the angular distributions. In any event the predominant interaction up to proton energies of 6 Mev is the capture of p- and d-wave protons in singlet states.

The general features of these angular distributions have been observed by Fuller[10] in his photodisintegration experiment. In his experiment,[26] the asymmetry coefficient appears to be a factor of two lower than an extrapolation of the results of this experiment. The isotropic component is essentially zero at what corresponds to 6-Mev proton energy in the $T(p,\gamma)$ reaction, but rises rapidly at higher energies.

(4) Extensions of the Experiment

An independent measurement of the absolute yield of the reaction seems desirable in view of the divergence of our result from those of other experiments. More accurate angular distributions, extended to higher energy, might settle the question of interaction in triplet states. A more accurate 90° yield curve, possibly taken with a large crystal with collimator and extended to higher energy, would be of use in the theoretical interpretation of the reaction. A coincidence search might clarify the question of possible cascade gamma rays or nuclear pairs. None of these extensions is presently being considered at this laboratory.

We are particularly indebted to Dr. Robert B. Day for information on absolute gamma-ray yield measurements and for discussions on many phases of the experiment. Many members of Groups P-3 and P-9 of this laboratory helped us by discussion and criticism of the experiment, construction of the apparatus, and operation of the electrostatic accelerators. We are grateful to Dr. Thomas R. Roberts for the many tritium gas analyses.

[26] The notation used in the two experiments is unfortunately not the same. Our a is approximately $\gamma/2b$ in Fuller's notation. Our K (Fig. 6) equals his b, and our b is his a/b.

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Disintegration of Carbon into Three Alpha Particles by 12–20 Mev Neutrons*

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The reaction $C^{12}(n,n'3\alpha)$ has been studied in C-2 emulsions exposed to fifteen discrete neutron energies in the range 12.3–20.1 Mev. Measurements were made of the range and space angles of the three alpha particles for over 2000 events. The observed cross section is 78 ± 15 mb at 12.6 Mev, goes through a broad maximum of 265 ± 47 mb at 16.9 Mev, and is 223 ± 40 mb at 20.1 Mev. It was found that not all the events are observed in the emulsion since (a) one prong may be too short and (b) two prongs which arise from the ground state of Be^8 may not be resolvable. A correction is made for these missed stars at four points giving: $\sigma_{corr}=190\pm50$, 230 ± 50, 316 ± 73, and 283 ± 59 mb at the bombarding energies of 12.9, 14.1, 15.5, and 18.8 Mev, respectively. Evidence is found for the excitation of the 9.6-Mev level in C^{12} and the ground state and 3-Mev level in Be^8, so that at least some of the events disintegrate via the mode $C^{12}(n,n')C^{12*}(\alpha)Be^{8*}(2\alpha)$. Six events appear to involve the 7.7-Mev level in C^{12}. The center-of-mass energy spectrum of the scattered neutrons may be fitted by a four-particle phase space distribution or a Maxwellian distribution. As a result of these measurements, carbon stars in nuclear track plates may be used as a neutron monitor with an accuracy of 15% at 14 Mev and 20% elsewhere in the 12–20 Mev range.

1. INTRODUCTION

CARBON-12 has been observed to disintegrate into three alpha-particles when bombarded by neutrons or gamma rays above the threshold energy of 7.28 Mev. Hänni, Telegdi, and Zünti[1] discovered the photodisintegration reaction in nuclear emulsions exposed to p-Li gamma-rays and this reaction has since been extensively investigated.[2] The neutron-induced reaction was found in early cloud-chamber experiments of Chadwick, Feather, and Davies.[3] Green and Gibson[4] studied 168 stars produced in nuclear emulsions by d-Li neutrons and found a cross section which rises from 23 mb at 10.8 Mev to 157 mb at 14.5 Mev. Their results were further analyzed by Livesey and Smith[5] who found evidence for the excitation of the known 9.6-Mev level in C^{12}, and tentatively another level at 11.8 ± 0.8 Mev. In the former case the breakup of C^{12*} leaves Be^8 in the ground state (the only state energetically possible) while the latter shows some indication of leaving Be^8 in the excited state at 3 Mev.

Perkin,[6] also using nuclear emulsions and d-Li neutrons with a maximum energy of 24 Mev, analyzed 485

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Hänni, Telegdi, and Zünti, Helv. Phys. Acta **21**, 203 (1948).
[2] See F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952); **27**, 77 (1955) for complete references to the photodisintegration work.
[3] Chadwick, Feather, and Davies, Proc. Cambridge Phil. Soc. **30**, 357 (1934).
[4] L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 296 (1949).
[5] D. L. Livesey and C. L. Smith, Proc. Phys. Soc. (London) **A66**, 689 (1953).
[6] J. L. Perkin, Phys. Rev. **81**, 892 (1951).

TABLE I. The neutron energy and energy spread for neutrons produced in a 3-cm tritium target by deuterons of average energy 3.36 Mev. The energy spread is calculated from the length of the target and the energy loss of the deuteron beam in the target.

Laboratory angle	Average laboratory energy (Mev)	Energy spread (Mev)
0°	20.1	0.08
20°	19.8	0.18
30°	19.4	0.28
40°	18.9	0.42
50°	18.3	0.54
60°	17.6	0.67
70°	16.9	0.76
80°	16.2	0.76
90°	15.4	0.73
100°	14.7	0.68
110°	14.1	0.60
120°	13.5	0.51
130°	13.0	0.35
140°	12.6	0.24
150°	12.3	0.15

stars and found indications for Be^8 levels at 2.65, 4.0, 7.25, and 9.8 Mev. The alpha particles were found to have an isotropic angular distribution in the center-of-mass system.

Jackson and Wanklyn[7] studied these events in a cloud chamber with p-Be neutrons of energy up to 45 Mev (80% of their events correspond to neutron energies below 25 Mev). Their preliminary results show that for neutron energies below 20 Mev part of the stars proceed through a C^{12} level at 10 ± 0.8 Mev and the ground state of Be^8, and the remainder give a range of excitation values of C^{12} with no indication of the 3-Mev level in Be^8. The center-of-mass energy distribution of the alpha particles and neutrons can be fitted by assuming a four-particle phase space distribution. Above 20-Mev neutron energy, the disintegration appears to go via the 3-Mev Be^8 level.

Kellogg[8] made an extensive investigation of all the charged particle reactions possible with 90-Mev neutrons on carbon and found a cross section for the three-alpha reaction of 9.8 ± 2.0 mb.

The present experiment, made with nuclear emulsions and $T(d,n)He^4$ neutrons which provided a monoenergetic neutron source, was undertaken to determine the $C^{12}(n,n'3\alpha)$ cross section from 12 to 20 Mev and to study further the possible modes of disintegration. The soaking of the emulsions in a glycerine solution to prevent their shrinking after development significantly improved the accuracy in the measurement of the alpha tracks.

2. EXPERIMENTAL PROCEDURE

Ilford C-2 nuclear track plates were exposed to the neutrons produced by 3.50-Mev deuterons from the large Los Alamos electrostatic accelerator incident upon a tritium gas target. The plates were positioned at 10° intervals from 0–160° with respect to the deuteron beam with the long axis of each plate pointed toward the center of the target. In this way data could be obtained simultaneously at neutron energies of 12–20 Mev. Table I lists the average neutron energy at each angle and the energy spread calculated from the length of the tritium target, and the energy loss in the gas. The plates were wrapped in black paper with a strip of 5-mil platinum next to the emulsion and fixed in position by 0.015-in. steel wires which were strung in an aluminum frame designed to present a minimum amount of scattering material. A separate exposure was made to the 14.1-Mev neutrons generated by the 250-kev deuterons, from the Los Alamos Cockcroft-Walton accelerator, incident upon a zirconium-tritium target, where the flux is accurately determined by counting the accompanying alpha-particles from the $T(d,n)\alpha$ reaction. The plates were processed by the A and B two-solution method,[9] and soaked, after washing, in a 10% glycerine solution to minimize shrinkage.

3. PLATE ANALYSIS

Figure 1 shows three carbon stars formed by 16.9-Mev neutrons, the three alpha particles originating from a common vertex. In scanning the plates all three-prong events were recorded. The following measurements were made on each prong of a star: (1) the projected length of the prong, i.e., the length in the plane of the emulsion; (2) the angle in the plane of the emulsion between the prong and the long axis of the plate, which is also the angle in the plane of the emulsion between the prong and the direction of the incident neutron; (3) the number of microns of dip between the vertex and the end of the prong. The dip measurement is the least precise of the three and limits the accuracy of the energy and momentum determination of each prong.

4. STAR CALCULATIONS

If the direction of the incident neutron is known, conservation of energy and momentum allows one to calculate the energy of the incident neutron as well as

Incident neutron direction
→

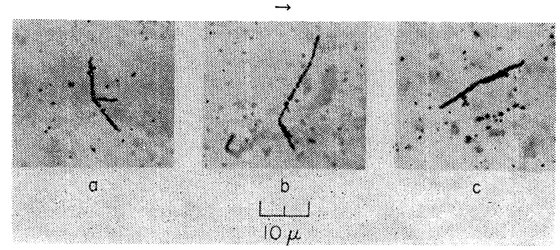

FIG. 1. Three typical carbon stars for $E_0=16.9$ Mev. In (b) and (c) the two prongs close together arise from Be^8 being left in its ground state. (c) illustrates the difficulty that often arises in resolving these two prongs. Only the thickness of the track and the scattering of the last grain of the shorter track indicate that these are actually two tracks.

[7] J. D. Jackson and D. I. Wanklyn, Phys. Rev. **90**, 381 (1953); J. D. Jackson (private communication).
[8] D. A. Kellogg, Phys. Rev. **90**, 224 (1953).
[9] M. Blau and J. A. De Felice, Phys. Rev. **74**, 1198 (1948).

the energy and direction of the emitted neutron from the measured energy and space angles of the three alpha particles. Assume the incident neutron moves along the x-axis. Then the energy of the incident neutron is given by

$$E_c=[(E_1+E_2+E_3-Q+X^2+Y^2+Z^2)/2X]^2,$$

and the energy and direction of the scattered neutron by

$$E_n=(X_0-X)^2+Y^2+Z^2,$$

$$\theta=\tan^{-1}\left(\frac{(Y^2+Z^2)^{\frac{1}{2}}}{X_0-X}\right).$$

E_i= the energy of the ith alpha particle. $X=X_1+X_2+X_3$ and similarly for Y and Z. X_i is the component of momentum of the ith particle along the x-axis. Momentum is taken as $(mE)^{\frac{1}{2}}$, with m in atomic mass units and E in Mev. θ is the polar angle of the scattered neutron with respect to the original neutron direction. $Q=-7.28$ Mev, the mass difference between C^{12} and three alpha particles.[10] All the above quantities are in the laboratory system.

E_c, E_n, and θ were calculated for at least a hundred stars at each energy. Since the incident neutron energy, E_0, was known for each plate, the calculation of E_c furnished a criterion as to whether or not each three-prong event was actually a carbon star produced by a neutron of energy E_0. Figure 2 shows the calculated energy for the case where the incident neutron energy is 14.1 Mev.

For purposes of calculating the cross section, a wide range of E_c was allowed since the stars which gave an E_c differing by several Mev from E_0 were usually ones where the measurement was difficult, most often because one or more prongs dipped steeply. In the calculation of excitation energies and angular distributions only stars for which $|E_c-E_0|\leqslant 2$ Mev were utilized.

The only other reaction in the emulsion which gives a three-pronged event is $N^{14}(n,2\alpha)Li^7$. Most of these will be eliminated by the calculation of E_c. In any case the maximum number of N^{14} events would be only 2% of the carbon stars, since the carbon-nitrogen ratio in the emulsion is 4.7 and Lillie[11] finds the $N^{14}(n,2\alpha)Li^7$ cross section to be 15 mb, 10% of the $C^{12}(n,n'3\alpha)$ cross section (Sec. 7).

5. DISINTEGRATION MODES

In the subject reaction, various modes of disintegration are possible: (1) $C^{12}(n,\alpha)Be^{9*}(n')Be^{8*}(2\alpha)$ (the notation Be^{8*} will be taken to include Be^8 in its virtual ground state as well as in its excited states); (2) $C^{12}(n,\alpha)Be^{9*}(\alpha)He^5(n')\alpha$; (3) $C^{12}(n,n')C^{12*}(\alpha)Be^{8*}(2\alpha)$; (4) $C^{12}(n,n')C^{12*}(3\alpha)$; or (5) the resultant four particles may be emitted at once, denoted by $C^{12}(n,n'3\alpha)$, rather than from any intermediate unstable nuclei formed along the way.

[10] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

[11] A. B. Lillie, Phys. Rev. **87**, 716 (1952).

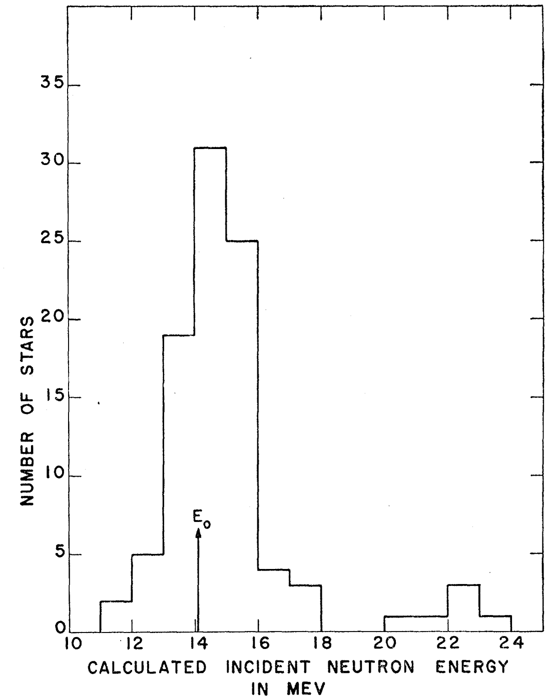

FIG. 2. Calculated incident neutron energy for the case where the incident neutron energy is 14.1 Mev.

The following procedure may be used to establish a particular disintegration chain. From the observed energy of one of the particles emitted, the excitation energy of the residual nucleus is calculated. Then the values of excitation energy thus obtained are compared with the known level scheme of the nucleus. This procedure is somewhat complicated in the present case because, in all, three alpha particles are emitted, and in (1) and (2) one cannot tell *a priori* which alpha is emitted from C^{13*} and which two come from the breakup of Be^{8*} (or from Be^{9*} and He^5). Thus in testing (1) and (2) one must use all three alpha particles, and the validity of the assumption that Be^{9*} is being formed would be evinced by the superposition of the levels of Be^9 on a continuous background of twice the integrated intensity of the levels. Calculations of this type show only a continuous distribution of values from the excitation of Be^9 with no sign of the known levels. An upper limit of 25% may be placed on the fraction of the reactions which proceed via (1) or (2).

Similarly the validity of (3) or (4) or a combination thereof may be established by calculating the excitation energy of the residual C^{12*}, by the following formula:

$$E_{ex}(C^{12})=E_1+E_2+E_3+7.28-(1/12)[X^2+Y^2+Z^2],$$

which has the virtue of permitting $E_{ex}(C^{12})$ to be calculated directly from the measurements on the three alpha particles rather than from a transformation to the center-of-mass system which requires also the use of the bombarding energy. The values of excitation energy for

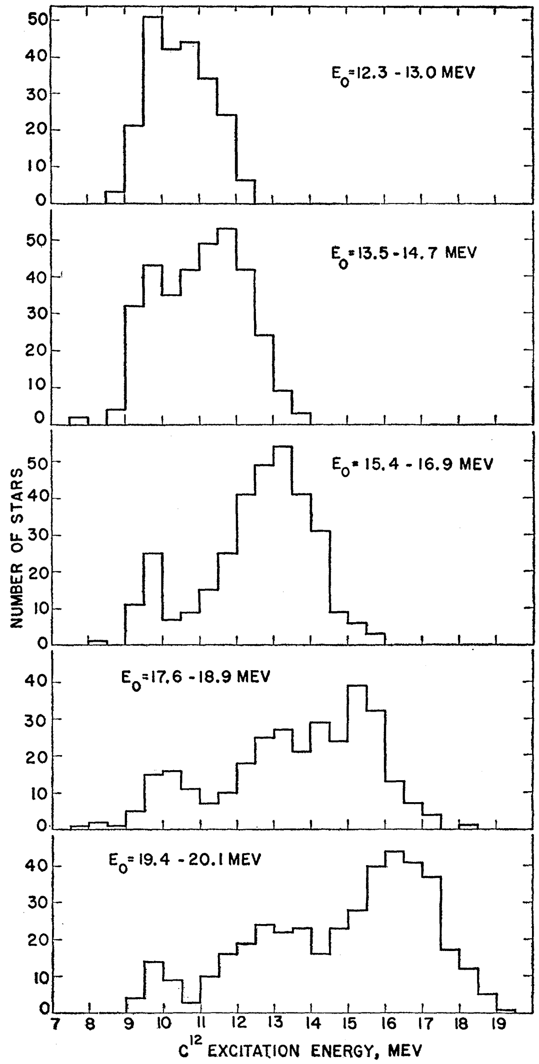

FIG. 3. Calculated values of the excitation energy of C^{12} for the five groupings of incident neutron energy 12.3–13.0, 13.5–14.7, 15.4–16.9, 17.6–18.9, and 19.4–20.1 Mev. In each case a peak is seen at 9.7±0.5 Mev, presumably the known level in C^{12} at 9.6 Mev. Above 10.5 Mev the peak shifts with increasing neutron energy. In this region the level spacing is less than the resolution of the experiment.

C^{12} are shown in Fig. 3. For each group of bombarding energies there appears a level at 9.7±0.5 Mev, presumably corresponding to the known level at 9.61 Mev.[2] Another peak is evident at higher excitation energy, but its energy does not remain constant as E_0 increases. The lack of resolved peaks above 9.6 Mev may be due to the fact that in this region the level spacing is less than the experimental resolution or that C^{12*} is not being formed with values of excitation energy greater than 9.6 Mev.

To distinguish between (3) and (4) the excitation energy of Be^{8*} may be calculated from

$$E_{ex}(Be^8)=E_1+E_2-0.1 -\tfrac{1}{8}[(X_1+X_2)^2+(Y_1+Y_2)^2+(Z_1+Z_2)^2],$$

where 0.1 is the excitation energy of the virtual ground state of Be^8. Again one cannot tell which two of the three alpha particles came from the Be^{8*}, so that three calculations must be done for each star, giving at most one-third correct values superimposed upon a two-thirds background of spurious values. The histograms of Fig. 4 illustrate the results. In each case there is a peak corresponding to the formation of Be^8 in its ground state. Furthermore, a star in which C^{12} was left in the 9.6-Mev level has sufficient energy to decay only to the ground state of Be^8. Events which give an excitation energy of C^{12} between 9 and 10.5 Mev are found also to give at least one value for the excitation energy of the ground state of Be^8, as indicated in Fig. 4. Now the two spurious values accompanying this true value may be removed, as is also shown in Fig. 4. The events corresponding to $E_{ex}(C^{12})>10.5$ Mev, show a peak at 3 Mev which may be identified with the well-known broad level in Be^8 at 2.91 Mev. The fact that the ground state of Be^8 is formed in more cases than the 9.6-Mev state in C^{12}, coupled with the absence of any indication of the formation of Be^{9*}, is further evidence, admittedly somewhat roundabout, for process (3), and therefore implies that C^{12*} is formed at excitations above 10.5 Mev.

Six events were found which had $E_{ex}(C^{12})$ in the interval 7.5–8.5 Mev. There is a level[2] in C^{12} at 7.68 Mev which is unstable by 0.31 Mev to breakup into an alpha particle plus Be^8 in the ground state. The Coulomb barrier would inhibit this disintegration although it might still compete with a γ transition to the 4.43-Mev level (a γ transition to the ground state has not been observed and would be strictly forbidden if the 7.68-Mev level is 0^+). A disintegration which proceeds through this level will be observable in the emulsion only when the motion of the C^{12} and Be^8 in the center-of-mass system is in the same direction as the center-of-mass motion thus combining to give the three alpha particles an energy in the laboratory system large enough to be observed. The resultant star would then have three prongs contained in a fairly small cone about the incident neutron direction. All six of the above events were of this type and also had a value of $E_{ex}(Be^8)$ in the range -0.5 to 0.5 Mev. Unfortunately no estimate may be made of the cross section, since at most only a small fraction of the events are observable as three-pronged stars. That the 7.7-level does disintegrate into three alpha particles was deduced by Miller *et al.*[12] from their failure to observe the recoil C^{12} nuclei from this level in the inelastic scattering of alpha particles.

It is of interest to calculate the distribution in alpha-particle energy which would result if (4) were the mechanism of the reaction for the events that do not go through the 9.6 C^{12} level, and the statistical assumption of equal probability in phase space is made for the alpha particles. The energy distribution for three alpha par-

[12] Miller, Rasmussen, and Sampson, Phys. Rev. **95**, 649 (1954).

ticles[13] is

$$P(E_\alpha)dE_\alpha=\mathrm{const}(E_\alpha)^{\frac{1}{2}}(E_{\max}-\tfrac{3}{2}E_\alpha)^{\frac{1}{2}}dE_\alpha,$$

where E_α is the alpha energy in the C^{12} center-of-mass system and $E_{\max}=E_{\mathrm{ex}}(C^{12})-7.28$ Mev, the energy available to the three alpha particles. To compare with Fig. 4 we may express the above formula as a function of

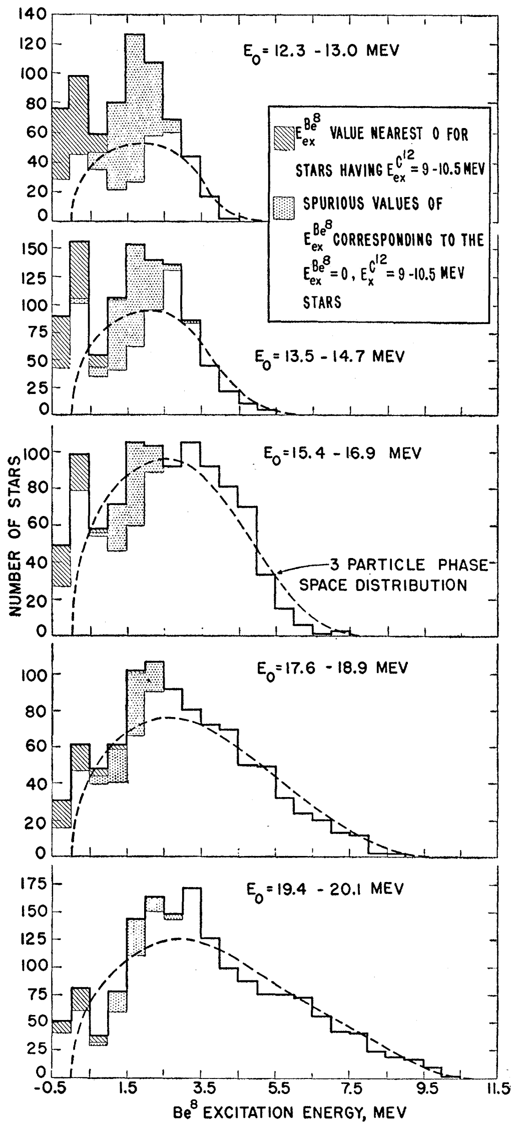

FIG. 4. Calculated values of the excitation energy of Be^8. Since this excitation energy must be calculated for each prong of the star, only one value in three can be valid. The lined parts of the histograms are where the excitation energy of Be^8 has a value nearest zero for the stars which have an excitation energy of C^{12} in the 9–10.5 Mev region. The dotted parts indicate the two corresponding spurious values. The dotted line is a theoretical phase space curve normalized to the remaining part of the histogram.

[13] Fokker, Kloosterman, and Belinfante, Physica **1**, 705 (1933–34); E. Fermi, *Elementary Particles* (Yale University Press, New Haven, 1951), p. 44.

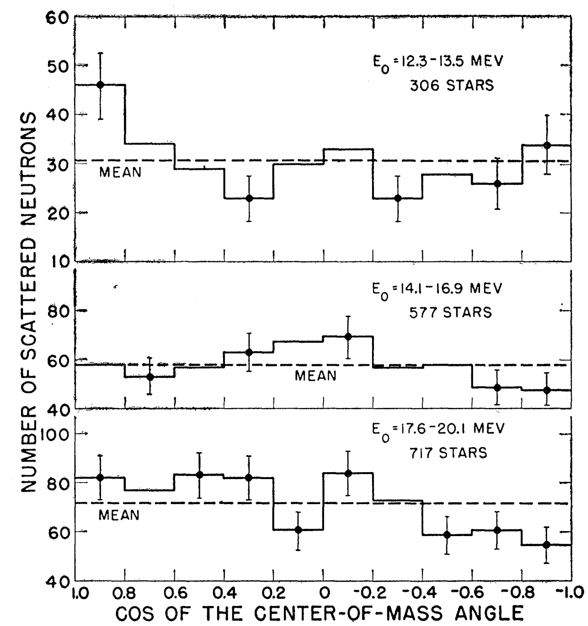

FIG. 5. Angular distribution of the scattered neutrons in the C^{13} center-of-mass system for the three groupings of incident neutron energy: 12.3–13.5, 14.1–16.9, and 17.6–20.1 Mev.

$E_{\mathrm{ex}}(Be^8)$, since $E_{\mathrm{ex}}(Be^8)=E_{\mathrm{ex}}(C^{12})-7.28-\frac{3}{2}E_\alpha$. Then

$$P[E_{\mathrm{ex}}(Be^8)]dE_{\mathrm{ex}}(Be^8)$$

$$=\frac{18}{\pi E_{\max}{}^2}[E_{\mathrm{ex}}(Be^8)]^{\frac{1}{2}}[E_{\max}-E_{\mathrm{ex}}(Be^8)]^{\frac{1}{2}}dE_{\mathrm{ex}}(Be^8).$$

From the experimental values for $E_{\mathrm{ex}}(C^{12})$ above 10.5 Mev and the above formula, the curves shown in Fig. 4 were derived. In each case it may be seen that the levels at 0 and 3 Mev rise well above the statistical curve. However, the fit to the high-energy tail becomes increasingly good as the bombarding energy increases.

A discussion of mechanism (5) which involves a phase space distribution among four particles will be given later.

6. ANGULAR DISTRIBUTIONS

In order to improve the statistics the data were combined into three groups: $E_0=12.3$–13.5 Mev; 14.1–16.9 Mev, and 17.6–20.1 Mev. The angular distribution of the scattered neutrons in the C^{13} center-of-mass system, Fig. 5, is isotropic within the experimental error; this implies that the angular distribution of the C^{12}'s is also isotropic. As a check, the angular distribution of the alpha particles in the C^{13} system was also computed, Fig. 6, and is essentially isotropic as it must be since the angular distribution of the C^{12}'s is isotropic. As a further check, the angular distribution in the C^{13} system of the first alpha particle emitted from the stars which had $E_{\mathrm{ex}}(C^{12})=9.6$, $E_0=12.3$–13.5 Mev, and $E_{\mathrm{ex}}(Be^8)=0$ Mev was plotted. This also must be isotropic, but as shown in Fig. 7 the plot rises almost linearly from zero

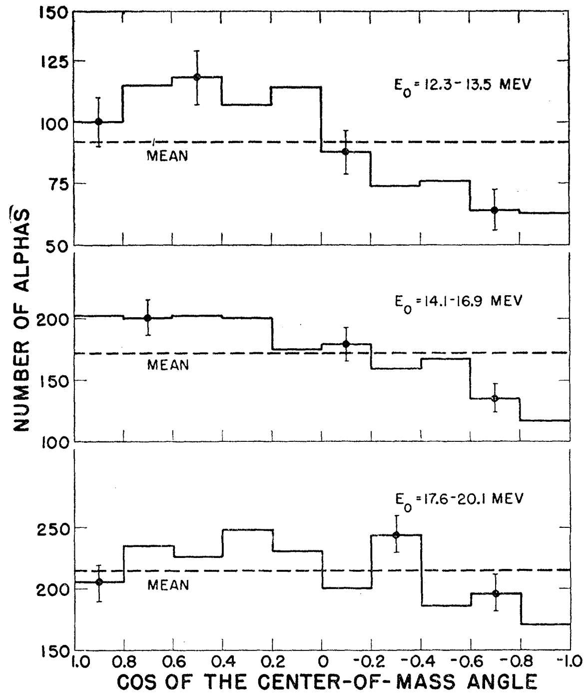

FIG. 6. Angular distribution of the alpha particles in the C^{13} center-of-mass system for the three groupings of incident neutron energy: 12.3–13.5, 14.1–16.9, and 17.6–20.1 Mev.

at 0° to a maximum at 180°. The interpretation of this result is that when a star disintegrates via the 9.6-Mev level in carbon it is less likely to be observed if the Be^8 is emitted in the backward direction. There are two reasons why a three-prong star may appear to the scanner to have only two prongs: (1) One alpha particle may have such a small energy in the laboratory system that it does not give a track long enough to be observable; and (2) when the reaction proceeds via the ground state of Be^8, the breakup energy of Be^8, 0.1 Mev, is so small that the two tracks may not be distinguishable as separate tracks, especially if their plane is perpendicular to the plane of observation. It is likely in most cases that a combination of these two effects causes a star to be missed.

One may now question the isotropy of the C^{12}'s, when only part of the disintegrations have been observed.

TABLE II. The four determinations of the observed cross section at 14.1 Mev.

Plate No.	No. of stars measured	No. of stars counted	Plate thickness (microns)	Neutron flux measured by proton recoils	Neutron flux measured by α-particle monitor	Observed cross section σ_{obs} in mb
UX-95	···	273	170	$1.30\cdot 10^8$	$1.36\cdot 10^8$	159
UX-96	···	378	170	$1.19\cdot 10^8$	$1.37\cdot 10^8$	160
UX-99	···	233	170	$1.15\cdot 10^8$	$1.36\cdot 10^8$	148
UX-103	57	···	160	$0.98\cdot 10^8$	$1.14\cdot 10^8$	145

Mean σ_{obs} at 14 Mev $=155\pm 23$ mb.

To investigate this point the angular distribution of the first alpha particle, $E_0=12.3$–13.5 Mev, was broken down into contributions from five different angles of emission of the C^{12}. Although the statistics are meager, the distribution of the first alpha is similar in each case, indicating that the direction of emission of the C^{12} has a minor effect on whether or not the star is observed.

7. CROSS SECTIONS

The plates irradiated at the Cockcroft-Walton were used to determine the observed cross section at 14 Mev. The flux on each plate was found by measuring proton recoils on the plates and by counting the accompanying alpha particles from the *d*-T reaction. Since the plate itself attenuates the flux to some extent, the alpha-counter result should always be high and so was used

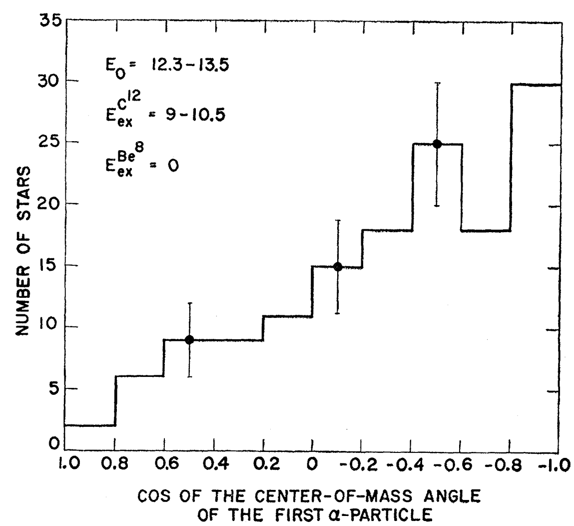

FIG. 7. Angular distribution of the first alpha-particle emitted in the chain $C^{12}(n,n')C^{12*}(\alpha_1)Be^{8*}(\alpha_2,\alpha_3)$ where the incident neutron energy lies between 12.3–13.5 Mev, the excitation energy of C^{12} lies between 9–10.5 and the excitation energy of Be^8 is zero.

only as a check of the reasonability of the answer given by the proton recoils. The number of carbon atoms per cc was taken as 1.37×10^{22}, the value given by Ilford[14] corrected to 30% relative humidity.[15] The emulsion thickness was measured by a dial gauge. The flux, number of stars counted, plate thickness, and observed cross section for each plate are tabulated in Table II.

The observed cross section at other energies in the 12–20 Mev range is

$$\sigma_{obs}(E)=\frac{t_{14}F_{14}N_EA_{14}}{t_EF_EN_{14}A_E}\sigma_{obs}(14),$$

where t is the emulsion thickness, F the neutron flux, N the number of carbon stars observed, and A the area

[14] Ilford technical leaflet, 1949.
[15] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report AERE *G/R* 664 (unpublished).

read on the plate. The angular distribution of the neutrons from the $T(d,n)He^4$ reaction has not been determined at $E_d=3.33$ Mev. To find the relative neutron flux at each angle, it is assumed that the angular distribution was the same as for the $He^3(d,p)He^4$ reaction, as is true at 10 Mev.[16] Additional support for this assumption is furnished by the fact that the mirror reactions $D(d,n)He^3$ and $D(d,p)T$ have the same angular distribution at 3.5 and 10.3 Mev.[17] The following least-squares fit was made to the data of Yarnell *et al.*[18] at 3.56 Mev:

$$d\sigma(\phi)=5.021+0.997\cos\phi-0.174\cos^2\phi-1.662\cos^3\phi+5.574\cos^4\phi;$$

it was then transformed to the laboratory system to give the relative flux at each angle. The attenuation of the

TABLE III. The observed cross section between 12.3 and 20.1 Mev. The last five plates are check plates. The check plate result has been averaged with the other plate at the same energy to give the values listed in the upper part of the table.

Plate No.	Average energy in Mev	No. of stars measured	No. of stars counted	Flux relative to 14 Mev	Plate thickness relative to 14 Mev	Observed cross section and total error in mb
C3-9	20.1	90	...	3.10	1.05	223±40
C3-8	19.8	94	...	2.63	1.00	241±43
C3-11	19.4	87	116	2.11	1.06	204±36
C3-7	18.9	92	205	1.78	1.01	183±32
C3-12	18.3	92	93	1.48	1.07	280±50
C3-6	17.6	91	...	1.40	0.95	244±48
C3-13	16.9	91	111	1.22	1.06	265±47
C3-5	16.2	96	110	1.18	1.04	279±50
C3-14	15.4	103	...	1.05	1.03	207±40
C3-4	14.7	95	...	0.90	1.05	192±37
C3-15	14.1	90	311	1.00	1.00	155±23
C3-3	13.5	93	...	0.96	0.99	135±26
C3-16	13.0	90	98	1.08	1.04	101±18
C3-2	12.6	72	87	1.20	1.02	78±15
C3-17	12.3	91	108	1.33	1.00	110±26
B10-b	20.1	83	...	3.35	1.0	
B11-8	19.8	92	...	2.95	1.0	
B10-a	19.4	113	...	2.39	1.0	
B11-7	18.9	...	80	2.84	1.0	
B10-15	14.1	...	198	1.00	1.0	

flux by the plate was determined experimentally and a correction applied when necessary.

The relative thickness of each plate was found by washing the glycerine out of the emulsion and measuring the final thickness of the area where the plate was scanned. Several of the plates were also chemically analyzed for their nitrogen content. The relative thicknesses found in this manner varied from the former determination by 12% at most. The observed cross section as a function of the bombarding energy is given in Fig. 8, and the pertinent data compiled in Table III.

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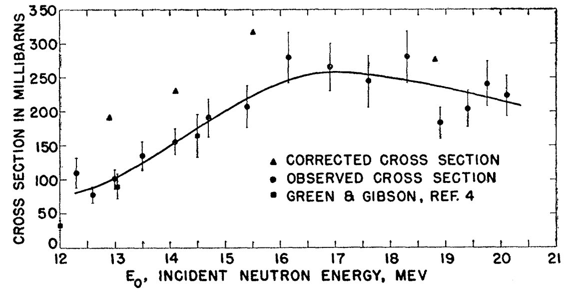

FIG. 8. The observed cross section for the formation of carbon stars for incident neutron energies from 12.3–20.1 Mev. Relative errors are shown. The squares are the values of Green and Gibson (reference 4). The triangles are the corrected cross section for the energy groupings: 12.3–13.5, 13–15.4, 14.1–16.9, and 17.6–20.1 Mev.

The following errors are present in the observed cross section at 14 Mev:

(1) Carbon content of the emulsion, emulsion thickness, area scanned, neutron flux, and statistical uncertainty—5%.

(2) Star identification, i.e., is the observed three-prong event actually a carbon star—10%.

(3) Star recognition. This contribution to the error arises from the variation in ability from one observer to another to recognize the borderline cases where the third prong is very short or barely resolvable from another prong. It was found that observers would differ at most in one star out of ten, so this uncertainty is estimated at 10%.

These errors combine for a total of 15% at 14 Mev.

Additional uncertainties present at other energies are:

(4) Relative emulsion thickness—5%.

(5) Relative angular distribution—2%, except below $E_0=12.5$ Mev—15%.

(6) Statistical uncertainty, which varied from 5% to 10%.

The cross section values of Green and Gibson[4] are also shown on Fig. 8. Although they are somewhat lower, the quoted errors overlap.

In Sec. 6 it was shown from the angular distribution of the first alpha in the case $E_0=12.3$–13.5 Mev, $E_{ex}(C^{12})=9.6$ Mev and $E_{ex}(Be^8)=0$ Mev, that not all the three-pronged events were being found. Since the angular distribution should be nearly isotropic, the correction factor must be something near two.

In correcting the observed cross section the following assumptions are made for the stars which do not go through the 9.6-Mev level in C^{12}: (1) All disintegrations proceed via the chain $C^{12}(n,n')C^{12*}(\alpha_1)Be^{8*}(\alpha_2\alpha_3)$; (2) if one of the three values for $E_{ex}(Be^8)$ calculated for a given star lies in the range -0.5 to $+0.5$ Mev, the disintegration went via the ground state of Be^8. These events are designated by $E_{ex}(C^{12})>10.5$, $E_{ex}(Be^8)=0$. (3) The cases not included in $E_{ex}(C^{12})>10.5$, $E_{ex}(Be^8)=0$ are assumed to decay via the 3-Mev state in Be^8 if one of their three values for $E_{ex}(Be^8)$ lies in the range 2–4 Mev.

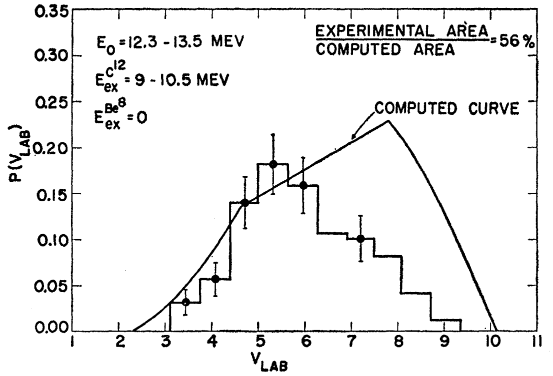

FIG. 9. Theoretical curve fitted to experimental laboratory velocity distribution for $E_0=12.3$–13.5, $E_{ex}(C^{12})=9$–10.5 and $E_{ex}(Be^8)=0$ Mev.

The method adopted to correct the observed cross section is the following: It was found that the shape of the calculated curve for the distribution in laboratory velocity of the first alpha particle was quite insensitive to the angular distribution assumed for the C^{12} or the first alpha. In categories where stars are missed (as indicated by the observed angular distribution of the first alpha), the computed curve, when normalized to fit the experimental points for small values of laboratory velocity, lies above the experimental curve for higher values of v_{lab} (Fig. 9). This corroborates the conclusion deduced from the angular distribution, i.e., all the stasr are observed only if the first alpha goes backward, and the Be^8 goes forward in the C^{13} center-of-mass system. A check on this procedure is furnished by the events where $E_0=17.6$–20.1 Mev, $E_{ex}(C^{12})=14$–19 Mev, and $E_{ex}(Be^8)=2$–4 Mev. One would expect to see most of these stars because of the large energies involved, and this is borne out, as the computed curve agrees with the experimental histogram within the statistical uncertainty over the entire range of v_{lab}.

The procedure for calculating the correction to the observed cross section then was to compute the theoretical laboratory velocity distribution for a particular E_0, $E_{ex}(C^{12})$, and $E_{ex}(Be^8)$ and fit it to the experimental curve over as large a range of v_{lab} as possible. The difference in area between the two curves is the correction that was added to the observed cross section. Table IV gives the various categories of E_0, $E_{ex}(C^{12})$, and $E_{ex}(Be^8)$, their corrections, and the total cross section for $E_0=12.3$–13.5, 14–16.1, and 17.6–20.1 Mev. A further point was computed for $E_0=14.1$ Mev from the data for $E_0=13$–15.4 Mev. Figure 8 depicts the corrected cross section as a function of E_0. The error in the corrected cross section is difficult to estimate. However, it was assumed that the calculation of the correction to be added to the observed cross section was good to 25% and this error combined with the one in the observed cross section is the uncertainty which is tabulated.

The corrected cross section does not include any contribution from the 7.7 level in C^{12}, as the data were insufficient to make any estimate of how many of these events were missed.

The cross section of 230 ± 50 mb for the $C^{12}(n,n')3\alpha$ process at 14 Mev may be correlated with other cross-section measurements on carbon at this energy. Levels in carbon excited by inelastic neutron scattering must decay (1) into three alpha particles, (2) by gamma emission, or (3) by the production of internal pairs. This last mode of decay has a small probability compared to gamma emission and so will be disregarded.[19] The cross section for gamma emission has been measured variously as 190,[20] 245 ± 35,[21] or 300 mb.[22] Any one of these added to the 230 mb agrees with the 0.5 ± 0.2 barn found for inelastic neutron emission.[23]

Furthermore the inelastic collision cross section as measured by the sphere technique[24] should be the sum of the above three processes plus (4), the reaction $C^{12}(n,\alpha)Be^9$, whose cross section was deduced to be 80 ± 20 mb[24] [all excited states of Be^9 are neutron-unstable, decaying according to $Be^{9*}(n)Be^{8*}(2\alpha)$ or $Be^9(\alpha)He^5(n)He^4$], and (5) a contribution from the elastic scattering at large angles, estimated as 50 mb.[24] If the 245 ± 35 mb value is taken for the gamma cross section, the sum of these five is 605 ± 70 mb, in good agreement with the 0.601 ± 0.006 barn found for the inelastic collision cross section.

TABLE IV. The corrected cross section as computed for the three points 12.9 (12.3–13.5), 15.5 (14.1–16.9), and 18.8 (17.6–20.1) Mev. The 14.1 (13.0–15.4) Mev point is not an independent one but was computed for comparison with other known cross sections at 14 Mev.

E_0 in Mev	$E_{ex}(C^{12})$ in Mev	$E_{ex}(Be^8)$ in Mev	Observed cross section in mb	Corrected cross section in mb	Corrected cross section and total error in mb
12.9	9–10.5	0	48	85	190 ± 50
	>10.5	−0.5 to 0.5	34	81	
	>10.5	2 to 4	18	24	
15.5	9–10.5	0	49	76	316 ± 73
	>10.5	−0.5 to 0.5	77	133	
	>10.5	2 to 4	96	107	
18.8	9–10.5	0	22	35	283 ± 59
	10.5–14	−0.5 to 0.5	24	39	
	10.5–14	2 to 4	52	52	
	>14	−0.5 to 0.5	19	30	
	>14	2 to 4	97	97	
	others		30	30	
14.1	9–10.5	0	48	76	230 ± 50
	>10.5	−0.5 to 0.5	62	105	
	>10.5	2 to 4	45	49	

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[20] Scherrer, Theus, and Faust, Phys. Rev. **91**, 1476 (1953).
[21] M. E. Battat and E. R. Graves, Phys. Rev. **97**, 1266 (1955).
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[23] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).
[24] E. R. Graves and R. W. Davis, Phys. Rev. **97**, 1205 (1955).

8. ENERGY DISTRIBUTIONS OF THE EMITTED PARTICLES

Although it has been shown that there is good evidence for the mode of disintegration $C^{12}(n,n')C^{12*}(\alpha)Be^{8*}(2\alpha)$, there is an alternative explanation that also provides a reasonably good fit to the experimental data. One may assume that instead of having unstable intermediate nuclei formed along the decay chain, four particles are produced immediately, and their energy distribution in the center-of-mass system may be fitted by the assumption of equal probability in phase space. It has been shown[7,25] that the resulting energy distribution for any one of the particles is

$$N(\epsilon)d\epsilon = \text{const}\,\epsilon^{\frac{1}{2}}(1-\epsilon)^2 d\epsilon, \tag{8.1}$$

where ϵ is the ratio of the energy of the particle to the maximum energy it can have. If this distribution is valid, a plot of $[N(\epsilon)/\sqrt{\epsilon}]^{\frac{1}{2}}$ *vs* ϵ should give a straight line intersecting the abscissa at unity. Plots of $[N(\epsilon)/\sqrt{\epsilon}]^{\frac{1}{2}}$ are shown in Figs. 10 and 11 for the neutron and alpha particles. Since it has been shown that a number of the carbon stars are not observed, it is surprising that the neutron distribution fits as well as it does over the whole range of bombarding energies. The alpha-particle distribution for the highest E_0 also fits well. The poor fit at the lower energies is not surprising in view of the larger percentage of stars which are unobserved. One may well ask why the phase space distribution provides such a good fit when there is definite indication of the excitation of individual levels in C^{12} and Be^8. At the lower bombarding energies this agreement for the neutron distribution may be fortuitous because of the larger fraction of the stars which are not observed. In the case of the higher energies more levels are available in C^{12} so that the neutron distribution could be the sum over many levels. Some of the stars which give values of $E_{ex}(C^{12}) > 10.5$ Mev may not form C^{12*} at all, but disintegrate at once into the four particles. Moreover, if the chain $C^{12}(n,n')C^{12*}(\alpha)Be^{8*}(2\alpha)$ is correct the energy distribution of the last two alpha particles would be expected to follow some sort of a statistical distribution in the center-of-mass system. The first alpha particle seems to proceed primarily through the 3-Mev state of Be^8 which has a width of 1 Mev. Thus even if Be^8 is formed for each star, two-thirds of the alpha distribution is of a statistical nature, which, coupled with the breadth of the 3-Mev state, could quite possibly be in accord with the curve predicted from phase space considerations. Thus the apparently anomalous result that the data show evidence for the intermediate unstable nuclei C^{12*} and Be^{8*} and also for the four-particle phase space distribution may be due to the cumulative effects of several levels in C^{12} and Be^8 and to the statistical nature of two-thirds of the alphas corresponding to this mode of disintegration. On the other hand it may very well be that both processes occur, with the fraction of times the four particles emerge simultaneously increasing as the bombarding energy is increased.

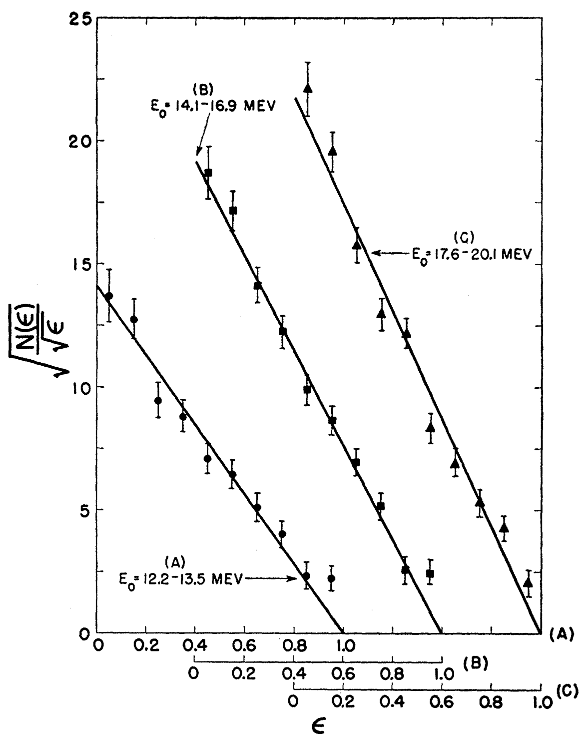

FIG. 10. Plot of the quantity $[N(\epsilon)/\sqrt{\epsilon}]^{\frac{1}{2}}$ *vs* ϵ for the scattered neutron where ϵ is the ratio of the neutron energy to the maximum neutron energy in the C^{13} center-of-mass system. $N(\epsilon)$ is the number of particles between ϵ and $\epsilon+d\epsilon$. This plot should be a straight line if the distribution in neutron energy follows a four-particle phase space distribution. The incident neutron energy groups are (A) 12.3–13.5, (B) 14.1–16.9, and (C) 17.6–20.1 Mev.

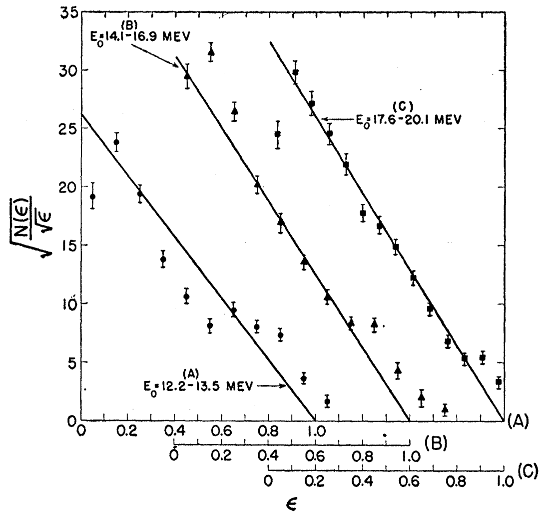

FIG. 11. Plots of the quantity $[N(\epsilon)/\sqrt{\epsilon}]^{\frac{1}{2}}$ *vs* ϵ for the alpha particles. The notation is the same as in Fig. 10.

[25] G. E. Uhlenbeck and S. Goudsmit, *Pieter Zeeman Verhandelingen* (Martinus Nijhoff, The Hague, 1935), p. 201.

Because the phase space distribution for four particles is already very similar to the Maxwell-Boltzman distribution (it becomes the same, of course, for a large number of particles), the neutron energy distribution may also be fitted by the evaporation equation[26]:

$$N(E)dE = \text{const} E e^{-E/T}. \tag{8.2}$$

The mechanism here would be that the neutron is evaporated from the compound nucleus, C^{13*}, and leaves C^{12*}, which then goes as $C^{12*}(\alpha)Be^{8*}(2\alpha)$. The experimental results do not distinguish between (8.1) and (8.2).

9. $C^{12}(n,n')3\alpha$ REACTION AS A NEUTRON MONITOR

Although not all the disintegrations of carbon into three alpha particles can be seen as three-prong events in the emulsion, it has been found feasible to utilize the observed cross section for carbon stars as a neutron monitor when the neutron source is a point source. As is evident from Fig. 2, the energy resolution is about 3 Mev and cannot compete with proton recoils in the emulsion where the energy resolution may be 0.3 Mev. However, at 14 Mev in a 200μ plate the ratio of observed carbon stars to proton recoils in a $10°$ cone which do not leave the emulsion is 3.5. This ratio increases rapidly with energy, because, while the n-p cross section and the probability that a proton recoil will remain within the emulsion both decrease with energy, the observed cross section for carbon stars increases with energy. At 20 Mev, this ratio is approximately 11.5.

In view of the estimated errors (Sec. 7), it is felt that carbon stars may be used to measure a neutron flux to 15% at 14 Mev and to about 20% elsewhere in the 12–20 Mev range. Realtive measurements may, of course, be made more accurately, especially if carried out by the same observer.

The authors would like to thank the Cockcroft-Walton and large electrostatic accelerator groups for their assistance in making the exposures and the plate analysts of the nuclear plate group for carrying out the microscope work. We are indebted to Dr. J. D. Jackson for making his phase space calculations available before publication. It is a pleasure to acknowledge the encouragement and many helpful suggestions of Dr. A. H. Armstrong.

[26] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 368.

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Angular Distributions for $Ti^{46,48}(d,p)Ti^{47,49}$ Reactions with 4.16-Mev Deuterons*

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Angular distributions of protons resulting from reactions of Ti^{46} and Ti^{48} with 4.16-Mev deuterons have been measured in the forward direction for several levels of the residual nuclei. For protons from the 1.35- and 1.70-Mev states of Ti^{49} the distributions show a peak at an angle about 5° larger than that expected from simple deuteron-stripping theory. The reaction to the ground state of Ti^{47} appears to proceed largely through the compound nucleus at this deuteron energy. The measured angular distribution of protons from the 1.40-Mev excited state indicates an assignment of $L=1$ for the captured neutron, hence odd parity and spin $\frac{1}{2}$ or $\frac{3}{2}$ to the level in Ti^{47}.

INTRODUCTION

THE stripping theory[1] of angular distributions for (d,p) and (d,n) reactions has proven a powerful tool in nuclear spectroscopy. In particular it has been possible to make parity assignments to many levels in the lighter nuclei, and in some cases spin assignments have also been possible. The extension to heavier nuclei, with moderate bombarding energy, has been hampered by the assumptions of the simple theory, in which both Coulomb effects and nuclear scattering of the incident deuteron and emergent nucleon are neglected. The present experiment, in addition to trying to provide information about the Ti^{47} and Ti^{49} nuclei, should be helpful in giving some indication as to how much the simple stripping theory breaks down when deuterons of energy less than the Coulomb barrier are used.

The angular distribution for the $Ti^{48}(d,p)Ti^{49}$ reaction has been measured by Bretscher *et al.*[2] using 10-Mev deuterons and by Pratt[3] with 2.6-Mev deuterons. The former are able to make definite assignments based on the simple stripping theory, and their results serve as a comparison to show deviations from the predicted angular distributions in the present experiment.

EXPERIMENTAL PROCEDURE

Thin targets of TiO_2 enriched in Ti^{46} and Ti^{48} were bombarded with 4.16-Mev deuterons from the Yale

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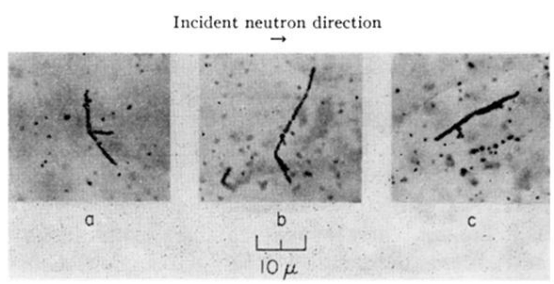

FIG. 1. Three typical carbon stars for $E_0=16.9$ Mev. In (b) and (c) the two prongs close together arise from Be^8 being left in its ground state. (c) illustrates the difficulty that often arises in resolving these two prongs. Only the thickness of the track and the scattering of the last grain of the shorter track indicate that these are actually two tracks.