Mechanism of the Reaction $C^{12}+p\rightarrow p+3\alpha$ at 29 Mev*

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A methane-filled expansion cloud chamber, operated at $\frac{1}{3}$ atmosphere, was used to study the $C^{12}+p\rightarrow p+3\alpha$ reaction. Two hundred events that satisfied momentum and energy conservation were accepted for analysis. One hundred forty-eight of these had all four prongs visible; the remaining fifty-two had only three visible prongs with the fourth prong directed into an invisible region of the chamber. One-quarter of the events proceeded via the Be^8 ground state and at least one-half via the 2.9-Mev level in Be^{8*}; possibly higher levels in Be^8 were also involved. Evidence for the participation of levels in C^{12} at 9.6, 16, 20, and 25 Mev was found. There is evidence that the $C^{12}(p,\alpha)B^9$ reaction also participates, with levels at 0 and 3.2±1.0 Mev. The possibility of the $C^{12}+p\rightarrow Li^5+Be^8$ reaction was investigated and it was concluded that it could account for at most five percent of the events. At least one example of the $C^{13}(p,d)3\alpha$ reaction was seen.

INTRODUCTION

ONE of the first successful analyses of a nuclear reaction in which the reaction products consisted of more than two particles was that of Dee and Gilbert[1] explaining the alpha-particle energy spectrum from $B^{11}(p,\alpha)Be^8$. Three alpha particles are produced in this reaction. For a bombarding energy of 200 kv the energy spectrum of the alpha particles can be divided into three groups[2]: (a) a homogeneous group, which contains about one percent of the alpha particles, at 5.7 Mev, (b) a broad group at 3.85 Mev, and (c) a continuous distribution extending from low energies to about 5 Mev, which contains roughly twice as many particles as Group 2.

These were interpreted by Dee and Gilbert as due to: (a) the reaction $B^{11}(p,\alpha)Be^8$, with the Be^8 formed in the ground state, (b) the reaction $B^{11}(p,\alpha)Be^{8*}$ with the Be^{8*} left in a state of excitation at 2.8 Mev. (The width of Group 2, 0.51 Mev full width at half-maximum, corresponds to a width of 0.77 Mev for this excited state), (c) the breakup of the excited Be^8 nuclei, $Be^8\rightarrow 2\alpha$.

In 1949, Hänni, Telegdi, and Zünti[3] observed three-prong stars in nuclear emulsions that had been exposed to the γ rays from protons on lithium. They determined the sum of the energies of the three prongs for each event (E_t), assuming them to be alpha particles. The distribution in E_t showed two peaks, one at 7.5 Mev and the other at 10.1 Mev. These values are in agreement with the known energies of 17.6 and 14.8 Mev for the lithium γ rays and the value of 7.4 Mev for the Q of the $C^{12}(\gamma,3\alpha)$ reaction. These stars were therefore identified as being due to this reaction produced in the carbon present in the emulsion.

The energy spectrum of the alpha particles from the stars due to the 17.6-Mev γ ray showed a continuum that went to 5.3 Mev and showed a marked peak at 4.7 Mev. This spectrum is similar to that obtained by Dee and Gilbert from the reaction $B^{11}+p\rightarrow 3\alpha$. The analysis was carried out in the same fashion and yielded similar results, i.e., a two-step process, in which the first step is a $C^{12}(\gamma,\alpha)Be^{8*}$ reaction where the Be^{8*} nucleus is left with an excitation energy of 3.0 Mev, and the second the breakup of the Be^{8*} into two alpha particles. They also noted stars that were interpreted as going through the ground state of Be^8.

Following this, many experimenters[4–11] have investigated the $C^{12}(\gamma,3\alpha)$ reaction at γ energies up to 300 Mev. The cross section as a function of energy shows two large peaks at γ energies of 19 and 29 Mev, with a marked minimum at 21 Mev. No events have been observed at energies above 42 Mev. Examination of some 2500 stars gives evidence that the two peaks are formed by the superposition of narrow resonances spaced at about 1-Mev intervals. The strongest of these lie at γ energies of 17.3, 18.3, 21.9, 24.3, 26.5, and 29.4 Mev. The presence of these multiple resonances and the strong minimum in the region of the giant (γ,n) resonance suggest a definite compound-nucleus reaction.[8]

At an energy of 17.6 Mev, the reaction proceeds predominantly via the 3.0-Mev level in Be^{8*} with about two percent going via the ground state. This preference for the 3.0-Mev excited level holds true for γ energies below about 19 Mev. For stars due to γ energies greater than 26 Mev the reaction seems to proceed via either the ground state in Be^8 (12 percent) or one of three levels in Be^{8*}, at 16.9, 17.8, or 16.4 Mev, with the 16.9-Mev level predominating. This level has $J=2$ and

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
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1 P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. (London) **154**, 279 (1936).
2 H. A. Bethe, Revs. Modern Phys. **9**, 217 (1937).
3 Hänni, Telegdi, and Zünti, Helv. Phys. Acta **21**, 203 (1948).
4 V. L. Telegdi and W. Zünti, Helv. Phys. Acta **23**, 745 (1950).
5 Goward, Telegdi, and Wilkins, Proc. Phys. Soc. (London) **A63**, 402 (1950).
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7 M. Elder and V. L. Telegdi, Helv. Phys. Acta **25**, 55 (1952).
8 F. K. Goward and J. J. Wilkins, Atomic Energy Research Establishment Report, GM/127, 1952 (unpublished); Proc. Roy. Soc. (London) **A217**, 357 (1953).
9 D. L. Livesey and C. L. Smith, Proc. Phys. Soc. (London) **A66**, 689 (1953).
10 C. H. Miller and A. G. W. Cameron, Can. J. Phys. **31**, 723 (1953).
11 S. D. Softky, Phys. Rev. **98**, 173 (1955).

even parity, and is possibly the analog of the Li^8 and B^8 ground states with isotopic spin $T=1$.

In the region between 19 and 26 Mev the mechanism of the reaction is uncertain. The proportion of events that go via the ground state of Be^8 increases with energy from about 5 percent to 18 percent in this region. Those events which go via the 3.0-Mev level in Be^8 can account for at most one-third of the events. It may be that higher levels in Be^8 are involved, or possibly even three-particle breakup in the remainder of the events. The present data are inconclusive on this point.

The breakup of C^{12} into three alpha particles has also been initiated by neutrons. Aoki[12] noted three-prong stars in a methane-filled cloud chamber exposed to Li+D neutrons. Their total energies were in agreement with the assumption of the reaction $C^{12}(n,n')3\alpha$. Most of the stars showed a random distribution of energy among the prongs, but there were some that had two short prongs and the other quite long. These have since been interpreted as events that went through the Be^8 ground level.

In 1949, Green and Gibson[13] exposed nuclear emulsions to neutrons from deuterons on lithium and observed three-prong stars. At the energies available the two possible reactions were

$$N^{14}+n\rightarrow Li^7+2\alpha-8.8 \text{ Mev},$$

$$C^{12}+n\rightarrow n'+3\alpha-7.4 \text{ Mev}.$$

The stars were analyzed to obtain the energies of the incident and scattered neutrons. The observations were sufficiently accurate to eliminate the possibility of the nitrogen reaction, and the stars were therefore identified as being due to the $C^{12}(n,n')3\alpha$ reaction.

The data of Green and Gibson were analyzed further by Livesey and Smith,[9] who found that the energy spectrum of the inelastically scattered neutrons showed two peaks corresponding to energy levels in C^{12} at 9.6 and 11.8 Mev. Those events which appeared to go via the 9.6-Mev level in C^{12} were all consistent with the assumption that they involved the ground state of Be^8. The events that corresponded to the 11.8-Mev level in C^{12} went via the broad 3.0-Mev level in Be^{8*}.

In this experiment methane was bombarded with 29-Mev protons to study the $C^{12}+p\rightarrow p+3\alpha$ reaction. It was expected that many of the above-mentioned features of the reaction mechanism would show up in the work. An investigation of this reaction is made difficult by the presence of three competing reactions, which yield the same end products and thus give the same appearance in a cloud chamber. The three possible reactions are

$$C^{12}(p,p')C^{12*}\rightarrow Be^8+\alpha\rightarrow 3\alpha, \quad (1)$$

$$C^{12}(p,\alpha)B^9\rightarrow Be^8+p\rightarrow p+2\alpha, \quad (2)$$

$$C^{12}(p,Li^5)Be^8\rightarrow p+3\alpha. \quad (3)$$

[12] H. Aoki, Proc. Phys.-Math. Soc. Japan **20**, 755 (1938).
[13] L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 296 (1949).

Reaction (1) is suggested as parallel to the $C^{12}(\gamma,3\alpha)$ and $C^{12}(n,n')3\alpha$ reactions in which C^{12} is formed in an excited state as an intermediate nucleus. The first step of Reaction (2) has been identified at a bombarding energy of 18 Mev.[14] Peaks in the alpha-particle spectrum corresponding to the ground and first excited levels of B^9 were seen, together with a large background of alpha particles at low energies. Reaction (3) is included as being energetically possible.

EXPERIMENTAL PROCEDURE

The cloud chamber was operated in the annex of the linear-accelerator building. The proton beam from the linear accelerator was deflected 10° by the steering magnet and sent down a 25-foot evacuated tube to the chamber. The last 10 feet of the beam tube was made of soft iron pipe with a 2-inch outside diameter and 0.25-inch walls. This was done so that the beam diameter was not greatly increased through deflection and momentum analysis of the beam by the fringing field of the Helmholtz coils. A 0.001-inch aluminum thin window covered the end of the beam tube. An air ionization chamber was placed between the end of the beam tube and the cloud chamber to permit the operator to adjust the machine for maximum beam intensity between pictures. Three collimators were used: the four-jaw collimator at the exit end of the linear accelerator; a carbon collimator with a diameter of 0.1 inch, placed at the exit of the steering magnet; and a carbon collimator of $\frac{1}{8}$-inch diameter at a distance of 15 feet along the beam tube, shadowed by a carbon clipper of $\frac{5}{32}$-inch diameter placed 1 foot away. The four-jaw collimator was used to limit the intensity of the beam entering the chamber. The carbon collimators defined the beam direction and diameter.

The air-cooled Helmholtz coils produced a peak field of 6870 gauss with a current of 2200 amperes when used in pulsed operation. Current was supplied by a 540-kw minesweeper generator with a 2-ton flywheel mounted between the motor and generator. The current pulse, synchronized with the cloud-chamber cycle, had a rise time of $2\frac{1}{2}$ seconds and remained stationary at its peak for about 0.2 second. A cycle time of about 2 minutes was used. This limit was imposed by the maximum temperature at which the magnet could be safely operated.

The cloud chamber was generally cylindrical in shape and was operated with its axis of rotation horizontal. It consisted of front and back volumes of 15-inch inside diameter, the front volume being 4 inches high and the back volume 5 inches. The beam entered the chamber through a thin window of 0.001-inch aluminum. Front and back volumes were separated by a lucite piston sealed by a diaphragm of $\frac{1}{32}$-inch gum rubber. Pantograph arms were used to keep the piston parallel to the front glass during the expansion. Black velvet over

[14] J. B. Reynolds, Phys. Rev. **98**, 1289 (1955).

a cheesecloth pad covered the piston on the front volume side. This was used as a black background for the photography and as a wick to supply water vapor to the top of the chamber. A clearing field was maintained between the piston and a grid of 3-mil tungsten wire mounted on a Lucite spacing ring just back of the front glass. Fiducial marks of known separation were scribed on the inside of the front glass.

Since it was desired to operate at a total pressure of about $\frac{1}{3}$ atmosphere, a cylindrical tank was put over the pop valve and evacuated before each expansion. The back-volume air pressure was controlled by a Moore regulator using a vacuum as the reference pressure. Slow expansions were obtained by the use of a solenoid valve which simultaneously connected the back volume to the vacuum tank and turned off the back-volume air supply.

Stereopairs were taken on Eastman Linagraph Ortho film with a matched pair of Wollensak Velostigmat 127-mm lenses operated at $f/8$. Illumination was by means of two General Electric FT422 flash tubes. Each tube was connected across a 256-microfarad capicator bank which was charged by a 2000-volt power supply.

The linear accelerator was operated at a repetition rate of 15 pulses per second. Each pulse was 600 μsec long. Synchronization with the cloud chamber equipment was effected by means of the linear accelerator equipment pulse, which preceded the beam by about 20 μsec. The cloud chamber control sequence operated the magnetic field, fast expansion, clearing field, and lights. The timing of the fast part of this sequence was recorded on paper tape with marks for chamber bottom equipment pulse and lights. The beam was brought into the chamber four milliseconds after the piston hit bottom and the lights were flashed 33 milliseconds after the beam. At the end of the fast sequence the linear accelerator beam was turned on to permit the operator to adjust for maximum beam. A pneumatically operated lead shutter prevented the beam from entering the chamber during this time. Two slow expansions were used, followed by a waiting period of 50 seconds until the beginning of the next cycle.

ANALYSIS OF THE DATA

After development, the film was scanned under a high-power stereoscopic viewer, and all events that appeared to consist of three or more concurrent tracks were listed. A sketch of the appearance of each event was made. The film was then put in the projection apparatus, which duplicated the geometry of the camera optics and produced full-sized images of the tracks on a translucent screen.

Measurements were made of dip angle, azimuthal angle, and range or slant radius of curvature for each track of the selected events. A correction was applied for the change in azimuth as the beam traversed the chamber. Density of ionization and characteristic endings were used to identify the particles. The errors in each type of measurement were investigated; a complete discussion can be found elsewhere.[15] All the selected events were read twice, and where discrepancies greater than the expected errors were noted, the film was read a third time.

The measured data, the assumed identity, the magnetic field, and the range-energy relation for the gas[15] were used to calculate the energy and the rectangular components of momentum for each prong of the selected events. Also, the errors in these quantities were calculated by propagation of the errors of measurement, assuming the latter to be independent. The error calculation was done to obtain a quantitative acceptance criterion for the events.

Each event read was identified as a three-, four-, or five-prong event according to the number of visible prongs. In order to separate those events caused by the $C^{12}(p,p')3\alpha$ reaction from all the three-, four-, and five-prong events read, the following identification procedure was used. The events of interest consist of four prongs; one (the proton) is lightly ionizing and the other three (the alpha particles) have much greater ionizing power. Furthermore, the total energy of the event is equal to the beam energy less the reaction energy, and the total momentum is equal to the incident momentum. Of course particle identification may sometimes be uncertain because of chamber condition or because the prong has a range of less than about 3 cm.

There were seven five-prong events consisting of a proton and four alpha particles, which were identified as examples of the $O^{16}(p,p')4\alpha$ reaction in the oxygen present in the water vapor. The total prong energies of each of these events ($\sim$14 Mev) were consistent with the identification, and the momentum balance was satisfactory. The alpha prongs were short, about 3 to 4 cm, so that one could easily be hidden by the opaque region of the beam. Therefore, those four-prong events which did not balance in longitudinal momentum and for which the total energy was about 14 Mev had to be investigated for the possibility that they were in fact oxygen events with the fifth prong hidden by the beam.

Among the four-prong events there were some that did not have the proper appearance. They had two lightly ionizing prongs. These events were investigated in the high-power stereoscopic viewer, and most of them were identified as the overlap of two elastic p-C scatters. In the five remaining events, one of the two lightly ionizing prongs was discarded and the event was calculated as a three-prong event. Subsequent calculations disposed of three of them.

The remainder of the four-prong events, 211 in all, were tested for energy and momentum balance to

[15] John L. Need, University of California Radiation Laboratory Report UCRL-2806 (unpublished).

determine whether they were the $C^{12}(p,p')3\alpha$ reaction. Where the identification of one or more prongs of an event was in doubt, that choice of identity was made which gave three alphas and one proton together with the smallest deviation from momentum balance. Furthermore, if the momentum balance could be improved by interchanging the particle identities of two of the prongs of an event, it was done. All the identities obtained by this requirement of best momentum balance were checked in the high-power stereoscopic viewer by another observer, and if the ionization did not check with the identity chosen, the event was not accepted. Only two events where the identity of two particles had been interchanged were accepted. Of those events where the initial particle identification was uncertain, eight were accepted.

Of the 211 events with four prongs visible that were assumed to be carbon events, 135 were accepted after the first balance. The remainder of the events were examined to see if any of them could be identified as oxygen events. A fifth prong was fabricated which balanced the momentum. The requirements for acceptance as an oxygen event were that this prong be directed into an invisible portion of the chamber and that the total energy of the event be about 14 Mev. Ten events met these requirements. The total number of oxygen events (17) is in agreement with the number expected from the amount of oxygen present in the chamber.

One event was identified as a $C^{13}(p,d)3\alpha$ reaction. The deuteron track had a radius of curvature equal to that of the beam, but with a density of ionization three times that of a beam proton. When it was identified as a C^{12} event, the total energy was greater than the beam energy; but when it was identified as a C^{13} event, the total energy was correct. Two other events were identified as possibly due to this reaction.

Those events left over, i.e., those not identified, were re-examined under the high-power stereoscopic viewer with the data cards at hand. More detail was visible in the viewer than was visible on the projector because a greater intensity of illumination was available. Each event was examined carefully to see if any reason could be found either to discard it or to adjust the data so that it would become acceptable. These reasons included excessive turbulence, possible overlap of two events, improper choice of the fourth prong when more than four prongs came from the same region, and a scatter that could change the measurement of the radius of curvature. Further, the cards were re-examined to see what adjustments were necessary to bring the event into balance. Forty events were discarded for one or more of the above reasons, but there were 23 that had the appearance of being good events. So that personal prejudice could be avoided, these events were reread by another member of the group. The result of this final examination was that only 5 of the events became acceptable. Of the others, 15 had momentum deviations that were outside the acceptable limits but still within twice these limits, i.e., they were probably true $C^{12}(p,p')3\alpha$ events rejected by the acceptance criteria.

The four-prong events were accepted on the basis of momentum and energy requirements. For each event the X, Y, and Z components of the total momentum were found. Properly, the X and Y components of the total momentum should have been zero and the Z component equal to the momentum of the incident proton (2.70 in the units used). An event was not accepted if the deviation from the proper value of any one of the three components of the total momentum was greater than the sum, over the prongs of the event, of the errors in that component. Further, those events were rejected for which the total energy differed from 21.6 Mev by more than the sum of the errors in the prong energies. (This value is equal to the beam energy less the reaction energy of 7.4 Mev for the $C^{12}\rightarrow 3\alpha$ reaction.) The simple sum of the errors was used, rather than the correct square root of the sum of the squares, for the sake of ease in computation. The simple sum lies between one and two times the value of the square root of the sum of the squares, and was considered to be a satisfactory criterion for selection.

For each of the 138 events with three visible prongs a fourth prong was fabricated to give perfect momentum balance. The events were accepted when the following requirements were met: (a) the deviation from 21.6 Mev of the sum of the energies of the four prongs was less than twice the sum of the errors in the energies of the three measured prongs; (b) the fabricated prong was directed into an invisible region of the chamber; and (c) the invisible particle was chosen so that the event had one proton and three alpha particles. Those three-prong events which met the energy requirement, 60 in all, were then examined under the high-power stereoscopic viewer to determine whether the prongs would or would not have been visible were they at the angles computed. Forty-six were accepted as bona fide $C^{12}(p,p')3\alpha$ events, since the fourth prong, as calculated, could not have been seen.

Because of the greater visibility into the opaque region when the film was viewed on the stereoscopic viewer, there were 14 additional events for which the fourth prong was found where computed. In six of these cases only the angles of the fourth prong could be read; it was impossible to make a reasonable estimate of the momentum. The momentum was chosen to give the minimum value of the sum of the deviations from momentum balance. For the remaining eight events it was possible to get all the measurements on the fourth prong and therefore these eight events were then considered as four-prong events. They were all acceptable. Of the three-prong events that did not meet the energy requirement, the great majority had an energy around 15 Mev. However, no further attempt was made to identify them.

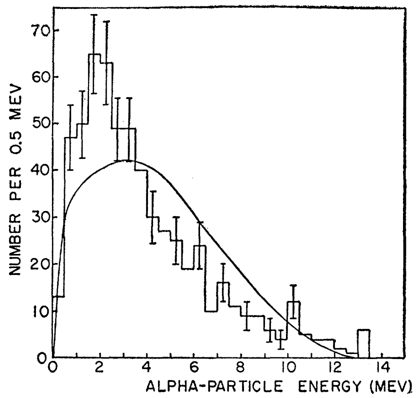

Fig. 1. Total center-of-mass energy distribution for alpha particles. The indicated errors are the statistical standard deviations.

The total number of events accepted was 200. One hundred and forty-eight of them had all four prongs visible; the other 52 had three prongs visible and the fourth calculated to be in the invisible region of the chamber. In order to check whether the three-prong events that were accepted had the same characteristics as the four-prong events, the average value of total energy of an event was determined for each group. The average total energy of a four-prong event was 21.9 Mev and that of a three-prong event was 21.7 Mev, which is in very good agreement. However, some differences between the two groups did show up later in the investigation. There were very few events among the three-prong group that had a high-energy alpha particle—only three out of 52, as compared to 55 out of 148 for the four-prong events. Also, the proportion of three-prong events decreased for higher excitation energies in C^{12}, with 32±7 percent in the 8.0- to 17.0-Mev group and 21±5 percent above that.

The shorter a track, the larger the solid angle for which it would be hidden by the beam; and these shorter tracks would be produced in the events where the proton or one alpha particle took away most of the energy. Also, in an event with a high-energy alpha particle, the transverse momentum required to balance the event would place the short tracks at large angles to the beam. Because of these considerations, and the fact that the various energy distributions did not show any significant differences between three- and four-prong events, all events were treated together.

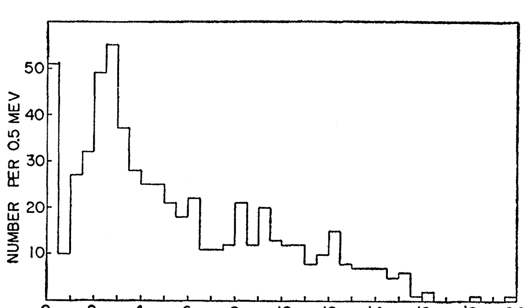

Fig. 2. Total distribution in E^*.

RESULTS

The first possibility to be checked was that of a direct four-particle breakup of the N^{13*} compound nucleus. This was done by plotting the energy distribution of the alpha particles in the center-of-mass system. The transformation to the center-of-mass system was carried out with the assumption that the incident proton had an energy of 28.9 Mev. The beam energy was determined by measuring the radii of curvature of the tracks of individual protons in pictures that contained only a few tracks.[15] If the reaction goes by way of a four-particle breakup, then the distribution in energy of the alpha particles is given by

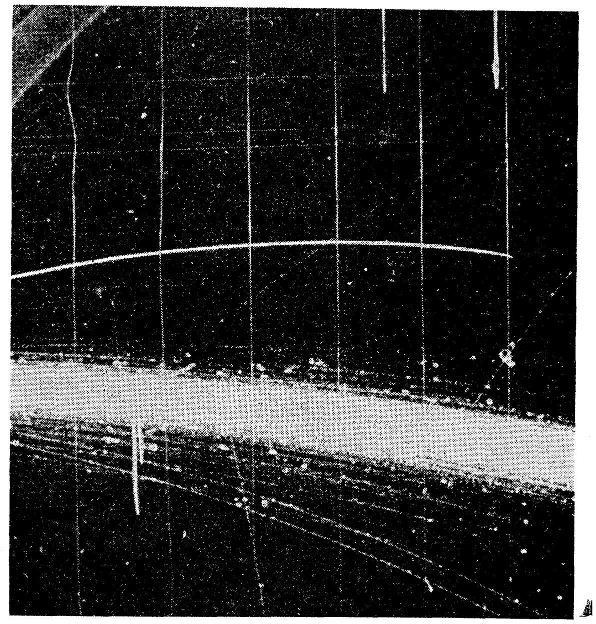

Fig. 3. An event in which the ground state of Be^8 was involved. The two alpha particles below the beam were produced by the decay of the Be^8 intermediate nucleus.

$$dN/dE = E^{\frac{1}{2}}(E_{\max} - E)^2,$$

where $E_{\max}$ is the maximum energy available to a single alpha particle in the breakup. This curve, normalized to the total number of alpha particles, together with the experimental energy distribution, is shown in Fig. 1. As can be seen, the agreement is not very good, and it was concluded that the great majority of events proceeded by some other mechanism.

Next, the possibility that Be^{8*} was involved as an intermediate nucleus in any of the reactions was investigated. For those events in which the reaction proceeded via Be^{8*}, two of the three alpha particles were produced in the breakup of the Be^{8*}. The vector that connects their end points is a direct measure of the excitation energy (E^*) of the Be^{8*}. Since it is not known which two of the three alpha particles were produced in the breakup of the Be^{8*}, the calculation of E^* was done for each of the three pairs of alpha particles belonging to each event, according to the expression

$$E^*=(E_i-E_j)/2-(E_iE_j)^{\frac{1}{2}}\cos\theta_{ij}.$$

The value $(E_iE_j)^{\frac{1}{2}}\cos\theta_{ij}$ is the scaler product of the two vectors representing the momenta of the alpha particles.

If all the events, or an appreciable fraction of them, have proceeded via definite levels in Be^8 there will be peaks in the E^* distribution corresponding to the levels involved. Because only one in three of the E^* values is significant, the peaks will be superposed on a continuous background. The E^* distribution for all the events is shown in Fig. 2. There are two marked peaks, one at 0.5 Mev and the other at 3.0 Mev. Of the 51 values of E^* less than 0.5 Mev, 43 lie at 0.1 Mev. The energy available for the breakup of the Be^8 ground state into two alpha particles is 96 kv; therefore the 51 events with one E^* value less than 0.5 Mev are interpreted as having proceeded via the ground state of Be^8 as an intermediate nucleus. Of these 51 values of E^* less than 0.5 Mev, only one could have arisen from the extreme edge of the broad level at 2.9 Mev. Figure 3 is a photograph of an event that was interpreted in this fashion. The two alpha particles below the beam are the two produced in the breakup.

Figure 4 gives the distribution in E^* for those 51 events with one value of E^* below 0.5 Mev which have been interpreted as having proceeded via the ground state of Be^8. This group will be referred to in the future as the ground-state group. The separation of those values of E^* greater than 0.5 Mev into two groups indicates that the ground state of Be^8 is produced in at least two types of reactions. The group around 2 Mev was produced by reactions in which the proton carried off most of the energy and which probably involved C^{12} excited to a few Mev above threshold as an intermediate nucleus. That group centered at 12 Mev was produced by events in which most of the energy was carried off by one of the alpha particles and involved either C^{12} in highly excited states or the low-lying states of B^9.

In Fig. 5 the E^* distribution for the other 149 events is shown. This group will be referred to in the future as the three-Mev group. The peak in the distribution in the vicinity of 3.0 Mev is interpreted as indicating that the great majority of these events went via the broad 2.9-Mev level in Be^{8*}. The indication of a subsidiary peak in the vicinity of 9.0 Mev is similar to that seen by Elder and Telegdi[7] in their study of the $C^{12}(\gamma,3\alpha)$ reaction with 32-Mev bremsstrahlung. Their interpretation was that possibly higher levels of Be^8 contribute to the reaction. The position of the peak, however, does not agree with the known levels

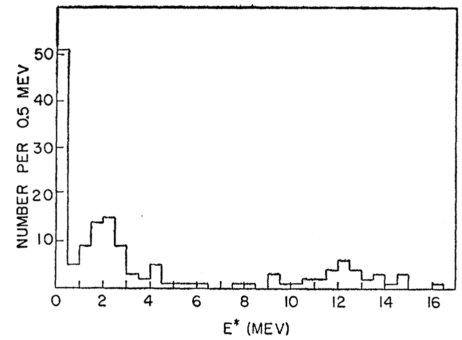

FIG. 4. Distribution of E^* for those events with one E^* value <0.5 Mev.

at 7.5 and 10.0 Mev.[16] Statistical fluctuations could account for the presence of this peak.

Further evidence for the possibility of the involvement of higher levels in Be^{8*} comes from the fact that 19 events had all E^*'s greater than 4.5 Mev, but the interpretation of these events remains uncertain. Their E^* distribution shows a peak at about 6.0 Mev. Of these events, 15 are consistent with the $C^{12}+p\rightarrow Li^5+Be^8$ reaction. The peculiar nature of these 19 events might also be due to errors in measurement; 16 of them had one or more alpha particles which had large errors because of exceptional difficulty in measurement.

The next step in the analysis was to consider all 200 events as though they had proceeded via levels in C^{12*}. The excitation energy of the $C^{12}(E_C)$ can be obtained in two ways: (a) by adding the energies of the three alpha particles in the rest frame of the carbon nucleus to the Q of the $C^{12}\rightarrow 3\alpha$ reaction; and (b) by subtracting 13/12 of the proton energy in the center of mass of the whole system from the total energy available in this center of mass. These two values for the excitation of the C^{12} nucleus should agree within the errors for those events which proceed either through C^{12*} or through states in B^9. The difference between them cannot, therefore, serve to differentiate the two types of events.

For low excitation energies, the three alpha particles stop in the gas, and the errors in measuring their

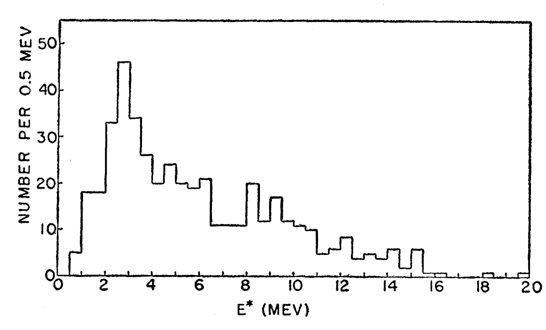

FIG. 5. Distribution in E^* for those events with no E^* value <0.5 Mev.

[16] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).

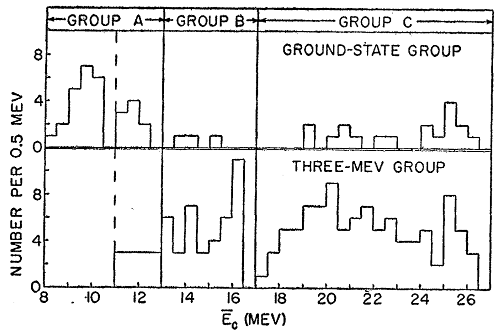

FIG. 6. Distribution in $\bar{E}_c$ for all events.

energies are generally small compared with the error in the determination of the proton energy. On the other hand, for high excitation energies, the error in the proton energy is small compared with the error in the sum of the alpha-particle energies. Therefore, three plots were made: (a) $E_c(p)$, calculated from the proton energy; (b) $E_c(\alpha)$, calculated from the sum of the alpha-particle energies in the C^{12*} rest frame; and (c) $\bar{E}_c$, a weighted average of (a) and (b). The values of $E_c(\alpha)$ and $E_c(p)$ were weighted inversely as the errors in the laboratory energy,

$$\bar{E}_c=\left(\frac{E_c(\alpha)}{\sum\Delta E_\alpha}+\frac{E_c(p)}{\Delta E_p}\right)\div\left(\frac{1}{\sum\Delta E_\alpha}+\frac{1}{\Delta E_p}\right).$$

A straight average was definitely not correct, and the method used had the advantage of being easy to calculate. The errors in the lab energies are not the same as the errors in the center-of-mass energies, but it seemed reasonable to assume that the relative magnitude of the alpha-particle and proton errors was not drastically changed by the transformation. The $\bar{E}_c$ distribution, shown in Fig. 6, was plotted separately for the ground-state group and the three-Mev group. The events were divided into three main groups as shown, which were then investigated separately.

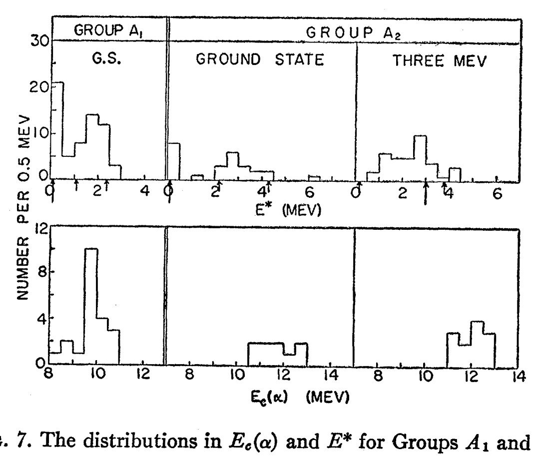

FIG. 7. The distributions in $E_c(\alpha)$ and E^* for Groups A_1 and A_2.

Group A: $8.0\leqslant\bar{E}_c<13.0$ Mev (42 Events)

Because all events with $\bar{E}_c<11.0$ Mev involved the ground state of Be^8, a further division at 11.0 Mev was made. The distributions in $E_c(\alpha)$ and E^* are shown in Fig. 7. The short arrows show the kinematic limits of E^* and the long arrows show the positions of the peaks to be expected. The limits and the locations of the peaks were calculated for events that went via appropriate levels in C^{12*} and Be^8. The interpretation of these distributions is as follows: Group A_1—the events proceeded via the 9.6-Mev level in C^{12} and the Be^8 ground state in a two-step process; Group A_2—the events went via the levels in C^{12*} in the region from 10.8 to 12.8 Mev to either the ground or first excited levels in Be^8, also in a two-step process, with 43 ± 17 percent having gone via the ground state.

Group B: $13.0\leqslant\bar{E}_c<17.0$ Mev (43 Events)

The values of $\bar{E}_c$ and E^* for this group are given in Fig. 8, separately for the ground-state and the three-Mev groups. The $\bar{E}_c$ distribution is fairly smooth, but one might say that the peak at 16 Mev is due to the 16.1-Mev level in C^{12}, which is known to emit alpha particles.[16] The small (7.5 ± 4.5 percent) involvement of the Be^8 ground state in Group B is consistent with the $C^{12}(\gamma,3\alpha)$ results[8] and also the $B^{11}(p,\alpha)Be^{8*}$ data.[2] The rest of the events appear to have gone via the 2.9-Mev level in Be^{8*}.

The assignment of the events in Groups A and B as proceeding via levels in C^{12*} is fairly certain. In Group A, all the alpha-particle energies in the center-of-mass system lie within the kinematic limits. For Group B, four events (out of 43) have alpha particles with energies that lie above the kinematic limits; however, the errors in the energies overlap the limit sufficiently to account for these. Were these higher-energy alpha particles produced directly in (p,α) reactions, they would correspond to B^9 produced in excited levels around 9 to 11 Mev. It is impossible to say that these four events are not produced in this fashion.

The events in these two groups were also examined to determine whether they could have been produced by the $C^{12}+p\rightarrow Li^5+Be^8$ reaction. Only three events (out of 85) could be so interpreted; one of these fits the Li^5 reaction better than the C^{12}. Further, all events in the Groups A and B had one $E^*<4.5$ Mev, so that they are consistent with transitions either through the ground state or the first excited level of Be^8.

Group C: $17.0<\bar{E}_c$ (115 Events)

The situation with respect to Group C is more complex. In addition to the C^{12} events, the low-lying levels of B^9 can give $\bar{E}_c$ values in this group as will the $C^{12}+p\rightarrow Li^5+Be^8$ reaction. Figure 9 shows the distribution of proton energies and the $\bar{E}_c$ distribution for all events in Group C plotted so that corresponding energies lie at the same abscissa. Three subgroups, as shown, were chosen. The cross-hatched regions show the distribution for the ground-state group. Both distributions show evidence of level structure at C^{12*} with levels at 20 and 25 Mev.

Strauch and Titus[17] report a level at 20±1 Mev produced by inelastically scattered protons of 96-Mev bombarding energy. Hecht[18] reports a level in the vicinity of 19.5 Mev, seen in inelastic scattering of 32-Mev protons. It seems possible that the level at 20 Mev found in this work is the same level reported by these workers.

A resonance at 1 Mev in the $B^{10}(d,\alpha)Be^8$ reaction has been reported by Whitehead.[19] This corresponds to a level in C^{12} at an energy of 26.3 Mev. Transitions to both the ground state and the first excited level in Be^8 were seen, the ground-state transitions occurring in about 25 percent of the cases. If all the events in Group C_3 are assumed to belong to the resonance, it follows that 27±10 percent went via the ground state. The level at 25±1 Mev seen in this work may possibly be identified with the level reported by Whitehead, or it could be the level seen by Goward and Wilkins[8] at an energy of 25.6 Mev, which decays by α emission.

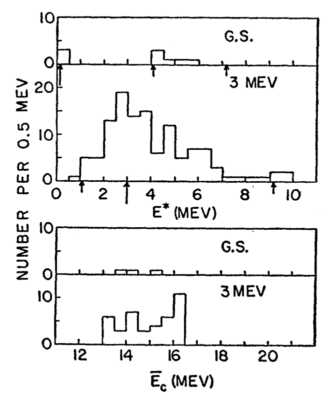

FIG. 8. The distributions in $\bar{E}_c$ and E^* for Group B.

The energy resolution and statistics of this experiment are insufficient to separate Group C_2 into any definite levels.

To determine the modes of decay of these levels in C^{12}, distributions in E^* were made for each subgroup separately. The statistics were poor, however. Therefore the total E^* distribution for all the events in Group C was plotted. It is given in Fig. 10. The long arrows show the positions of the expected peaks and the short arrows the limits of the continuum. These locations were calculated on the assumption that the events were due to C^{12} levels and went via either the 2.9-Mev level or the ground state of Be^8. The experimental results agree very nicely for the ground-state group. In the three-Mev group, however, the agreement

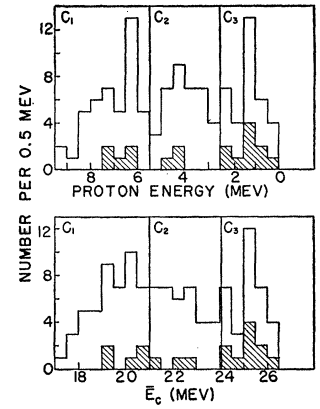

FIG. 9. The distributions in proton energy (E_p) and $\bar{E}_c$ for Group C.

is not so good. The peak at 3.0 Mev does not account for enough of the events. It would seem surprising if none of the events went via the 2.9-Mev level, in view of the fact that the ground state participated. From the height of the distribution at 3.0 Mev it is estimated that between one-third and one-half of the events in the three-Mev group proceeded via the 2.9-Mev level. The peak in the vicinity of 8.0 Mev is compatible with statistical fluctuations, but it might become more definite with more data. If it is considered to be real then it can be interpreted as indicating that higher levels in Be^{8*}, possibly the 7.5- and 10.0-Mev levels, participated in the reaction from these high levels in C^{12}. All 19 of the events with all E^* values greater than 4.5 Mev are included in this distribution. The possibility of three-particle breakup is not excluded, and this mechanism could account for as much as one-third of the events in the three-Mev group of Group C.

The above analysis of Group C has been carried out on the assumption that C^{12} levels participated in all the events. It is known[14] that the $C^{12}(p,\alpha)B^9$ reaction occurs at 18-Mev bombarding energy, and it is highly unlikely that it does not occur with 29-Mev protons; therefore the assumption that all events proceeded via

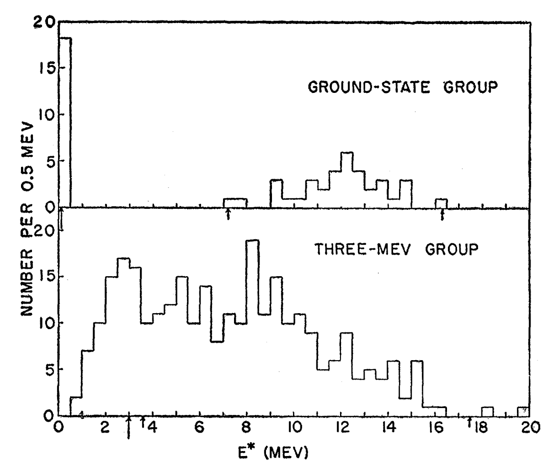

FIG. 10. The distributions in E^* for Group C.

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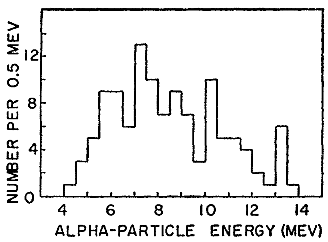

FIG. 11. The distribution in energy of the most energetic alpha particle of each event in Group C.

levels in C^{12} is probably not justified. The conclusions about the proportion of events that proceeded via levels in Be^8 made from the E^* distribution, however, are not changed. The shape of the E^* distribution is chiefly determined by the Be^8 levels involved, and is only slightly dependent upon the nucleus from which the Be^8 was formed.

In order to analyze the data for evidence of the $C^{12}(p,\alpha)B^9$ reaction, a plot was made of the energy distribution of the most energetic alpha particle from each event in Group C. Figure 11 presents the results. The distribution shows evidence for groups at 13 and 10 Mev, which correspond to the ground state, and a level at 4 Mev. There is no evidence for the known level at 2.4 Mev (which would appear at an alpha-particle energy of 11.5 Mev); however, the statistics are not good and the energy resolution is about ± 1.5 Mev.

As a further examination of the levels of the B^9 reaction, a transformation to the B^9 rest frame was carried out for all the events in Group C. The transformation was effected by adding 4/9 of the velocity components of the most energetic alpha particle to the velocity components of the other three particles. Then the energies of the proton and the two alpha particles in the B^9 rest frame were determined. The sum of these energies was plotted against the energy of the most energetic alpha particle. Only those events which fell within 1.5 Mev in E_α of the expected line were considered. On the basis of calculations, all the events, whether they proceeded via C^{12} or B^9, should lie in this region of acceptance. The grouping in evidence in Fig. 12, however, would come about only if some of the events proceeded via B^9 levels. The combination of the peaks in the energy spectrum of the most energetic alpha particles, together with the grouping in Fig. 12, gives good evidence for the participation of B^9 levels in the reaction. The position of the second group in Fig. 12 is at 3.5 ± 1.0 Mev. This corresponds to an excitation energy of 3.2 ± 1.0 Mev for the B^9, which is in better agreement with the value of 2.4 Mev for the known level.

The question still remains as to the decay mechanism of the B^9. The five events in the B^9 ground-state group have one value of E^* less than 0.5 Mev. However, there is only 0.28 Mev available for the breakup of the ground state of B^9 into two alpha particles and a proton, so that even if the breakup went directly to a proton and two alpha particles there would be one value of E^* less than 0.5 Mev. Thus, the fact that these five events have such a value of E^* is not necessarily an indication that Be^8 in the ground state was involved. Of the twelve events in the second group in Fig. 12, six have one value of E^* less than 0.5 Mev. There is about 3.5 Mev available for the breakup from this level, and the presence of one value of E^* less than 0.5 Mev for an event is good evidence that the Be^8 ground state was involved in the reaction. The other six events in this group are consistent with decay through the 2.9-Mev level of Be^8.

The last point to be examined is the possibility of the $p+C^{12}\rightarrow Be^8+Li^5$ reaction. This is a two-body reaction, and therefore the energy of the Be^8 in the center of mass will have one of several unique values, depending on the states in which the Be^8 and Li^5 are formed. Only the ground state and the 2.5-Mev level[16] of Li^5 are accessible with the energy available. The energy of the Be^8 in the center of mass is given by

$$E_{Be}=E_{\alpha i}+E_{\alpha j}-E_{ij}^*$$

(that is, the energy is the sum of the kinetic energies in the center-of-mass system of the two alpha particles produced in the Be^8 decay minus the Be^8 excitation energy). A more convenient value to calculate is the relative energy of the Be^8, ϵ_{Be}. It is given by

$$\epsilon_{Be}=(E_i+E_j-E_{ij}^*)/(19.2-E_{ij}^*).$$

The value 19.2 Mev is the kinetic energy available to the Li^5 and Be^8 when they are both formed in their ground states. For the ground state of Li^5 the ϵ_{Be} values lie between 0.87 and 0.92, and for the 2.5-Mev Li^5 level, between 0.72 and 0.78. The proper choice of the two alpha particles produced in the Be^8 decay for each event has been facilitated by the E^* determination.

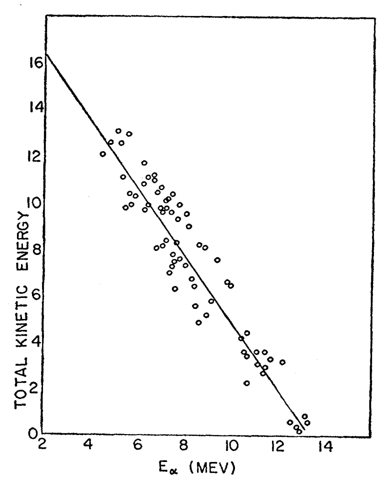

FIG. 12. Selected events plotted with the energy of the most energetic alpha particle of each event as abscissa and the sum of the kinetic energies of the proton and the other two alpha particles in the B^9 rest frame as ordinate.

The calculation of ϵ_{Be} was carried out for all events. For those events in the ground-state group the pair of alphas which produced the low value of E^* were chosen. For the other events, each pair that produced an E^* between 1.5 and 4.5 Mev, or, if none, then that pair which gave the lowest E^* value, was chosen. Only three events (out of 85) in Groups A and B could have proceeded in this fashion. For Group C there are 49 that are consistent with the Li^5 possibility. The ϵ_{Be} distribution from the events of Group C is given in Fig. 13. When there were two ϵ_{Be} values for an event, the choice was made in a predetermined random fashion. Also shown in the figure (dotted line) is the ϵ_{Be} distribution to be expected from the events of Group C if they go via C^{12} in the proportions determined above, normalized to the same number of events. The agreement between the two curves is excellent. The experimental peak at 0.65 Mev is below the peak at 0.75 expected for the Li^{5*} reaction, and there is no evidence for a peak around 0.90 that would be produced in the Li^5 ground-state reaction. Therefore, there seems to be no evidence for any large contribution to the events from this reaction, with at most five percent of the events having been produced in this fashion.

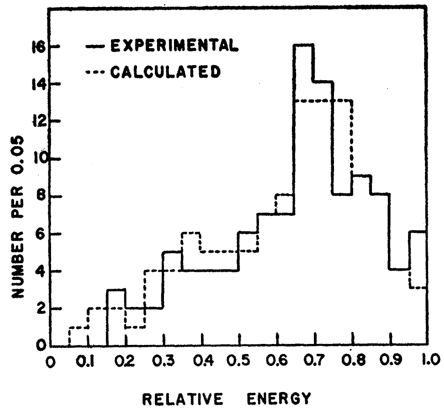

FIG. 13. The distribution in ϵ_{Be} for Group C.

SUMMARY

It was confirmed that both the ground state and the 2.9-Mev level of Be^8 were involved as intermediate nuclei in the reaction. The possibility of the participasion of higher levels was not excluded. About one-fourth of all events proceeded via the Be^8 ground state and a minimum of one-half by way of the 2.9-Mev level.

Definite evidence for the participation of levels in C^{12} was seen. Levels were identified at 9.6, 16, 20, and 25 Mev. The 9.6-Mev level went only to the Be^8 ground state. Those levels in the vicinity of 12 Mev decayed to either the ground state or the 2.9-Mev level of Be^8 with equal probability. For the levels between 13 and 16 Mev, less than five percent of the events went to the Be^8 ground state and the rest were consistent with transitions through the 2.9-Mev level. The decay mechanism of the 20- and 25-Mev levels is uncertain because any given event could equally well be interpreted as having proceeded in any of several ways. However, if we assume that these events did go via these two levels in C^{12}, then 16 ± 9 percent and 27 ± 10 percent respectively for the 20 and 25-Mev levels decayed into the Be^8 ground state. It was estimated that between one-half and one-third of the remaining events assigned to these levels in C^{12} proceeded via the 2.9-Mev level in Be^{8*}. The mechanism of the remaining events was undecided, with a good possibility that the 7.6-Mev level in Be^8 was involved in some of them.

For the one event identified as $C^{13}(p,d)3\alpha$, the analysis was consistent with the following reaction scheme:

$C^{13}(p,d)C^{12*}$ (excited to the 9.6-Mev level),

$C^{12*}\rightarrow Be^8+\alpha$ (ground state),

$Be^8\rightarrow 2\alpha$.

The investigation of the possibility of the B^9 reaction showed that the ground state and the first excited state of B^9 were produced and decayed into two alpha particles and one proton. The mechanism of the decay of these levels was undecided though all the events were consistent with the participation of either the ground or 2.9-Mev levels of Be^8.

In the $C^{12}+p\rightarrow Li^5+Be^8$ reaction it was found that although 52 of the events, 49 of which were in Group C, were consistent with this reaction, the distribution in relative energies of the Be^8 nuclei was fitted quite well by the distribution to be expected from the events when they were considered as having proceeded via levels in C^{12}. It was estimated that this reaction could account for no more than five percent of the events.

The mechanism $C^{12}(p,p')C^{12*}$ with the subsequent decay of the excited C^{12} into three alpha particles has been confirmed as the principal mode of the reaction $C^{12}(p,p')3\alpha$. Emission of an alpha particle from the C^{12} excited levels to either the ground or 2.9-Mev levels in Be^8 is favored over direct tripartition into three alpha particles. The reaction may also go via the mode $C^{12}(p,\alpha)B^9$ with at least the ground and first excited states of B^9 participating. Here, also, Be^8 is formed as an intermediate nucleus.

For the excited levels of C^{12} the modes of decay are in agreement with the data from photodisintegration experiments.[7–9] The fact that no events were seen corresponding to the 7.6-Mev level in C^{12} can be explained by the results of the inelastic scattering of 32-Mev protons by carbon,[18] in which the number of protons corresponding to the 7.6-Mev level was very much smaller than the number from the 9.6-Mev level. This result was also seen at 96-Mev bombarding energy.[17]

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Mirror Reactions $H^3(d,n)He^4$ and $He^3(d,p)He^4$

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Experimental data for these two reactions in the low-energy region from 64 to 954 kev (center-of-mass) have been analyzed assuming only (1) a well-defined nuclear surface, (2) charge symmetry, and (3) a single entrance channel. The one-level resonance formula was not used in this work. The results indicate consistency over the entire energy range between experiment, the hypothesis of charge symmetry, and basic assumptions of reaction theory.

RECENT experiments on the $H^3(d,n)He^4$ reaction[1–5] and the $He^3(d,p)He^4$ reaction[6–9] have shown that both reaction cross sections have a maximum in the low-energy region (near 65 kev and 260 kev, respectively[10]). Beyond about 300 kev the two excitation curves appear to merge. The experimental data have been fairly well fitted by means of the one-level resonance formula.[4–6,9] However, the reduced entrance widths for the two reactions were found in reference 6 to differ by a factor of 14, a result grossly at variance with charge symmetry. This discrepancy has been traced to the neglect of an alternative set of dispersion formula parameters.[9] When the proper sets of parameters for the two reactions are compared, it is found that the reduced entrance widths, as well as the reduced exit widths, differ by less than 50 percent.[9] The cross section data beyond 400 kev are not well fitted by the dispersion formula.

In this note, we report a theoretical analysis of the same data in which the one-level dispersion formula is not used and the expansion of the logarithmic derivative about a resonance energy is not made. We have assumed (1) a well-defined nuclear surface at which the internal (nuclear) and external (Coulomb) wave functions are joined in the usual way, (2) charge symmetry, and (3) a single entrance channel. In accordance with assumptions (1) and (3), the reaction cross section can be expressed in terms of the real and imaginary parts of the dimensionless logarithmic derivative of the radial wave function at the nuclear surface $f(E)$:[11,12]

$$\sigma_{r,l}=(2l+1)g_r\pi\lambda\!\!\!^{-2}\cdot\frac{-4s_l\,\mathrm{Im}f}{(\mathrm{Re}f-\Delta_l)^2+(\mathrm{Im}f-s_l)^2}, \qquad (1)$$

where $s_l(E)$ and $\Delta_l(E)$ are defined in reference 11 and g_r is a statistical weight for channel r. We attempt to determine $f(E)$ from experiment. The assumption of charge symmetry is formulated as follows: the real and imaginary parts of f are the same for the mirror reactions at corresponding energies and corresponding channel radii. There is then but a single function $f(E)$ for both reactions, neglecting the effect of Coulomb forces on the internal wave functions and also the difference in the exit channel penetrabilities ($Q\sim18$ Mev). The channel radius R defining the nuclear surface is assumed to be the same for both reactions. The incident energy[10] for the first (H^3+H^2) reaction, E_1, should correspond to a slightly higher energy for the second (He^3+H^2) reaction, E_2, because of the difference in Coulomb forces. Thus $f(E_2)\equiv f(E_1)$ and $E_2=E_1+\epsilon$

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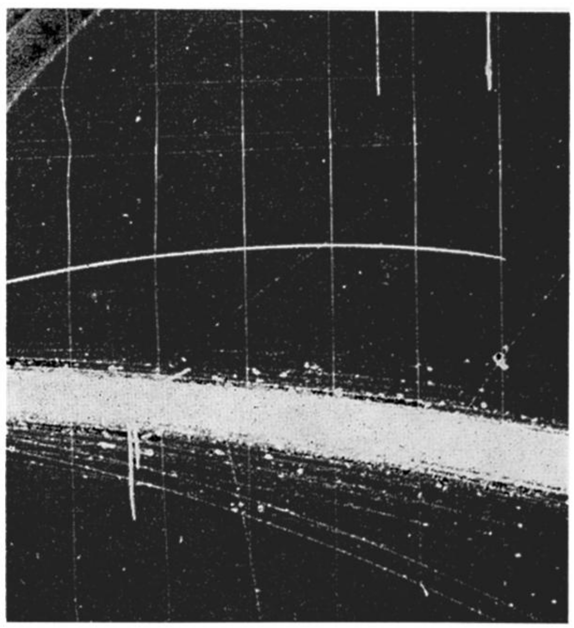

FIG. 3. An event in which the ground state of Be^8 was involved. The two alpha particles below the beam were produced by the decay of the Be^8 intermediate nucleus.