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Magnetic Analysis of the $Be^9(p,p')^*Be^9$ and $Be^9(p,pn)Be^8$ Reactions*

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The energy distribution of protons from the bombardment of Be^9 with protons has been investigated by precision magnetic analysis in the region of excitation from the ground state through the 2.43-Mev state. A broad distribution of protons was found with a cutoff corresponding to a Q of -1.675 ± 0.002 Mev in Be^9. The asymmetry of the observed group and the proximity of the observed Q-value to the separation energy of a neutron from Be^9 suggests that the group consists of protons from the three body disintegration $^*B^{10}\rightarrow Be^8+p+n$, but the possibility of inelastic scattering to a state in Be^9 cannot be excluded. An excitation energy of 2.432 ± 0.004 Mev was found for the inelastic proton group from the known state, and a natural width $\leqslant 1$ kev is ascribed to this state from experiments conducted at optimum resolution.

FOR some time the 2.43-Mev state of Be^9 has been believed to be the first excited state of this nucleus. However, a possible state at about 1.7 or 1.8 Mev of excitation has recently been reported.[1,2] These reports are based upon scintillation spectrometer and low resolution magnetic spectrometer studies of the charged particle reactions leading to states in Be^9. In order to investigate this region of excitation in Be^9 with an instrument of greater precision, The Rice Institute annular magnet has been employed to obtain spectra of the protons scattered from this nucleus. The region of excitation from the ground state through the 2.43-Mev state was examined.

The apparatus and techniques are those described in an earlier paper[3] with the exception of changes in the incident beam alignment procedures which have sufficiently lowered the background so that the detection of weak particle groups has become possible. These changes consisted of completely defining the width of the beam by slits in tubing external to the magnet gap, and utilizing the traveling slit[3] only to determine the position and angle of the incident beam with respect to the target and to shield the target and target slits from particles which have suffered small-angle scattering at the external defining slits. The position measurements were made electrically, by determining the edges of the beam with the insulated traveling slit, rather than by direct definition of the beam by this slit. An order of magnitude reduction in the background level has been accomplished by these means.

BROAD PROTON GROUP

Figure 1 is a plot of the proton spectrum obtained with the annular magnet. The region of excitation from the ground state to about 1.4 Mev has been omitted from the plot as the background in this region showed no structure. In addition to groups corresponding to the ground state and 2.43-Mev state, a broad distribution of protons appears. In order to establish that this proton group is associated with the Be^9 nucleus, the high energy edge of the group was observed at three different bombarding energies. The results of these experiments are shown in Fig. 2, with a scale showing excitation in Be^9, and also in Table I, which lists the computed Q values. The agreement of these Q values establishes conclusively that this group is associated with the interaction of the incident protons and Be^9 nuclei.

The arrows of Fig. 1 indicate the points where the background level was normalized. These points represent the range of momenta accepted in a single exposure of a plate. The normalization is necessary since the background level, while statistically constant over a single plate, differed from plate to plate due to the alignment procedure. The plates on which the background was constant were corrected to an average value, and the plates upon which the broad distribution appeared were matched to the adjoining plates to give a smooth distribution. All of these corrections were such that they could not materially affect the shape of the distribution.

Three possible mechanisms can be reasonably considered to explain the observed broad distribution: the two-stage process $Be^9(p,n)B^9(p)Be^8$, the three-body breakup $Be^9(p,pn)Be^8$, and the inelastic scattering to a state in Be^9.

The two-stage process proceeding through a state in B^9 can be eliminated: while this process would

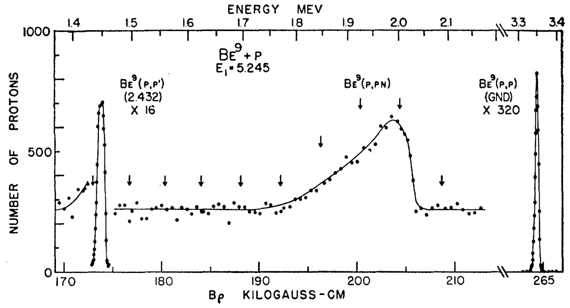

FIG. 1. Spectrum of protons from the Be^9+p reaction. Bombarding energy 5.245 Mev. The target was a 15 microinch Be foil.

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[1] Moak, Good, and Kunz, Phys. Rev. **96**, 1363 (1954); Almquist, Allen, and Bigham, Phys. Rev. **99**, 631(A) (1955).

[2] L. L. Lee and D. R. Inglis, Phys. Rev. **99**, 96 (1955).

[3] Gossett, Phillips, and Eisinger, Phys. Rev. **98**, 724 (1955).

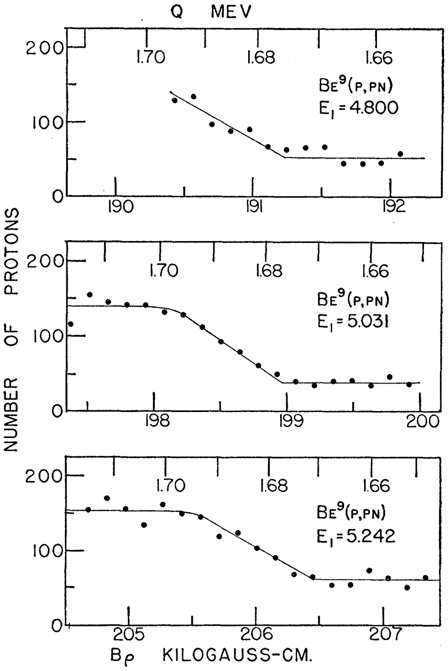

FIG. 2. High energy cut-off of the broad group, $B^{10} \rightarrow p+n+Be^8$, at different bombarding energies. The top scale of each plot represents excitation energy in the nucleus Be^9.

produce an asymmetric distribution, the energy of the proton group would not behave with change of bombarding energy as the observed group does. Moreover, this hypothesis would require, for the proton group observed, the existence of a state in B^9 below 1 Mev. The work of Ajzenberg and Buechner[4] and of Marion, Bonner, and Cook[5] indicate that no such state exists.

A possible explanation of the spectrum in Fig. 1 is that a three-body mechanism is operative. The observed broad distribution and the proximity of the observed Q-value to the neutron separation energy both favor this hypothesis. Such three-body effects were observed in the work of Ajzenberg and Buechner[4] on the $Be^9(p,n)B^9$ reaction. Their results show a continuum of neutrons which rise sharply towards lower energies. They suggested that these neutrons are due to the three-body breakup.

The expected momentum distribution from the three-body disintegration has not been worked out exactly. A treatment of this problem without consideration of the proton and neutron penetrabilities was considered by Uhlenbeck and Goudsmit,[6] who obtained a distribution symmetrical about half the maximum proton energy. Calculations indicate, however, that the inclusion of these penetrabilities in the computation will considerably affect the results, peaking the proton distribution towards higher momenta. However, the low energy side of the proton distribution function does not increase as rapidly with energy as was observed.

Although the momentum distribution is not easily calculated for this problem, it may readily be shown that the maximum energy protons for the three-body breakup correspond to zero relative velocity between the neutron and the Be^8 nucleus. While this information validates the calculation of the Q value in the usual manner,[3] it indicates that the line shape analysis,[7] normally applied to discrete groups, does not apply in this case, since this situation is more analogous to a neutron threshold, and would thus be expected to show the $E^{l+\frac{1}{2}}$ dependence generally observed for neutrons. Unfortunately, the statistical errors for the leading edge of the observed distribution are not sufficiently accurate to permit other than a linear fit. However, such a penetrability argument could be the explanation for the discrepancy between the Q value observed by the annular magnet, -1.675 ± 0.002 Mev, and that observed by Mobley and Laubenstein,[8] who obtained a Q value of -1.666 ± 0.002 Mev for the (γ,n) threshold. The discrepancy is well explained if p-wave neutrons are assumed.

TABLE I. Summary of observed Q values for the broad group.

Bombarding energy (Mev)	Q value (Mev)
4.7996	−1.6752
5.0308	−1.6768
5.2423	−1.6712
5.2445	−1.6758
5.2537	−1.6776
Mean:	−1.675±0.002

The published evidence for the existence of a state in Be^9, in the region of the broad group observed with the annular magnet was based on the reaction $Li^7(He^3,p)Be^9$ and $B^{11}(d,\alpha)C^{13}$. The observed groups could be due to the three-body decay schemes: $B^{10} \rightarrow p+n+Be^8$ and $C^{13} \rightarrow \alpha+n+Be^8$. It may be shown that in these three-body disintegrations the Q value observed for the maximum energy charged particles corresponds to the binding energy of a neutron in Be^9. The earlier spectra[1,2] all exhibit distributions which can be interpreted as continua, not inconsistent with a three-body breakup.

The possibility of explaining the observed group by inelastic scattering to a state in Be^9 cannot be excluded. Whereas a Breit-Wigner resonance shape will not explain the distribution function, it is possible to fit the shape with a state of about 150-kev width when effects of the neutron threshold are considered. This large

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[4] F. Ajzenberg and W. W. Buechner, Phys. Rev. **91**, 674 (1954).

[5] Marion, Bonner, and Cook, this issue [Phys. Rev. **100**, 91 (1955)].

[6] G. E. Uhlenbeck and S. Goudsmit, *Zeeman, Verhandlungen* (M. Nyhoff, The Hague, 1935), pp. 201–211.

[7] K. F. Famularo and G. C. Phillips, Phys. Rev. **91**, 1195 (1953).

[8] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).

value would imply that this width is due to s-wave neutrons emission, so that the state would be $\frac{1}{2}+$, contrary to the independent particle model prediction.‡ Thus, if such a state in Be^9 exists at about 1.7 Mev of excitation it must have the unique property of lying partly in the bound, electromagnetic, region and partly in the virtual region of excitation and is probably a $\frac{1}{2}+$ state. The fact that the rather rapid low-energy fall-off of the group cannot be entirely accounted for by simple arguments based on barriers under the three-body hypothesis might perhaps be regarded as favoring this latter mechanism, although a quantum treatment of the three-body problem might show otherwise.

No definite conclusions can be made at present as to which of the latter two mechanisms are responsible for the observed line shape. A further study of this level, perhaps through the $B^{11}(d,\alpha)Be^9$ reaction, as observed by Lee and Inglis,[2] but with the available low background, high resolution spectrometer could establish the mechanism responsible for the observed group.

TABLE II. Summary of observed Q values for 2.43 state of Be^9.

Bombarding energy (Mev)	Q value (Mev)
4.6117	−2.4321
5.2434	−2.4325
5.2434	−2.4276
5.2445	−2.4321
5.2537	−2.4354
Mean:	−2.432±0.004

2.43-MEV STATE OF Be⁹

A study of the well known 2.43-Mev state of Be^9 was conducted in conjunction with the study of the three-body disintegration. A summary of the Q values obtained in five bombardments is contained in Table II. On the basis of a systematic analysis of the possible sources of error, an error of ±0.004 Mev is assigned. A comparison with other values[9–11] reported for this state is contained in Table III.

Since the observed protons of the group corresponding to this state had energies of about 1.05 and 1.45 Mev for the 4.61- and 5.25-Mev bombardments, respectively, it was necessary to consider the possible energy losses in the surface contaminant layers of the Be^9 foil. Fortunately, in this case a means of evaluating this loss was available. The α-particle group from the $Be^9(p,\alpha)^*Li^6$ group, leaving Li^6 in the 2.187 state, appeared in the momentum region near the proton group from the 2.43 state of Be^9. Since the energy loss of the α particles in the contaminant layer was a factor of 8 greater than that of the protons for the energies observed, it was possible to obtain a fairly sensitive estimate of the thickness of the contaminant layer from the difference between the observed Q value for the α group and that observed by Browne *et al.*[9] The losses for the protons were then computed for this thickness and the Q values corrected accordingly. It was found that corrections of less than 1 kev were required for protons in cases where reasonably fresh foils were used. In one extreme case, where the foil had been bombarded a number of times previously and showed quite heavy discoloration, a correction of only 3 kev was indicated.

TABLE III. Comparison of observed Q values (Mev) with other determinations.

Experiment	Reported value	Reference
$Be^9(p,p')^*Be^9$ mag spec	−2.432±0.004	Present work
$Be^9(p,p')^*Be^9$ elec spec	−2.433±0.005	9
$B^{11}(d,\alpha)^*Be^9$ mag spec	−2.422±0.005	10
$B^{11}(d,\alpha)^*Be^9$ mag spec	−2.431±0.006	11

The observed width, shown in Fig. 1, of the proton group from the 2.43-Mev state, as compared to the width of the proton group from the ground state, was that to be expected from the additional energy loss of the lower energy protons in the foil. Since this method did not provide a very adequate means of

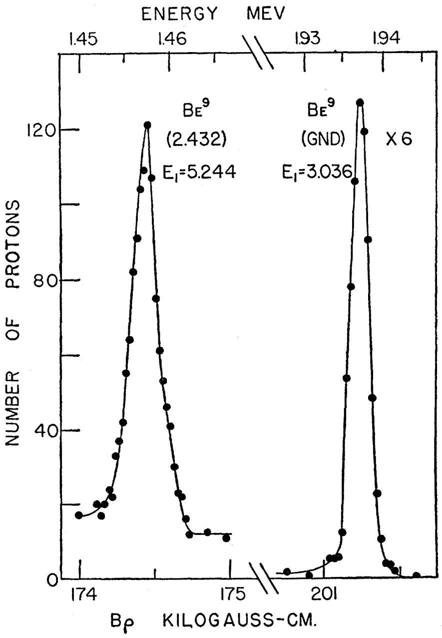

FIG. 3. Comparison of observed widths of proton groups for scattering from the 2.43 Mev and ground states of Be^9.

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‡ *Note added in proof.*—Calculations by T. Lane (private communication) yield evidence for an S state at about this energy in Be^9.

[9] Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).

[10] Van Patter, Sperduto, Huang, Strait, and Buechner, Phys. Rev. **81**, 233 (1951).

[11] R. B. Elliott and D. J. Livesay, Proc. Roy. Soc. (London) **A224**, 129 (1954).

TABLE IV. Observed cross sections at $E_p = 5.245$ Mev.

Particle group	σ mb/steradian	Angle of observation degrees
Ground state	23 ±10	174.2±1.9
Broad group	1.2	172.3±1.9
2.43-Mev state	3.6± 1.1	170.7±1.9

determining the natural width of the state, a more sensitive method was devised. For this experiment a very thin beryllium target was evaporated onto a carbon foil. The proton group for the 2.43 state was then observed with a bombarding energy of 5.25 Mev, and the ground state group observed at a bombarding energy of 3.00 Mev, computed to give the protons the same energy loss in the physical thickness of the target. The results of this experiment are shown in Fig. 3. Both groups show a thickness at half maximum of 3.2 kev.

All controllable quantities were adjusted to produce equal effects on the two proton groups. Three factors then remain which could affect the observed widths; these are: the natural width of the state, changes in the spectrometer width, and changes in the energy spread of the incident beam at the two different energies. Since it is believed that each of these factors should produce a greater observed width for the group from the 2.43-Mev state, it is concluded that this state has no observable natural width. An upper limit of 1 kev may be set for the natural width to take into account any factors which may not have been considered.

Since the 2.43-Mev state of Be^9 is about 766 kev unbound to neutron emission, an appreciable width would be expected for this state, if low angular momentum neutron emission were possible. The fact that a narrow width is observed for the proton group implies that a high centrifugal barrier exists for the neutrons. Calculations indicate that a lower limit of $J=5/2$ may be set for the state on this basis.

An estimate may be made of the cross sections for the proton groups of Fig. 1. The values and the angle at which they were observed are listed in Table IV. These values should be accurate to approximately ±30%, except in the case of the broad group, where the cross section is somewhat indeterminate from our data.

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(p,γ) Cross Sections

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Several (p,γ) cross sections were measured by activation with protons from 8 to 22 Mev. The dependences on incident energy and target mass are very slight, whereas a compound nucleus model would predict variations by many orders of magnitude. It seems probable, therefore, that the observed reactions are due to high-energy gamma transitions taking place prior to compound nucleus formation. The magnitudes involved indicate that these transitions have single-particle dipole matrix elements.

EXPERIMENTAL

CROSS sections and excitation functions for several (p,γ) reactions were measured by stacked foil-induced activity techniques with the internal circulating beam of the Oak Ridge 86-inch cyclotron. The absolute cross sections were determined by the ratio method as described previously.[1]

The $\mathrm{C}^{12}(p,\gamma)\mathrm{N}^{13}$ cross section was measured by observing the 10-min activity in an isotopically enriched[2] sample of carbon-12. A small (~10%) correction was applied for the activity from the (p,n) reaction on C^{13} which was present in 0.05% abundance. The sample contained a considerable amount of copper as impurity, so the cross section was determined relative to the known cross section of the $\mathrm{Cu}(p,n)$ reaction.[3] The amount of copper impurity was determined by an activation analysis carried out in the Oak Ridge graphite reactor. The (p,γ) excitation function could not be extended to high energies because a 10-min activity from $\mathrm{Cu}^{63}(p,pn)\mathrm{Cu}^{62}$ is induced in copper by protons above 15 Mev.

The $\mathrm{Fe}^{54}(p,\gamma)\mathrm{Co}^{55}$ cross section was determined by comparing the activity of 18-hr Co^{55} with that of 44-min Mn^{51} produced by the (p,α) reaction, in an isotopically enriched[2] sample of $\mathrm{Fe}^{54}{}_2\mathrm{O}_3$. This measurement was not possible above the threshold of the $\mathrm{Fe}^{56}(p,2n)$ reaction (~15 Mev) since that reaction also leads to Co^{55}. The cross section for the $\mathrm{Fe}^{54}(p,\alpha)$ reaction was measured by bombarding stacks of natural iron foils and comparing the Mn^{51} activity in the low-energy foils with the Co^{55} activity in the high-energy foils, where the $(p,2n)$ cross section is known.[1]

The cross section and excitation function for the $\mathrm{Ni}^{60}(p,\gamma)\mathrm{Cu}^{61}$ activity was measured by bombarding

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[1] B. L. Cohen and E. Newman, Phys. Rev. **99**, 718 (1955).

[2] Enriched stable isotopes were obtained from the Isotope Research and Production Division of this laboratory.

[3] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta **24**, 3 (1951).