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Further Investigation of $N^{15}+p$ Reactions*

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Excitation functions at nine angles for the reaction $N^{15}(p,\alpha_0)C^{12}$ are reported for incident proton energies from 0.9 to 1.3 Mev. At a laboratory angle of 140° the excitation function has been extended to 2.9 Mev. In addition to previously reported resonances near 1.03 and 1.21 Mev, corresponding to O^{16} states at 13.08 and 13.24 Mev, an anomalous behavior is observed near 1.87 Mev. Additional evidence for such behavior near this energy has been obtained from the $N^{15}(p,\alpha_1\gamma)C^{12}$ reaction. The qualitative features of the $N^{15}(p,\alpha_0)C^{12}$ data are shown to be consistent with the assignments $J=1^-$, $J=1^-$, and $J=3^-$ for the 0.34, 1.03, and 1.21-Mev resonances respectively. Fitting Breit-Wigner curves to the measured excitation function of $N^{15}(p,\alpha_1\gamma)C^{12}$ near 1.64 and 1.98 Mev has yielded $E_R=1.640\pm0.003$ Mev ($\Gamma=68\pm3$ kev) and $E_R=1.979$ ±0.003 Mev ($\Gamma=23\pm2$ kev) for these previously reported resonances (O^{16} states at 13.65 and 13.97 Mev). It is shown that $\Gamma_p/\Gamma\ll1$ for the resonance at 1.98 Mev.

I. INTRODUCTION

THE reactions occurring when N^{15} is bombarded with protons have been the subject of many investigations, and considerable information about the O^{16} nucleus has resulted from these studies. However, certain ambiguities remain, and it has seemed worthwhile to extend some of these earlier measurements. In particular, more detailed knowledge of the $N^{15}(p,\alpha_0)C^{12}$ reaction ($Q=4.96$ Mev), referred to hereafter as the (p,α_0) reaction, has appeared desirable. Excitation functions for the (p,α_0) reaction reported by Schardt *et al.*,[1] and by Jacobs *et al.*,[2,3] have indicated resonances for incident proton energies at 0.34 ($J=0^+$ or 1^-), 1.03 ($J=1^-$), 1.21 ($J=3^-$), 3.00 ($J=4^+$), 3.35 ($J=2^+$), and 3.52 ($J=1^-, 2^+, 3^-, 4^+$) Mev. Angular distributions of the α_0 particles for proton energies up to 0.98 Mev have been measured by Cohen and French[4] and by Neilson *et al.*[5] It was hoped that extending these angular distributions to higher incident proton energies would make possible a continuation of the previous analysis.[4]

During the course of this work, it became of interest to investigate certain aspects of the $N^{15}(p,\alpha_1\gamma)C^{12}$ reaction ($E_\gamma=4.43$ Mev, $Q=0.53$ Mev), referred to hereafter as the $(p,\alpha_1\gamma)$ reaction, and of the elastic scattering of protons from N^{15}. These results are also included in this report.

II. EXPERIMENTAL PROCEDURE

The proton beam for the present work was obtained from the 3-Mev electrostatic accelerator at this laboratory and was analyzed with a 90-degree cylindrical electrostatic analyzer. The target was placed at the object position of a 180-degree double-focussing magnetic spectrometer, which could be set to accept particles at any laboratory angle between 0° and 145° with respect to the incident beam. A cesium iodide crystal near the exit slit of the spectrometer served as the particle detector, and a cylindrical sodium iodide crystal, 1.5 in. in diameter and 2 in. long, was used to detect the 4.43-Mev gamma radiation from the $(p,\alpha_1\gamma)$ reaction.

The N^{15} target was prepared in an electromagnetic isotope separator by bombarding a beryllium foil with 20-kev $(N^{15})_2{}^+$ ions. This foil had an equivalent thickness of 25 kev for 1-Mev protons, and approximately 3×10^{17} N^{15} atoms/cm^2 were deposited in its surface. In passing through the target thickness containing N^{15}, 1-Mev protons underwent an energy loss of about 3 kev. Bombarding this target with a

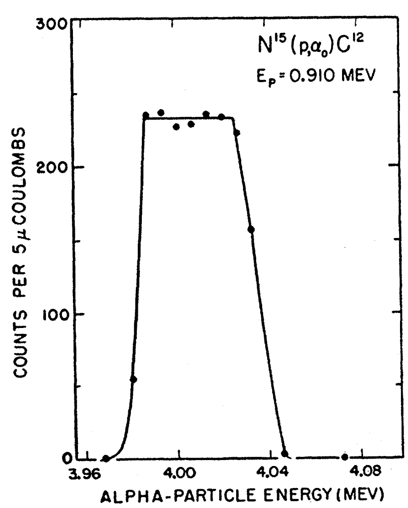

FIG. 1. Momentum profile of the α particles from the reaction $N^{15}(p,\alpha_0)C^{12}$. The incident proton energy was 0.91 Mev, and the observations were made at a laboratory angle of 140°.

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[1] Schardt, Fowler, and Lauritsen, Phys. Rev. **86**, 527 (1952).
[2] Jacobs, Bashkin, and Carlson, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956).
[3] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957).
[4] A. V. Cohen and A. P. French, Phil. Mag. **44**, 1259 (1953).
[5] Neilson, James, and Barnes, Phys. Rev. **92**, 1084(A) (1953).

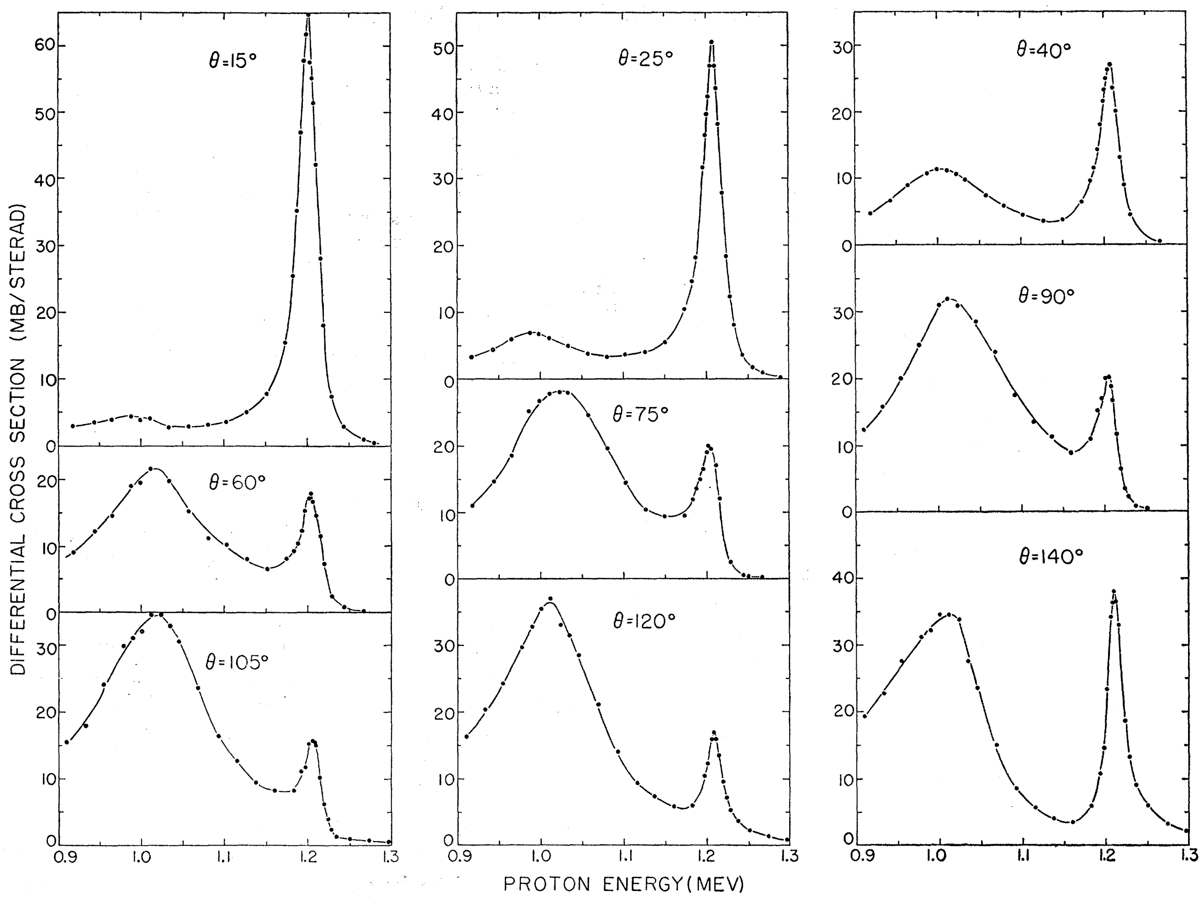

FIG. 2. Excitation functions of the reaction $N^{15}(p,\alpha_0)C^{12}$ at nine angles for incident protons with energies between 0.90 and 1.30 Mev.

0.5-microampere proton beam resulted in no detectable loss of nitrogen.

For all measurements, the plane of the target was at an angle of 45° with respect to the incident proton beam. When the spectrometer was used to analyze the scattered or reaction particles, the surface of the target which contained the N^{15} faced the entrance to the spectrometer. Therefore, for observations at angles less than 90°, the incident protons passed through the beryllium foil before encountering the surface containing the N^{15}. Corrections to the energy scale have been made for this fact.

A typical momentum profile of the α_0 particles obtained at a bombarding energy of 0.91 Mev is shown in Fig. 1. The spectrometer was set to accept particles at 140° with respect to the incident beam for this profile. The width of the profile is approximately that due to the spectrometer resolution since the energy spread of the α-particle group was less than 10% of the spectrometer window width. Thus, only a small fraction of the spectrometer window was filled at each point, resulting in this flat-topped profile whose height is directly proportional to the cross section for the $(p\alpha_0)$ reaction. The absolute cross section at 1.03 Mev given by Schardt *et al.*[1] has been used to normalize these relative values.

III. RESULTS

Excitation functions for the (p,α_0) reaction at nine angles and for incident proton energies between 0.90 and 1.30 Mev are shown in Fig. 2. Angular distributions have been deduced from these excitation functions, and these distributions at six different incident proton energies are shown in Fig. 3. The $\cos\theta$ and $\cos^2\theta$ terms reported previously[4,5] are confirmed, and above 1.10 Mev, $\cos^3\theta$ and $\cos^4\theta$ terms appear.

Shown in Fig. 4 is the excitation function for the (p,α_0) reaction at an angle of 140°, for incident proton energies from 0.90 to 2.90 Mev. In addition to the previously reported resonances near 1.03 and 1.21 Mev, a striking anomaly near 1.87 Mev is observed. A careful investigation of the $(p,\alpha_1\gamma)$ reaction from 1 to 2 Mev has also been made, with special attention to the region from 1.8 to 2.0 Mev. The excitation function of the 4.43-Mev gamma radiation, shown in Figs. 5 and 6, shows a small but definite anomaly between the two previously reported resonances[3,6] at

[6] A. A. Kraus, Phys. Rev. 94, 975 (1954).

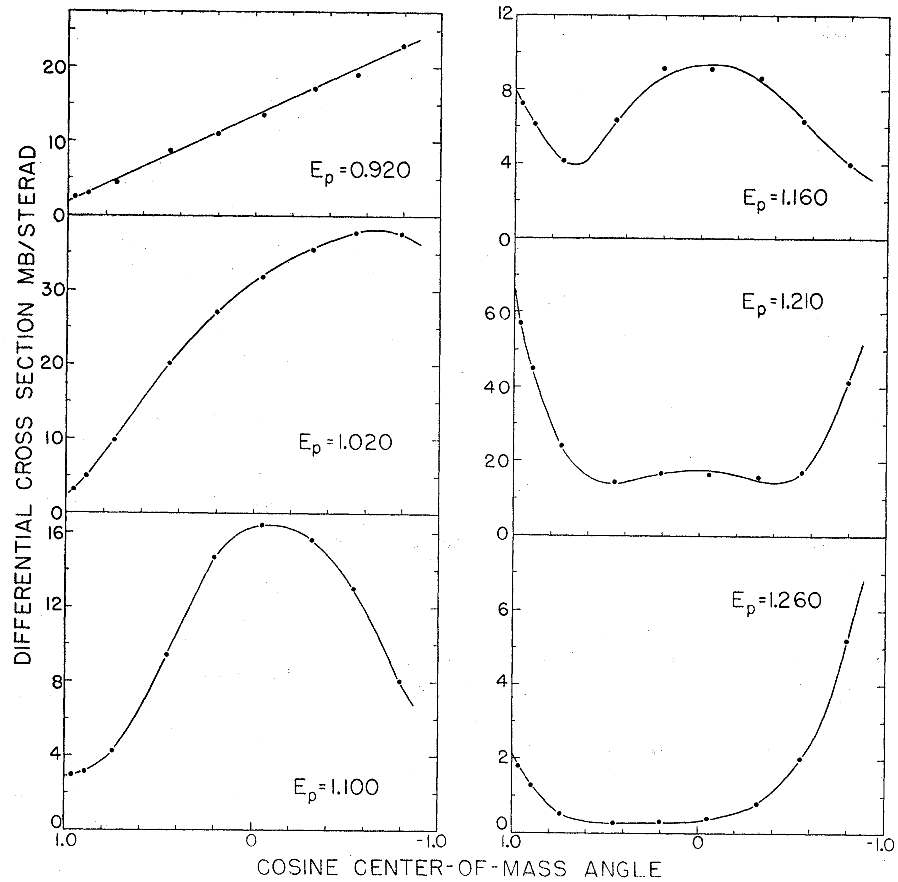

FIG. 3. Angular distributions at six incident proton energies for the reaction $N^{15}(p,\alpha_0)C^{12}$. The proton energies given in the figure are in Mev.

1.64 and 1.98 Mev. That anomalies occur in this region for both the (p,α_0) and $(p,\alpha_1\gamma)$ reactions may indicate the existence of a new O^{16} level (or levels) near 13.9-Mev excitation, but the possibility that the anomalies arise from interference effects from neighboring resonances cannot be excluded. A preliminary survey of $N^{15}(p,p)N^{15}$

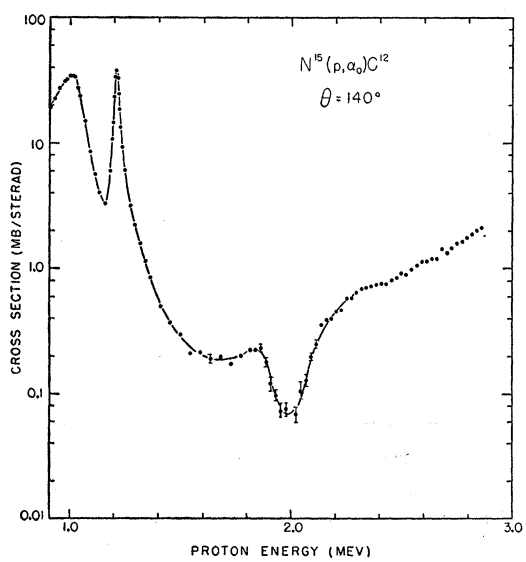

FIG. 4. Excitation function at a laboratory angle of 140° for the reaction $N^{15}(p,\alpha_0)C^{12}$, for incident protons with energies between 0.90 and 2.90 Mev. Note the logarithmic ordinate scale.

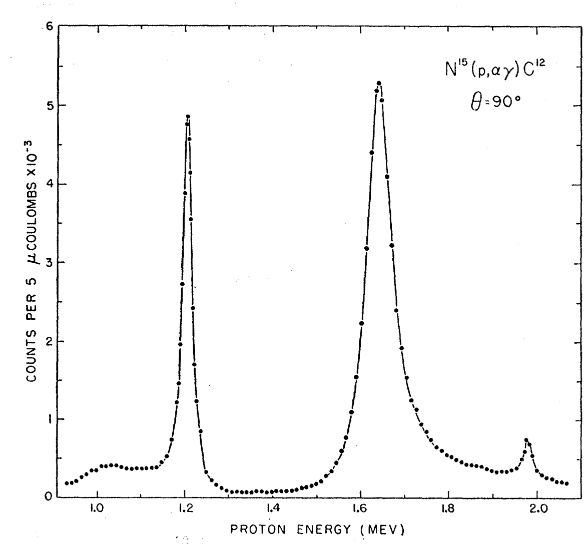

FIG. 5. Excitation function for the 4.43-Mev gamma radiation from the reaction $N^{15}(p,\alpha_1\gamma)C^{12}$ for incident proton energies from 0.9 to 2.1 Mev, at $\theta=90°$.

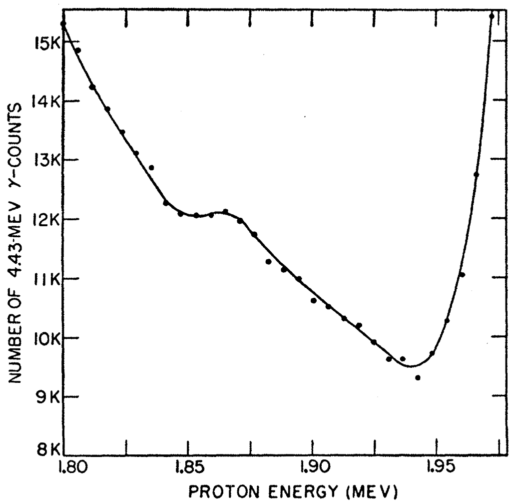

FIG. 6. Excitation function for 4.43-Mev gamma radiation at $\theta=0°$, showing structure near 1.87 Mev. Note the suppressed zero in the ordinate scale.

for incident proton energies between 1.8 and 2.0 Mev, at scattering angles of 144° and 125° 16′, has been made in a further investigation of the structure near 1.87 Mev. No anomalies are observed at either 1.87 or 1.98 Mev. An anomaly as large as 6% of the nonresonant scattering cross section would have been detectable.

Fitting the upper two of the prominent resonances in Fig. 5 with Breit-Wigner functions yields $E_R=1.640\pm0.003$ Mev ($\Gamma=68\pm3$ kev) and $E_R=1.979\pm0.003$ ($\Gamma=23\pm2$ kev), respectively. The resonance energies are referred to the $Li^7(p,n)Be^7$ threshold at 1.881 Mev.

IV. DISCUSSION

It is evident from the complexity of the angular distributions of Fig. 3 that the $N^{15}(p,\alpha)C^{12}$ reactions are characterized by strong interferences between resonances. In particular, the appearance of terms in $\cos\theta$ implies interference between states of opposite parity. In an earlier analysis of distributions obtained below $E_p=0.96$ Mev, Cohen and French[4] sought to account for the $\cos\theta$ term on the assumption that the 0.34-Mev resonance had $J=0^+$ and interfered with the $J=1^-$, 1.03-Mev resonance. On the other hand, the $C^{12}(\alpha,\alpha)$ work of Bittner and Moffat[7] requires $J=1^-$ for the 0.34-Mev resonance. Furthermore, it can be shown by detailed application of the one-level formula of Wigner and Eisenbud[8] that p-wave formation of the level in question is quite unlikely. In Fig. 7 are shown two attempts to fit the (p,α_0) excitation function of Schardt *et al.*[1] with the one-level formula. The dashed curve in the figure is based on the assumption of p-wave formation, with $\Gamma_p/\Gamma=0.034$ and with a reduced width θ_p^2 for protons ten times the single-particle limit. Because of the strong energy dependence of the level shift,[9] the assumption of infinite reduced width would only increase the breadth of the curve shown by 8%. The solid curve of Fig. 7 has been calculated for s-wave formation with $\theta_p^2=0.13\times3\hbar^2/2MR$, $\Gamma_p/\Gamma=0.034$, and appears to give a more satisfactory account of the observations. It may be concluded that the 0.34-Mev resonance has $J=1^-$ and that still another level, possibly the broad $J=0^+$ state at 11.25-Mev excitation,[7] is responsible for the fore-and-aft asymmetry in the distributions.

The angular distribution of the α_0 particles at the the 1.21-Mev resonance (see Fig. 3) was analyzed in

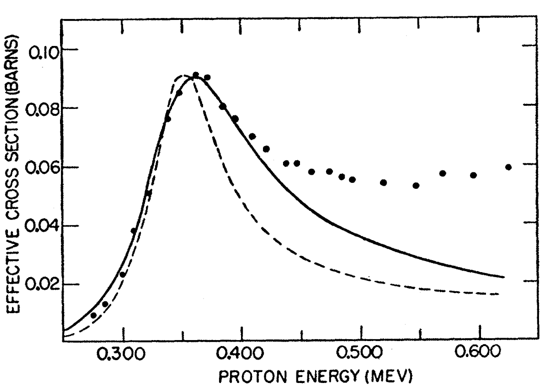

FIG. 7. Excitation function for the reaction $N^{15}(p,\alpha_0)C^{12}$ for incident protons with energies between 0.25 and 0.60 Mev. The points are experimental data taken from Schardt *et al.*[1] The dashed and solid curves have been calculated from the one-level dispersion formula for p- and s-wave formation, respectively.

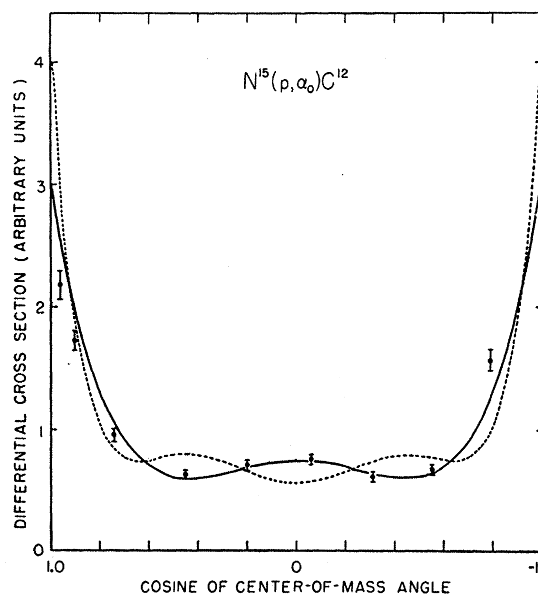

FIG. 8. Angular distribution of the α particles from $N^{15}(p,\alpha_0)C^{12}$ for incident protons of 1.21-Mev energy. The solid curve has been calculated for $l_p=2$, $l_\alpha=3$, and $J=3^-$ while the dashed curve is for $l_p=3$, $l_\alpha=4$, and $J=4^+$.

[7] J. W. Bittner and R. D. Moffat, Phys. Rev. **96**, 374 (1954).
[8] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947).
[9] R. G. Thomas, Phys. Rev. **81**, 148 (1951).

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

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

ACKNOWLEDGMENTS

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

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

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

I. INTRODUCTION

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

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

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

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

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

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

II. GENERAL METHOD

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

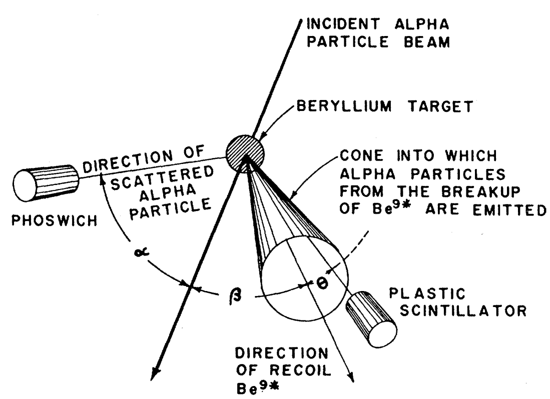

Fig. 1. The experimental arrangement for observing the breakup fragments from Be^{9*} in coincidence with inelastically scattered α particles.

* Supported in part by the U. S. Atomic Energy Commission.
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