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ABSTRACT

A beryllium target has been bombarded with 12-Mev protons, 24-Mev deuterons, and 48-Mev alpha particles. With the three projectiles, the differential cross sections for inelastic scattering leading to the formation of the 2.43-Mev state have been measured. Application of inelastic-scattering theory leads to the assignment for this level, spin 5/2 and odd parity.

A very weak inelastic proton group has been found which could correspond to a level in Be^9 at $\sim$ 1.8 Mev. The observation of inelastic alpha-particle groups corresponding to levels at 6.8 and 11.3 Mev makes definite the assignment of isotopic spin 1/2 to these states. The data obtained are not inconsistent with the existence of levels at 3.1 and 4.8 Mev.

The pickup reaction $Be^9(p, d)Be^8$ (ground state) was observed. Although the distribution is peaked forward as predicted by Butler, the shape is the same as that found at other energies. Such behavior is not consistent with the quantitative aspects of the theory.

The reactions $Be^9(p, np')Be^8$ and $Be^9(\alpha, n\alpha')Be^8$ have been studied. Analysis of the angular distributions suggests that those processes in which the charged particle retains most of the energy occur predominantly by direct interaction.

Finally, the elastic scattering of protons, deuterons, and alpha particles has been observed. Analysis of these distributions assuming a black nucleus gives reasonable agreement with the positions of the diffraction effects. The radii of interaction that are necessary are large but consistent within themselves and with those that fit the inelastic data.

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INTRODUCTION

Although the beryllium nucleus was early the subject of considerable experimental investigation,[1] its energy-level structure is poorly and incompletely determined. This is in part due to its very low neutron-binding energy. As a consequence, nuclear reactions involving Be^9 are generally accompanied by a considerable amount of multibody breakup, for the escape of a neutron leads to alpha-unstable Be^8. Furthermore because the excited states of Be^9 decay predominantly by particle emission, the level structure cannot be investigated by gamma-ray analysis.

Shown in Fig. 1 is the energy-level diagram for Be^9.[1] Levels above the proton threshold have been excluded for simplicity. Data published since 1954 have also been included.

Theoretical study of Be^9 has been limited. Haefner[2] has treated the loosely bound neutron as a perturbation to an alpha-particle model of Be^8. In the j-j coupling limit of the shell model,[3] the properties of the lowest levels should be due to the single $p_{3/2}$ neutron. Recent extensions[4] of the shell model

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to intermediate coupling are laborious but appear to be more realistic. Unfortunately, with so little experimental data available, the predictions of these models can hardly be put to a rigid test.

The present inelastic-scattering experiments were carried out with four goals in mind:

(1) To verify the existence of the 1.8-Mev level and to determine the cross section for its formation,

(2) To study the cross sections for formation of the 2.43-Mev state and hence resolve the disagreement in parity between the results of Ribe and Seagrave[5] and of Finke,[6]

(3) To see if the analysis of proton, deuteron, and alpha-particle data would permit an unambiguous spin assignment for that state, and

(4) To examine as many of the more highly excited states as reaction kinetics and energy resolution would allow.

During the course of these measurements it was convenient to determine the cross sections for elastic scattering. These are of interest because they permit determinations of the radius of the beryllium nucleus and assist in the analysis of the inelastic data. A comparable radius of interaction may be derived from measurements on the $Be^9(p,d)Be^8$ pickup reaction. In order to obtain the desired inelastic data it was necessary to examine critically the charged-particle spectra due to multibody breakup. This examination has revealed that direct interaction also plays an important role in these reactions.

EXPERIMENTAL

The external beam of protons, deuterons or alpha-particles from the 60-inch cyclotron at Crocker Laboratory was used. Descriptions of this and of the 36-inch scattering chamber in which the measurements were carried out are already published.[7,8] Further details, with particular application to the present experiments, may be found in a Radiation Laboratory report.[9]

The detector consisted of a three-chamber proportional counter which permitted identification of the scattered particles by their pulse height in the first chamber and determination of their energy by range measurement. The counter could be positioned by remote control at laboratory angles between 5° and 167° from the beam direction. These were measured and could be reproduced to within 0.1°. The finite acceptance angle of the counter was about 1°.

After passing through the target, a 1-mil beryllium foil, the beam was collected in a Faraday cup. A conventional 100% negative-feedback electrometer and standard condenser permitted absolute measurement of the beam current. The energy of the incident beam was measured by range determination with the Faraday cup as detector. Average values (with total energy spread in brackets) for these experiments were as follows:

protons 12.0 (0.2) Mev
deuterons 24.0 (0.4) Mev
alpha particles 48.0 (0.8) Mev.

Beam alignment was checked and the angular spread of the incident beam measured by scanning the collimated beam with a narrow slit in front of the Faraday cup. These measurements were facilitated by the use of an auxilliary beam monitor in the form of a NaI crystal and photomultiplier which viewed the target at a permanently set laboratory angle of 20°. Combination of the angular spread in the incident beam and of the finite acceptance angle of the detector leads to an angular resolution somewhat better than 2°. The differential cross sections presented have not been corrected for this finite resolution.

RESULTS

A. Proton Bombardments

The complete charged-particle spectrum was measured at 25° and 65° in the laboratory frame. The 65° results are shown in Fig. 2. The observed peaks are identified as follows:

I. Elastic scattering from oxygen (present as a contaminant);

II. Elastic scattering from beryllium;

III. Proton group which may be interpreted as corresponding to a level in Be^9 at ~1.8 Mev but which may have another origin (see discussion);

IV. Inelastic-proton group corresponding to the level in Be^9 at 2.43 Mev;

V. Deuteron group from the reaction $Be^9(p, d)Be^8$(ground state) with, possibly, a small contribution of inelastic protons (3.1-Mev level);

VI. Mixture of deuterons from the reaction $Be^9(p, d)Be^{8*}$(2.9-Mev level) and inelastic protons (4.8 Mev level).

The 6.8-Mev level clearly manifested itself at 25° where the inelastic-proton energy was great enough to permit scanning above and below the peak. In the light of this, the bump in Fig. 2 at 15 mg/cm^2 is presumably significant and due to inelastic scattering to that same level. The maximum range of protons from the three-body reaction $Be^9(p, np')Be^8$ is shown by the arrow to the right of peak IV. All ranges less than this are kinematically possible.

The 25° data are essentially the same. As mentioned, a peak corresponding to the 6.8-Mev level was visible. Because of a considerable increase in the general continuum, peak VI was not so prominent. The small peak III was completely obscured by an elastic peak fifty times larger than that at 65°.

The elastic group was measured at suitable intervals from 7° to 167°. Where visible the oxygen elastic peak was generally about 1% of the beryllium peak. The cross sections for elastic scattering obtained from these data are shown by the solid points of Fig. 3.

Peak III was examined in detail at several forward angles. Poorer resolution, due to the necessity of a reflection target at scattering angles beyond 90°, precluded the possibility of detecting it in backward directions. In Fig. 4, which shows data for three angles, the abscissa were converted from range to excitation energy assuming the reaction $Be^9(p, p')Be^9$. Table I summarizes the observed excitation energies and formation cross sections and includes the results of less reliable measurements at 40°. The peak shapes are consistent with a level width of $\sim$0.2 Mev.

Table I

Characteristics of the 1.8-Mev "level" in Be^9

θ_L (deg)	θ_{CM} (deg)	Excitation energy (Mev)	$\frac{d\sigma}{d\Omega}$ for $Be^9(p,p')Be^9$ (mb/sterad)
40°	44.5°	1.65 ± .10	~0.5
50	55.4	1.76 ± .03	0.17 ± .08
65	71.5	1.82 ± .03	0.15 ± .06
90	97.0	1.91 ± .03	0.16 ± .08

Peaks IV and V and the continuum in their vicinity were scanned at suitably chosen forward and backward angles. The differential cross sections for the inelastic scattering and for the pickup reaction are shown in Figs. 5 and 6. The significance of the curves will be discussed in a later section. The total integrated cross section for the reaction $Be^9(p,d)Be^8$ is 40 mb. For the inelastic scattering $Be^9(p,p')Be^{9*}$ (2.43 Mev), the same quantity is 110 mb.

Considerable 3-body breakup was observed in the proton bombardments. While such a reaction does not manifest itself by the presence of a discrete-energy particle group, it can nevertheless be studied by the method outlined in the Appendix. The results of such an analysis for the reaction $Be^9(p,np')Be^8$ are shown in Fig. 7. The ordinate gives the differential cross section for the formation of the Be^8 ground state and the scattering of the proton through an angle θ where the available kinetic energy has been shared in such a way that in the center-of-mass we have $0.90\ E_{p'}^{max} \leq E_{p'} \leq E_{p'}^{max}$.

B. Alpha-Particle Bombardments

Complete alpha-particle spectra were taken at laboratory angles of 14.5°, 29.8° and 62.5°. Figure 8 shows the results for the largest angle. Data at the other angles were essentially the same. Peak I contains particles elastically scattered from beryllium. The second peak corresponds to the 2.43-Mev level while peaks III and IV correspond to the higher states at 6.8 and 11.3 Mev, respectively. Elastic scattering from oxygen was again evident but is not shown. Identification of weak particle groups corresponding to levels at 1.8 and 3.1 Mev was impossible because of insufficient resolution. There seems to be no clear indication of the 4.8- and 7.9 Mev levels, although conditions for their observation were more favorable. If these levels are broad or only weakly excited, their presence may have been masked by the prevailing continuum. No attempt was made to observe protons in these measurements.

The elastic and 2.43-Mev inelastic peaks were studied at some 35 angles from 5° to 90° in the laboratory frame. Figure 9 shows the differential elastic-scattering cross section. The differential cross section for inelastic scattering and the formation of the 2.43-Mev state is shown in Fig. 10. The total cross section for this reaction, up to $\theta_{CM} = 120^{\circ}$, is 50 mb; if a flat angular dependence is assumed at greater angles, the total integrated cross section is 56 mb.

As in the case of the proton bombardments, a considerable continuum was observed. Since its beginning occurred close to the calculated onset of the three-body reaction $Be^9(a, na')Be^8$, it was interpreted in that way. Because of the compression of the energy scale ($\frac{dE}{dX}$ is greater for alpha particles than for protons), the analysis of the type discussed in the Appendix may have included additional contributions due to an unresolved 4.8-Mev level and 3-body reactions in which the ground state of Be^8 is not involved. Figure 11 shows the data with these other reactions assumed to be negligible. The ordinate is the differential cross section for the reaction $Be^9(a, na')Be^8$ in which the scattered alpha particle retains most of the energy so that we have $0.90\ E_{a'}^{max} \leq E_{a'} \leq E_{a'}^{max}$. The slight structure visible is probably not real, since it corresponds closely to that observed in the cross section for the formation of the 2.43-Mev state and presumably has its origin in slightly incorrect treatment of the experimental data.

C. Deuteron Bombardments

The same beryllium target was bombarded with 24-Mev deuterons, and the charged-particle spectra studied as before. A large neutron flux compounded the difficulties of making the observations so that the data here are neither so complete nor so well established. At all angles, substantial charged-particle backgrounds were observed, with the target both in and out.

Figure 12 shows the partial charged-particle spectrum taken at a laboratory angle of 25.6°. Even under the elastic group, peak I, the background is appreciable. The strongly excited 2.43-Mev level accounts for peak II while peak V corresponds to the 6.8-Mev state. The slight bump, labeled IV, is presumed to be due to the 4.8-Mev level. The origin of peak III is not so clearly understood. Its position corresponds closely to that projected for an inelastic deuteron group from the 3.1-Mev level in Be^9. However, tritons from the possible reaction $Be^9(d, t)Be^{8*}$ (2.9-Mev state) should have a similar range. It was not possible to identify these particles by discrimination in the detector owing to the weakness of the group and to the background consisting mainly of proton recoils. While it is probable that (d, t) reactions do occur, as found at other bombarding energies,[10] it is possible that peak III (visible also in the 30° and 15° data) is partially due to a contribution from the inelastic-deuteron group. A weak group corresponding to the 1.8-Mev level would have been masked by the background. For the same reason, the onset of the (d, nd') reaction was not visible.

Experimental points for the elastic differential cross section are shown by the solid circles of Fig. 13. The inelastic cross section for scattering to the 2.43-Mev state is shown in Fig. 14. Measurements at more forward angles were impossible because of the large elastic cross section. This swamping may be taken as evidence that the probability of inelastic scattering continues to decrease for $\theta < 15°$. For this reaction, the total cross section, which is rather insensitive to the behavior at small angles, is 44 mb. Analysis of the continuum was not possible in this case; in addition to the neutron-initiated background, other multibody processes, $Be^9(d, pn)Be^9$ and $Be^9(d, p2n)Be^8$, can compete with the $Be^9(d, nd')Be^8$ reaction.

DISCUSSION

A. Elastic Scattering

The solid curves of Figs. 3, 9 and 13 represent the Rutherford cross sections for scattering from a point charge. When the observed data are divided by these cross sections, the dashed curves result. Interference effects are prominent. Except at small angles corresponding to large distances of closest approach, these ratios are greater than unity. The accuracy of the absolute normalizations are strikingly demonstrated in two instances, however, by the fact that the measured absolute differential cross sections are very close to the Rutherford cross sections at the smallest angles.

One of the simplest ways to interpret elastic-scattering data is to assume that the nucleus is opaque to particles that in a classical picture would "hit" the nucleus.[11] Particles that "miss" are assumed to proceed without interaction. Such a picture is, of course, the more valid, the greater the observed ratio to Rutherford scattering. Under these assumptions, the problem reduces to a simple one in optics, and roughly speaking we have

$$2kR \left\{ \sin \frac{\theta_{i+1}}{2} - \sin \frac{\theta_i}{2} \right\} = \pi$$

where k is the wave number of the scattered particle,

R is the interaction radius, and

θ_i is the angle at which the i^{th} maximum is observed.

A similar relation holds for the angles at which minima occur. Table II lists the angles of maxima and minima and the values of R calculated from the above formula for each of the three elastic-scattering processes observed. It is apparent that such a rough explanation of the origin of the interference effects is not completely adequate. However, it is logical to expect consistency not only among the values obtained from proton, deuteron, and alpha-particle elastic data but also with the radius parameters derived from the inelastic data to be discussed in the next subsection.

The elastic parameters are consistent with a radius for the beryllium nucleus, $r_{Be} = (3.4 \pm 0.2) = (1.65 \pm 0.10)\ A^{1/3}$ fermi if it is assumed that $r_p = 1.2$, $r_\alpha = 1.5$, and $r_d = 1.6$ fermi. This proton radius is reasonable. While the radius of the alpha particle[12] is, no doubt, nearer 2.3 fermi, a smaller effective value is in line with that generally found when the alpha particle is in the Coulomb field of a nucleus. Blatt and Weisskopf, for example, choose the effective radius under such conditions to be 1.2 fermi.[13] Elastic scattering experiments by Igo, Wegner, and Eisberg at 40 Mev yielded the value (1.60 ± 0.23) fermi.[14] The fact that the deuteron radius above is considerably smaller than the so-called "radius of the deuteron" is not surprising.[15] If a collision took place at a time when the neutron and proton were widely separated and outside the range of their mutual forces, scattering of the deuteron as a whole would not be expected. Therefore, 1.6 fermi is a satisfactory effective deuteron radius. The large size of the beryllium nucleus presumably reflects the smallness of its binding energy.

Table II

Interaction radii obtained by diffraction analysis of elastic scattering

Incident particle	Position of Feature: Maxima (deg)	Position of Feature: Minima (deg.)	R (fermi)	Mean R (fermi)
p		8 ± 1		
			4.4 ± 0.1	
		72 ± 1		
				4.6 ± 0.1
	45 ± 2			
			4.8 ± 0.2	
	117 ± 2			
α	12.2 ± 1.0			
			5.2 ± 0.4	
	29.0 ± 1.0			
			4.4 ± 0.3	
	49.5 ± 1.0			
			5.3 ± 0.4	
	68 ± 1			
			5.0 ± 0.4	
	90 ± 2			
				4.9 ± 0.2
		20.0 ± 0.5		
			5.2 ± 0.2	
		37.0 ± 0.5		
			4.5 ± 0.3	
		57.5 ± 1		
			4.6 ± 0.4	
		80 ± 2		

Table II (cont.)

Incident particle	Position of maxima (deg.)	Position of minima (deg.)	R (fermi)	Mean R (fermi)
d	20.5 ± 1.0			
			5.0 ± 0.2	
	51 ± 1			
			5.3 ± 0.3	
	84 ± 2			
			5.2 ± 0.3	
	131 ± 3			
				5.0 ± 0.1
		32.5 ± 1.0		
			4.8 ± 0.2	
		65.5 ± 1.0		
			4.6 ± 0.2	
		109 ± 2		
			4.9 ± 0.2	
		152 ± 1		

The above analysis is based on a rather rough postulate, namely, total absorption of particles incident on the nucleus itself. Furthermore, the model does not allow for a region of smooth variation from no nuclear matter to the maximum nucleon density. Unfortunately, in the very light nuclei, more realistic optical-model analyses[16] do not yield unique values for the parameters involved. Nevertheless, the proton data have been incorporated with the results of a wide survey of elastic scattering carried out at this laboratory,[17] and such an analysis is in progress. It is hoped that a similar survey and analysis of elastic alpha-particle scattering will soon be undertaken. At 48 Mev, data are already available for the elements C and Mg,[18] and Ag, Au, and Pb,[8] in addition to Be reported here.

B. The 2.43-Mev State

The differential cross sections for the inelastic processes, (p, p'), (α, α'), and (d, d'), leading to the 2.43-Mev excited state of Be^9 have been determined. All three show maxima in or near the forward direction and were analyzed using direct-interaction theories.[19,20]

(i) Inelastic deuteron scattering

Figure 14 shows the arbitrarily normalized theoretical ($\ell = 2$) distribution[20] for the reaction $Be^9(d, d')Be^{9*}$ (2.43-Mev state). The radius of interaction for best agreement with the experimental data is 5.60 fermi. The first peak fits well; the second, while agreeing in position with the second experimental maximum, is several times too small. This same discrepancy can be noted in other inelastic deuteron distributions.[21] With a = 3.40 fermi, the theoretical curve for $\ell = 1$ can reproduce the first maximum, but the second then falls at $\theta = 95°$. The poorer agreement and particularly the small interaction radius $a = r_0 A^{1/3} + r_d$ make such an interpretation highly unlikely.

For $\ell = 2$, application of the selection rules[22] leads to the assignment 1/2, 5/2 or 7/2, all odd parity, for the 2.43-Mev state. The absence of a dominant $\ell = 0$ fit, eliminates the possibility of spin 3/2.

(ii) Inelastic alpha-particle scattering

The prediction of direct -reaction theory[19] for the inelastic (2.43-Mev state) alpha-particle scattering from beryllium is shown in Fig. 10. The curve, drawn for $\ell = 2$ and $a = 5.40$ fermi, has been arbitrarily normalized. In this case the value of the interaction radius was chosen to give optimum fit of the positions of the minima at 29° and 47°. Except for the measurements for $\theta < 15^{\circ}$, which are subject to large errors, the agreement between theory and experiment is remarkable. The best fit for $\ell = 1$ requires an interaction radius $a = 4.63$ fermi, but this curve fits the width of the first maximum very poorly and places the higher-order maxima and minima at too large angles. If $\ell = 2$ is accepted, the selection rules for a spinless particle lead again to $J_f = 1/2,\ 5/2$, or 7/2, all odd parity.

(iii) Inelastic proton scattering

Figure 5 shows the observed results for the formation of the same level by inelastic-proton scattering. Its interpretation by simple direction-interaction theory is not immediately obvious because the forward maximum is so broad. Other inelastic proton data at the same bombarding energy show a similar behavior.[23] The greatly reduced ratio of the maximum-to-minimum cross section indicates that one or more of the following complications is involved:

(1) An appreciable amount of the excitation takes place via compound nucleus formation.

(2) Direct interaction proceeds with considerable penetration of the protons into the nucleus.[24]

(3) More than a single ℓ value is involved in the direction process.

(4) Coulomb and nuclear-distortion effects are particularly strong.[25]

It is impossible to show conclusively which of these is involved here, since the calculation of the effect of each on the cross section is, to a large degree, subject to the whim of the calculator. No doubt all are involved to some extent. The following qualitative arguments can be made, however, to show which could account for the observations in a reasonable way.

Because the Coulomb barrier is only 1.8 Mev, and the beryllium nucleus is small, one would not expect Coulomb and nuclear distortion effects to play a major role in this case. The (p, d) cross section, measured at the same bombarding energy, confirms this expectation. While it is true that the (p, d)-reaction cross section appears to be anomalous in so far as the interaction radius is concerned (see below), its shape is definitely of the undistorted Butler type.

The (p, d) cross section cannot provide arguments about the magnitude, in inelastic proton scattering, of the other possible complications, because the fact that a deuteron is involved in the first-named reaction assures that compound nuclear effects will be small and inhibits contributions to the direct reaction from the interior of the nucleus. As discussed in another paper, successful competition between two ℓ-values is possible only for the (p, p') reaction and arises because spin flip can occur.[22]

It is difficult to be dogmatic about compound-nucleus contributions because of the uncertainty in the shape of the differential cross section arising from such a mechanism. If only one level of the compound state is involved or if a statistically large number are involved, the angular distribution of the evaporated particles must be symmetric with respect to 90^{o}. On the other hand, if two or only a few levels of opposite parity are involved, this restriction is lifted. In any case, one can be guided by the fact that the cross section, expanded in the form $\sum_n A_n \cos^n\theta$, can contain values of n no larger than 2L, where L is the smaller of the highest partial wave absorbed from the incident beam and the spin of the compound level with the highest angular momentum. Rough estimates of the level spacing and level widths of the compound nucleus that would be involved here (B^{10*} with excitation energy 17.4 Mev) indicate that the statistical assumption would not be justified. From the nature of such a calculation it is impossible to say whether one level or several would contribute. Computation of the classifical impact parameters and barrier-transmission factors shows that s- and p-waves should have appreciable reaction amplitudes and that d-waves might contribute. It is therefore just possible that at least two high-spin levels of opposite parity participate, say 2+ and 3-, and all terms up to $\cos^4\theta$ arise. The observed cross section can be adequately fitted by such an expression.

Three lines of reasoning, however, favor interpreting at least part of the cross section in terms of direct interaction:

(1) A rough estimate of the cross section for compound nucleus formation, using the familiar asymptotic expression,[26] yields the value 600 mb. Because the compound nucleus is excited 9 Mev above the threshold for neutron emission, one would expect de-excitation to occur by this means in the majority of cases. It is difficult, therefore, to entertain the idea that the 110-mb cross section for the reaction $Be^9(p, p')Be^{9*}$ (2.43-Mev state) arises mainly by decay of the compound nucleus.

(2) Examination of the (p, np') cross section, involving changes of proton energy of about 2.5 Mev, Fig. 7, shows that direct reaction is an important mechanism at 12-Mev bombarding energy.

(3) While inelastic proton scattering[23] from carbon does not show the normal shape for direct interaction processes, angular correlation measurements[27] indicate that an appreciable amount of this reaction must, nevertheless, take place directly.

Accordingly, attempts have been made to explain the observed cross section in terms of the combination of compound-nucleus formation and direct interaction.

Curve 2 of Fig. 5 illustrates the best fit for a single ℓ-value together with an isotropic contribution from the compound nucleus. The parameters involved are $\ell = 0$, a = 1.8 fermi and $\left(\frac{d\sigma}{d\Omega}\right)_{CM} = 2.5$ mb/sterad. While the agreement is satisfactory, such an interpretation seems unlikely in view of the smallness of the radius of interaction.

More plausible radii,[28] though a poorer fit, are obtained using combined $\ell = 0$ and $\ell = 2$ distributions and a contribution from compound-nucleus formation. The dashed curves of Fig. 5 have been calculated (arbitrary normalization) for $\ell = 0$ and $\ell = 2$ using radii of interaction of 4.5 and 5.5 fermi. A typical result of the addition of such direct interaction terms and a compound-nucleus cross section $\left(\frac{d\sigma}{d\Omega}\right)_{CM} = 5 - 3\cos^2\theta$ is shown by Curve 1. While it is not quite possible to find a combination that avoids a double-humped sum, it is reasonable to expect that minor departures from simple, direct reaction patterns could smooth this to agree with observation. The implications of the contribution of two ℓ-values in inelastic proton scattering are discussed at length elsewhere.[22] Applied to this case, it is thought that the $\ell = 2$ contribution corresponds to proton scattering without spin flip, while the $\ell = 0$ contribution (diminished so that it does not dominate over the contribution from higher ℓ-values) is allowed only when spin flip does occur. The selection rules therefore lead to the conclusion that the final state has angular momentum 1/2 or 5/2 and odd parity.

(iv) Level properties

The work of Ribe and Seagrave, a study of the reaction $B^{10}(n, d)Be^{9*}$, has shown that the spin of the 2.43-Mev level is 3/2, 5/2, 7/2 or 9/2 and the parity odd.[5] That result and those obtained here lead to the unambiguous assignment 5/2 - for this level.[29] At first sight the 31.3-Mev inelastic-proton-scattering data do not seem to be consistent with this.[6] As the authors point out, however, a poorer fit to their data is possible for $\ell = 2$ and radius of interaction 4.15 fermi. Not only does this interpretation permit a final-state assignment of 5/2 -, but it also yields a radius of interaction of more appropriate magnitude.

Spin 5/2 and odd parity is in accord with the intermediate-coupling shell-model prediction for the 2.43-Mev state.[4] The alpha-particle model gives the same result.[2] This assignment is also consistent with the observed level width[30] and with the observation that de-excitation proceeds almost entirely by neutron emission.[31] In the transition to the Be^8 ground state, the neutron will carry off three units of orbital angular momentum. A rough calculation for the probability of this process gives a partial width of about 1 kev. The partial width for magnetic-dipole radiation to the Be^9 ground state would be of the order of 1 ev.

C. The Three-Body Reactions $Be^9(p, np')Be^8$ and $Be^9(a, na')Be^8$

Cross sections for the reactions $Be^9(p, np')Be^8$ and $Be^9(a, na')Be^8$, in which more than 90% of the available energy is retained by the charged particle, are shown in Figs. 7 and 11 respectively. Their strong asymmetry makes it obvious that direct interaction is the dominant reaction mechanism. If compound nucleus formation were involved, one would expect considerably smaller and more isotropic differential cross sections.

The process involved may be inelastic scattering in which the final state is not bound. The scattered particles will suffer arbitrary linear- and angular-momentum changes because the neutron can have any (quantized) angular momentum in addition to a wide range of energies. The spherical Bessel functions of the Austern, Butler, and McManus theory[19] must, therefore, be averaged over appropriate k' and summed over ℓ. Approximate calculations of the differential cross sections have been carried out and the results are shown as solid curves in Figs. 7 and 11. The radii of interaction used were those that best fit the corresponding inelastic-scattering data. Because each computation involves only one assignable parameter, viz. the scale factor, the close agreement between theory and experiment is as remarkable as that obtained in any direct interaction. The spectral shape resulting from such a mechanism would, at the high-energy end, be mainly determined by the phase space available to the neutron. Because this increases as the energy of the scattered particle decreases, one would expect the number of events to increase with decreasing charged-particle energy. At lower scattered-particle energies, the issue is complicated by Coulomb effects and by the decreasing probability of direct interaction for events in which the momentum change of the incident particle is comparable to the incident momentum. Examination of Figs. 2, 8 and 16 shows that the high-energy end of the spectrum agrees qualitatively with expectation; the lower-energy part cannot be investigated experimentally.

A second type of direct interaction is also possible. This is a reaction similar to heavy-particle stripping;[32] a reaction in which the incident charged particle causes the loosely bound neutron to be stripped from its Be^8 core and then itself succeeds in escaping capture by that core. The cross section for such a reaction is not expected to be large. Without going into the details here, it can be stated that the neutron will travel in essentially the backward direction with low energy. From the kinematical equations it then follows that the scattered charged particle will have an energy distribution peaked sharply around a value close to the maximum possible. It is clear, therefore, that this mechanism is not involved in the data of Figs. 7 and 11. It is highly probable, however, that the small proton group (peak III) in Fig. 2 is the result of this effect.

D. The Possible 1.8-Mev State

Data have been obtained which appear, on the surface, to be consistent with a level in Be^9 at ~ 1.8 Mev. In the preceding paragraph, however, a process has been described which is capable of explaining these same data in terms of a 3-body reaction.[33] Preliminary calculations of this effect have already been presented;[34] more detailed considerations are in progress and will be published in the near future. It is the intent of this discussion to assume that the level actually exists, and then to see what characteristics it would have to have in order to be consistent with the data.

Observed values of the excitation energy are listed in Table I. Although errors have been estimated liberally, consistency among the values measured at different angles is poor.[35] The mean excitation energy, 1.83 ± 0.03 Mev, does not entirely agree with other determinations.[36, 37, 38] The shape of the observed proton peak suggests that the level width is probably about 0.2 Mev. Only a 1/2-state could have such a width. If this is true, de-excitation by gamma-ray emission should occur only once in a million decays. Kurath has shown that, in intermediate coupling, there is a 1/2 - state near the 5/2 - state at 2.43 Mev,[4] but the theory is not able to decide which is the lower-lying.

In the angular interval $50^\circ \leq \theta \leq 100^\circ$, the differential cross section for the inelastic scattering of 12-Mev protons is only 0.16 mb/sterad. This is a factor of 60 less than that for the formation of the 2.43-Mev state. Since a peak corresponding to its excitation was not observed in the alpha-particle and deuteron data, it is possible only to set an upper limit, 0.5 mb/sterad , for the cross section for formation by inelastic alpha-particle or deuteron scattering. Other workers have observed the excitation of this level in various reactions,[36,37,38,39] but, unfortunately, few absolute cross sections are available. It is strange that, in the reaction $Li^7(He^3,p)Be^{9*}$, the peaks corresponding to the 2.43-Mev and 1.8-Mev levels are of comparable magnitude; in all other instances, the 1.8-Mev level has been much-less-strongly excited.

It is obvious that any theory of the 1.8-Mev state must account for this anomalous behavior. Small cross sections could result from a fortuitous cancellation of matrix elements, but it is tempting to conjecture that this level must be quite different in structure from the ground state and 2.43-Mev level. In the shell model this might mean that the 1.8-Mev state does not arise from the p^5 configuration. In the alpha-particle model, core excitation may be involved. If collective modes are present in Be^9, the 1.8-Mev state could have K = 1/2 and the other low-lying states K = 3/2.

E. Other States

In this work it has not been possible to make any clear observations with respect to the 3.1-Mev level. However, it is thought that the inelastic deuteron measurements do confirm its existence. It is clear that this state is not as prominent in inelastic scattering as the 2.43-Mev state. This implies that the cross section for formation is considerably smaller than that for the other state and/or that the 3.1-Mev state has an appreciable width. Rasmussen et al. indicate that the level width is perhaps 0.3 Mev.[38] If this is true, then the spin and parity is very probably 1/2 -. On the other hand, Allen reports $\Gamma < 0.1$ Mev.[40]

The reaction $Li^7(He^3,p)Be^{9*}$ seems to provide evidence for a level with excitation energy ~4.8 Mev and width about 1 Mev.[36] In that experiment the proton group corresponding to the 4.8-Mev state is as prominent as the group due to the 2.43-Mev state. In the 31-Mev proton inelastic-scattering data, there is some indication of the existence of a weakly excited level at about 5 Mev.[6] Fry has observed an event in nuclear emulsion which is best interpreted as the decay of Li^9 to an excited state of Be^9 at 4.4 ± 0.8 Mev.[41] In the proton-scattering data reported herein, conditions were not favorable for the observation of such a level because of an overlapping deuteron group from a competing reaction. No evidence of the level was found in the alpha-particle bombardments and only the weakest indication in the deuteron-scattering data. If the heavy-particle stripping mechanism is successful in discounting the evidence for a level at 1.8 Mev, then this same mechanism could predict an "apparent level" at ~4.8 Mev even if one does not really exist. This is because 4.8 Mev bears the same relation to the Be^{8*} + n threshold (4.6 Mev) as 1.8 Mev does to the Be^* + n threshold (1.666 Mev). Because the excited state of Be^8 has a width of 1 Mev,[42] the 4.8-Mev "level" would appear at least as broad. It is not clear, however, whether the cross section for such a process is sufficiently large to completely account for the observations. The emulsion event could be assigned to another level.

The existence of more highly excited states at 6.8 and 11.3 Mev is confirmed. Both states, which appear to be quite broad, were prominent. Because of uncertainties in the magnitude of the continuum underlying the peaks corresponding to these levels, quantitative cross-section measurements were not possible. Formation of these states in alpha-particle scattering implies that they are isotopic-spin doublets. No evidence for a level at 7.9 Mev was found but the search was only cursory. Levels above 11.3 Mev could not be detected.

F. The Reaction $Be^9(p,d)Be^8$

The application of Butler stripping theory[43] to (d, p) and (p, d) reactions is well established. Figure 6 shows the experimental data together with the theoretical cross section (normalized for best fit in the region 10° to 30°) for the reaction $Be^9(p,d)Be^8$. The parameters used are $\ell = 1$ and radius of interaction 4.50 fermi. The fit is excellent, the orbital angular momentum is in agreement with the known initial and final spins and parities, and the interaction radius compares favorably with that found in elastic proton scattering at the same energy.

With the reporting of the present results at 12 Mev, data for this reaction are now available at bombarding energies of 5 to 8,[44] 12, 16.5,[45] 22,[46] and 31.3 Mev.[6] This case, therefore, presents the opportunity to test stripping theory for one reaction at a variety of energies. In Fig. 15 the available differential cross sections are shown arbitrarily normalized. Apart from a slight tendency for the measured values to separate at angles greater than 70°, there is no evidence that the shape varies with energy. This is not at all what is to be expected from simple Butler theory unless the radius of interaction is itself a strong function of energy. It is hard to see how the revisions to the theory that include Coulomb interaction could lead to any improvement because, for $Z = 4$, such effects should be small. Bhatia et al. have pointed out that Butler's formula behaves in a "special" or "singular" manner when the neutron binding energy is zero.[47] Because this condition is nearly satisfied in the case of beryllium, it is possible that the theory is not valid in this instance.

It would be interesting if another stripping reaction were measured over a wide range of energies and a similar comparison made. If the interaction radius were again found to be a function of energy, it would be clear that something more subtle than the binding energy of the neutron is involved.

G. Further Conclusions

Continued experimental investigation will be necessary before the true level structure of Be^9 can be clarified. Because of the prevalence of 3-body reactions, the prospect of obtaining unambiguous data from inelastic scattering is not bright. Clear evidence for levels would follow detection of de-excitation gamma rays. Unfortunately, the large particle widths of the Be^{9*} states offer little hope for the success of such searches. However, a possibility does seem to exist, namely, the examination of the beta spectrum (and accompanying neutrons) from the decay of Li^9. The fact that Li^9 is a delayed-neutron emitter[48] indicates that this decay proceeds through one or more excited states of Be^9.

ACKNOWLEDGMENTS

It is a pleasure to thank Professor A. C. Helmholz for his continued interest and advice in this work. The invaluable assistance of Drs. Robert E. Ellis, Franklin J. Vaughn, and Homer E. Conzett in setting up the cyclotron runs and taking data is gratefully acknowledged. The author is indebted to Professor David R. Inglis for several stimulating discussions. The late Mr. G. Bernard Rossi, Mr. W. B. Jones, and the other members of the 60-inch cyclotron staff provided excellent accelerator operation and frequently assisted beyond the call of duty. This work was greatly facilitated by Mr. Fred Vogelsberg, who maintained the counting-area electronics.

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APPENDIX

It is common procedure to determine from a charged-particle spectrum the cross sections for reactions that yield discrete energy groups. It is shown here that it is also possible to obtain cross sections for multibody reactions which yield continuum spectra provided, of course, that their origin is unique. In particular, it has been possible to measure differential cross sections for the reactions $Be^9(p, np')Be^8$ and $Be^9(a, na')Be^8$ in which the charged particle is emitted with 90% or more of the maximum energy permitted. The results of these measurements have been presented above.

For the sake of clarity, the particular case of the (p, np') reaction is discussed. Generalization is largely a matter of notation. First consider the 3-body breakup in the center-of-mass frame. Because the system has no net momentum, the momentum vectors $\vec{P}_n$, $\vec{P}_p$, and $\vec{P}_N$ ($\vec{P}_{Be^8}$) are necessarily coplanar. If one chooses a coordinate system in this plane so that $\vec{P}_p$ is directed along the x-axis, the kinematical equations are

$$P_p + P_n \cos \phi_n + P_N \cos \phi_N = 0$$

$$P_n \sin \phi_n + P_N \sin \phi_N = 0, \text{ and}$$

$$\frac{P_p^2}{2m_p} + \frac{P_n^2}{2m_n} + \frac{P_N^2}{2m_N} = \mathcal{E} ,$$

where the angles are measured in the usual sense, the m's refer to the masses of the particles involved, and $\mathcal{E}$ is the energy of the system. The maximum value of P_p (and hence of the proton energy E_p) is obtained when $\phi_n = \phi_N = 180^\circ$ and $P_n/m_n = P_N/m_N$. It is easy to show that

$$(E_p)_{max} = \frac{(P_p)^2_{max}}{2m_p} = \frac{m_n + m_N}{m_p + m_n + m_N} \mathcal{E} .$$

When the proton does not take maximum energy, the neutron and the Be^8 nucleus are allowed to have various energies and angles. They do not have complete freedom, however, until $x \equiv \frac{E_p}{(E_p)_{max}}$ is sufficiently small. In particular, the angles are confined to the solid cones given by

$$\cos\phi_n \leq -\left[\frac{m_n + m_N}{m_p\, m_n}\left\{m_p + m_N x - \frac{m_N(m_p + m_n + m_N)}{m_n + m_N}\right\}\right]^{1/2}$$

and

$$\cos\phi_N \leq -\left[\frac{m_n + m_N}{m_p\, m_N}\left\{m_p + m_n x - \frac{m_n(m_p + m_n + m_N)}{m_n + m_N}\right\}\right]^{1/2} .$$

As a consequence, when the proton takes near maximum energy, the other two particles are closely confined in a small-angle cone. It may also be shown that they recoil with nearly equal velocities.[49]

Preparatory to transforming to the laboratory frame, consider now that the proton momentum is actually at angle θ with respect to some space-preferred x-axis (i.e., the direction of incidence of the initial proton). Equations for the angles and energies of the neutron and recoil nucleus are now extremely cumbersome (azimuthal symmetry has been lost); however, these do not concern us. If one puts in the features of the initial collision and transforms to the laboratory, it is easy to show that

$$\mathcal{E} = E_i\left[1 - \frac{m_p}{m_p + m_n + m_N}\right] + Q,$$

and

$$A\left(\frac{E_f}{E_i}\right)^{1/2} = \cos\theta_L + \left\{\cos^2\theta_L + B\right\}^{1/2} ,$$

where

$$A = \frac{m_n + m_p + m_N}{m_p} ,$$

$$B = \left(\frac{m_n + m_p + m_N}{m_p}\right)^2 \frac{E_p}{E_i} - 1,$$

E_i = laboratory energy of the incident proton,

E_f = laboratory energy of the final proton,

Q = energy release in the reaction = - 1.666 Mev, and

θ_L = laboratory angle of observation of the final proton, corresponding to θ in the center-of-mass.

With the equations above it is possible to determine, for any laboratory angle θ_L, the laboratory energies corresponding to any desired center-of-mass proton energies.

In order to obtain a meaningful result for the relative differential cross section of such a reaction, it is imperative to take measurements at various angles of the number of scattered protons within some constant center-of-mass energy interval. The interval chosen in this investigation was $0.90\ (E_p)_{max} \leq E_p \leq (E_p)_{max}$. After calculation of the equivalent laboratory energies, and their equivalent ranges, it was possible to identify the corresponding interval of the observed proton spectra. As an example, these limits are shown by the arrows R_H and R_L in Fig. 16 which illustrates the observed data for $\theta_L = 21^\circ$. Because the 2.43-Mev inelastic peak and the pickup deuterons are superimposed on the continuum in this region, it was necessary to interpolate between the end point and a region where nothing interfered with the observation of the continuum alone. These interpolations were done linearly for simplicity. Once the areas of the triangles of continuum so defined have been determined, calculations of the cross sections follow in the same way as those for a conventional reaction follow the determination of peak areas. The transformation from laboratory to center-of-mass was carried out using the $\frac{d\Omega_L}{d\Omega}$ and the θ_L-to-θ correspondence appropriate to the median proton energy $0.95\ (E_p)_{max}$.

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29. The assignment 5/2 - would still be valid in the unlikely event that the interpretation of Curve 2, Fig. 5, were correct.

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49. It is this fact that has led to the consideration of potential scattering or other interaction between neutron and Be^8 to explain the 1.8-Mev "level".

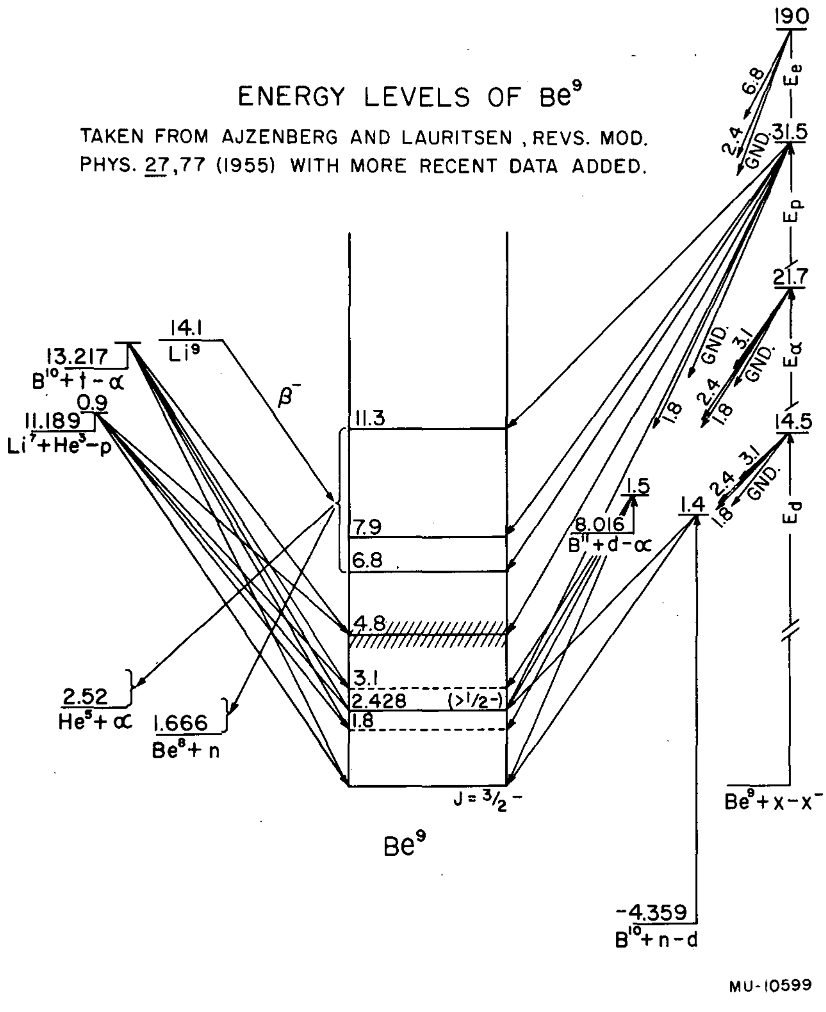

Fig. 1. The energy-level diagram for Be^9. (Taken from Ajzenberg and Lauritsen, Revs. Mod. Phys. 27, 77 (1955), with more recent data added.) States above the proton threshold have been omitted for simplicity.

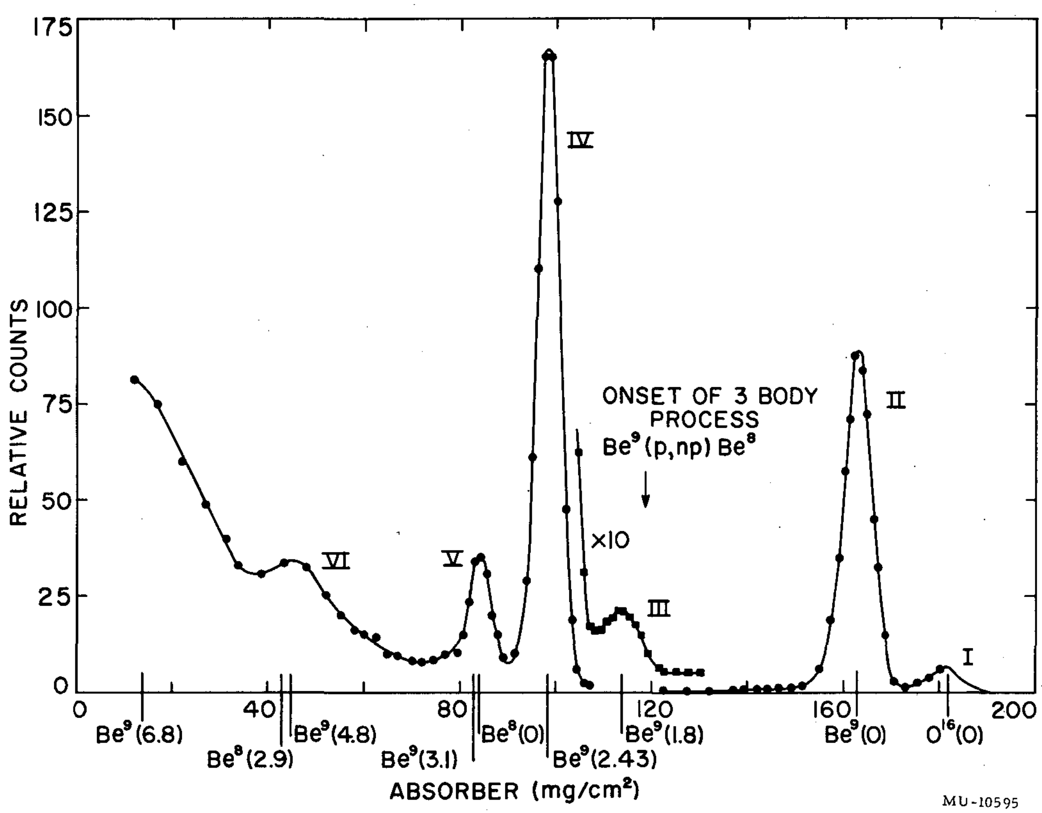

Fig. 2. Charged particles from the proton bombardment of beryllium. The short leaders along the abscissa indicate the expected positions of the peaks corresponding to the final states by which they are labeled. The numbers in parentheses refer to excitation energies.

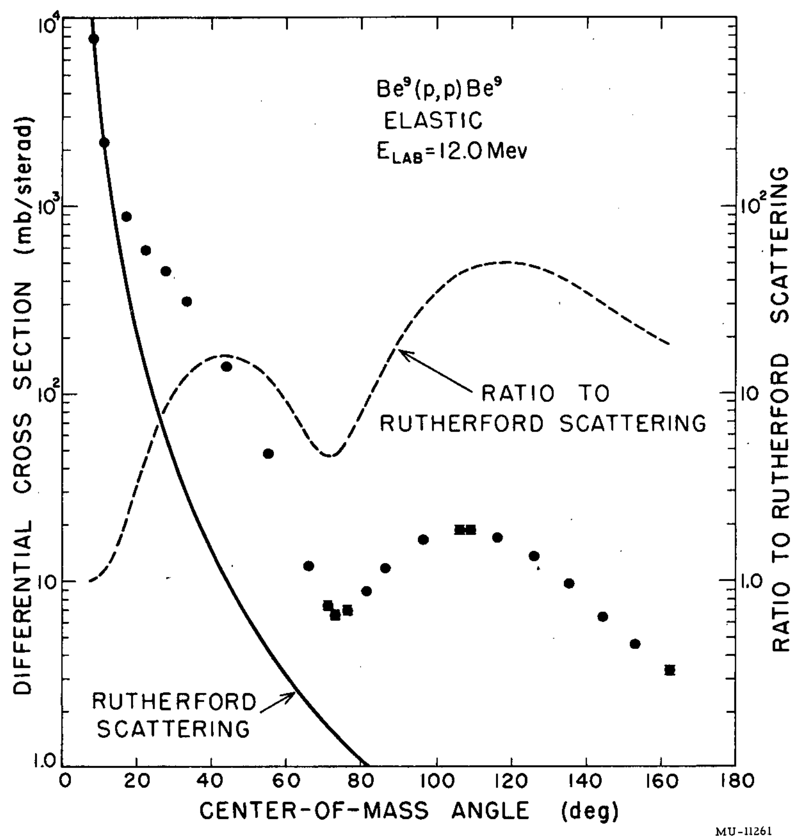

Fig. 3. The differential cross section for elastic proton scattering by beryllium. The laboratory energy was 12 Mev. Experimental errors are less than the size of the points.

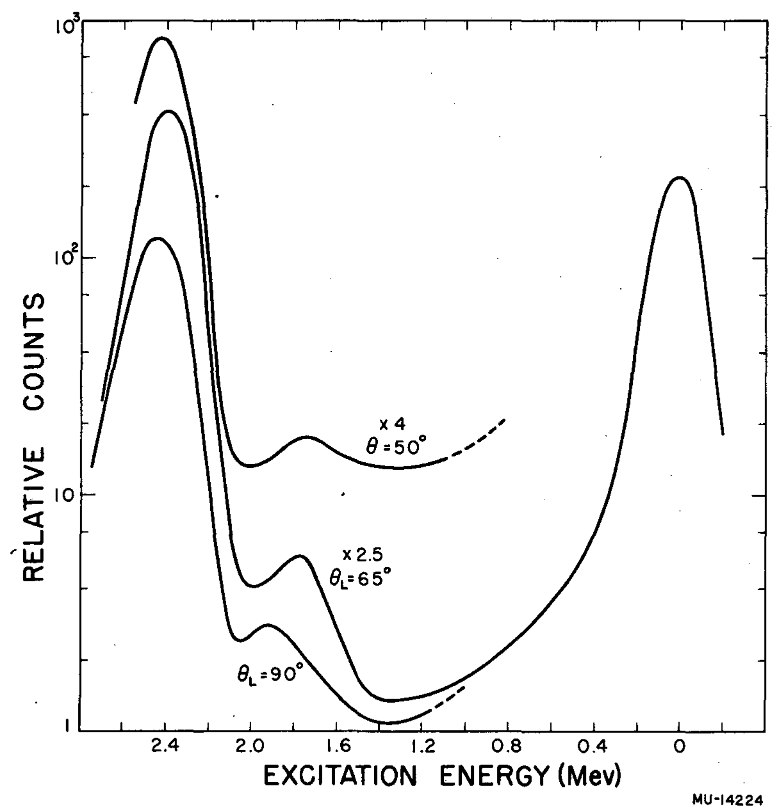

Fig. 4. Spectra of protons scattered by beryllium. The bombarding energy was 12 Mev.

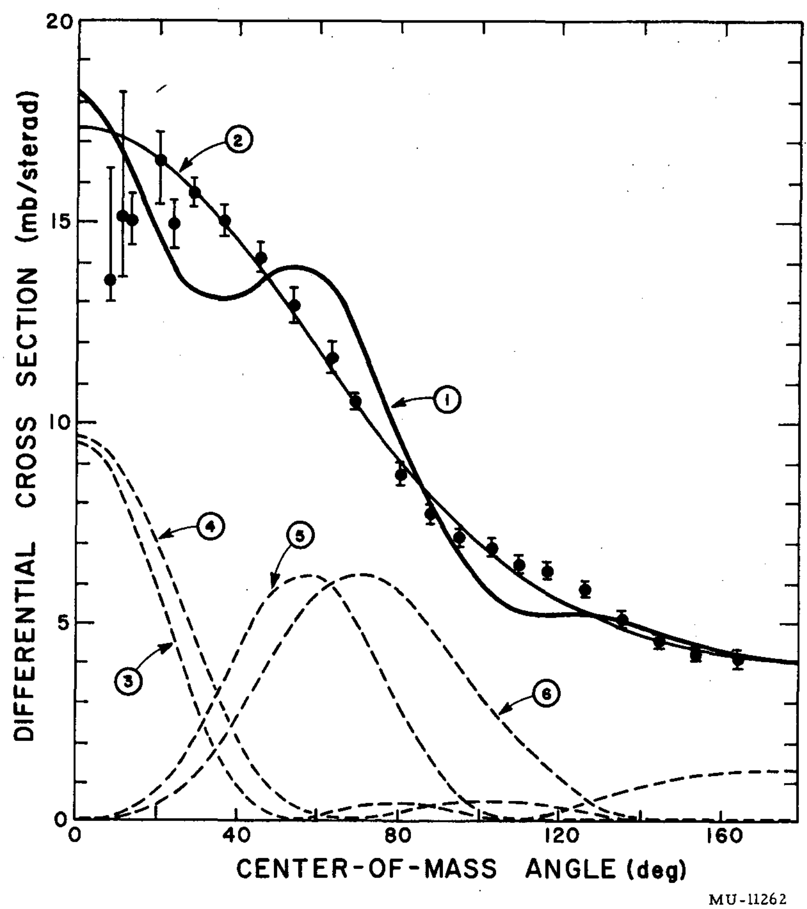

Fig. 5. The differential cross section for the formation of the 2.43-Mev state of Be^9 by inelastic proton scattering. The laboratory energy was 12 Mev. The solid curves are discussed in the text. The dashed curves (abritrary normalization) have been derived from the direct interaction theory of Austern, Butler, and McManus as follows: 3 --ℓ = 0, a = 5.5 fermi; 4 --ℓ = 0, a = 4.5 fermi; 5 --ℓ = 2, a = 5.5 fermi; and 6 --ℓ = 2, a = 4.5 fermi.

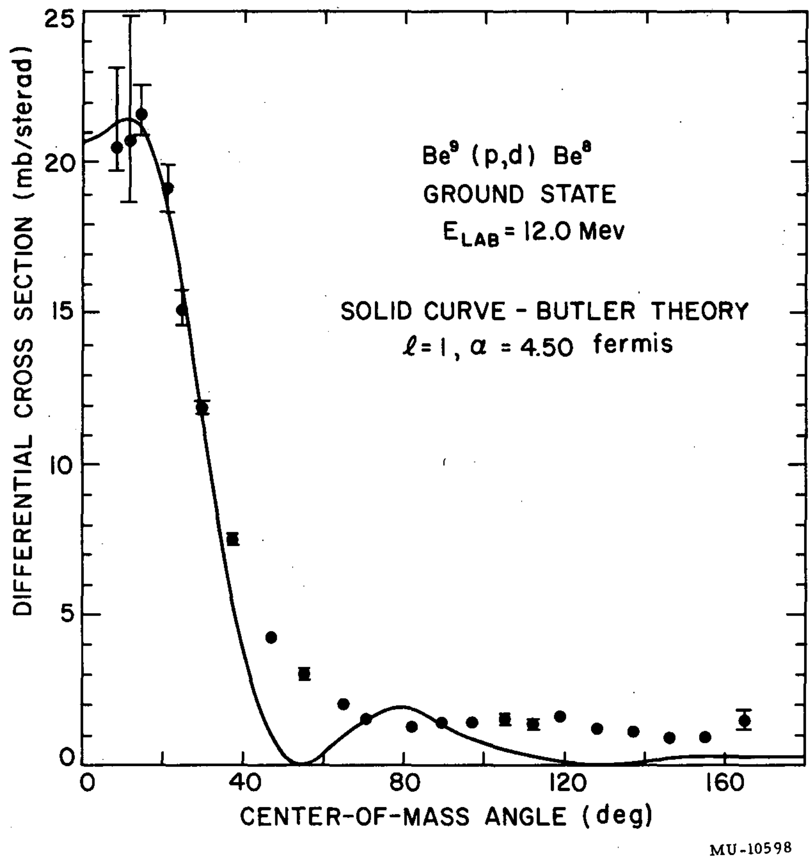

Fig. 6. The differential cross section for the reaction Be^9 (p, d)Be^8 at 12 Mev.

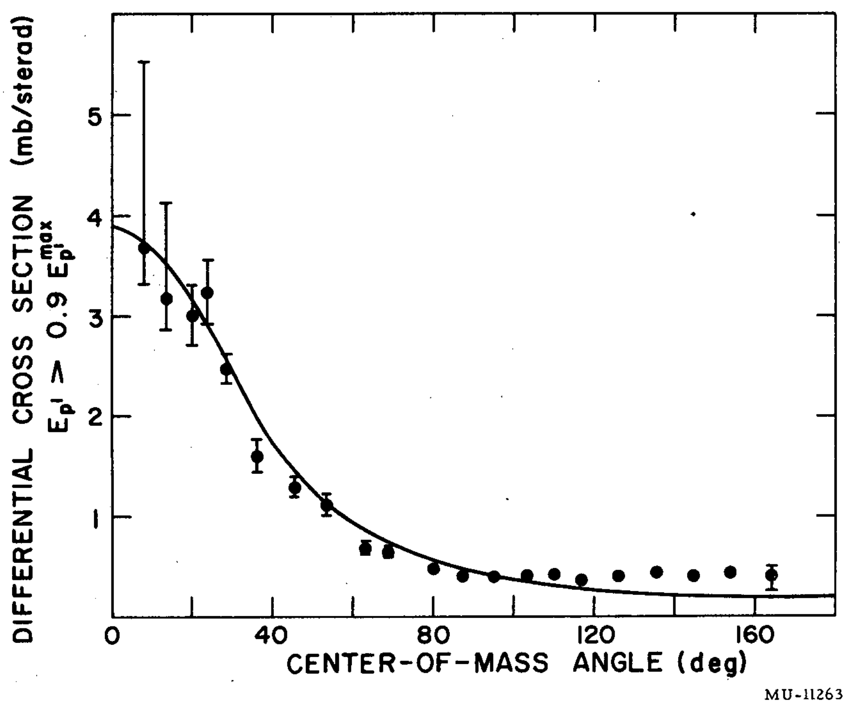

Fig. 7. The differential cross section for the reaction Be^9 (p, np')Be^8 in which the scattered protons retain at least 90% of the available center-of-mass kinetic energy. The incident energy was 12 Mev. Notice that the abscissa is the angle of scattering of the proton. The solid curve is derived from direct-reaction theory, with a = 4.5 fermi, including terms $\ell \leq 2$.

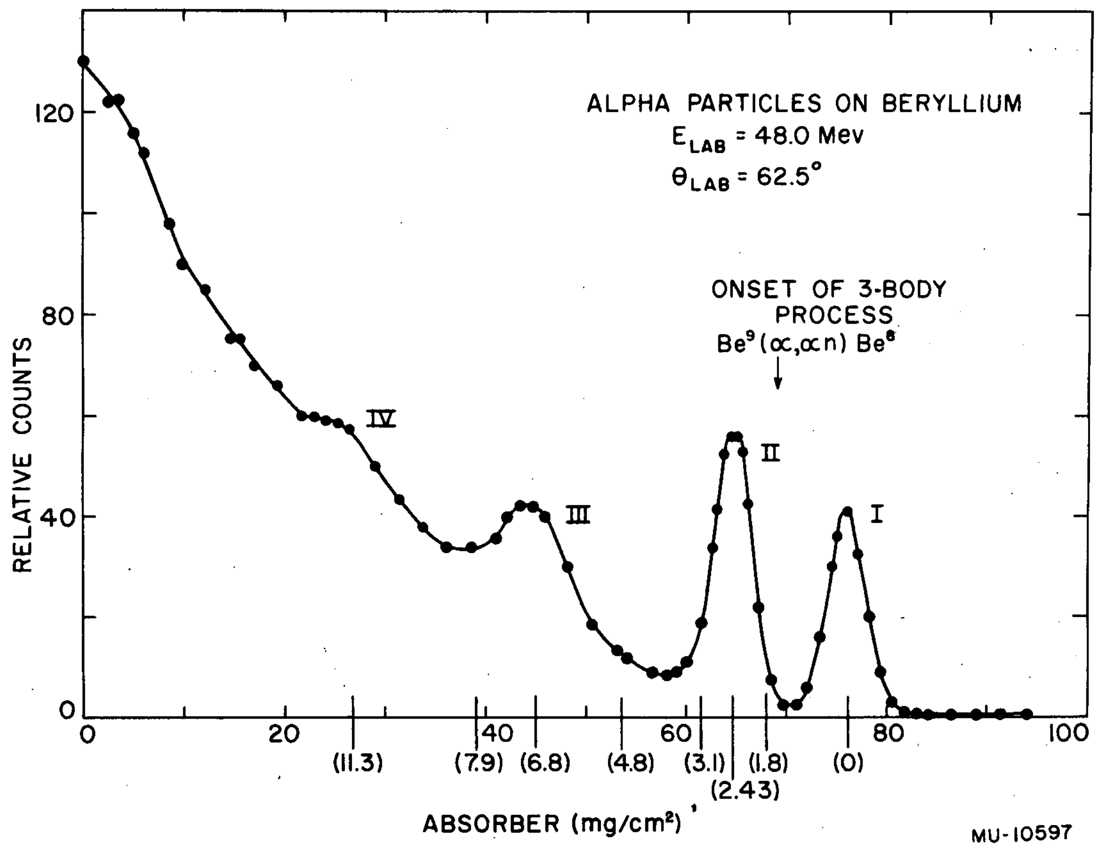

Fig. 8. Alpha-particle spectrum from beryllium bombarded with 48-Mev alpha particles. The short leaders along the abscissa indicate the expected positions of particle groups.

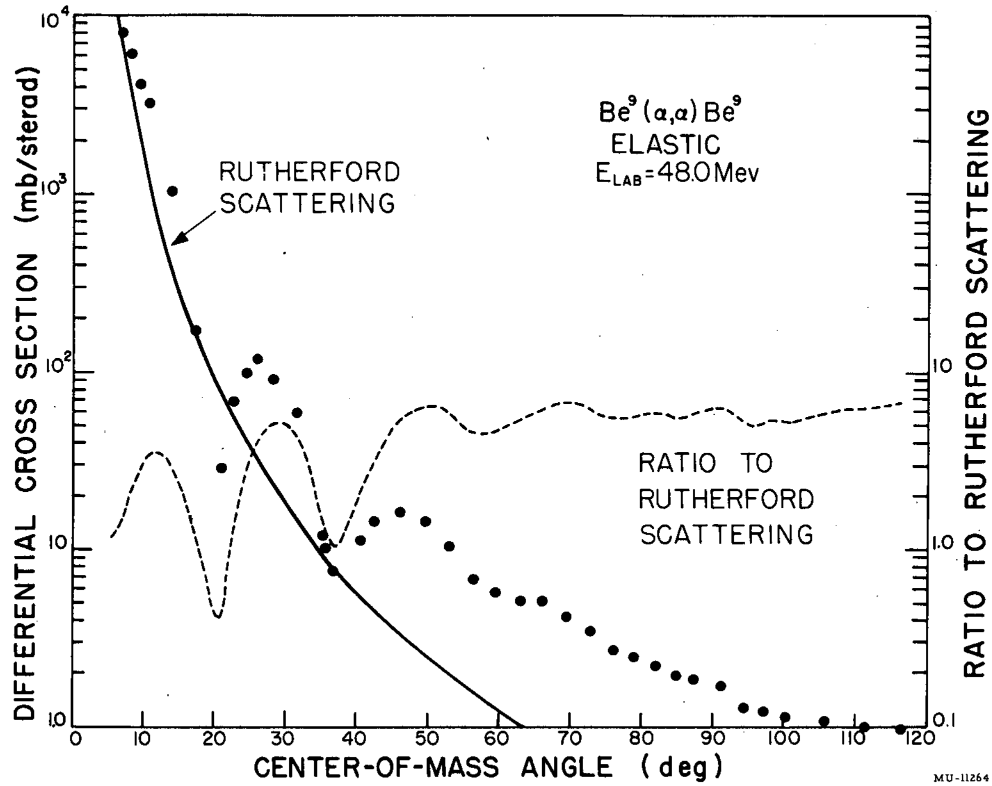

Fig. 9. The differential cross section for elastic alpha-particle scattering by beryllium. The laboratory energy was 48 Mev. Except where shown, experimental errors are smaller than the size of the points.

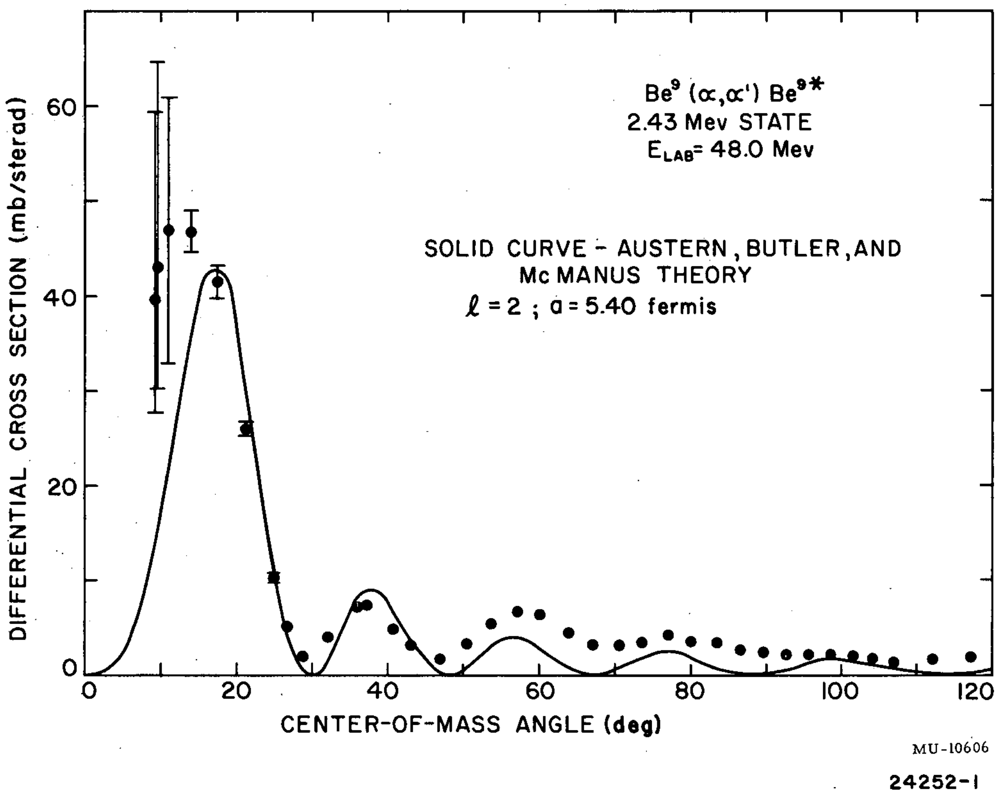

Fig. 10. The differential cross section for the formation of the 2.43-Mev state of Be^9 by inelastic alpha-particle scattering. The laboratory energy was 48 Mev.

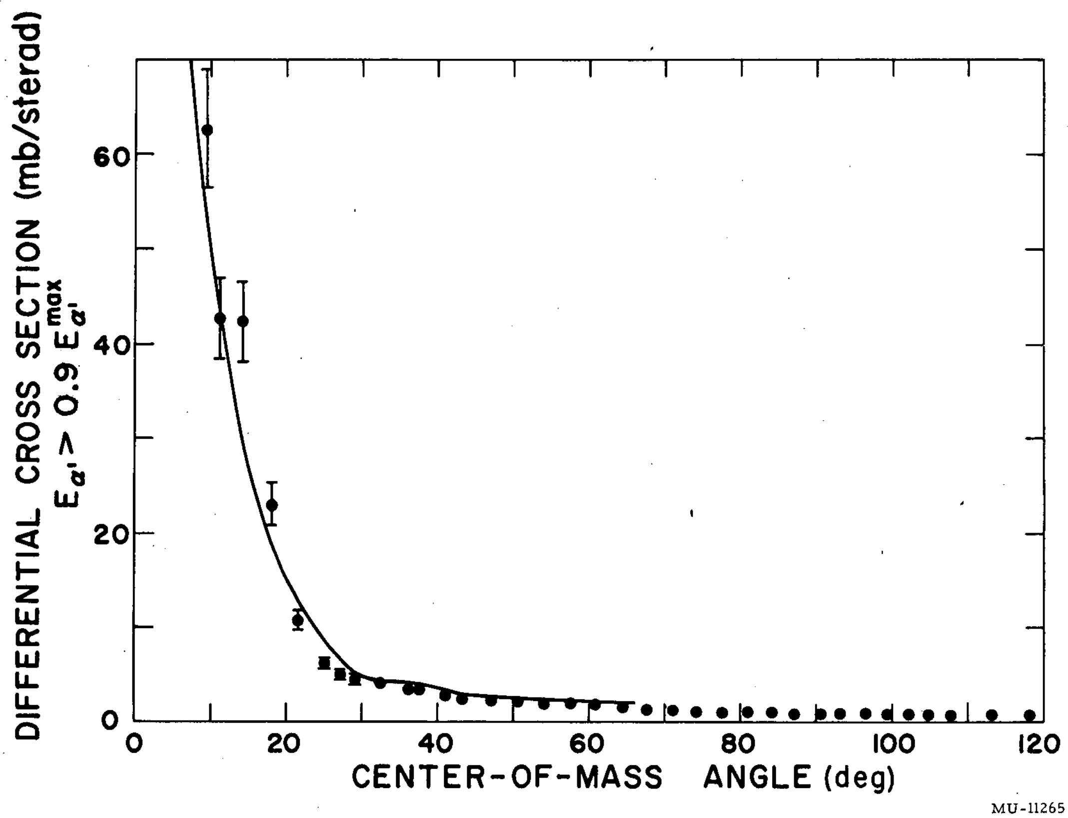

Fig. 11. The differential cross section for the reaction $Be^9(\alpha, n\alpha')Be^8$ in which the scattered alpha particles retain at least 90% of the available center-of-mass kinetic energy. The incident energy was 48 Mev. Notice that the abscissa is the angle of emission of the scattered alpha-particle. The solid curve is obtained from direct-reaction theory, with a = 5.40 fermi, including terms $\ell \leq 2$.

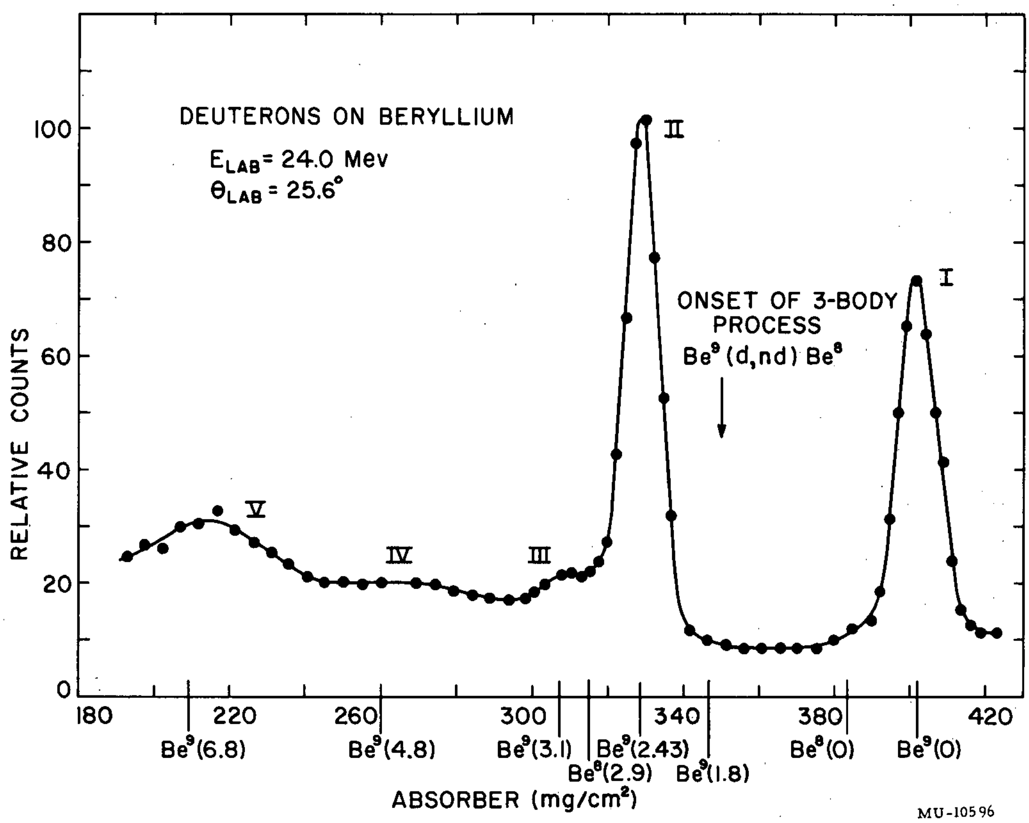

Fig. 12. Charged particles from the deuteron bombardment of beryllium. The short leaders along the abscissa indicate the expected positions of the peaks corresponding to the final nuclear states by which they are labeled.

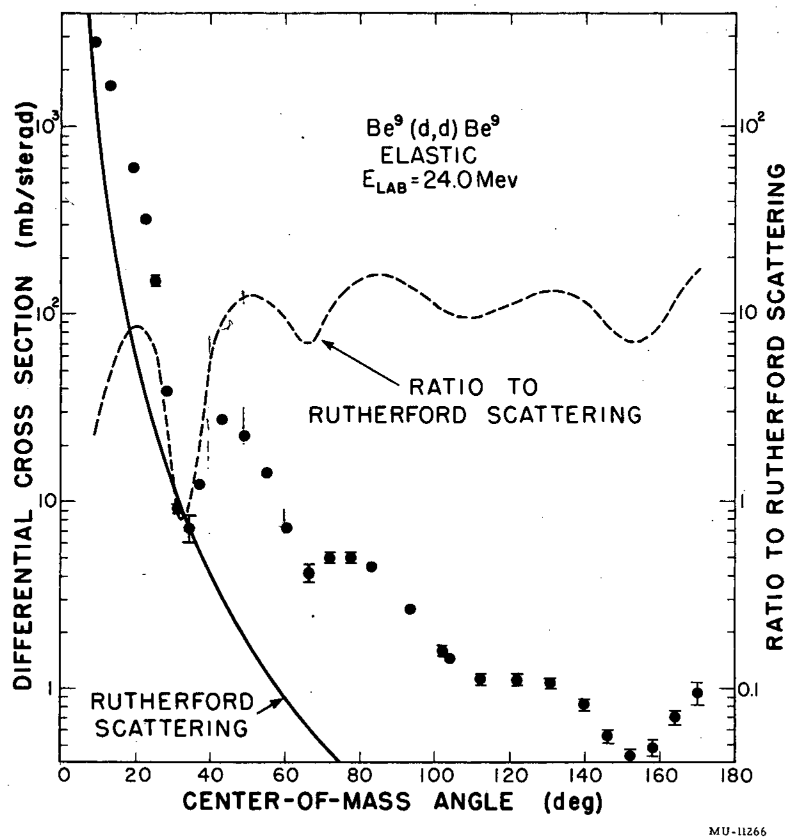

Fig. 13. The differential cross section for the elastic scattering of deuterons by beryllium. The laboratory energy was 24 Mev. Except where shown, experimental errors are smaller than the size of the points.

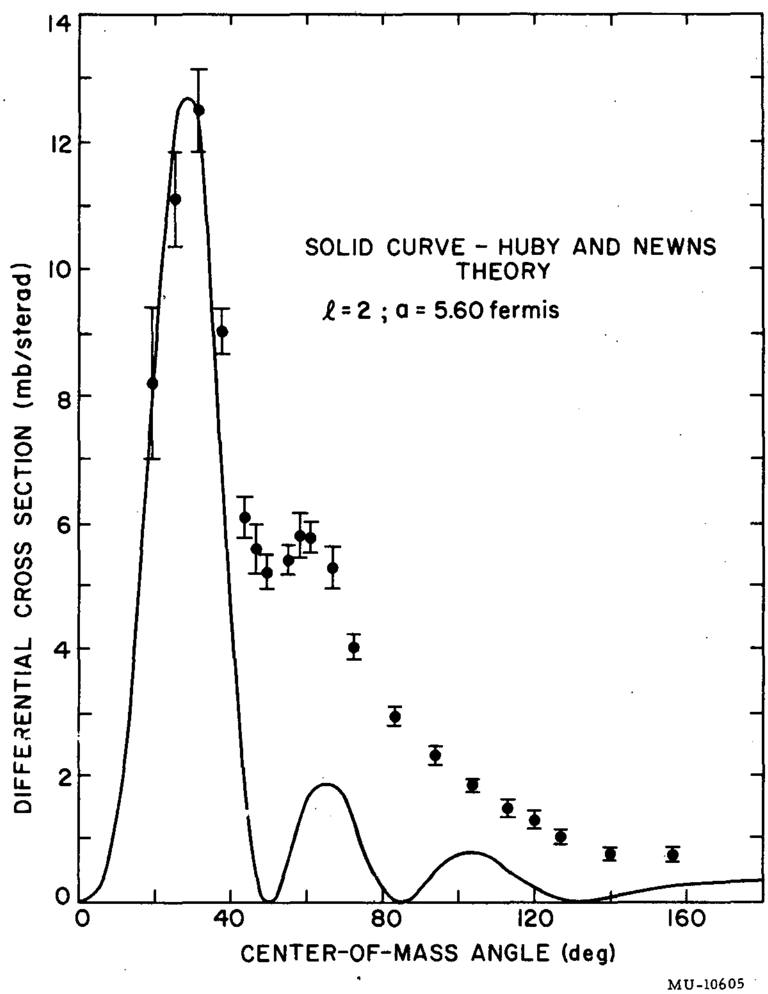

Fig. 14. The differential cross section for the formation of the 2.43-Mev state of Be^9 by inelastic deuteron scattering. The laboratory energy was 24 Mev.

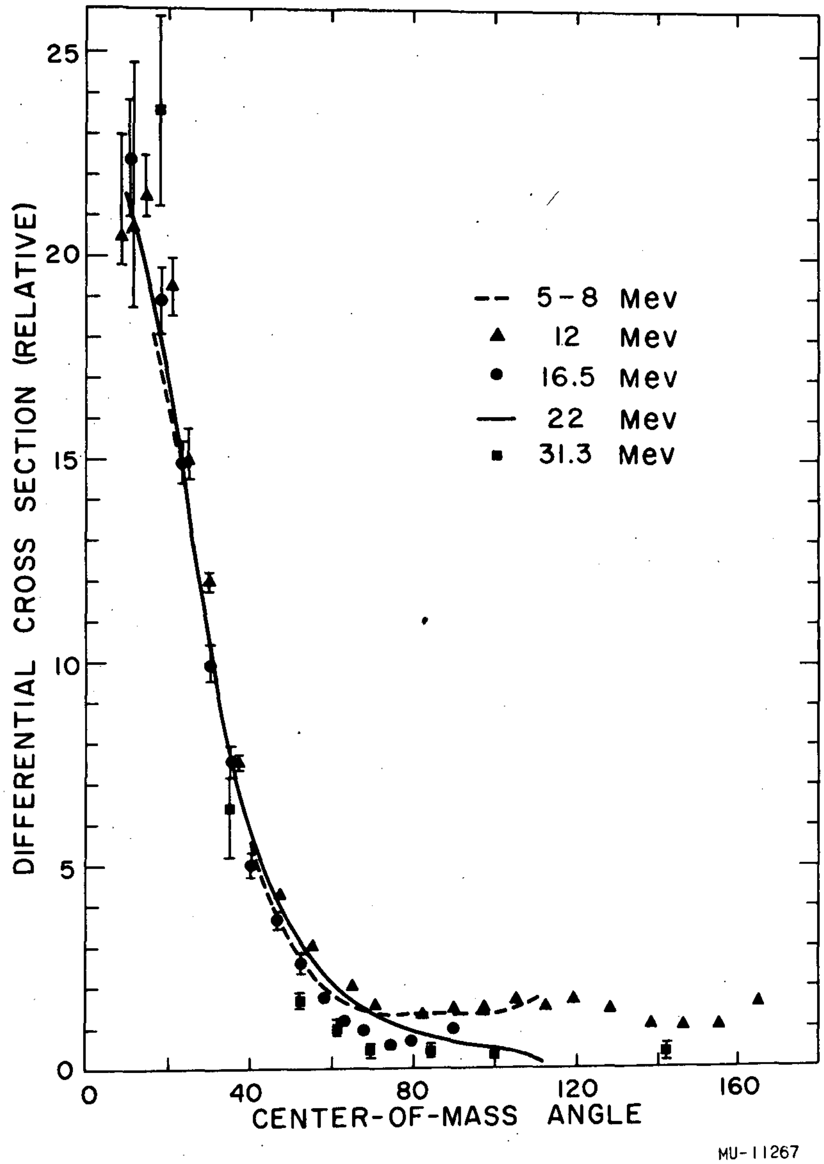

Fig. 15. The shape of the differential cross section for the reaction $Be^9(p, d)Be^8$ at various bombarding-proton energies. The data were obtained from the references cited in the text.

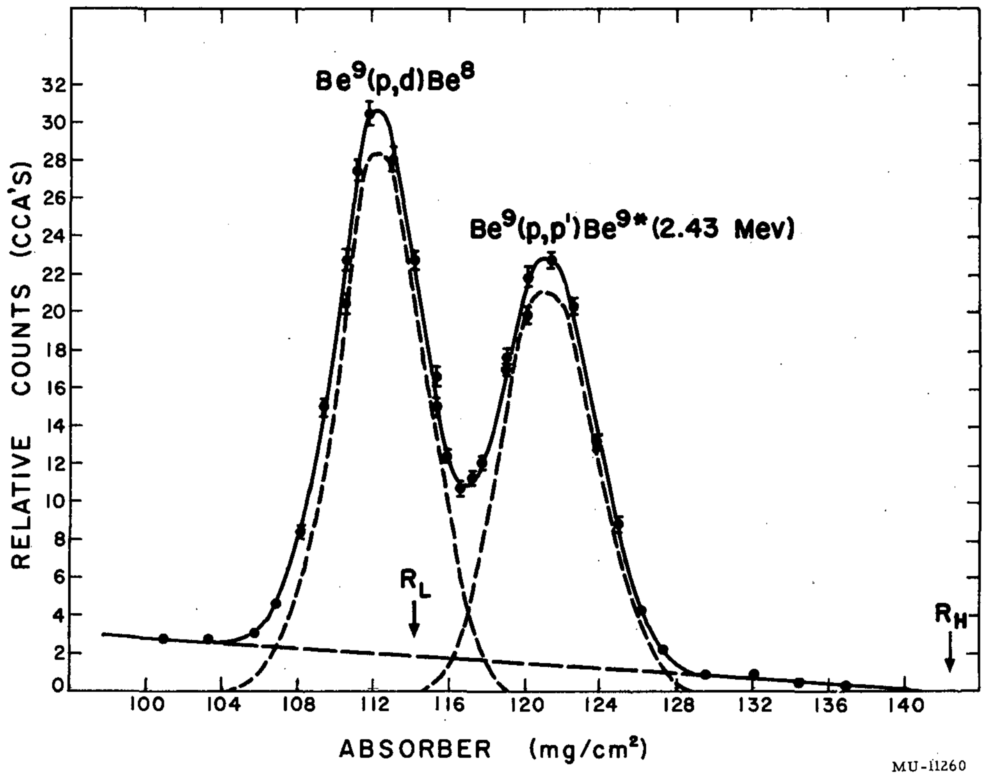

Fig. 16. Part of the charged-particle spectrum from the proton bombardment of beryllium, showing the separation of overlapping peaks from the 3-body continuum. The arrows R_H and R_L designate the ranges of scattered protons of energies $E_p = (E_p)_{max}$ and $E_p = 0.90\ (E_p)_{max}$, respectively (see Appendix). The angle of observation was 21° and the bombarding energy 12 Mev.