(α,n) Type Reactions in Light Nuclei*

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Two independent methods utilizing a recoil proton telescope and a neutron threshold detector have been used to study a series of (α,n) reactions. The following Q values have been observed: $B^{10}(\alpha,n)N^{13}-3.85\pm0.3$, (-3.2 ± 0.3), -2.5 ± 0.3, -1.3 ± 0.3 Mev; $B^{11}(\alpha,n)N^{14}-4.8\pm0.3$, -3.85 ± 0.3, -3.15 ± 0.3, -2.0 ± 0.3, 0.0 ± 0.3 Mev; $F^{19}(\alpha,n)Na^{22}-5.0\pm0.2$, -4.25 ± 0.2, -3.8 ± 0.2, -3.15 ± 0.2, -2.45 ± 0.2, -2.0 ± 0.2 Mev; $P^{31}(\alpha,n)Cl^{34}-5.7\pm0.2$ Mev. An excitation function has also been obtained for the 1.58-second β^+ activity in Cl^{34} with an observed threshold at -5.7 ± 0.3 Mev.

I. INTRODUCTION

Studies of nuclear reactions in which neutrons are emitted have in most cases been made by means of photoplates. However, it has always been considered useful to supplement this technique by an electronic counting method so that, for example, a relatively fast survey of a reaction can be made prior to the more accurate but more time-consuming plate work.

In this laboratory Worth[1] showed that a proton recoil telescope could be used for fast-neutron spectroscopy. Later Tucker[2] demonstrated the usefulness of the slow-neutron threshold method for studying endothermic reactions. Accordingly it was decided to redevelop these two techniques and use them in conjunction with one another to look for levels arising from bombarding targets with the 8-Mev Yale cyclotron alpha beam.

II. RECOIL PROTON TELESCOPE

In this apparatus, shown in Fig. 1, neutrons leaving the target at 0° and impinging on the Mylar window give, in perhaps 1 in 10^6 cases, a proton recoiling down the argon-filled counter telescope. Such protons are detected by a double-coincidence count in standard electronics apparatus. A remotely controlled foil changer permits the range of these protons in aluminum to be determined whence the neutron energy is inferred.

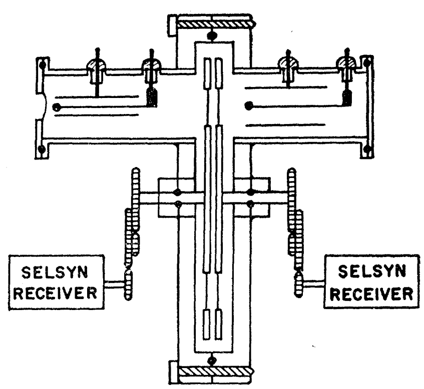

Fig. 1. The counter telescope.

The transparent Mylar window thus serves to provide a hydrogenous radiator while at the same time it can be made thin enough to allow the counters and associated equipment to be tested with a polonium alpha source.

The equipment was checked, and the counter correction and beam energy determined, by performing two preliminary experiments, namely the reactions $H^2(d,n)He^3$ and $B^{10}(\alpha,p)C^{13}$.

III. NEUTRON THRESHOLD METHOD

Slow-neutron thresholds were obtained using the apparatus shown in Fig. 2. The apparatus consisted of a helium-filled range cell to vary the energy of the cyclotron alpha beam and a shielded BF_3 proportional counter to detect the slow neutrons emitted in the forward direction. In order to enhance the efficiency of the counter for the threshold neutrons, one centimeter of paraffin was interposed between the target and the counter. The alpha beam entered the 52.5-cm range cell through a gridded Mylar foil equivalent in stopping power to 0.82 cm of air. The beam then passed through helium gas and was incident upon thick targets of the material under bombardment. In calculating Q values, the stopping power of Mylar was taken to be 0.113.[3] The atomic stopping power of helium was measured to

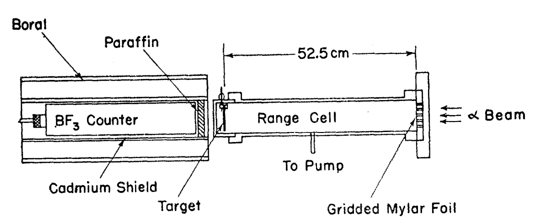

Fig. 2. The slow-neutron threshold detector.

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[1] D. C. Worth, Phys. Rev. **78**, 378 (1950).

[2] E. B. Tucker, Phys. Rev. **83**, 473 (1951).

[3] Phelps, Huebner, and Hutchinson, Phys. Rev. **95**, 441 (1954).

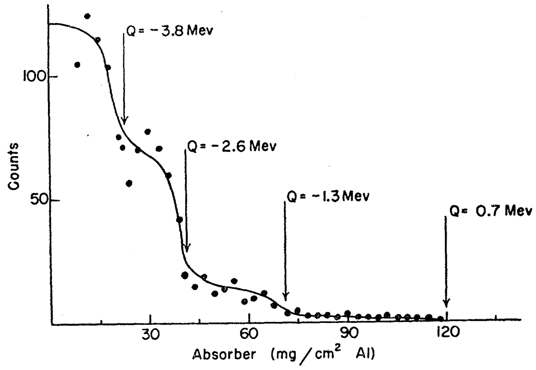

FIG. 3. Integral range curve for the reaction $B^{10}(\alpha,n)N^{13}$.

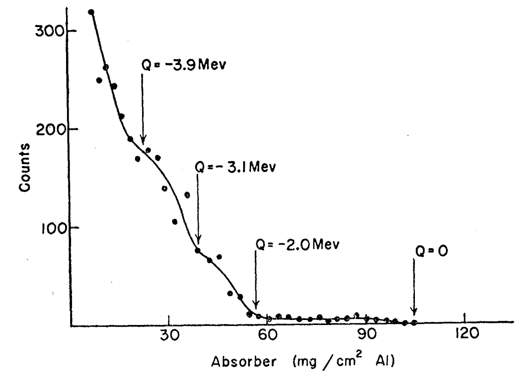

FIG. 5. Integral range curve for the reaction $B^{11}(\alpha,n)N^{14}$.

be 0.35±0.01 in agreement with the results of Mano.[4] The energy of the alpha beam was 8.15±0.05 Mev.

The chief difficulty encountered in operation was the large and fluctuating neutron background. This background was found to depend upon the circulating beam in the cyclotron and not on the beam striking the target. The background was minimized by wrapping the counter in cadmium sheeting and then enclosing the counter in a Boral box. Even with these precautions the background was still formidable and care was required to maintain constant operating conditions during a run.

This method relies upon the preferential sensitivity of the counter system for low-energy neutrons to distinguish neutron thresholds from resonances in fast neutron production. In some runs, added discrimination against fast neutrons was employed by setting an upper as well as a lower limit on acceptable pulse size.

IV. REACTION $B^{10}(\alpha,n)N^{13}$

The results for this reaction are presented graphically in Figs. 3 and 4 for the telescope and threshold detector respectively. Thick targets of separated isotope (96% B^{10}) painted onto lead backing were bombarded with a roughly analyzed 8-Mev beam of alpha particles. The curves are the averages of runs taken on two different days. Data were taken on some six other occasions in an effort to check results which are not in accord with those of other workers. The ground-state Q value as deduced from the telescope work is about 400 kev lower than the accepted value. There seems little doubt that this is a consequence of the low counting rate and is of no numerical significance. Unfortunately the threshold method is of no use here because the reaction is exothermic. Taking a Q value of 1.1 Mev for the ground state one obtains evidence for levels at 2.4 and 3.6 Mev of excitation which fit the known level structure of N^{13} within the claimed accuracy. Both methods would suggest the existence of a further level at about 4.95 Mev. The presence of a group of neutrons corresponding to a $Q=-3.2$ Mev is not seen with the telescope although it appeared consistently with the threshold method.

V. REACTION $B^{11}(\alpha,n)N^{14}$

In this case also, low counting rates prevent the observation of the true end point by the telescope method (Fig. 5), but neutrons leading to the first and second excited states at 2.3 and 3.95 Mev respectively are in evidence. This latter level also appears in the threshold detector work of Fig. 6, along with the 4.9-Mev level. Both methods suggest the existence of a group of neutrons from a reaction with $Q=-3.15\pm0.3$ Mev.

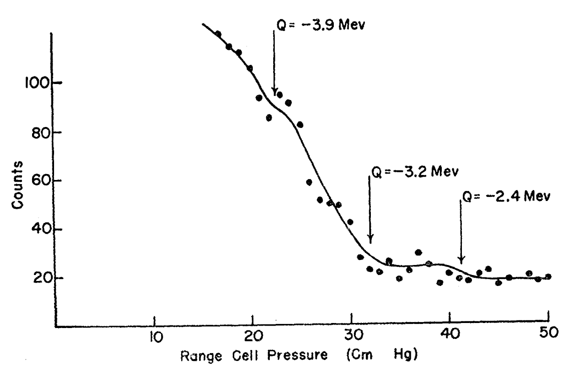

FIG. 4. Slow-neutron threshold curve for the reaction $B^{10}(\alpha,n)N^{13}$.

[4] G. Mano, J. phys. radium 5, 628 (1934).

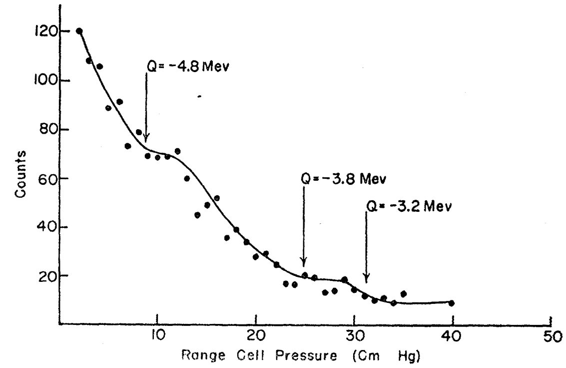

FIG. 6. Slow-neutron threshold curve for the reaction $B^{11}(\alpha,n)N^{14}$.

VI. $F^{19}(\alpha,n)Na^{22}$ REACTION

The target materials used for this reaction were CuF and Teflon. However, the Teflon targets tended to deteriorate over the long runs required so that CuF targets were employed most of the time. It was found that the neutron yield from Cu was negligible at our bombarding energies.

The experimental results are displayed in Figs. 7 and 8. Figure 7 shows the average of nine integral range curves obtained with the recoil telescope using thin targets. Figure 8 shows a typical neutron threshold curve for thick target bombardment. The Q values and excitation energies E^* obtained with the two methods are tabulated in Table I.

In comparing the data obtained by the two different methods, good over-all agreement is seen. The ground state is not observed with the threshold method because of the considerable background counting rate. The ground state Q value deduced from the telescope data is in good agreement with the value -1.92 Mev computed from the β^+ end point.[5] The level at 0.45 Mev is presumably to be identified with the level at 592 kev observed by Heydenberg and Temmer.[6] A level at 1.66-Mev excitation in Na^{22} has been suggested by Ashmore and Raffle[7] on the basis of a (d,α) reaction using natural Mg. Such a level would be $T=0$ if isotopic spin selection rules held. It is not possible to identify the level observed here at 1.8 Mev with the $T=0$ level because a $T=1$ level to correspond to the 1.28-Mev level in Ne^{22} is expected in the same region. The other Q values have not been previously observed.

TABLE I. A summary of the results.

Reaction	Telescope Q Mev	Threshold Q Mev	Mev Q	E^* Mev
$B^{10}(\alpha,n)N^{13}$	−3.8	−3.9	−3.85±0.3	5.0 ±0.3
		−3.2	(−3.2 ±0.3)	(4.3 ±0.3)
	−2.6	−2.4	−2.5 ±0.3	3.6 ±0.3
	−1.3		−1.3 ±0.3	2.4 ±0.3
$B^{11}(\alpha,n)N^{14}$		−4.8	−4.8 ±0.3	4.8 ±0.3
	−3.9	−3.8	−3.85±0.3	3.85±0.3
	−3.1	−3.2	−3.15±0.3	3.15±0.3
	−2.0		−2.0 ±0.3	2.0 ±0.3
	0.0		0.0 ±0.3	0.0 ±0.3
$F^{19}(\alpha,n)Na^{22}$		−5.0	−5.0 ±0.2	3.0 ±0.2
	−4.2	−4.3	−4.25±0.2	2.25±0.2
		−3.8	(−3.8 ±0.2)	(1.8 ±0.2)
	−3.1	−3.2	−3.15±0.2	1.15±0.2
	−2.4	−2.5	−2.45±0.2	0.45±0.2
	−2.0		−2.0 ±0.2	0.0 ±0.2
$P^{31}(\alpha,n)Cl^{34}$		−5.7	−5.7 ±0.2	0.0 ±0.2

[5] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[6] N. P. Heydenberg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).
[7] A. Ashmore and J. F. Raffle, Proc. Phys. Soc. (London) **A64**, 754 (1951).

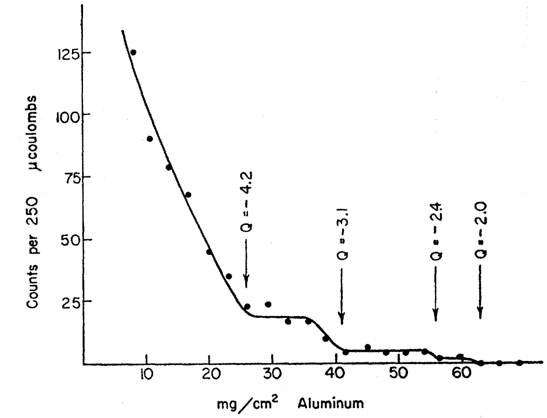

FIG. 7. Integral range curve for the reaction $F^{19}(\alpha,n)Na^{22}$.

VII. $P^{31}(\alpha,n)Cl^{34}$ REACTION

Although initial attempts to study this reaction using the recoil telescope were unsuccessful a small number of low-energy neutrons were observed indicating that the Q value was highly negative. The threshold method was more successful. Figure 9 shows a typical neutron threshold curve. This curve was obtained by using a 1.70-cm Mylar entrance foil. The value is in accord with the β^+ decay data of Ruby and Richardson.[8]

Arber and Stähelin[9] have shown that the long known 33 minute activity in Cl^{34} is due to an isomeric state at 142 kev in Cl^{34*}. They discovered the existence of a short-lived daughter activity from the ground state of Cl^{34}. Stähelin and Preiswerk[10] later measured the half-life of the daughter activity by direct excitation and found it to be 1.58 seconds. The latter authors assigned the activity to Cl^{34} by showing that the excitation function for the production of the 1.58-second activity was of the same from as that of the 33-minute activity over

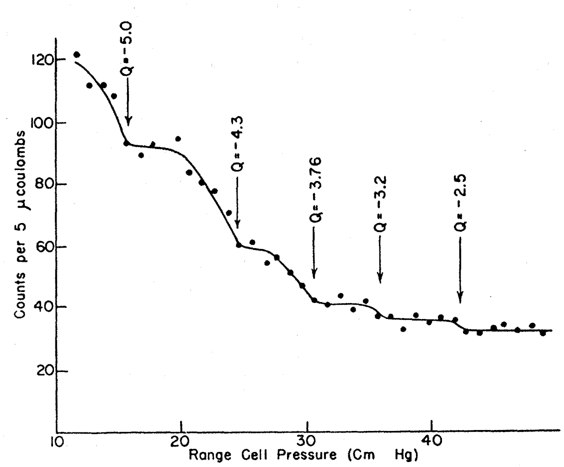

FIG. 8. Slow-neutron threshold curve for the reaction $F^{19}(\alpha,n)Na^{22}$.

[8] L. Ruby and J. R. Richardson, Phys. Rev. **83**, 698 (1951).
[9] W. Arber and P. Stähelin, Helv. Phys. Acta **26**, 433, 584 (1953).
[10] P. Stähelin and P. Preiswerk, Nuovo cimento **10**, 1219 (1953).

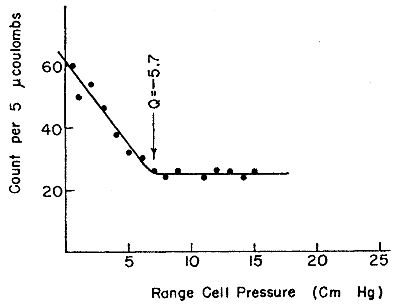

FIG. 9. Slow-neutron threshold curve for the reaction P^{31}-$(\alpha,n)Cl^{34}$.

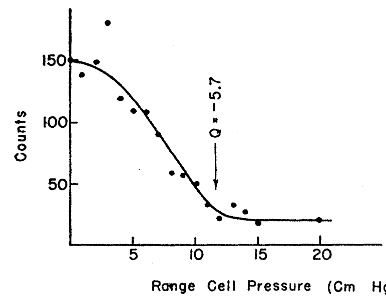

FIG. 10. The 1.58-sec β^+ activity from the reaction $P^{31}(\alpha,n)$-$Cl^{34}(\beta^+)S^{34}$.

a wide energy range for the $Cl^{35}(\gamma,n)Cl^{34}$ reaction. An excitation function of the 1.58-second activity has been obtained by using the range cell shown in Fig. 2. To obtain the excitation function, the target was first bombarded for many half-lives at a known energy. The cyclotron was then turned off and the resultant activity was monitored for several half-lives using a NaI scintillation counter. The excitation function is shown in Fig. 10. The observed threshold Q at -5.7 ± 0.3 Mev coincides with the slow-neutron threshold, thus corroborating the conclusions of Stähelin that the ground state of Cl^{34} is a $T=1$, $J=0^+$ level.

VIII. CONCLUSION

The results of this work are presented in Table I. Clearly, available counting rates restrict the attainable resolution to about 200 kev, but the two methods when used in conjunction allow one to investigate level structures which are often not accessible to other methods.

The authors wish to thank Professor E. C. Pollard for suggesting this work and for many helpful discussions.

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$B^{10}+\alpha$ Reactions

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An investigation of the $B^{10}(\alpha,p)C^{13}$ reaction has shown no evidence for the occasionally reported levels in C^{13} at 0.7 Mev and 4.4 Mev. The latter level may in the past have been confused with the ground-state transition in the $B^{10}(\alpha,d)C^{12}$ reaction.

A PREVIOUS $B^{10}(\alpha,p)C^{13}$ experiment carried out in this laboratory[1] gave some questionable evidence for the occasionally reported[2] level at 0.7 Mev in C^{13}. Since our early experiment, we have improved the resolution of our particle-detecting scintillator; it is now 7% for a 7-Mev proton. Using the $Al^{27}(\alpha,p)Si^{30}$ reaction as a standard for calibration purposes as before,[1] we have repeated the $B^{10}(\alpha,p)C^{13}$ reaction in a search for the 0.7-Mev level. A thin target of 96% B^{10} deposited on a 0.0001-in. gold backing was used. Charged particles were observed at 90° to the beam of 8.1-Mev alpha particles.

The results of the experiment were as follows: the ground state Q-value obtained was 4.08 ± 0.03 Mev with a relative yield of protons of 100. A group of protons with a relative yield of 60 was observed corresponding to a level in C^{13} at 3.07 ± 0.05 Mev. Another group with a relative yield of about 600 was found corresponding to a level in C^{13} at 3.86 ± 0.05 Mev. This group presumably is an overlap of the levels at 3.68 and 3.86 Mev observed by other investigators.[2] There was no indication of any proton group due to a 0.7-Mev level in C^{13}. If such a group does exist, its yield is less than 7% of that of the ground-state group.

In addition to the groups reported above, another was found with a relative yield of about 300, corresponding to a possible level in C^{13} at 4.42 ± 0.09 Mev. That this group does *not* correspond to such a level, and was in fact due to deuterons rather than protons, was demonstrated by additional runs in which an absorber was placed in front of the scintillator. The loss of energy in the absorber was characteristic of deuterons rather than protons. The deuterons can be attributed to the ground state transition in the reaction $B^{10}(\alpha,d)C^{12}$; the measured Q-value was 1.36 ± 0.09 Mev.

[1] Pieper, Stanford, and von Herrmann, Phys. Rev. **98**, 1185 (1955).
[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952); **27**, 77 (1955).