some detail, in view of an existing ambiguity in the assignment of this state.[10] The angular distribution of α_1 particles appears to require $J=4^+$; the elastic scattering, on the other hand, requires $J=3^-$, as does also the (α_1,γ) angular correlation. The experimental (p,α_0) distribution obtained in the present work is replotted in Fig. 8, along with theoretical curves calculated for the choices $J=3^-$ and $J=4^+$. It is apparent that better agreement is obtained with the former assignment, although in the absence of precise information on possible interference effects, $J=4^+$ cannot be excluded. The integrated (p,α_0) cross section obtained from the data of Fig. 8 is 300 mb at the resonance energy of 1.21 Mev; the result similarly obtained at the 1.03-Mev resonance is 340 mb.

[10] F. B. Hagedorn, Phys. Rev. 108, 735 (1957).

The cross section for the $(p,\alpha_1\gamma)$ reaction at the 1.98-Mev resonance reported by Bashkin and Carlson[3] indicates $\Gamma_p/\Gamma=0.98$ or 0.02. The absence in the present experiments of any anomaly in the elastic scattering is consistent only with the latter choice.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to Professor R. F. Christy, Professor T. Lauritsen, and Professor W. A. Fowler for several helpful discussions during the course of this work.

PHYSICAL REVIEW VOLUME 108, NUMBER 4 NOVEMBER 15, 1957

Breakup of Be^{9*} (2.43 Mev)*

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(Received July 31, 1957)

The breakup of Be^{9*} from the 2.43-Mev state has been studied. The level was excited by inelastic scattering of 42-Mev alpha particles and the breakup was studied by examining coincidences between inelastically scattered alpha particles and particles from the breakup. It was found that decay from this state proceeds less than 10% of the time by neutron emission to the ground state of Be^8 and less than 1% of the time by gamma emission to the ground state of Be^9. The low neutron-emission probability is consistent with the usual 5/2− spin-parity assignment for this state.

I. INTRODUCTION

THIS is a report of an investigation of the decay of Be^9 from its well-known excited state at 2.43 Mev.[1] As in similar investigations of light nuclei, the general purpose is to obtain information about the structure of the nucleus involved. When Be^9 decays from the 2.43-Mev state it might do so by the emission of either a neutron, an alpha particle, or a photon. The specific object of this experiment was to determine the relative probability of these modes of decay:

(1) $Be^{9*}\rightarrow Be^8+n+0.76$ Mev;
$Be^8\rightarrow He^4+He^4+0.10$ Mev,

(2a) $Be^{9*}\rightarrow He^5+He^4$; $He^5\rightarrow He^4+n$,

(2b) $Be^{9*}\rightarrow He^4+He^4+n+0.86$ Mev,

(3) $Be^{9*}\rightarrow Be^9+\gamma+2.43$ Mev.

Previous investigations[2,3] of this level have indicated that decay proceeds primarily through mode (1). Apparently modes (2) were not given serious consideration.

II. GENERAL METHOD

The breakup of Be^{9*} (2.43 Mev) can be conveniently studied if the excitation is produced by inelastic scattering of medium-energy alpha particles. The general method is indicated in Fig. 1. Alpha particles are inelastically scattered in a beryllium target and are

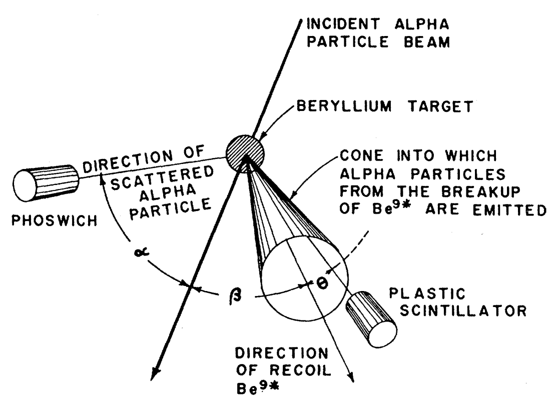

FIG. 1. The experimental arrangement for observing the breakup fragments from Be^{9*} in coincidence with inelastically scattered α particles.

* Supported in part by the U. S. Atomic Energy Commission.
[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).
[2] G. A. Dissanaike and J. O. Newton, Proc. Phys. Soc. (London) A65, 675 (1952).
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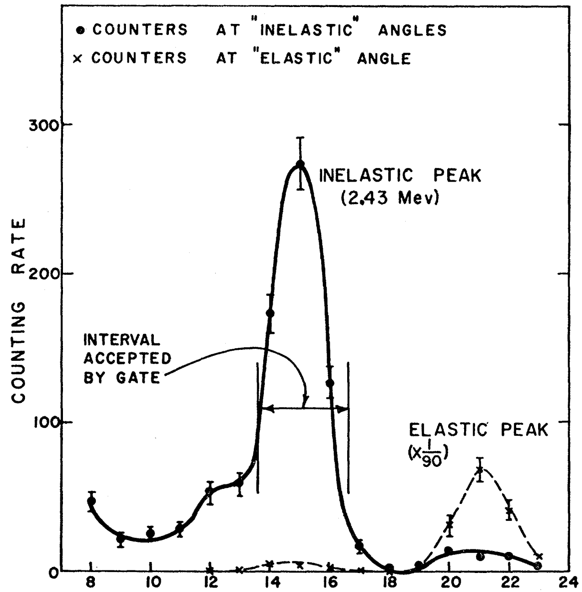

FIG. 2. Pulse-height distributions in the phoswich due to alpha particles scattered from beryllium. The alpha particles are observed in coincidence with particles in the breakup detector.

observed in an energy sensitive detector held at a fixed angle, α. The energy and angle of the scattered alpha particle determine the recoil energy and angle, β, of the struck nucleus. Thus, by selecting alpha particles whose energy corresponds to scattering from a particular level one can, with coincidence techniques, label events in which both the state of excitation and the momentum of the recoiling nucleus are known.

In the subsequent decay of the excited nucleus, different decay modes will be characterized by different angular and energy distributions for the charged decay products. The simplest distinguishing features of the distributions are the extreme limits on angle and energy imposed by kinematic considerations alone. In mode (1) the neutron carries off much of the available energy and therefore the kinematic limits for alpha particles from the breakup will be considerably tighter for mode (1) than for mode (2). It follows from the fact that the He^5 ground state level is very wide[1] that the limits for modes (2a) and (2b) are identical. In the electromagnetic transition of mode (3) the recoiling nucleus is almost undeviated.

In the present experiment the beryllium foil was bombarded by 42-Mev alpha particles from the University of Washington cyclotron. The detector of scattered alpha particles was placed at the angle $\alpha=60°$, where inelastic scattering from the 2.43-Mev level is relatively prominent[4] and the recoil nuclei gain appreciable momentum. The nuclei then recoil at $\beta=46.8°$. The maximum possible deviations of a breakup alpha particle from this central direction are 9.5° for mode (1) and 15.4° for mode (2). In mode (3) the beryllium nucleus cannot be deviated by more than 0.3°.

Several features of this method make it useful in this, and similar problems: (a) the decay fragments are confined to a convenient angular region; (b) the decay fragments are brought into a convenient energy region (the alpha-particle energies extend from 3.7 Mev to 10.9 Mev in the laboratory although in the Be^{9*} rest frame they cannot exceed 0.5 Mev); and (c) decay by electromagnetic transitions can be detected with high efficiency by observation of the recoil nuclei. This technique is now being used at this laboratory to study the decay of C^{12} from the 7.65-Mev level. Similar arrangements might be useful in the study of the range and Coulomb scattering of recoil ions produced in the elastic scattering of high momentum incident particles.

III. DETECTION EQUIPMENT

The inelastically scattered alpha particles were identified using a version of the $dE/dx-E$ method in which the type of particle and its energy are determined from the observation of the energy loss in successive phosphors. In the present arrangement a "phoswich" was used composed of a 38 mg/cm² plastic phosphor and a 269 mg/cm² CsI(Tl) phosphor viewed by a single phototube. Two pulses were taken from the phoswich. One output, essentially due to the plastic, identifies the particle as an alpha particle and provides a pulse for fast coincidence work. A second output, essentially due to the CsI, determines the particle energy. Further details of the phoswich arrangement are described elsewhere.[5]

To see if this detector could be used to select the desired alpha-particle group, pulse-height distributions were displayed on a twenty-channel analyzer and are shown in Fig. 2. The analyzer was gated by coincidences between the phoswich and the breakup particle detector. With the latter detector at the calculated angle for elastic scattering, there is a well-defined peak in the alpha-particle distribution arising from the plentiful coincidences with recoiling nuclei. At angles of the breakup detector accessible only to inelastic events another well defined peak appeared at a lower energy, corresponding to scattering from the 2.43-Mev level. (The identification of this level was confirmed to within 0.1 Mev with the aid of an independent calibration of pulse height *versus* energy.) A shoulder on the low-energy side of this peak may be due to scattering from the level at about 3.0 Mev.[1] By restricting consideration to events falling within the gating interval shown in Fig. 2, the maximum possible contribution of this level is reduced to about 3%. Tests with copper oxide and polyethylene targets, and further examination of the data obtained with a beryllium target, indicate that

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contributions to this interval from oxygen and carbon impurities and from other states of Be^9 do not exceed 5%.

The breakup particles were detected in a 16-mg/cm^2 plastic phosphor. Only alpha particles from modes (1) and (2) or recoiling nuclei from mode (3) can be detected with appreciable efficiency in this counter. To minimize discrimination against very-short-range particles, the counter was used with no covering window.

As much of the experimental analysis depends on a knowledge of the alpha-particle momenta, a momentum calibration was obtained and is shown in Fig. 3. Points for this curve were obtained by using natural alpha particles and alpha particles from the breakup, with and without thin aluminum absorbers. The calibration points did not extend over the full experimental energy interval and therefore a slight extrapolation was necessary at both ends. At the low-energy end the severe nonlinearity of the plastic makes the calibration somewhat uncertain.

The momentum resolution was also less sharp for low-energy than for high-energy alpha particles. Most of the data were taken with a beryllium target whose stopping power for alpha particles was equal to that of 1.0 mg/cm^2 of aluminum. Energy loss in this "thick target" introduces a spread of the order of 10% in momentum for the low-energy alpha particles. Additional data were taken with a "thin target" about $\frac{1}{5}$ as thick. Here the resolution is probably limited by the counter which introduces a spread in momentum of about 5% for low-energy particles. These effects imply that the information obtained for the low-energy alpha particles is not as reliable or detailed as that obtained for the high-energy particles, and therefore the latter should be favored where possible in the analysis below.

The detectors were placed in a 23-in. scattering chamber[6] which was equipped with two independently movable counter trays. Each detector had a $\frac{1}{8}$-in.$\times\frac{1}{4}$-in. defining aperture at a distance of about 4 in. from the target.

The desired data in this experiment are the energy and angular distributions of alpha particles from the breakup of Be^{9*} (2.43-Mev). These can be obtained by studying events characterized by a coincidence between any particle in the breakup counter and a particle in the phoswich which gives an energy pulse corresponding to scattering from the 2.43-Mev level. This over-all coincidence was established by conventional fast-slow coincidence techniques. The resulting signal was used to gate a twenty-channel analyzer on which was displayed the spectrum of the breakup counter.

As a check against possible spurious effects, for instance protons in the phoswich, a second method of data collection was simultaneously used in which the two phoswich outputs and the output from the breakup counter were displayed on an oscilloscope trace. The trace was triggered by a fast coincidence between the two detectors and was photographed, giving complete information about each coincident event. As no significant differences were found between the photographic and analyzer data, either could be used. Minor considerations led to the use, in the analysis below, of the analyzer information for the "thick-target" data and the photographic information for the "thin-target" data.

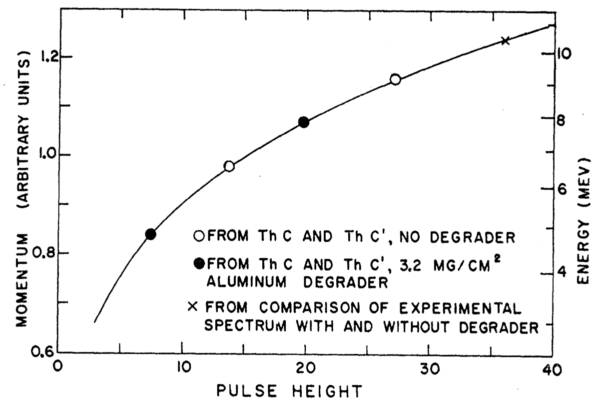

FIG. 3. Calibration curve of momentum and energy as a function of pulse height for alpha particles in the breakup detector. The curve includes a correction for the average energy loss in the (thick) target.

IV. RESULTS

The experimental procedure was to obtain momentum distributions of the particles from the breakup of Be^{9*} at various angles θ of the breakup detector. This information is exhibited in three ways:

(a) A crude over-all picture can be obtained from the angular distribution of Fig. 4 where the total number of breakup particles, irrespective of energy, is plotted as a function of the angle θ.

(b) More detailed information can be obtained by considering the energies of the breakup alpha particles at each angle. This is done in the momentum map of Fig. 5. Points on this map represent alpha-particle positions in momentum space. The circles represent the extreme positions allowed for decays via modes (1) and (2). An alpha particle is carried to the point at the center of the circles by the motion of the recoiling Be^{9*}. The distance of a point from the center is proportional to the momentum gained in the breakup. For convenience in visual interpretation, a weighting factor was applied to the observed data to make the two-dimensional density of points in Fig. 5 proportional to the three-dimensional density of events in momentum space. For instance, were the actual momentum distribution isotropic, the map of Fig. 5 would then also look isotropic.

[6] We are grateful to Dr. P. T. Demos of the Massachusetts Institute of Technology and Dr. W. E. Wright of the Office of Naval Research for arranging to lend this scattering chamber to the University of Washington.

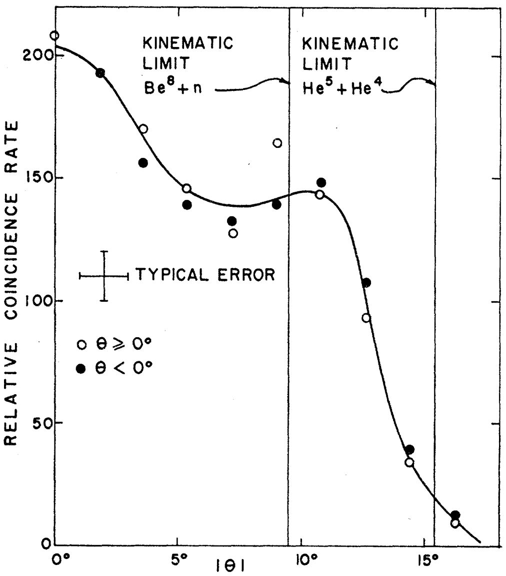

FIG. 4. The angular distribution of particles from the breakup of Be^{9*} (2.43 Mev). $\theta=$(angle of breakup detector) − (angle of recoil of Be^{9*}). See Fig. 1.

(c) The data described in (a) and (b) were taken with the thick beryllium target. To obtain momentum density distributions with better resolution, additional runs were made with the thin target. Results obtained with the breakup detector at $\theta=0°$ are shown in Fig. 6.

The information of Figs. 4, 5, and 6 was first examined for internal consistency. For instance, one would expect symmetry about the recoil Be^{9*} direction. Comparison of the solid and open points in the angular distribution of Fig. 4, and inspection of the over-all features of the momentum map of Fig. 5, indicate that such symmetry was obtained. One would likewise expect that there would be no events beyond the kinematic limit for mode (2). This expectation is reasonably well fulfilled in the data of Figs. 4, 5, and 6. Only about 8% of the observed points of Fig. 5 fall outside the greater kinematic limit. (The positions of the experimental points and of the limiting circles were calculated independently.) The points appearing outside the limits in Fig. 5, as well as the tail extending beyond the kinematic limit in the momentum distribution of Fig. 6, are probably in part associated with the difficulties at low momentum mentioned above. There may be an additional small contribution due to impurities in the target. It is believed that these discrepancies are not large enough to affect significantly the analysis below.

The experimental information can be used to set an upper limit on the probability of electromagnetic transitions via mode (3). The absence of a sharp spike at 0° in Fig. 4 and the absence of a large cluster of events along the 0° line of Fig. 5 indicate that such transitions are not numerous. A more quantitative upper limit can be established by examination of the 0° momentum distribution of Fig. 6. A small peak near the center of the distribution may be due to decay via mode (3). The pulse height of events comprising this peak is slightly less than the pulse height produced by Be^9 nuclei recoiling after elastic scattering, and therefore these events could be due to the recoil Be^9 from mode (3) decay. If one assumes that this peak is due to such recoils, and takes into account the large geometric efficiency for observing these relatively well-collimated events, one would infer a 0.3% probability for decay via mode (3). Allowing for the uncertainty in determining the shape of this peak, it is concluded that gamma emission is responsible for less than 1% of all decays. However there is no conclusive evidence that these events are due to recoil nuclei, and it is therefore quite possible that the actual contribution of gamma decay is much smaller than 1%.

Further examination of the distributions makes it possible to set an upper limit on neutron emission to the ground state of Be^8. Events outside the mode (1) kinematic limit cannot be due to this decay, while events within the limit may be due either to mode (1) decay or decay via other modes. It is evident from Figs. 4 and 5 that an appreciable number of events lie outside the limit for mode (1). A detailed analysis of the data represented in Fig. 5 shows that only 0.20 ± 0.05 of the observed alpha particles lie within this limit.

Inspection of the momentum distribution of Fig. 6 shows that many of the events within the sphere defined by the mode (1) limit are near the outer edge of this sphere and are presumably associated with the two large peaks whose centers lie in the region consistent only with mode (2). (These peaks are equidistant from the center of the Be^{9*} rest frame and correspond to alpha particles emitted forward and backward in the breakup of Be^9. The peak at low laboratory momentum is lower and wider, in part at least, because of poorer resolution.) It seems probable therefore that much of the inner-sphere contribution is due to mode (2) decays, especially in view of the large relative volume contained in shells of large radius.

This conclusion is strengthened by consideration of the expected momentum density distribution for decays via mode (1). Neglecting departures from isotropy in the two decays of mode (1), one can show that the number of events per unit volume in momentum space is inversely proportional to the momentum in the Be^{9*} frame. Therefore the density distribution should be decreasing near the limiting edge, rather than increasing sharply as in Fig. 6. A mode (1) density distribution can be estimated using this momentum dependence. To normalize, all of the events near the center, including the "recoil" peak, were ascribed to mode (1). It is then found that only about $\frac{1}{4}$ of the events within the inner sphere can be due to mode (1) decays. This would suggest an upper limit for mode (1) decays of about 5%. To allow for uncertainties in the calculation, it is finally concluded that neutron emission to the ground

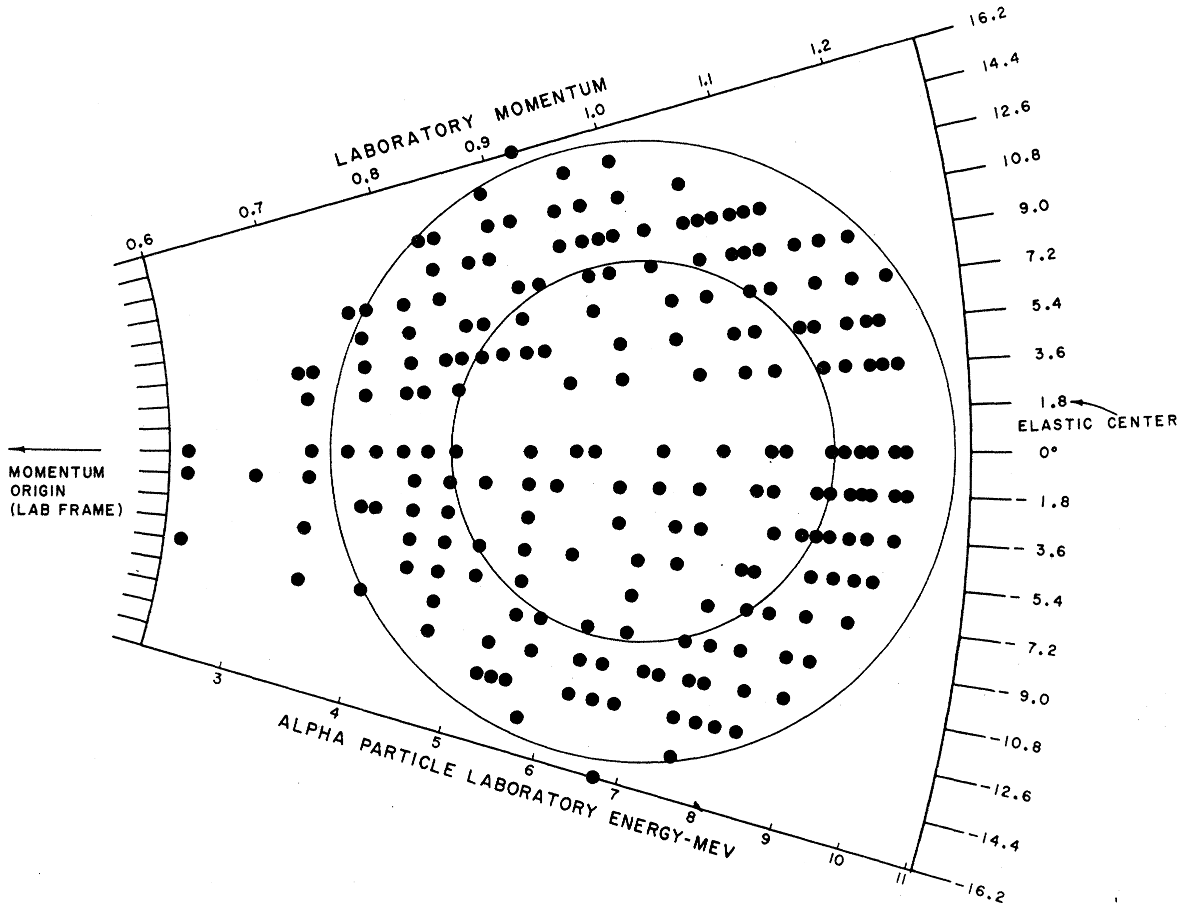

FIG. 5. The distribution in momentum space of alpha particles from the breakup of Be^{9*} (2.43 Mev). The laboratory momentum, p, of an alpha particle is expressed in arbitrary units such that $p=1$ at the center of the Be^{9*} rest frame. Each dot represents five events of a weighted momentum distribution in which each observed event is given a weight equal to $1/p$. (This provides the type of weighting indicated in the text.)

state of Be^8 is responsible for less than 10% of all decays from the Be^{9*} 2.43-Mev level. This is an upper limit and there is no evidence in the present work that there is any such neutron emission.

It is possible to make rather qualitative comments concerning the angular distribution in the Be^{9*} frame of the alpha particles from the breakup. A test for symmetry about 90° can be made by determining the ratio of the area under the forward peak to the area under the backward peak in the 0° momentum distribution of Fig. 6. If one uses a somewhat arbitrary assignment of events to these peaks, the ratio is estimated to be 1.2 ± 0.3. These peaks presumably represent a characteristic group. The angular distribution for events in this momentum group can in principle be found from the data represented in Fig. 5. Considering this momentum group alone, further analysis indicates a minimum in the neighborhood of 50° where the density is of the order of half the density at 0°. Inadequate statistics and resolution prevent more detailed conclusions. In summary, the experimental results are approximately consistent with symmetry about 90° but are probably not consistent with isotropy.

V. DISCUSSION

As few of the decays proceed via modes (1) and (3), it is presumed that they proceed primarily via modes (2a) and (2b). The present experimental information does not readily distinguish between these modes. In particular, the kinematic limits are identical for the two modes and the shape of the momentum distribution of Fig. 6 can be understood qualitatively in terms of either mode.

A characteristic feature of this distribution is the peak at relatively high Be^{9*} rest-frame momentum. If one assumes that breakup proceeds via mode (2a), this peak can be interpreted as being due to two opposing effects which arise in the decay to He^4+He^5. The Coulomb and angular-momentum barriers will favor breakup with high momentum. On the other hand, the rest mass of He^4+He^5 (evaluated at the center of the He^5 ground state) is 0.1 Mev higher than

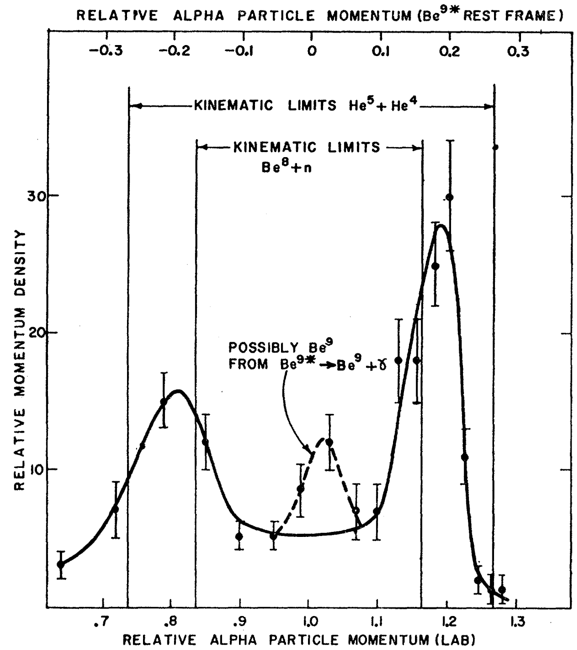

FIG. 6. Density in momentum space of alpha particles from the breakup of Be^{9*} (2.43 Mev). The data were taken at $\theta=0°$ by means of the thin target.

that of the Be^{9*} (2.43-Mev).[7] Decay is still possible in view of the 0.7-Mev width of the level,[1] but low momentum of the breakup particles will be favored. The position of the peak in the momentum distribution is determined by the combination of these effects. The observed alpha particles will of course include alpha particles from the breakup of He^5. These will be spread over a wide region in momentum.

If decay proceeded via mode (2b), the observed peak at relatively high momentum could reasonably be ascribed to the Coulomb interaction between the alpha particles which must be present in any model.

A further complication is suggested by the possibility of decay by neutron emission to the first excited state of Be^{8*}. This state, at 2.90 Mev, is about 1.2 Mev wide,[1] and decay to this level might be possible in a manner analogous to the decay to He^5. However, here the energy deficiency is about three times the half-width and it seems more appropriate to consider this mode to be a variant of mode (2b) rather than to correspond to a transition to a specific resonant state.

The main experimental conclusion is that decay of Be^{9*} from the 2.43-Mev level proceeds less than 10% of the time by emission of a neutron to the ground state of Be^8. Although not in accord with previous experimental indications, this conclusion is not unexpected on theoretical grounds. According to the currently available evidence, the 2.43-Mev level probably has spin $\frac{5}{2}$ and negative parity. This assignment is suggested by the experimental information on pickup[8] and inelastic scattering.[4,9,10] It is also predicted by the alpha-particle model[11,12] and is the most probable prediction of the intermediate-coupling shell model.[13,14] Using an argument based primarily on angular-momentum considerations, Henley and Kunz[15] have shown that if Be^{9*} (2.43 Mev) has this spin and parity, then on any reasonable model, decay by neutron emission to the ground state is improbable. Thus, were neutron decay observed to be dominant, a contradiction with theory would arise. The present result that neutron decay is not dominant is consistent with the known information relating to the 2.43-Mev level of Be^9. However it does not appear to be possible to use the information on the relative probability of neutron or alpha-particle emission to distinguish between currently favored models of Be^9.

ACKNOWLEDGMENT

We are very grateful to Dr. E. M. Henley for discussions concerning the results of calculations on this problem and to him and Dr. J. S. Blair for many illuminating conversations. We would like to express our appreciation to the crew and staff of the University of Washington cyclotron for their help in making the experiment possible.

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