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Neutrons from the He^3 Bombardment of B^{10}*

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The neutron spectrum from the $B^{10}(He^3,n)N^{12}$ reaction has been studied at $\bar{E}(He^3)=2.54$ and 3.60 Mev by the method of proton recoils in nuclear emulsions. The Q value of the $B^{10}(He^3,n)N^{12}$ reaction has been measured to be 1.46±0.06 Mev. The mass of N^{12} is then 12.02255±0.00007 amu. The data also indicate excited states of ${}_7N^{12}$ at 1.06±0.08, 1.56±0.08, (1.97±0.10), 2.35±0.08, 3.18±0.15, and 3.46±0.15 Mev, in good agreement with the known levels of the mirror nucleus, ${}_5B^{12}$. At $\bar{E}(He^3)=2.54$ Mev, the angular distribution of the ground state neutrons is isotropic within statistics in the center-of-mass system, while at $\bar{E}(He^3)=3.60$ Mev, the angular distribution is peaked forward: $I(0°)/I(140°)=2.9\pm0.7$, in the center-of-mass system.

I. INTRODUCTION

With the increasing availability of well resolved beams of He^3 particles accelerated to a few Mev, scores of studies have been made of He^3-induced reactions in the light nuclei, in particular by the Van de Graaff groups at Oak Ridge, Chalk River, and the Naval Research Laboratory. A number of (He^3,p) reactions have been studied and have led, for instance, to very useful information on the levels of the $T_z=0$ nuclei $[T_z\equiv(N-Z)/2]$: Be^8,[1,2] C^{12},[2-5] and N^{14}.[6]

On the other hand, there has been very little work done on (He^3,n) reactions. The only studies made of states of $T_z=-1$ nuclei through (He^3,n) reactions have been by the neutron thresholds method,[6-8] and there has been no previous attempt to study the reaction $B^{10}(He^3,n)N^{12}$. The information on N^{12} has been very meager. Alvarez[9,10] has studied the reaction $C^{12}(p,n)N^{12}$ and the subsequent beta decay of N^{12}. He found the threshold energy for the $C^{12}(p,n)N^{12}$ reaction to be 20.0 Mev, $E_{\beta^+}(\max)=16.6\pm0.2$ Mev and $\tau_{\frac{1}{2}}(N^{12})=(12.5\pm1)\times10^{-3}$ sec. If one assumes the Wapstra[11] values for the atomic masses of C^{12}, H^1, and n, Alvarez' results lead to a mass of 12.0228±0.0002 amu and to an atomic mass excess $(M-A)$ of 21.2±0.2 Mev for N^{12}. There has been no information on the excited states of N^{12}.

We decided to study the reaction $B^{10}(He^3,n)N^{12}$ to determine more accurately the mass of N^{12}, to locate the first few excited states of N^{12}, and to compare the excitation energies with those of the levels[12] of the mirror nucleus, B^{12}, and with the first few $T=1$ states in C^{12}, and to investigate the mechanism of a (He^3,n) reaction at bombarding energies near the Coulomb barrier.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Chalk River Exposures

The target was a 100-microgram/cm² B^{10} layer deposited in the electromagnetic separator at Harwell[13] on 2-μ Au plated on 0.005-in. Cu. The percentage of B^{10} was approximately 99%. The energy of the incident He^3 particles was measured to be 2.596±0.010 Mev, and the total exposure was of 4.2×10^4 microcoulombs (with an uncertainty of approximately 30%). A background exposure was made at 2.509±0.008 Mev with the beam hitting the copper backing for 1.5×10^4 microcoulombs. The neutrons were detected in both exposures by the method of proton recoils in nuclear emulsions. The Ilford C-2 nuclear emulsions, 400 microns thick, were wrapped in aluminum foil and mounted by means of binder clips to the blades of an aluminum camera. The plates were exposed at 10 angles to the incident He^3 beam (0°, 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°) and at a distance of $4\frac{1}{4}$ inches from the center of the target. The plates were developed

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[13] We are indebted to Dr. M. L. Smith of the Atomic Energy Research Establishment, Harwell, England, for supplying the B^{10} targets.

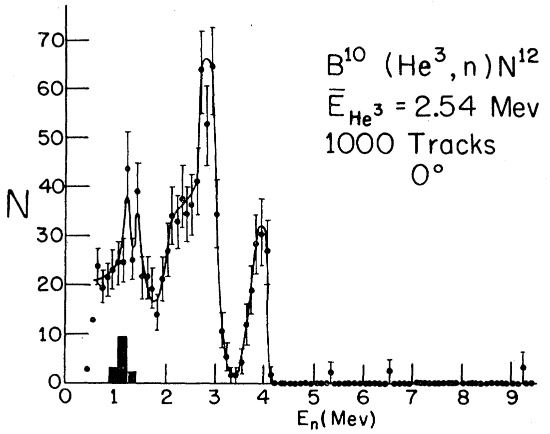

FIG. 1. Data at 0° (in the laboratory system) and at $\bar{E}(He^3) = 2.54$ Mev. N is the corrected number of neutrons per 100-kev interval. E_n is the neutron energy (see text for further details).

by a method described earlier.[14] The density of tracks satisfying acceptance criteria[14] varied from 2200 to 4000 tracks/cm^2 in the B^{10} exposure depending on the angle. In the background exposure the density of tracks on the 0° plate was 22 tracks/cm^2. The scanning and the measurement of the tracks were carried out with a Leitz binocular research microscope. An oil immersion objective (100×) was used together with a pair of 10× eyepieces. A total of 4813 tracks were measured at the ten angles. At five of these angles, only proton recoil tracks corresponding to ground state neutrons were measured.[15] This was done since none of the excited states of N^{12} can be said to have been clearly resolved and it is thus only the angular distribution of the ground state neutrons which is likely to be meaningful.

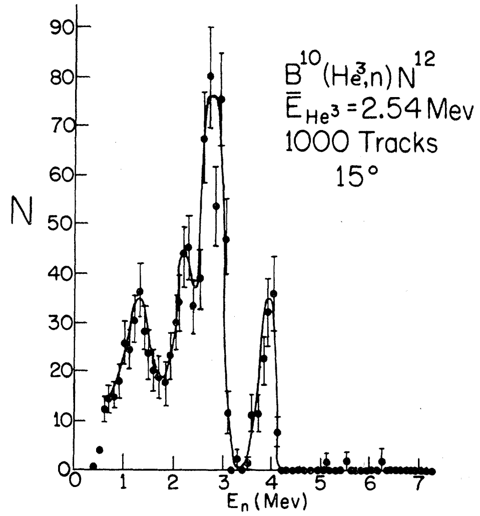

FIG. 2. The 15° data (see also caption of Fig. 1).

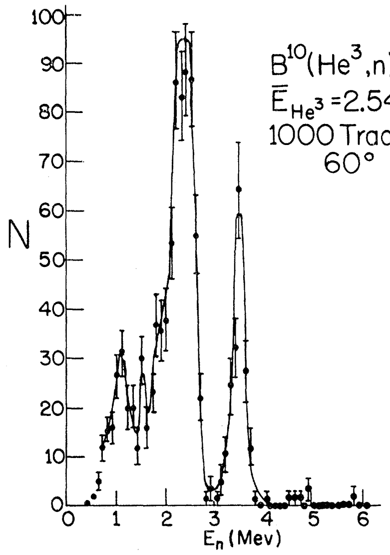

FIG. 3. The 60° data (see also caption of Fig. 1).

The range-energy table of Gibson, Prowse, and Rotblat[16] was used to convert the lengths of proton recoil tracks to neutron energies. These were then tabulated in 100-kev intervals, and the number of tracks in each interval was corrected[14] for variation of the *n-p* scattering cross section and geometry. The fractional error assigned to the number of neutrons in each energy interval is the reciprocal of the square root of the number of neutrons in the interval. The data are shown as Figs. 1–4. The ground state neutron group appears at $E_n = 3.9$ Mev (0°) to $E_n = 2.8$ Mev (135°). Background measurements were carried out only at 0°.

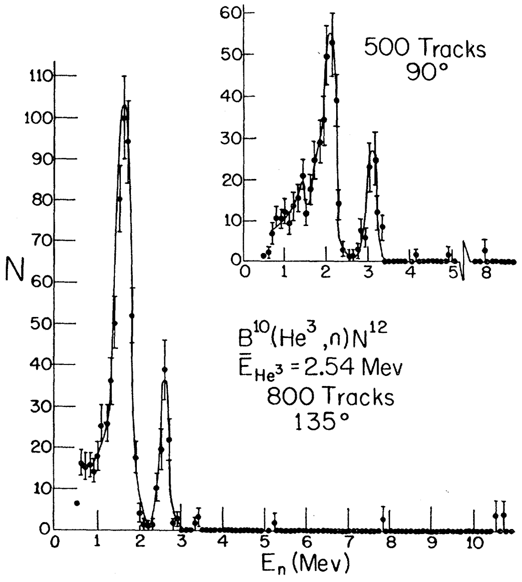

FIG. 4. The 90° and 135° data (see also caption of Fig. 1).

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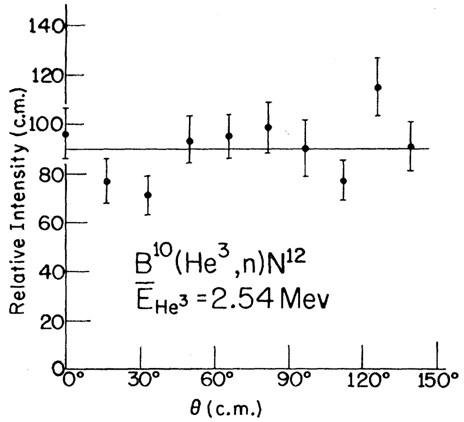

FIG. 5. The angular distribution of the ground state neutrons at $\bar{E}(He^3) = 2.54$ Mev in the center-of-mass system. The intensity units are arbitrary.

The observed background, plotted to scale, is shown on Fig. 1 as the dark histogram at $E_n \sim 1.1$ Mev. The background tracks are probably due to the $C^{12}(He^3,n)O^{14}$ reaction ($Q = -1.1585 \pm 0.003$ Mev[6]). The high plateau on which the neutron groups due to excited states of N^{12} are superimposed is due to the three-particle breakup $B^{10} + He^3 \rightarrow n + (C^{11} + p)$ with a calculated[11] $Q = 0.980 \pm 0.009$ Mev and an energy cutoff which should appear at $E_n = 3.6$ Mev (0°) to $E_n = 2.3$ Mev (135°) and does so. The ground state group which is particle-stable is cleanly resolved. The angular distribution of the ground state neutrons at $\bar{E}(He^3) = 2.54$ Mev (this "average" energy value is the incident energy less half the target thickness) is shown as Fig. 5. The errors indicated are statistical errors only.

B. Brookhaven Exposure

The experimental setup used was similar to that discussed in part A. The target was a 100-microgram/cm² B^{10} layer deposited at Harwell[13] on 0.01-inch Ni. The energy of the He^3 particles was 3.65 ± 0.07 Mev, and the total exposure was of only 8×10^3 microcoulombs (with an uncertainty of approximately 30%) because of operating difficulties. This low exposure resulted in a density of proton recoil tracks in the emulsions approximately 15% of the density in the Chalk River plates. For this reason, a full spectrum was obtained only at 0° (see Fig. 6). In order to obtain the angular distribution of the ground state neutrons in the least tedious way, scanning was done with an objective-eyepiece combination of (45×)(10×). Only ground state neutrons were accepted, providing that the other usual acceptance criteria[14] were met by the corresponding proton recoil tracks, and these tracks were measured in the usual way with the (100×)(10×) objective-eyepiece combination. The ground state neutron groups at all angles measured (0°, 15°, 30°, 45°, 60°, 90°, 120°, 135°) are clearly resolved[15] and it is believed that the resulting angular distribution (shown as Fig. 7) is meaningful. It is based on a total of 386 proton recoil tracks.

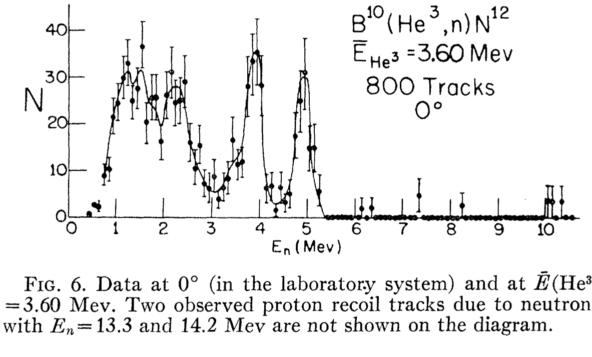

FIG. 6. Data at 0° (in the laboratory system) and at $\bar{E}(He^3) = 3.60$ Mev. Two observed proton recoil tracks due to neutrons with $E_n = 13.3$ and 14.2 Mev are not shown on the diagram.

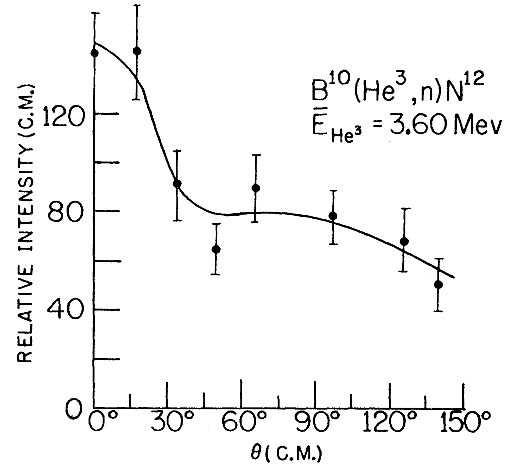

FIG. 7. The angular distribution of the ground state neutrons at $\bar{E}(He^3) = 3.60$ Mev in the center-of-mass system. The intensity units are arbitrary and are not the same as those shown in Fig. 5.

III. DISCUSSION OF RESULTS

A. Background

Before trying to determine the location of the states of N^{12}, the question of background from contaminants must be discussed. The Q value of the $O^{16}(He^3,n)Ne^{18}$ reaction is -2.966 Mev,[11] which means that no neutrons due to this reaction can be observed in either exposure. The main contamination in the region of interest appears to be that from C^{12} [$C^{12}(He^3,n)O^{14}$ $Q_0 = -1.16$ Mev]. The $C^{12}(He^3,n)O^{14}$ reaction contributes the neutron group at 1.2 Mev (0°) and probably contributes to the neutron groups centered at 1.3 Mev (15°) and 1.1 Mev (60°) [Chalk River exposure], and at 2.2 Mev (0°) [Brookhaven exposure]. The $C^{13}(He^3,n)O^{15}$ reaction has Q values of 7.18, 1.91, 1.04, 0.34, 0.27 (etc.) Mev corresponding to the transitions to the ground state and the excited states of O^{15}. It is only the neutron groups corresponding to the excited states of O^{15} which would appear in the region of the first few states of N^{12}. Since C^{13} is only a one percent isotope of natural carbon, and since very few high-

TABLE I. Excited states of N^{12} from $B^{10}(He^3,n)N^{12}$.

	Q values (in Mev)							E_x [c]
	0° [a]	0° [b]	15° [a]	60° [a]	90° [a]	135° [a]	Best value	(in Mev)
1	0.41	0.46	0.41	0.34	0.39	0.34	0.40±0.06	1.06±0.08
2	−0.12		−0.09	−0.11			−0.10±0.06	1.56±0.08
3				−0.51			(−0.51±0.10)	(1.97±0.10)
4	−0.87	−0.90	−0.96	−0.90			−0.89±0.06	2.35±0.08
5		−1.72					−1.72±0.15	3.18±0.15
6		−2.00					−2.00±0.15	3.46±0.15

[a] $\bar{E}(He^3)=2.54$ Mev. [b] $\bar{E}(He^3)=3.60$ Mev. [c] Based on $Q_0=1.46\pm0.06$ Mev.

energy proton recoil tracks were observed which might be ascribed to the ground state of O^{15}, it is believed unlikely that C^{13} neutrons could cause any difficulties in the location of the states of N^{12}. In both exposures B^{11} was present in the target to the extent of approximately one percent. The Q values of the $B^{11}(He^3,n)N^{13}$ reaction are 10.18, 7.81, 6.67, 6.62, 3.80, 3.27, 2.78 (etc.) Mev. It is the transitions to the higher states of N^{13} which would provide neutrons in the region of interest. However, the small number of proton recoil tracks which could be assigned to the ground state and the first few excited states of N^{13} is so small that again it is believed that there is little likelihood of a sufficient number of neutrons occuring from $B^{11}(He^3,n)N^{13}$ in the region of the $B^{10}(He^3,n)N^{12}$ reaction to lead to uncertainty in the location of the excited states of N^{12}. No other contaminants appear likely to be present.

B. Mass of N^{12}

The ground state group was well resolved at all angles in both the Chalk River and the Brookhaven exposures. From the plates exposed at Chalk River (data taken at 10 angles), the $B^{10}(He^3,n)N^{12}$ ground state Q value is 1.46±0.04 Mev. From the plates exposed at Brookhaven (data taken at eight angles), $Q_0=1.46\pm0.08$ Mev (the errors indicated are the standard deviations). We adopt $Q_0=1.46\pm0.06$ Mev. Using the Wapstra[11] atomic masses for B^{10}, He^3, and n, we find $M(N^{12})=12.02255\pm0.00007$ amu, and $(M-A)=21.00\pm0.06$ Mev. These values may be compared with the previous values of 12.0228±0.0002 amu and 21.2±0.2 Mev obtained by Alvarez.[9,10]

C. Excited States of N^{12}

The excited states of N^{12} are not cleanly resolved. This is due in part to the three-particle background on which the discrete neutron groups are superimposed, and in part to the small separation of some of the levels. At no single angle are all the levels clearly visible, but by combining the information from all the angles studied (see Table I), we obtain excitation energies of 1.06±0.08, 1.56±0.08, (1.97±0.10), 2.35±0.08, 3.18 ±0.15, and 3.46±0.15 Mev for the N^{12} levels, assuming $Q_0=1.46$ Mev. The agreement with the known levels of B^{12} and with the $T=1$ states of C^{12} in the same excitation region is extremely good (see Fig. 8). This is another indication of the validity of the hypotheses of the charge symmetry (${}_5B_7{}^{12}$ and ${}_7N_5{}^{12}$) and charge independence ($A=12$ triad) of nuclear forces. It should be pointed out however that we are by no means certain of having resolved all the states of N^{12} with $E_x\leq3.5$ Mev. In fact, the group corresponding to the state at 1.06 Mev is wider than would normally be expected for a neutron group to a single level at that particular neutron energy. However, the unknown three-particle background makes it difficult to accurately estimate the width of the group. The state at 1.97 Mev which is postulated on the basis of a single high point at a single angle is, of course, very dubious.

D. Cross Sections

At $\bar{E}(He^3)=2.54$ Mev, the differential cross section for formation of the ground state at 90° (lab) $=(0.41_{-0.12}{}^{+0.16})$ mb/sterad. If one assumes an isotropic

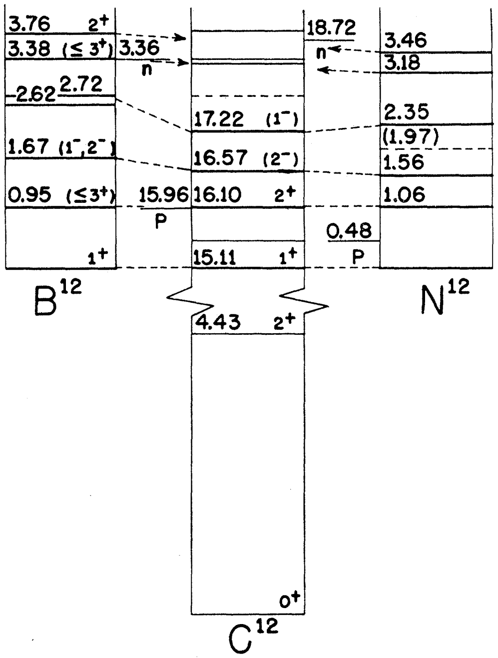

FIG. 8. The mass 12 isobaric triad. The levels whose energies are indicated are believed to be $T=1$ states. Corrections have been made for Coulomb energy differences and the n-p mass difference. [See, e.g., T. Lauritsen and F. Ajzenberg-Selove, *American Institute of Physics Handbook*, (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 8-e.]

distribution in the center-of-mass system, the cross section for formation of the ground state is then $(5.2_{-1.6}^{+2.1})$ mb. At $\bar{E}(\mathrm{He}^3)=3.60$ Mev, the differential cross section for formation of the ground state at 0° (lab) $=0.73\pm0.30$ mb/sterad.

It is of interest to compare the cross section for formation of the first $T=1$ state in C^{12}, at 15.1 Mev, in the reaction $\mathrm{B}^{10}(\mathrm{He}^3,p)\mathrm{C}^{12}$ with the cross section for the analogous state in N^{12}, the ground state, formed in the isobaric reaction $\mathrm{B}^{10}(\mathrm{He}^3,n)\mathrm{N}^{12}$ (see Fig. 8). The ratio of the two cross sections is predicted[17] to be 2 $[\sigma(\mathrm{He}^3,n_0)=2\sigma(\mathrm{He}^3,p_{15.1})]$. The cross section for formation of the 15.1-Mev state of C^{12} at $E(\mathrm{He}^3)=2.54$ Mev is 2.4 ± 0.25 mb.[18] Our value $\sigma(\mathrm{He}^3,n_0)=(5.2_{-1.6}^{+2.1})$ mb at the same energy is in good agreement with the prediction based on the charge independence of nuclear forces.

E. Angular Distributions

At $\bar{E}(\mathrm{He}^3)=2.54$ Mev, the angular distribution of the ground state neutrons is found to be isotropic within statistics in the center-of-mass system. At $\bar{E}(\mathrm{He}^3)=3.60$ Mev, the distribution of the ground state neutrons is peaked forward in the center-of-mass system: $I(0°)/I(140°)=2.9\pm0.7$.

The neutron groups at $E_n=2.85$ Mev (0° and 15°), 2.40 Mev (60°), 2.11 Mev (90°), and 1.66 Mev (135°) [Chalk River exposure], which correspond to one or more excited states of N^{12} at 1.06 Mev, are superimposed on the three-particle background from the $\mathrm{B}^{10}(\mathrm{He}^3,np)\mathrm{C}^{11}$ reaction. The difficulty in meaningfully subtracting the three-particle background and the impossibility of knowing with certainty whether more than one state is involved make it difficult to attach much significance to an angular distribution of the neutrons to the 1.06-Mev state(s). However, the relative intensities of the neutron groups were computed, and we find that, in the center-of-mass system, the intensity of the neutrons to the first excited state of N^{12} is essentially the same within statistics at 0° (258±16), 17° (232±13), 67° (264±12), and 97° (281±17) but that there is a fairly large increase in intensity in the backward direction (at 140°: 460±20). [The background was not subtracted in these calculations. The numbers in parentheses are the relative intensities in arbitrary units; these units are the same as those shown in Fig. 5.]

Schiffer *et al.*[2] have studied the yield and angular distribution of protons from the $\mathrm{B}^{10}(\mathrm{He}^3,p)\mathrm{C}^{12}$ reaction to the ground and 4.43-Mev states of C^{12} in the energy range $E(\mathrm{He}^3)=1.3$ to 4.9 Mev. The excitation curves show several broad and overlapping resonances. In particular two prominent resonances occur at $E(\mathrm{He}^3)=2.0$ Mev ($\Gamma\sim0.5$ Mev) and 3.7 Mev ($\Gamma\sim0.7$ Mev) corresponding to excitations of 23.2 and 24.5 Mev in N^{13}. The angular distributions of p_0 and p_1 show asymmetries which become more pronounced at the higher energies but no detailed comparison is possible with the (He^3,n) angular distributions since the states reached in C^{12} via the (He^3,p) reaction have a completely different character from the N^{12} states. It has been pointed out by Schiffer[2] that the observed asymmetries of (He^3,p) reactions may be the result of interference between broad overlapping states of the compound system together with the added complexity of an admixture of some form of direct interaction. One might perhaps expect that the complicated readjustment required of the five protons from B^{10} $[(1s)^2(1p_{\frac{3}{2}})^3]$ and the two protons from He^3 $[(1s)^2]$ to form the seven proton structure N^{12} $[(1s)^2(1p_{\frac{3}{2}})^4(1p_{\frac{1}{2}})]$ would favor a compound nucleus process.

Bromley *et al.*[6] have studied the angular distribution of the neutrons to the ground state of O^{14} in the reaction $\mathrm{C}^{12}(\mathrm{He}^3,n)\mathrm{O}^{14}$ at $E(\mathrm{He}^3)=1.89$, 2.16, 2.40, and 2.51 Mev. At the lower energies, near the threshold, where the angular momentum barrier favors the emission of *s*-wave neutrons the distributions are nearly isotropic; however they become strongly asymmetric as the bombarding energy is increased.

The (He^3,n) reactions studied to date, therefore, show strong asymmetries at the higher energies. This may be evidence for a direct interaction mechanism in (He^3,n) as in (He^3,p) reactions but detailed theoretical studies of such reactions are not available to compare with experiment. Thus analysis of the mechanism involved in these reactions is not possible at this time.

IV. ACKNOWLEDGMENTS

This experiment could not have been carried out by us without the aid and support of the Van de Graaff groups at Chalk River and Brookhaven. We are particularly indebted to D. A. Bromley, H. E. Gove, A. E. Litherland, and the Van de Graaff operations staff of the Chalk River Laboratory, and to M. J. Scott, A. Timpe, R. Lindgren, W. Selove, C. Turner, and D. E. Alburger of the Brookhaven National Laboratory.

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