# Scattering of 18.4-MeV Alpha Particles by Beryllium*†

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(Received 11 October 1963)

The differential cross sections for inelastic (1.75-, 2.43-, and 3.04-MeV states) and elastic scattering of 18.4-MeV alpha particles from a self-supporting 176-$\mu$g/cm$^2$ beryllium foil have been measured using silicon surface-barrier detectors. The elastic and inelastic (1.75- and 2.43-MeV states) angular distributions exhibit marked diffraction patterns with regularly spaced maxima which systematically diminish in amplitude with increasing scattering angle. However, the elastic cross section, after reaching a minimum at about 90°, shows a definite tendency to increase again at back angles reaching 63 mb/sr at 174.4°. In the case of the inelastic scattering to the 2.43-MeV state, this tendency is suggested but not clearly indicated by the present results. The angular distributions associated with scattering to the 1.75- and 3.04-MeV states only extend to about 90°, which precluded any generalization concerning large-angle scattering. An analysis of the angular distributions associated with the ground state and the 2.43-MeV state was made in terms of the Blair diffraction model, assuming that these states are members of the $K=\frac{3}{2}$ rotational band and that the spin of the 2.43-MeV state is $\frac{5}{2}$. This analysis yielded an interaction radius of 5.7 F and 0.44 for the magnitude of the collective rotational deformation parameter. The angular distributions associated with the 1.8-MeV anomaly and 2.43-MeV state were also analyzed in terms of the direct-interaction theory of Austern, Butler, and McManus. Satisfactory fits were obtained for the 1.8-MeV anomaly with $j_1^2(x)$ and for the 2.43-MeV state with $j_2^2(x)$ using an interaction radius of 5.93 F. Under the assumptions of the applicability of the direct-interaction model and the constancy of the interaction radius, the assignment for the state associated with 1.8-MeV anomaly is argued to be $\frac{1}{2}^+$. Its anomalous shape was fit, assuming a three-particle decay mode $Be^8+n+\alpha'$, with an $S$-wave potential-scattering final-state interaction between the neutron and the $Be^8$ characterized by a scattering length of 30 F. The width of the 3.04-MeV state was measured by fitting various calculated line shapes to the experimental spectrum and was found to be 300±50 keV.

## I. INTRODUCTION

THE results of a large number of experimental and theoretical investigations concerning the nucleus $Be^9$ have been reported.[1] The energy-level diagram and a graphical representation of pertinent experimental information concerning $Be^9$ as presented in a recent compilation of nuclear data[1b] has been reproduced in Fig. 1. The level structure is uncertain and incomplete. Furthermore, most of the properties of the various known levels are uncertain. The principal causes of this situation are associated with the heavy-particle instability of the excited states of $Be^9$. In particular the study of alpha scattering from $Be^9$ is made difficult by the presence of alpha particles associated with certain of these heavy-particle decay modes. In addition, the practical requirement of a finite geometry for reasons of counting statistics and the relatively large recoil energy of this light target nucleus serve to dictate a compromise experimental arrangement with rather poor energy resolution. The use of lighter incident particles reduces this latter effect. For these reasons most of the investigations of $Be^9$ through elastic and inelastic scattering experiments have used protons or deuterons.

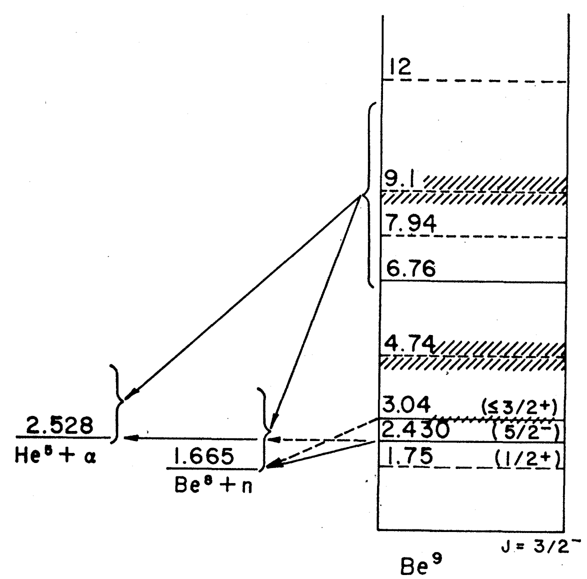


FIG. 1. The energy-level diagram of $Be^9$ and a graphical representation of related experimental information as presented in Ref. 1(b).

* Work supported in part by the U. S. Atomic Energy Commission.

† This report is based on a part of a thesis submitted by B. T. Lucas to the faculty of Purdue University in partial fulfillment of the requirements for the degree of Ph.D. in physics. For a previous report of some of the preliminary results of this investigation see B. T. Lucas, S. W. Cosper, and O. E. Johnson, Bull. Am. Phys. Soc. 8, 291 (1963).

‡ Purdue University XR Fellow, September 1961 to September 1963.

§ National Defense Education Act Fellow, September 1960 to September 1963.

[1] The reader is referred to the following compilations of nuclear data for a summary and interpretation of the experimental and theoretical work concerning $Be^9$: (a) F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1960); (b) T. Lauritsen and F. Ajzenberg-Selove, *Nuclear Data Sheets–Energy Levels of Light Nuclei, May 1962* (National Academy of Sciences–National Research Council, Washington, D. C., 1962). Unless otherwise specified the level structure and individual level properties proposed for $Be^9$ in the latter reference will be assumed. However, in cases where specific quantitative values and/or interpretations are under discussion, a full bibliographical reference to the original report will be made.

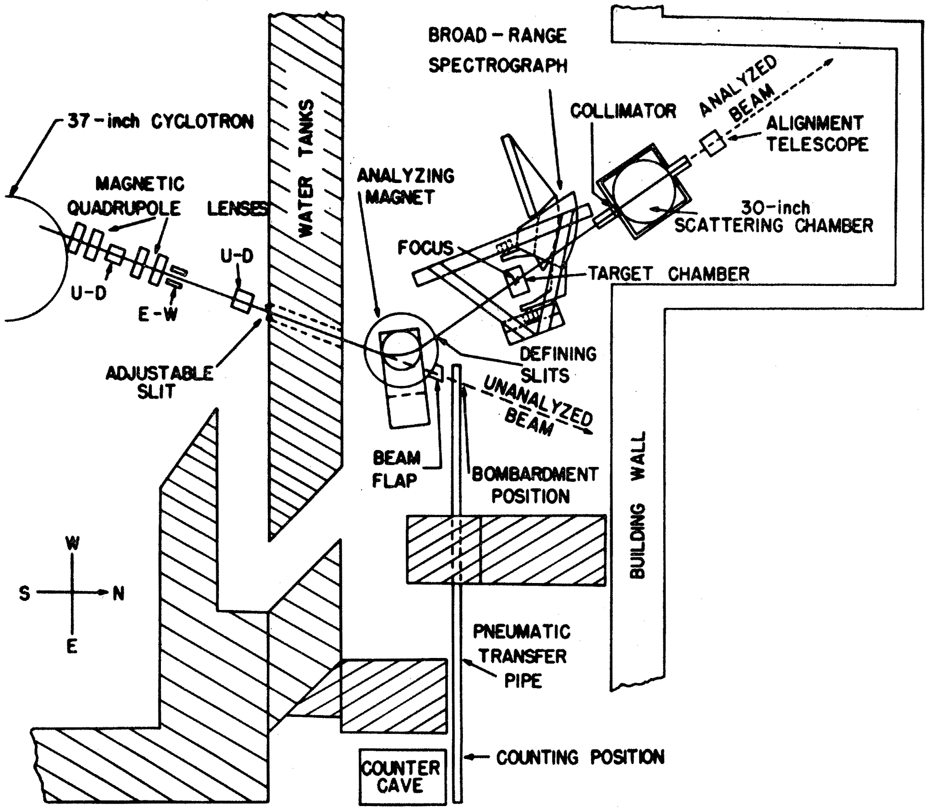


FIG. 2. The floor plan of the cyclotron experimental area.

The present investigation was undertaken with two interrelated goals. First, the experimental results obtained from elastic and inelastic alpha scattering from $Be^9$ were to be compared with the predictions of the various direct-interaction theories of nuclear scattering in order to investigate their applicability and range of validity. Secondly, in those instances for which reasonable agreement between experiment and a particular theoretical formulation was found, an attempt would be made to use predictions of this theory to establish the properties of the states of the $Be^9$ nucleus.

## II. EXPERIMENTAL

The floor plan of the cyclotron experimental area is shown in Fig. 2. The external alpha-particle beam from the Purdue University 37-in. cyclotron is focused by two strong-focusing quadrupole lenses[2] and positioned at the entrance slit of a uniform-field momentum analyzing magnet[3] with the aid of horizontal and vertical steering magnets. In momentum analysis the beam is deflected through a nominal angle of 55° and is focused at the center of the target chamber of the broad-range magnetic spectrograph.[4] From this focal point the beam diverges and travels 60 in. before striking the primary aperture of the beam collimating system associated with the 30-in. scattering chamber[5] in which the present measurements were performed. The beam energy for this experiment was 18.38 MeV with a nominal rms spread of 60 keV.

The beam collimating system is made up of a primary circular aperture, an assembly of 3 antiscattering baffles, and a $\frac{1}{16}$-in.-diam final defining aperture. The primary and final apertures are 6 in. apart with the final aperture located 15 in. from the center of the chamber. This collimating system provides a circular beam spot at the position of the target with a diameter of 5/64 in.

The scattering chamber is equipped with two radial arms which carry the detector assemblies and can be rotated together or independently about the axis of the chamber. Each arm is equipped with an externally controlled screwdrive for adjusting the target-to-detector distances. The azimuthal angular positions of the arms can be reproducibly adjusted to ±0.1 degree and the radial target-to-detector distance can be set reproducibly to ±0.010 in.

One detector assembly consists of a silicon surface-barrier detector mounted on a carriage behind two

[2] Research in Nuclear Physics Progress Report No. 4, 15 June 1954, Purdue Research Foundation, Lafayette, Indiana (unpublished).

[3] Research in Nuclear Physics Progress Reports: No. 6, 1 June 1956; No. 7, 15 June 1957; and No. 8, 15 June 1958, Purdue Research Foundation, Lafayette, Indiana (unpublished).

[4] Research in Nuclear Physics Progress Reports: No. 8, 15 June 1958; No. 9, 15 June 1959; No. 10, 15 June 1960; No. 11, 15 June 1961, Purdue Research Foundation, Lafayette, Indiana (unpublished).

[5] Research in Nuclear Physics Progress Reports: No. 11, 15 June 1961; and No. 12, 15 June 1962, Purdue Research Foundation, Lafayette, Indiana (unpublished).

remotely controllable four-position wheels. One wheel carries four different size defining apertures and the other carries three aluminum-foil energy degraders. A primary collimator assembly precedes the aperture and degrader wheels. Except where specifically stated otherwise, the experimental measurements were made using a circular defining aperture with a $\frac{7}{32}$ in. diameter and a nominal target-to-detector distance of 5.5 in. In this geometry the azimuthal acceptance angle is 2.3° and the effective solid angle subtended by the detector is 0.001 sr. The experimental measurements at laboratory angles from 20° to 150° at 5° intervals were made using this detector assembly.

The detector assembly which is mounted on the other rotating arm consists of a silicon surface-barrier detector identical to the first detector and a collimating system that defines the same counter geometry as the detector assembly described above. However, this assembly is designed to permit measurements at extreme angles in the forward and backward direction, to within 7.5° of the beam in this experiment. All the experimental points measured in the ranges from 7.5 to 20° at 2.5° intervals, 22.5 to 47.5° at 5° intervals, and 150 to 170° at 5° intervals were measured using this small-angle detector.

The energy calibration of the detector system was accomplished using a $Bi^{212}$-$Po^{212}$-$Po^{214}$ alpha source and the elastic alpha groups from the carbon and oxygen contaminants which were present in the target. The detectors were operated at 200-V bias at angles less than 90° and 5-V bias for angles greater than 90°, providing depletion depths corresponding to the ranges of 30- and 10-MeV alpha particles, respectively. The use of the lower bias voltage provided effective discrimination against the protons from the reaction $Be^9(\alpha,p)B^{12}$. The detector signals were amplified by a charge-sensitive preamplifier, inverted, and further amplified. The pulses were then processed in a modified Radiation Counter Laboratories model 20609 256-channel pulse-height analyzer.

The target was a self-supporting, metallic beryllium foil. The target thickness, determined by observing the energy loss of $Bi^{212}$-$Po^{212}$-$Po^{214}$ alpha-particle groups in passing through it, was found to be $176\pm8$ $\mu$g/cm$^2$. Analysis of the reaction data using the known elastic cross sections for $C^{12}$ and $O^{16}$ at 18.0 and 18.3 MeV, respectively,[4] yielded an equivalent target thickness for each of these impurities of $13\pm4$ $\mu$g/cm$^2$.

The beam was collected in a cylindrical Faraday cup (2-in. diam and 8-in. height) and the current was electronically integrated by a circuit based on the design of Higinbotham and Rankowitz.[6]

The systematic error in the absolute cross-section measurements arising from uncertainties in target thickness, beam integration, and experimental geometry is estimated to be ±15%.

[6] W. A. Higinbotham and S. Rankowitz, Rev. Sci. Instr. 22, 688 (1951).

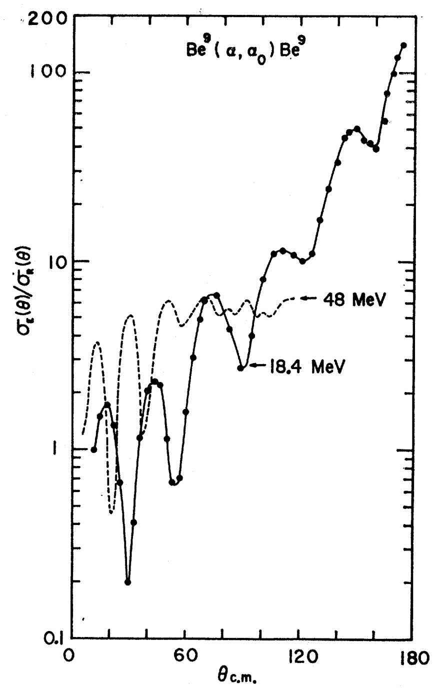


FIG. 3. The ratio of the experimental differential elastic-scattering cross section of alpha particles from $Be^9$ to the Rutherford cross section as a function of the center-of-mass scattering angle for incident alpha-particle energies of 18.4 MeV (solid curve) and 48 MeV (dashed curve). The 48-MeV curve was taken directly from a graph presented in Ref. 7.

## III. RESULTS AND DISCUSSION

### A. The Ground State and 2.43-MeV State

Measurements of the differential elastic-scattering cross section of alpha particles from $Be^9$ have been reported for two bombarding energies, 48 MeV[7] and 44 MeV.[8] The ratio of the experimental differential elastic-scattering cross section to the Rutherford cross section $\sigma_E/\sigma_R$, which resulted from the investigation of Summers-Gill[7] (48 MeV) and that from the present study (18.4 MeV), are shown in Fig. 3.[9] In each case the diffraction pattern is quite prominent at forward angles. The pattern persists with less pronounced minima and maxima at backward angles in the 18-MeV data. However, the 48-MeV results show the ratio to be roughly constant from 70 to 120°. It is interesting to note that while the $\sigma_E/\sigma_R$ ratios at these two different energies are approximately equal at 70°, the lower energy curve shows a general tendency to continue increasing at the backward angles, a trend which cannot be inferred from the general behavior of the high-energy results. Unfortunately, though rather complete angular

[7] R. G. Summers-Gill, University of California Radiation Laboratory Report UCRL-3388, April 1956 (unpublished); and Phys. Rev. 109, 1591 (1958).

[8] G. W. Farwell and D. D. Kerlee, Bull. Am. Phys. Soc. 1, 20 (1956).

[9] A detailed report of the 44-MeV results has not appeared in the open literature.

distributions have been measured for many light nuclei using a nominal alpha-particle energy of 18 MeV, the high-energy measurements are not complete enough to allow a similar comparison of the relative behavior of the high- and low-energy $\sigma_E/\sigma_R$ ratios at angles greater than 90° for other light nuclei. Since this rise in the elastic cross section at backward angles is not understood at the present time, a more complete study of the energy dependence of this effect for various light nuclei could possibly be of help in gaining insight as to its origin. In addition, it has been convincingly demonstrated by Corelli, Bleuler, and Tendam,[10] by means of a compilation of data for elastic scattering of 18- to 18.7-MeV alpha particles from C, O, Ne, Al, S, Ar, Cu, and Ag, that the $\sigma_E/\sigma_R$ ratio tends to rise higher at backward angles as the mass number decreases. The results of the present investigation are consistent with this generalization.

An attempt was made to fit the angular distribution corresponding to elastic scattering with a theoretical expression derived on the basis of a black-nucleus or

TABLE I. Compilation of experimental interaction radii for some light nuclei obtained by analysis of elastic alpha-scattering data.

| Nucleus | $E_\alpha$ (MeV) | $R$ ($10^{-13}$ cm) | References[a] |
|---|---|---|---|
| $Li^6$[b] | 31.5 | 4.5[c] | e |
| $Be^9$ | 18.4 | 5.68 | Present |
| | 48 | 4.9 | f |
| | 48 | 5.0 | g(f) |
| $C^{12}$ | 18.0 | 7.9 | h |
| | 31.5 | 4.4 | e |
| | 38 | 4.97 | i |
| | 40 | 5.1 | j |
| | 40 | 5.1 | g(j) |
| | 40 | 4.4 | k |
| $N^{14}$ | 19 | 5.89 | l |
| | 38 | 5.32 | i |
| | 40 | 5.37 | j |
| $O^{16}$ | 18.3 | 4.35 | h |
| | 38 | 5.09 | i |
| | 40 | 5.64 | j |
| | 40 | 5.64 | g(j) |
| $F^{19}$ | 38 | 5.52 | i |
| $Ne^{20}$ | 18.0 | 6.36 | m |
| | 18.0 | 6.16 | g(m) |
| $Mg^{24}$ | 22.8 | 6.02 | n(o) |
| | 28 | 5.98 | n |
| | 31.5 | 5.4 | e |
| | 31.5 | 5.90 | n(e) |
| | 34 | 5.87 | n |
| | 41 | 5.98 | n |
| | 43 | 6.4[d] | p |
| | 48 | 6.06 | n(q) |
| $Al^{27}$ | 11.9 | 5.9 | r |
| | 18.7 | 6.4[d] | s |
| | 40 | 5.5 | k |
| $P^{31}$ | 18.2 | 6.28 | t |
| $S^{32}$ | 18.1 | 6.7 | h |
| | 43.0 | 6.19 | g |
| $Ar^{40}$ | 18.0 | 6.95 | m |
| | 40 | 6.38 | j |
| | 40 | 6.38 | g(j) |
| $Ca^{40}$ | 43 | 6.65[d] | p |

[a] Notation means data taken from Ref. f is analyzed in Ref. g.
[b] Separated isotope. For other nuclei assume normal isotopic abundance.
[c] Analysis by simple diffraction model (see Ref. 12) unless specified otherwise.
[d] Analysis by direct-interaction Born approximation.
[e] H. J. Watters, Phys. Rev. 103, 1763 (1956).
[f] See Ref. 7.
[g] See Ref. 12.
[h] See Ref. 10.
[i] J. Aguilar, W. E. Burcham, J. Catalá, J. B. A. England, J. S. C. McKee, and J. Rotblat, Proc. Roy. Soc. (London) A254, 395 (1960).
[j] A. I. Yavin and G. W. Farwell, Nucl. Phys. 12, 1 (1959).
[k] G. Igo, H. E. Wegner, and R. M. Eisberg, Phys. Rev. 101, 1508 (1956).
[l] W. D. Ploughe, Ph.D. thesis, Purdue University, 1961 (unpublished) (L. C.: Mic. 61-5755, University Microfilms, Inc., Ann Arbor, Michigan); and Phys. Rev. 122, 1232 (1961).
[m] L. Seidlitz, E. Bleuler, and D. J. Tendam, Phys. Rev. 110, 682 (1958); and Bull. Am. Phys. Soc. 1, 29 (1956).
[n] J. S. Blair, G. W. Farwell, and D. K. Daniels, Nucl. Phys. 17, 641 (1960).
[o] C. Hu, S. Kato, Y. Oda, and M. Takeda, J. Phys. Soc. Japan 14, 549 (1959).
[p] G. B. Shook, Phys. Rev. 114, 310 (1959).
[q] F. J. Vaughn, Ph.D. thesis, University of California, 1955 (unpublished), and University of California Radiation Laboratory Report 3175, 1955 (unpublished).
[r] M. P. Konstantinova, E. V. Myakinin, A. M. Romanov, and T. V. Tsaryova, Zh. Eksperim. i Teor. Fiz. 41, 49 (1961) [English transl.: Soviet Phys.—JETP 14, 38 (1962)].
[s] O. H. Gailar, E. Bleuler, and D. J. Tendam, Phys. Rev. 112, 1989 (1958).
[t] This interaction radius is the result of a preliminary analysis of data from a study of alpha-particle scattering from $P^{31}$ presently in progress at this laboratory.

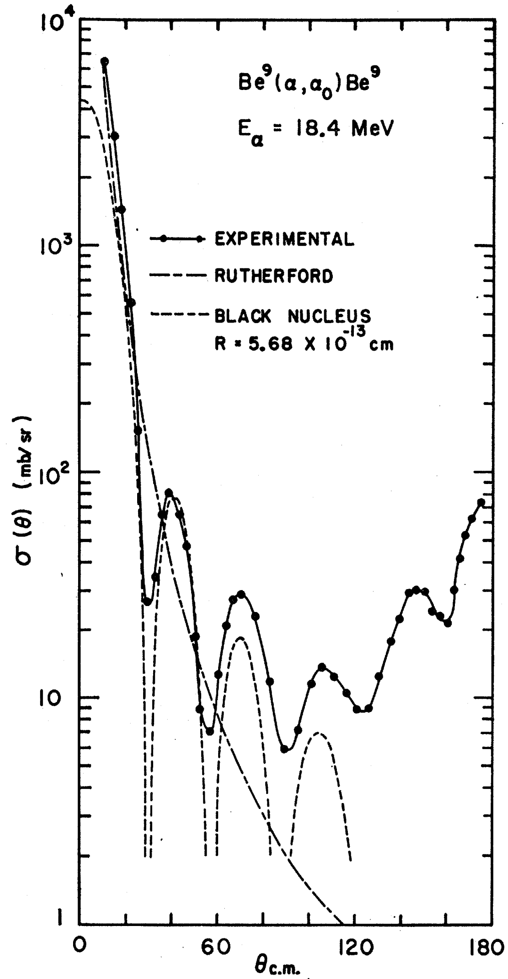


FIG. 4. The Rutherford, black-nucleus, and experimental differential cross sections for the elastic scattering of 18.4-MeV alpha particles from $Be^9$.

[10] J. C. Corelli, E. Bleuler, and D. J. Tendam, Phys. Rev. 116, 1184 (1959).

diffraction model.[11] This model corresponds to scattering from a perfectly absorbing spherical nucleus. In the Fraunhofer approximation[12] the elastic differential cross section is given by

$$\sigma_E(\theta)=(kR^2)^2[J_1^2(x)/x^2], \quad (1)$$

where $k$ is the center-of-mass wave number of the incident alpha particle, $R$ is the interaction radius, $\theta$ is the center-of-mass scattering angle, $x=2kR\sin\theta/2$, and $J_1(x)$ is the ordinary Bessel function of first order. The effective interaction radius is the only adjustable parameter and there is no arbitrary normalization. In Fig. 4 are shown the experimental, Rutherford, and black-nucleus cross sections. The value of $R$ obtained through a compromise fitting of the first three maxima is $5.68\times10^{-13}$ cm. Although the agreement between experiment and theory for the magnitude and angular position of the first maximum is quite good, it becomes systematically poorer at larger angles. A discrepancy of this general nature is not completely unexpected since the Fraunhofer approximation assumes small-angle scattering.

The interaction radius for $Be^9$ resulting from the black-nucleus analysis in the present experiment is considerably larger than the value of $4.9\pm0.2\times10^{-13}$ cm derived by Summers-Gill from his 48-MeV data.[7] If the simple point of view is taken that the interaction radius reflects the intrinsic alpha-particle radius and in some measure its finite DeBroglie wavelength,[13] then a larger radius should result from the lower energy investigation of a given nucleus. The results of the present investigation are consistent with the expectation based on this naive picture. In Table I is presented a representative compilation of the experimental interaction radii derived from elastic alpha-scattering data from lighter nuclei for which, in most cases, a comparison among high- and low-energy values may be made. The $R$ value derived from a given set of experimental data will of course depend on the model used in the analysis, although the more or less subjective criteria used to judge the best $R$ value could in this circumstance be an important contributing factor in obscuring possible systematic trends. In Fig. 5 is shown a plot of the $R$ values from Table I against $A^{1/3}$. The solid line is given by $R=aA^{1/3}+b$ with $a=1.414\pm0.036$ and $b=2.19\pm0.20$. This is a least-squares fit made by Kerlee, Blair, and Farwell[14] to the interaction radii derived from the elastic scattering of alpha particles from 28 nuclei with $A>50$ as determined by a general "crossover-point" criterion of the sharp-cutoff model.[15] The $R$ values for the lighter nuclei seem to cluster about this line, but there is considerable spread. In contrast, the average

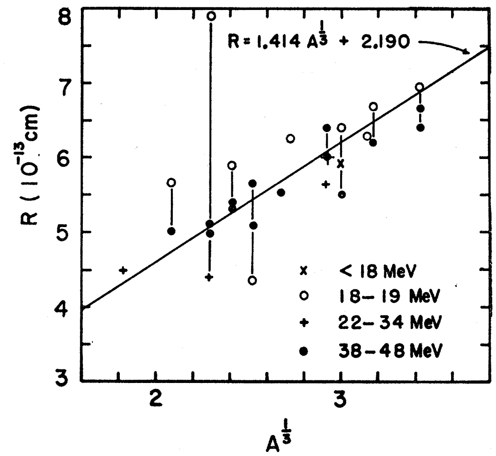


FIG. 5. The interaction radii from Table I are plotted against $A^{1/3}$. The average $R$ value is plotted for those cases in which different analyses of the same data yield different results. If, for a given $A$, two or more values lie close together, then one representative point for each energy range is plotted. The solid line was least-squares fit to interaction radii derived from the analysis of the results of elastic alpha-particle scattering from nuclei with $A>50$ using the sharp-cutoff model (see Ref. 14).

deviation for the heavier nuclei was only 0.75% with one case 3%, 7 between 1% and 2%, and 20 less than 1%. The fact that this line seems to describe the average interaction radius for the light nuclei suggests the close relationship between the sharp-cutoff and black-nucleus models. The data presented in Table I and Fig. 5 suggest no generalization concerning the energy dependence of the interaction radius for light nuclei other than perhaps a tendency for the 18-MeV values to be the largest and lie above the line.

A previous study by Blair and Henley[16] concerning the inelastic scattering of alpha particles from $Be^9$ was based on an alpha-particle model in which $Be^9$ was assumed to consist of a neutron strongly coupled to an alpha-particle dumbbell. A selection rule was found which favors those transitions induced by inelastic scattering to excited states which are in the same rotational band as the ground state. Their identification of the 2.43-, 5.8-, and 11.3-MeV[17] states as the spin $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ members of the $K=\frac{3}{2}$ rotational band built on the ground state is then supported by the experimental observation that these transitions do appear to be favored in alpha scattering while the transitions to the 1.8-, 3.1-, and 4.8-MeV levels are inhibited.[18] The fact that the relative spacings of these levels assigned to the $K=\frac{3}{2}$ band are roughly predicted by this model may also be taken as weak support for its applicability.[18] The $Be^9$ ground-state spin and parity are known with certainty to be $\frac{3}{2}^-$ and while the spin and parity of the

[11] J. S. Blair, Phys. Rev. **108**, 827 (1957).
[12] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[13] R. M. Eisberg and C. E. Porter, Rev. Mod. Phys. **33**, 190 (1961).
[14] D. D. Kerlee, J. S. Blair, and G. W. Farwell, Phys. Rev. **107**, 1343 (1957).
[15] J. S. Blair, Phys. Rev. **95**, 1218 (1954).
[16] J. S. Blair and E. M. Henley, Phys. Rev. **112**, 2029 (1958).
[17] There had been some weak evidence for a level at 11.3 MeV in $Be^9$ and this level was tentatively included in the level scheme of Ref. 1(a). The recent level scheme presented in Ref. 1(b) now indicates the possibility of a level at 12 MeV and no longer includes the possibility of a level at 11.3 MeV.
[18] W. T. Pinkston, Phys. Rev. **115**, 963 (1959).

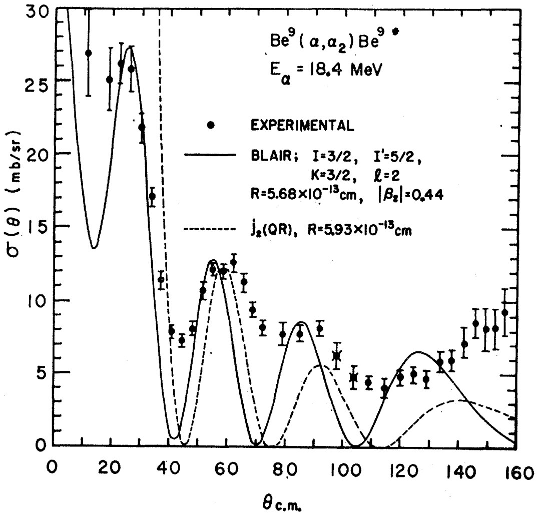


FIG. 6. The inelastic differential cross section for 18.4-MeV alpha-particle scattering to the 2.43-MeV, ($\frac{5}{2}^-$)-state of $Be^9$. The indicated errors are probable errors estimated on the basis of counting statistics and decomposition uncertainties. The solid line represents Blair-model predictions (solid curve) and was normalized to the first and second experimental maxima. The direct-interaction plane-wave Born-approximation prediction (dashed curve) was normalized at the second experimental maximum. The crosses indicate those points which were corrected for the inelastically scattered alpha particles from the carbon and oxygen contaminants.

2.43-MeV level are not known with complete certainty, they are most probably $\frac{5}{2}^-$.

The Fraunhofer diffraction treatment was extended by Drozdov[19] and Inopin[20] to include inelastic scattering from an ellipsoidally-deformed absorbing nucleus. A further generalization due to Blair[12] treats an absorbing nucleus with deformations of arbitrary multipolarity. The expressions for the scattering cross sections were developed using the adiabatic approximation, and the assumption of a totally absorbing nucleus; and only terms in the expansion of the scattering amplitude which are linear in the deformation parameter were retained. The Blair expression for the inelastic cross section for rotational excitations adopting the spin assignments of Blair and Henley[16] is

$$\sigma_{2.43}(\theta)=[9(kR^2)^2/280\pi]\beta_2^2[J_0^2(x)+3J_2^2(x)]. \quad (2)$$

Comparison of Eq. (2) with Eq. (1) shows that the elastic, and inelastic scattering cross section to states within the same rotational band as the ground state, and hence of the same parity, will be out of phase. This is an example of a more general rule inherent in the Blair formalism for scattering from collective states which says that the inelastic differential cross section associated with no-parity (parity) change excitations is out of (in) phase with the elastic differential cross section.

[19] S. I. Drozdov, Zh. Eksperim. i Teor. Fiz. 28, 734 (1955) [English transl.: Soviet Phys.—JETP 1, 588 (1955)].

[20] E. V. Inopin, Zh. Eksperim. i Teor. Fiz. 31, 901 (1956) [English transl.: Soviet Phys.—JETP 4, 784 (1957)].

The magnitude of $\beta_2$ may be determined by evaluating Eq. (2) using the $R$ value derived through the fitting of the elastic angular distribution and then normalizing the resulting theoretical curve to the inelastic angular distribution at small scattering angles. Using the data from the present investigation this procedure yields $|\beta_2|=0.44$. A comparison of the theoretical curve and experimental points is presented in Fig. 6. The first and second maxima are the points of normalization.

The corresponding expression for the elastic cross section including the collective term is

$$\sigma_E(\theta)=(kR^2)^2[J_1^2(x)/x^2] + [(kR^2)^2/80\pi]\beta_2^2[J_0^2(x)+3J_2^2(x)], \quad (3)$$

where, again, $x=2kR\sin\theta/2$. The collective term in Eq. (3) requires that the phase rule be qualified in a minor manner since the relative size of the first term will decrease at larger angles and the elastic cross section will tend to get in phase with the no-parity

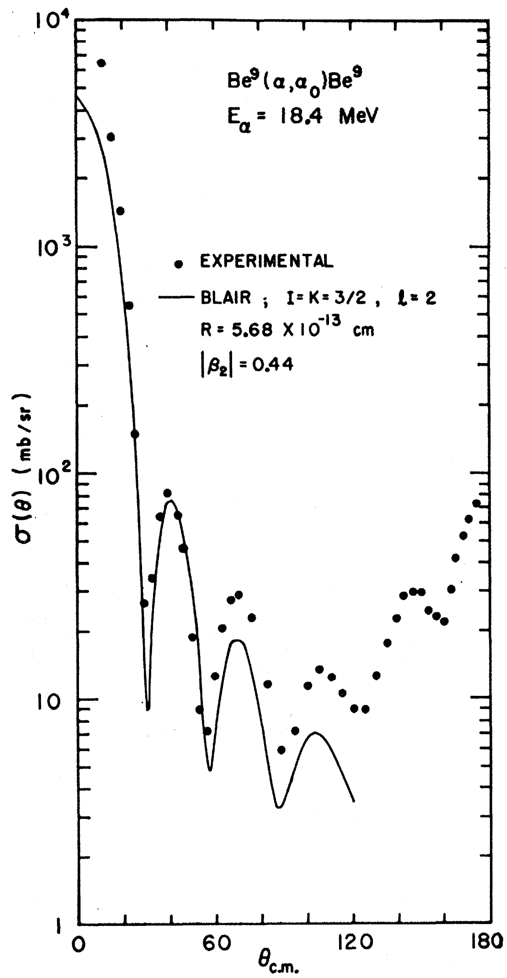


FIG. 7. The experimental differential cross section for elastic scattering of 18.4-MeV alpha particles from $Be^9$. The solid curve is the prediction of the Blair model calculated from Eq. (3) assuming an interaction radius of 5.68 F.

TABLE II. The differential cross section for the elastic scattering of 18.4-MeV alpha particles by $Be^9$.

| $\theta_{c.m.}$ | $\sigma(\theta)$ (mb/sr) | Probable error[a] | $\sigma_E/\sigma_R$ | $\theta_{c.m.}$ | $\sigma(\theta)$ (mb/sr) | Probable error | $\sigma_E/\sigma_R$ |
|---|---|---|---|---|---|---|---|
| 10.82 | 6520 | 650 | 1.00 | 94.67 | 6.96 | 0.31 | 3.99 |
| 14.42 | 3070 | 240 | 1.50 | 100.40 | 11.7 | 0.4 | 7.97 |
| 18.02 | 1460 | 64 | 1.72 | 105.93 | 13.7 | 0.4 | 10.9 |
| 21.60 | 553 | 19 | 1.34 | 111.27 | 12.5 | 0.5 | 11.4 |
| 25.17 | 150 | 2 | 0.661 | 116.37 | 10.6 | 0.5 | 10.8 |
| 28.73 | 26.5 | 0.8 | 0.197 | 121.27 | 8.85 | 0.44 | 10.0 |
| 32.28 | 34.6 | 0.8 | 0.404 | 125.93 | 8.94 | 0.35 | 11.0 |
| 35.81 | 65.2 | 1.2 | 1.14 | 130.40 | 12.5 | 0.6 | 16.6 |
| 39.33 | 81.7 | 1.2 | 2.05 | 134.67 | 17.3 | 0.7 | 24.5 |
| 42.83 | 65.4 | 1.0 | 2.28 | 138.73 | 22.3 | 0.8 | 33.5 |
| 46.30 | 47.4 | 0.9 | 2.22 | 142.62 | 28.4 | 1.2 | 44.8 |
| 49.75 | 18.4 | 0.6 | 1.12 | 146.33 | 29.6 | 1.2 | 48.6 |
| 52.58 | 8.89 | 0.40 | 0.669 | 149.88 | 29.6 | 1.3 | 50.5 |
| 56.58 | 7.04 | 0.31 | 0.694 | 153.30 | 24.7 | 1.2 | 43.3 |
| 59.95 | 12.6 | 0.5 | 1.54 | 156.58 | 23.4 | 1.1 | 42.1 |
| 63.30 | 20.7 | 0.6 | 3.07 | 159.75 | 21.6 | 1.2 | 39.8 |
| 66.62 | 27.2 | 0.7 | 4.85 | 162.83 | 29.6 | 1.5 | 55.5 |
| 69.88 | 29.1 | 0.7 | 6.14 | 165.81 | 41.3 | 1.2 | 78.5 |
| 76.33 | 22.9 | 0.7 | 6.54 | 168.73 | 52.2 | 1.6 | 100 |
| 82.62 | 11.6 | 0.4 | 4.31 | 171.60 | 62.0 | 2.0 | 120 |
| 88.73 | 5.89 | 0.27 | 2.76 | 174.42 | 72.0 | 6.3 | 140 |

[a] Errors are estimated on the basis of counting statistics.

change inelastic cross section. This effect is small, if not negligible, for forward angle scattering.

The experimental points and the curve calculated from Eq. (3) using the value of $|\beta_2|$ extracted from the inelastic data and the value of $R$ obtained from the simple diffraction analysis, Eq. (1), are shown in Fig. 7. A detailed comparison of the black-nucleus and Blair-model curves of Fig. 4 and Fig. 7, respectively, results in the conclusions that the collective contribution to the elastic cross section fills in the minima, causes a very slight shift of the diffraction pattern to larger angles, and causes a slight broadening of the maxima. The analyses of the 48-MeV data of Summers-Gill[7] by Blair and Henley[16] on the basis of the alpha-particle model described above yielded $R\approx5.5\times10^{-13}$ cm, and by Blair[12] on the basis of this more recent model of his yielded $R=5.0\times10^{-13}$ cm and $|\beta_2|=0.46$. These and the present results are consistent with a large prolate ellipsoidal deformation for $Be^9$. Comparison of Figs. 4 and 6 shows that the elastic and inelastic cross sections are indeed out of phase as predicted for no-parity change transitions by the Blair-model phase rule.

The theoretical inelastic angular distribution according to the direct-interaction theory of Austern, Butler, and McManus[21] (ABM theory) for $l=2$ is proportional to $j_2^2(QR)$, the spherical Bessel function of second order, where $Q$ is the magnitude of momentum transfer, and $R$ is the interaction radius. The dashed curve in Fig. 6 is proportional to the function $j_2^2(QR)$ for $R=5.93\times10^{-13}$ cm. This value of the interaction radius was obtained by fitting the second maximum of $j_2^2(QR)$ (the first maximum is not shown) to the maximum in the experimental data at about 59°. This was also the point of normalization. This $R$ value is in agreement with the $5.68\times10^{-13}$ cm obtained from a Blair-analysis of the elastic scattering results in this investigation and is slightly higher than the $5.40\times10^{-13}$ cm reported by Summers-Gill[7] from a similar ABM analysis of the 48-MeV inelastic data. The ABM theory appeared to fit the 48-MeV results better than those obtained at 18.4 MeV. The 18.4-MeV angular distribution does not appear to peak as strongly at forward angles as the ABM theory predicts. In addition, the Blair model yields the best prediction of the relative heights of the maxima while the ABM model appears to predict the spacing of the maxima better.

[21] N. Austern, S. T. Butler, and H. McManus, Phys. Rev. **92**, 350 (1953).

TABLE III. The differential cross section for the inelastic scattering of 18.4-MeV alpha particles from the 2.43-MeV state in $Be^9$.

| $\theta_{c.m.}$ | $\sigma(\theta)$ (mb/sr) | Probable error[a] | $\theta_{c.m.}$ | $\sigma(\theta)$ (mb/sr) | Probable error |
|---|---|---|---|---|---|
| 11.20 | 26.9 | 3.0 | 85.33 | 7.82 | 0.54 |
| 18.63 | 25.1 | 2.1 | 91.60 | 8.16 | 0.49 |
| 22.35 | 26.2 | 1.4 | 97.66 | 6.34[b] | 0.87 |
| 26.03 | 25.8 | 1.5 | 103.50 | 4.85[b] | 0.83 |
| 29.73 | 21.8 | 1.0 | 109.11 | 4.50 | 0.37 |
| 33.38 | 17.1 | 0.6 | 114.48 | 4.11 | 0.65 |
| 37.05 | 11.4 | 0.6 | 119.60 | 4.82 | 0.46 |
| 40.68 | 7.84 | 0.37 | 124.48 | 4.95 | 0.55 |
| 44.30 | 7.27 | 0.39 | 129.11 | 4.69 | 0.57 |
| 47.88 | 8.14 | 0.49 | 133.50 | 5.91 | 0.69 |
| 51.46 | 10.7 | 0.6 | 137.66 | 5.96 | 0.73 |
| 54.98 | 12.2 | 0.4 | 141.60 | 7.16 | 0.96 |
| 58.51 | 12.0 | 0.5 | 145.33 | 8.60 | 0.95 |
| 61.98 | 12.6 | 0.6 | 148.87 | 8.15 | 1.47 |
| 65.44 | 11.3 | 0.6 | 152.23 | 8.19 | 1.40 |
| 68.85 | 9.41 | 0.49 | 155.44 | 9.36 | 1.63 |
| 72.23 | 8.18 | 0.49 | 158.51 | 8.81 | 1.66 |
| 78.87 | 7.77 | 0.76 | | | |

[a] Errors are estimated on the basis of counting statistics and decomposition uncertainties.
[b] Corrected for carbon and/or oxygen impurities in target.

The experimental values of the absolute differential cross sections for elastic scattering and inelastic scattering to the 2.43-MeV state are given in Tables II and III, respectively.

### B. The 1.8-MeV Anomaly

The existence of a state in $Be^9$ at about 1.6 MeV was first proposed by Guth and Mullin[22] on the basis of a theoretical interpretation of the yield and angular distribution of neutrons from the $Be^9(\gamma,n)Be^8$ reaction. The previous work by Davis and Hafner[23] on the reaction $Be^9(p,p')Be^9$ had yielded evidence for only a 2.41-MeV state. The investigations involving the reactions $B^{11}(d,\alpha)Be^9$ by Van Patter *et al.*,[24] and $Be^9(p,p')Be^9$ by Browne *et al.*,[25] Cowie *et al.*,[26] and Arthur *et al.*[27] subsequent to the suggestion of Guth and Mullin provided no supporting experimental information. However, later studies of Moak *et al.*[28] involving the reaction $Li^7(He^3,p)Be^9$, by Almqvist *et al.*[29] through the $B^{10}(t,\alpha)Be^9$ reaction, and by Lee and Inglis[30] using the $B^{11}(d,\alpha)Be^9$ reaction, did provide some evidence for a 1.8-MeV state in $Be^9$. Many of the investigations since have verified the existence of a subtle anomaly which corresponded to a nominal $Be^9$ excitation energy of 1.8-MeV.

Gosset *et al.*[31] performed a high-resolution measurement of the inelastically scattered protons from $Be^9$ using magnetic analysis. The experimental proton spectrum showed a broad distribution of protons with a sharp cutoff which corresponded to a $Q=-1.675\pm0.002$ MeV. On the basis of the marked asymmetry of this observed group and the proximity of the observed $Q$ value to the $Be^9$-neutron separation energy, they suggested the possibility that the proton anomaly might be a manifestation of the three-body disintegration of an excited state of the compound nucleus $B^{10*}\rightarrow Be^8+p+n$. The studies of Rasmussen *et al.*[32] involving the inelastic scattering of alpha particles and deuterons also yielded some evidence for a level in $Be^9$ at $1.74\pm0.1$ MeV. Their analysis of the $(d,d')$ results on the basis of expressions derived by Watson[33] indicated that this anomalous deuteron distribution could be explained by a three-body disintegration of the compound nucleus, $B^{11*}\rightarrow Be^8+n+d$, with a final-state $S$-wave potential-scattering interaction between $Be^8$ and the neutron. Bockelman *et al.*[34] reported a similar analysis of their $Be^9(p,p')Be^9$ and $B^{11}(d,\alpha)Be^9$ reaction data in which reasonable fits to both the anomalous proton and alpha-particle distributions were achieved. Miller[35] reinvestigated the anomalous inelastic deuteron distribution associated with the reaction $Be^9(d,d')Be^9$ with relatively high statistical accuracy. He analyzed these data under the same assumptions as Rasmussen *et al.*,[32] accounting for finite resolution, and was able to fit the anomalous distribution with a neutron scattering length of $20\times10^{-13}$ cm. He also reanalyzed the high-resolution results of Bockelman *et al.*[34] This made it possible to compare the fits achieved using the same parameters for data from different laboratories using different reactions, under different experimental conditions: $Be^9(p,p')Be^9$, $\theta=130°$, $E_p=7.080$ MeV; $B^{11}(d,\alpha)$ $Be^9$, $\theta=130°$, $E_d=7.007$ MeV; $Be^9(d,d')Be^9$, $\theta=25°$, $E_d=10.93$ MeV. The fits were judged to be satisfactory. Miller also pointed out that the large value of the scattering length required to fit these distributions is consistent with the predictions of Ford and Bohm[36] concerning the variation of the average neutron scattering length with mass number, and also implies the existence of a nearby resonance. On this basis he suggested a spin $\frac{1}{2}$ state in $Be^9$ near the neutron binding energy and argued further for an assignment of $\frac{1}{2}^+$ on the grounds that the value of the associated intermediate-coupling parameter would fit more smoothly into the systematic trend of this parameter as a function of mass number than the value associated with a $\frac{1}{2}^-$ assignment.[37] Marion has been quoted[38] as asserting that the assumption of $P$-wave resonance will also yield an acceptable fit for the elastic-scattering data. Therefore, it would appear that a definitive spin and parity assignment can not be made on the basis of a final-state-interaction analysis. Furthermore, the smoothness of the systematic trend of the intermediate-coupling parameter as a function of mass number as a reliable basis for spin and parity assignments can be seriously questioned.[39]

Summers-Gill[7] proposed a type of three-body breakup to explain the anomaly in the $Be^9(p,p')Be^9$ distribution that he refers to as "heavy-particle stripping," a reaction in which the incident charged particle causes the loosely bound neutron to be stripped from its $Be^8$ core and then escape capture by the core. This model pre-

[22] E. Guth and C. J. Mullin, Phys. Rev. **76**, 234 (1949).
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[24] D. M. Van Patter, A. Sperduto, K. Haung, E. N. Strait, and W. W. Buechner, Phys. Rev. **81**, 233 (1951).
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[26] D. B. Cowie, N. P. Heydenburg, and G. C. Phillips, Phys. Rev. **87**, 304 (1952).
[27] J. C. Arthur, A. J. Allen, R. S. Bender, H. J. Hausman, and C. J. McDole, Phys. Rev. **88**, 1291 (1952).
[28] C. D. Moak, W. M. Good, and W. E. Kunz, Phys. Rev. **96**, 1363 (1954).
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[30] L. L. Lee Jr. and D. R. Inglis, Phys. Rev. **99**, 96 (1955).
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[33] K. M. Watson, Phys. Rev. **88**, 1163 (1952).
[34] C. K. Bockelman, A. Leveque, and W. W. Buechner, Phys. Rev. **104**, 456 (1956).
[35] D. W. Miller, Phys. Rev. **109**, 1669 (1958).
[36] K. W. Ford and D. Bohm, Phys. Rev. **79**, 745 (1950).
[37] The assignment $\frac{1}{2}^+$ had been originally suggested by Guth and Mullin in Ref. 22.
[38] This assertion has only been documented in the open literature to the extent of the private communication indicated in Ref. 15 of Ref. 18 in the present paper.
[39] Y. C. Tang, F. C. Khanna, R. C. Herndon, and K. Wildermuth, Nucl. Phys. **34**, 421 (1962).

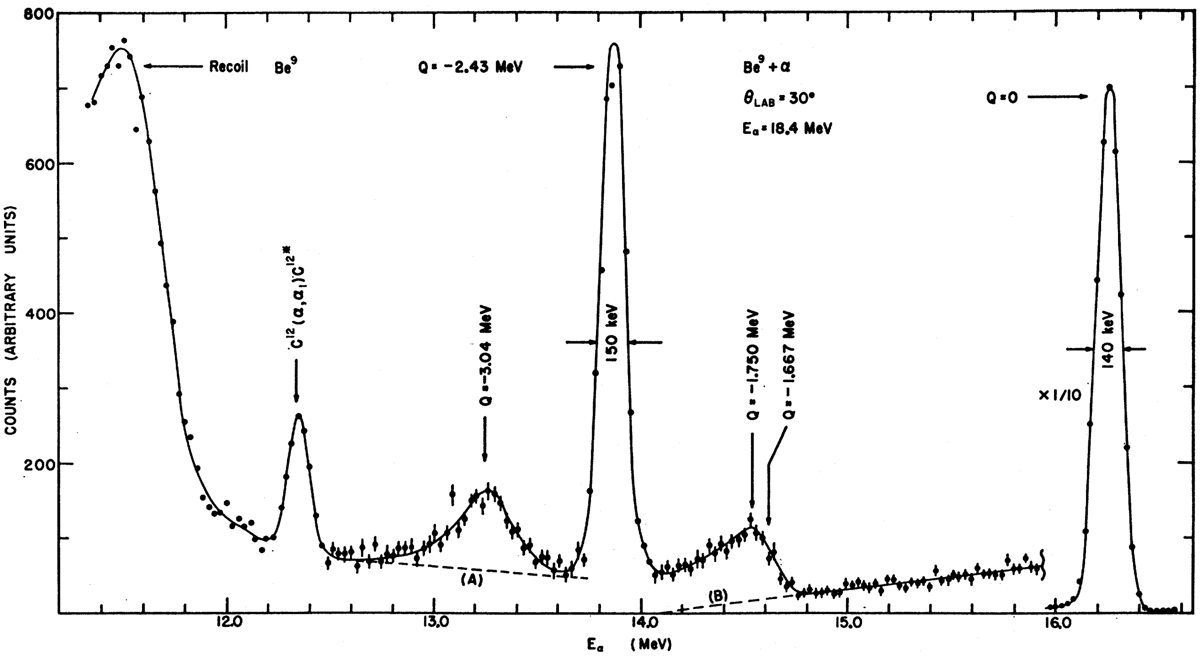


FIG. 8. The charged particle spectrum from the bombardment of a 176 $\mu$g/cm$^2$ beryllium target by alpha particles at a laboratory energy of 18.4 MeV. The spectrum was accumulated at a laboratory angle of 30° with a detector acceptance angle of about 1°. The vertical arrows on the figure indicate the expected positions of the inelastic alpha-particle groups corresponding to the indicated excitations of the $Be^{9*}$ nucleus, and the alpha-particle group corresponding to inelastic scattering from carbon.

dicts a definite angular dependence for the energy of the "peak" of the anomaly. Summers-Gill[7] observed a slight energy shift with angle in the $(p,p')$ reaction. Miller[35] observed no energy shift in the $(d,d')$ reaction, and the present investigation yielded no evidence for a systematic energy shift with angle.

It has been proposed by Spencer *et al.*[40] that the 1.8-MeV anomaly is "not a state at all in the usual sense of representing an energy situation of $Be^9$ that is unusually stable due to attractive forces." This statement has been interpreted by Tang *et al.*[39] as meaning "the 1.7-MeV anomaly is not a state at all in the usual sense of a strong interaction between the neutron and the $Be^8$ nucleus." The former authors suggest that the peaked anomaly can be explained by assuming the phenomenon of spatial localization[41] following from the assumption that the compound nucleus breaks up through a sequence of two-body decays and assert further that only an extremely weak interaction in the $n$-$Be^8$ system need be assumed. Tang *et al.*[39] argue that the experimental fact that the anomaly occurs at an energy less than 100 keV above the neutron threshold cannot be explained by assuming a very weak $n$-$Be^8$ interaction if a realistic size for the localization volume is assumed. In addition, Barker and Treacy[42] show that the experimental inelastic proton distribution measured by Spencer *et al.*[40] in the vicinity of $Q=-1.7$ MeV can be explained satisfactorily in terms of states "in the usual sense." They further assert that there is no obvious reason for the absence of a nuclear interaction between $Be^8$ and the neutron.

Recently, Symons and Treacy[43] have reported evidence obtained from a study of the $C^{12}(p,\alpha)B^9$ reaction for an excited state of $B^9$ at $1.7\pm0.2$ MeV with a reduced width of 1.0 MeV. This, of course, implies the existence of an analogous level in the mirror nucleus $Be^9$. Studies involving the inelastic scattering of electrons from $Be^9$ have shown the existence of a $(\frac{1}{2}+)$ level in $Be^9$ at about 1.7 MeV.[44,45] Corman *et al.*[46] have recently reanalyzed $Be^9(\gamma,n)Be^8$ results using an improved calculational procedure due to Francis *et al.*[47] and concluded that there is a $2S$ state in $Be^9$ bound by from 14 to 28 keV.

In the present investigation, the experimental spectra for scattering angles less than 90° showed evidence for a very weak, peaked, asymmetric alpha-particle distribution on the high-energy side of the 2.43-MeV alpha group (see Fig. 8). This distribution is presumably the 1.8-MeV anomaly discussed above. If it is assumed that this peaked distribution corresponds to a "normal" state, then the energy of the associated level in $Be^9$ can

[40] R. R. Spencer, G. C. Phillips, and T. E. Young, Nucl. Phys. **21**, 310 (1960).
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[42] F. C. Barker and P. B. Treacy, Nucl. Phys. **38**, 33 (1962).
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[45] H. Nguyen Ngoc, M. Hors, and J. Perez Y. Jorba, Nucl. Phys. **42**, 62 (1963).
[46] E. G. Corman, J. E. Sherwood, and W. John, Phys. Letters **4**, 146 (1963).
[47] N. C. Francis, D. T. Goldman, and E. Guth, Phys. Rev. **120**, 2175 (1960).

be found in the usual manner. For angles less than 50°, the "peak" was well enough resolved to allow a reasonably unambiguous energy assignment. However, at the larger angles the resolution became progressively poorer, and the distribution became less intense, making the energy assignments less certain. The energy calibration was established by assuming the energy of the ground-state and 2.43-MeV state alpha-particle groups. In Table IV are presented the $Q$ values of this hypothetical level in $Be^9$ which were derived from the "peak" energies measured at various laboratory angles. The errors are estimated probable errors based on an appraisal of the calibration procedure and uncertainties in locating the "peak" of the distribution. It can be seen that there is no systematic shift with angle contrary to what would be expected on the basis of the Summers-Gill[7] "heavy-particle stripping."

Retaining the assumption that the 1.8-MeV "peak" is associated with a "normal" state at 1.8 MeV in $Be^9$, an angular distribution may be constructed in the usual manner. It was assumed that this "peak" was superimposed on an alpha-particle continuum resulting from the low-energy tail associated with the intense ground-state group and the multiparticle reactions

$$\alpha + Be^9 \rightarrow 3\alpha' + n - 1.573 \text{ MeV} \qquad (4a)$$

$$\rightarrow \alpha' + Be^8 + n - 1.667 \text{ MeV}. \qquad (4b)$$

In order to decompose the spectrum in the region of 1.8 MeV, it was assumed that the continuum could be represented by a straight line drawn through regions in which only the continuum was present and extrapolated to the point of intersection with the low-energy tail from the ground-state group (see Fig. 8, dashed lines A and B). The upper limit on the number of counts assigned to the "peak" corresponded to making no correction for the continuum, and the lower limit was set by subtracting those counts in the estimated continuum from the total number of counts in the energy interval associated with the peak. The differential cross section in the center-of-mass system was calculated from these limits in the usual way taking $Q = -1.8$ MeV (see Fig. 9). The bars in Fig. 9 connect the limiting values of the differential cross section and do not represent statistical errors. The solid circles in Fig. 9 represent the average of the limiting values of the cross section. The angular distribution exhibits a marked oscillatory structure, the qualitative features of which appear to be independent of which of the sets of limiting points is considered. The solid curve is proportional to $j_1^2(QR)$, the relative inelastic cross section from the ABM direct-interaction theory[21] assuming $l=1$ and $R=5.93$ F. It is interesting to note that the value of the interaction radius is the same as that used in fitting the direct-interaction theoretical cross section with $l=2$ to the 2.43-MeV state (see Fig. 7). The spin of the 1.8-MeV state is most probably $\frac{1}{2}$. Consequently, within the framework of this direct interaction theory, the angular-momentum transfer is restricted to $l=1$ and $l=2$, where $l=1$ implies a parity change transition and $l=2$ corresponds to no parity change. The value of the interaction radius required to fit $j_2^2(QR)$ to the 1.8-MeV angular distribution is 7.2 F, a value considerably higher than those used in fitting the data associated with elastic scattering and scattering to the 2.43-MeV state, so $l=2$ is excluded. This argument implies an even parity assignment for the 1.8-MeV state.

In Fig. 10 is presented an angular distribution of a portion of the estimated continuum within a 500-keV interval directly under the 2.43-MeV alpha-particle group. The indicated probable errors are estimated from counting statistics and decomposition uncertainties. It is quite evident that this distribution does not exhibit any of the oscillatory structure that is so prominent in

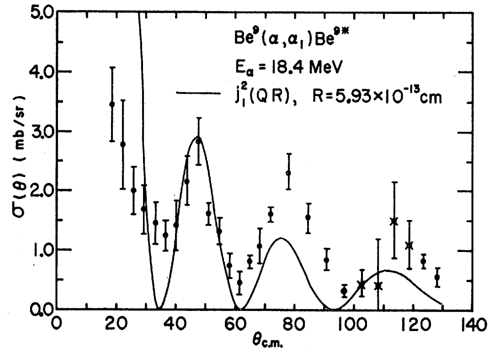


FIG. 9. The inelastic differential cross section for 18.4-MeV alpha-particle scattering to the 1.8-MeV "state" in $Be^9$. The vertical bars do not represent statistical errors, but represent the upper and lower limits placed on the cross section based upon the estimated contribution of the continuum (see text). The solid points represent the average of these limiting values. The solid curve is the direct-interaction Born-approximation prediction normalized at the second maximum (first maximum not shown). The crosses indicate those points that were corrected for the inelastically scattered alpha particles from the C and O impurities in the target.

TABLE IV. The $Q$ values of the hypothetical level in $Be^9$ as determined from the "peak" energy of the anomalous inelastic alpha-particle distribution observed at various laboratory angles.

| $\theta_{Lab}$ | $Q$-Value (MeV) |
|---|---|
| 22.5 | 1.80±0.05 |
| 25.0 | 1.81±0.05 |
| 30.0 | 1.78±0.05 |
| 32.5 | 1.87±0.05 |
| 35.0 | 1.83±0.05 |
| 37.5 | 1.79±0.05 |
| 40.0 | 1.80±0.05 |
| 50.0 | 1.90±0.05 |
| 55.0 | 1.82±0.08 |
| 60.0 | 1.87±0.10 |
| 65.0 | 1.80±0.10 |
| 70.0 | 1.75±0.10 |
| Av. | 1.82±0.02[a] |

[a] In the calculation of the average $Q$ value each experimental value was weighted inversely proportional to the square of its estimated probable error.

Fig. 9. The strong forward peaking and otherwise structureless features of this distribution are quite similar to what was obtained by Summers-Gill[7] in his analysis of the upper 10 percent of the continuum. The small peak located at about 38° is probably due to imperfect decomposition because of its proximity to a maximum in the angular distribution for the 2.43-MeV state.

If the alpha-particle distribution associated with the 1.8-MeV anomaly does arise from a final-state interaction of the type discussed above, then alpha particles associated with this process should be present in the 500-keV interval under the 2.43-MeV group. The angular distribution in Fig. 9 corresponds to the counts in a 500-keV interval centered at an energy corresponding to a $Be^9$ excitation of 1.8 MeV. The marked difference between the angular distributions of Figs. 9 and 10 suggests the angular distribution of the observed alpha particles is a strong function of the corresponding relative energy of the $Be^8$-$n$ system. On the other hand, if the contribution from the final-state interaction is small in this energy interval under the 2.43-MeV group and the major contribution is due to the alpha particles associated with an uncorrelated multibody final state, then the present result might be expected.

The experimental configuration which was used in the accumulation of the data for the angular distributions was a compromise between good resolution and counting statistics dictated by a practical limitation on cyclotron time. Consequently, the resulting data was not adequate for the study of the shape of the 1.8-MeV anomaly. A series of measurements were made in which extended counting periods were tolerated using a

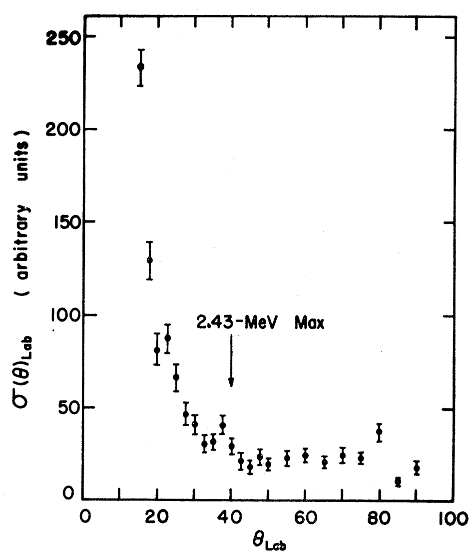


FIG. 10. The angular distribution in laboratory coordinates of a portion of the alpha-particle continuum within a 500-keV interval directly under the 2.43-MeV alpha group. The indicated probable errors are estimated from counting statistics and decomposition uncertainties. The arrow indicates the approximate angular location of the prominent maximum in the 2.43-MeV state angular distribution.

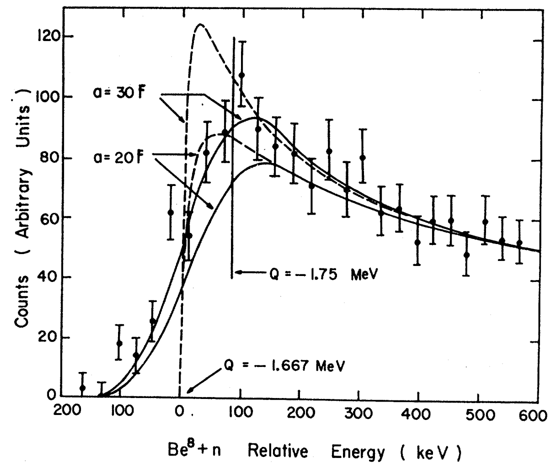


FIG. 11. The 1.8-MeV anomalous alpha-particle distribution from the $Be^9(\alpha,\alpha')Be^9$ reaction at an incident alpha energy of 18.4 MeV and a laboratory angle of 30°. The energy scale is the relative energy of the neutron and $Be^8$ assuming the three-body disintegration indicated in reaction (4b). The solid circles represent the experimental points corrected for the low-energy tail associated with the intense elastic group. The indicated probable errors are based on counting statistics. The dashed curves result from an evaluation of the theoretical alpha-particle spectrum assuming an $S$-wave potential-scattering final-state interaction between $Be^8$ and the neutron with the scattering length values: 20 F, Miller's "best" value (see Ref. 35), and 30 F, the value judged to yield the "best" fit to the present data. The solid curves represent the respective theoretical spectra corrected for finite resolution. The arrows indicate the positions of alpha-particle groups that would be associated with $Q$ values of −1.667 and −1.750 MeV for "normal" states in $Be^9$.

$\frac{3}{32}$-in.-diameter counter defining aperture. A spectrum obtained at a laboratory angle of 30° with this improved resolution and better statistics is shown in Fig. 8. The marked asymmetry of the anomalous distribution is clearly evident. It should be pointed out that the distribution is superimposed on the tail of the intense ground-state alpha group, presumably due to imperfect collimation. The validity of a linear extrapolation of this low-energy tail for purposes of spectral decomposition may be judged by considering the dashed line B in Fig. 8.

Miller's study[35] of the 1.8-MeV anomaly involving the analysis of data from the $(d,d')$,[35] $(d,\alpha)$,[34] and $(p,p')$[34] reactions assuming a final-state interaction as previously discussed was extended to the reaction $(\alpha,\alpha')$ in the present investigation. The effect of finite experimental resolution was accounted for by folding a triangular approximation to the experimental resolution curve, to be discussed later, into the theoretical spectra corresponding to various values of the scattering length $a$. The corrected theoretical spectra were then normalized to the experimental data about 550 keV above threshold. The corrected and uncorrected theoretical spectra together with the experimental data are plotted against the relative energy of the neutron and $Be^8$ assuming the three-body breakup described by (4b). The value of the scattering length which yielded the

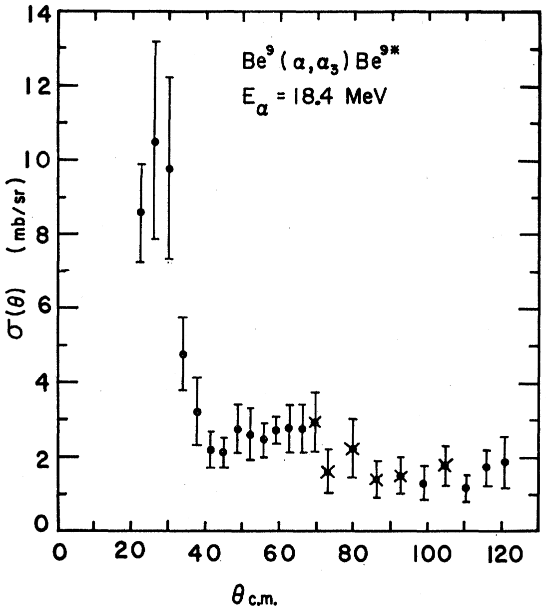


FIG. 12. The inelastic differential cross section for 18.4-MeV alpha-particle scattering to the 3.04-MeV state of $Be^9$. The indicated probable errors are estimated on the basis of counting statistics and uncertainties associated with the decomposition of the experimental spectrum. The crosses indicate those points which were corrected for the contributions from certain inelastic alpha-particle groups associated with scattering from the carbon and oxygen impurities in the target.

best fit to the present data was ~30 F. The subjective judgment as to the goodness of fit and the statistical accuracy of the present data preclude the assignment of a meaningful error to this number. However, it may be concluded with certainty from Fig. 11 that the present data does require a scattering length in excess of 20 F. It should be pointed out that in the present case as the scattering length is increased, even though the theoretical spectra become increasingly more peaked, the resolution-corrected spectra differ only slightly from one another. That is, for values of $a > 30$ F the corrected shape becomes increasingly less sensitive to the value of $a$, the finite experimental resolution being the dominating factor. Since Miller[35] has discussed the inadequacies and ambiguities associated with this type of analysis and its attendent assumptions, no further discussion of it will be made here.

### C. The 3.04-MeV State

The existence of a 3.04-MeV state in $Be^9$ has been well established. It has been observed by many investigators using a wide variety of nuclear reactions.[7,28–30,32,34,40,48,49] Although a unique spin assignment has not been made for this state, Bockelman *et al.*[34] have presented an argument for a spin $\leq\frac{3}{2}$. An anisotropic angular distribution of photoneutrons corresponding to the 3.04-MeV state in the $Be^9(\gamma,n)Be^8$ reaction has been observed and has been reported as being consistent with an electric dipole transition, implying a spin $<\frac{5}{2}$ and odd parity.[49] The results of electron scattering from $Be^9$ support this latter assignment.[44]

In the present investigation a broad, weak inelastic alpha-particle group which corresponded to a $Be^9$ excitation of about 3.04 MeV was observed in all experimental spectra accumulated at angles less than 90°. The corresponding experimental $Q$ value was determined to be $-3.04\pm0.03$ MeV. This alpha-particle group was superimposed on a continuum presumably arising from the heavy-particle breakup of $Be^9$. In order to reduce this data to an angular distribution, a consistent procedure was adopted for the decomposition of the spectrum in the vicinity of 3.04 MeV. The differential cross section for inelastic alpha-particle scattering corresponding to 3.04-MeV excitation of $Be^9$ is presented in Fig. 12. The angular distribution shows no pronounced structure except strong forward peaking and possibly a broad maximum centered at about 60°. The large errors and attendant scattering in the experimental points are due to poor counting statistics, poor resolution, and the uncertainties in spectral decomposition necessitated by the concurrence of inelastic alpha groups from carbon and oxygen impurities in the target, and alpha particles from the heavy-particle breakup of $Be^9$.

The spectrum presented in Fig. 8 shows the broad, nearly symmetric shape of the 3.04-MeV alpha-particle group. Experimentally determined widths for this state

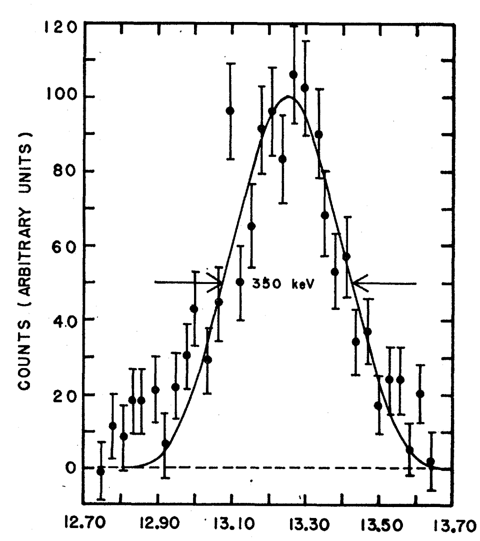


FIG. 13. The alpha-particle group inelastically scattered from the 3.04-MeV state of $Be^9$ measured at a laboratory angle of 30°. The alpha-particle energies are expressed relative to the laboratory system, and the points are those which resulted from the decomposition of a portion of the spectrum shown in Fig. 8. The solid curve was calculated by folding a triangular resolution function with a 150-keV FWHM into a triangular distribution function with a 300-keV FWHM.

[48] C. D. Moak, A. Galonsky, R. L. Traughber, and C. M. Jones, Phys. Rev. **110**, 1369 (1958).
[49] M. J. Jakobson, Phys. Rev. **123**, 229 (1961).

have been reported by a number of investigators: Almqvist *et al.*,[29] <300 keV; Rasmussen *et al.*,[32] about 300 keV; Bockelman *et al.*,[34] >280 keV; and Spencer *et al.*,[40] 250±50 keV. The natural width of the 2.43-MeV state is a few kilovolts at most,[7] and is, therefore, small compared to the experimental width. The experimental shape of the alpha-particle group associated with the 2.43-MeV state closely corresponds to the experimental resolution function at that energy. This line shape could be approximated reasonably well by an isosceles triangle with a full width at half-maximum of 150 keV. In order to obtain a quantitative estimate of the natural width of the 3.04-MeV state, it was assumed that the natural shape of the state could also be approximated by an isosceles triangle. The resolution function was then folded into a series of isosceles triangles having various halfwidths and the resulting calculated line shape was compared with the experimental data. The best-fitting calculated line shape corresponded to a natural line-width (FWHM) of 300 keV. The curve is shown in Fig. 13 superimposed on the experimental points. The natural line width was determined by this procedure to be 300±50 keV.

### D. Other States

There was no evidence found for alpha-particle groups corresponding to higher excited states of $Be^9$, although interference from recoil $Be^9$ nuclei, protons from the $Be^9(\alpha,p)B^{12}$ reaction, and deuterons from the $Be^9(\alpha,d)B^{11}$ reaction could mask these groups if they were weakly excited and/or of considerable width.


### ACKNOWLEDGMENTS

The authors would like to take this opportunity to thank Professor D. W. Miller and Professor M. B. Sampson of Indiana University for the loan of the beryllium target used in this investigation. The unstinting effort of F. G. Hobaugh and K. R. Runck in the operation of the cyclotron over the extended periods required for this investigation is gratefully acknowledged.