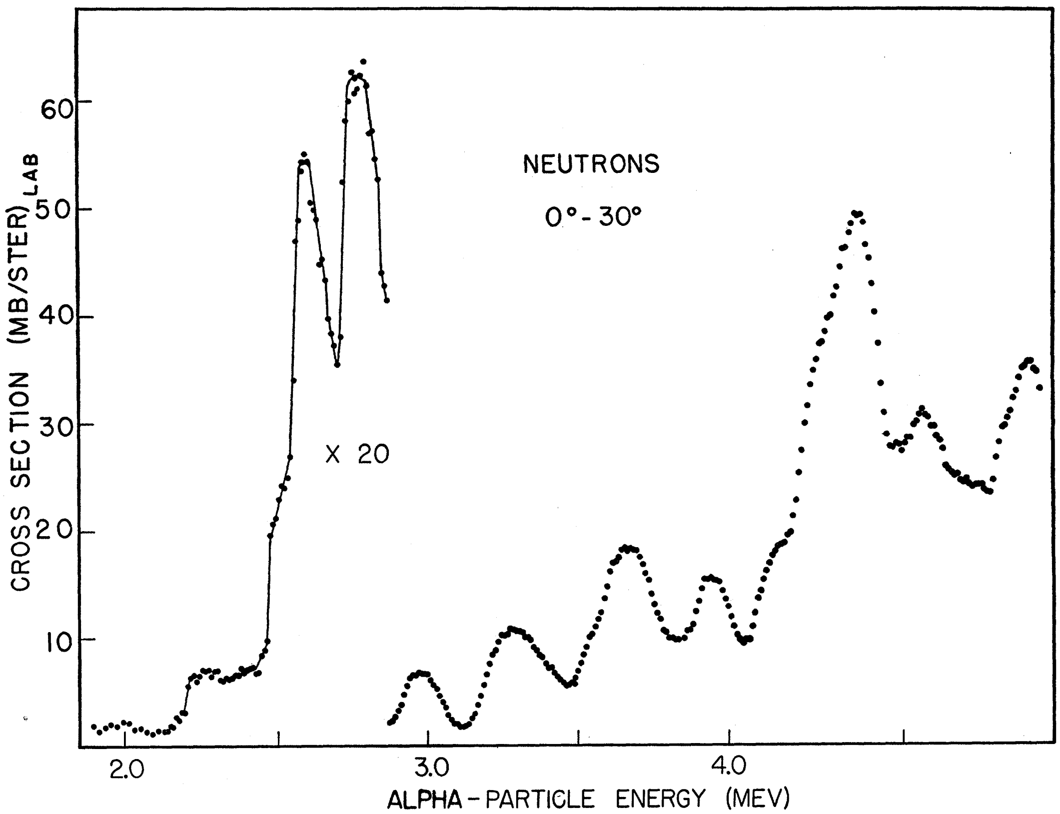

FIG. 6. Neutron yield from the α-particle bombardment of a 40% enriched O^{18} target. The target thickness varies from 90 kev to 130 kev. Many of the resonances are narrower than the target thickness and so the differential cross sections are the average values over the target thickness.

$O^{16}(d,n)$ cross section and the enrichment of the oxygen used, one can calculate the amount of O^{18} in the target. Since several steps were involved in the calculation of the cross section it is not believed to be accurate to better than $\pm 50\%$. Also, since most of the resonances are narrower than the target used, the resonance cross sections are actually higher than would appear from the scale on the excitation curve, which are averages over the target thickness. The energies of the 13 excited states in Ne^{22} calculated from the resonances are given in Table V. No other excited states in Ne^{22} have been observed above an excitation of 4.9 Mev.

DISCUSSION

Whereas some measure of similarity might have been expected between (α,n) reactions on similar nuclei, such as Be^9 and C^{13}, which are similar on the basis of the α-particle model, their excitation curves turned out to be quite different. The $C^{13}(\alpha,n)O^{16}$ reaction is characterized by a large number of narrow resonances with very little overlapping between the levels, especially at higher bombarding energies. In the region between bombarding energies of 3.5 and 4 Mev the nonresonant yield appears to be essentially zero, with the resonances all being less than 20 kev wide. The α-particle bombardment of Be^9, on the other hand, yields neutrons in the same region of bombarding energy that show several broad overlapping states and a large steadily rising yield. Only one comparatively narrow state was observed from this reaction, at 3.98 Mev with a width of 60 kev. It appears that if the levels in the compound nucleus are single-particle states so that their widths are to be explained entirely on the basis of penetrabilities, then α particles with an angular momentum of at least three are needed to explain widths of less than 30 kev. Angular distribution studies on these reactions are now in progress in this laboratory. Definite spin and parity assignments might explain the differences observed in these two reactions.

There is a large difference between the yields in the $B^{10}(\alpha,n)$ and $B^{11}(\alpha,n)$ reactions at the lower bombarding energies. At the higher bombarding energies the cross sections are not strikingly different. The cross section of the $B^{10}(\alpha,p\gamma)$ reaction at the lower energies indicates that the cross sections for compound nucleus formation from B^{10} plus alphas and B^{11} plus alphas are not especially different.