integration in the Coulomb field, Be^8 could enter the target nucleus whereas the alpha particle would be scattered. The alpha particle might carry off a wide range of energies, resulting in a broad peak for the $(C,\alpha xn)$ cross-section curve. If now $\sigma(C,\alpha)$ is the total cross section for reactions involving (C,α) stripping, the cross section for the $(C,\alpha 4n)$ reaction is

$$\sigma_{(C,\,\alpha 4n)}=\sigma(C,\alpha)\cdot(\bar{G})^4P_{4n}. \qquad (3)$$

$(\bar{G})^4$ is taken from data on the reaction $Pu^{242}(\alpha,4n)Cm^{242}$ to be 8×10^{-3}.[12] P_{4n} is always less than one and $\sigma_{(C,\,\alpha 4n)}$ is a measured value. At 76 Mev we obtain $\sigma(C,\alpha)>10$ millibarns.

The sharp-peak component of the $(C,\alpha 4n)$ curve might actually be due to the evaporation of alpha particles from the compound system. In this case, an order-of-magnitude estimate of the partial level width for alpha emission $[G_\alpha=\Gamma_\alpha/\Gamma_t]$ can be obtained. If the alpha particle is evaporated first, the cross section for the $(C,\alpha 4n)$ reaction may be expressed as follows:

$$\sigma(C,\alpha 4n)=\sigma_c(E_C)G_\alpha(\bar{G})^4\cdot P_{4n}. \qquad (4)$$

Here, $(\bar{G})^4$ is again taken from data on the reaction $Pu^{242}(\alpha,4n)Cm^{242}$.[12] P_{4n} is always less than 1 and $\sigma(C,\alpha 4n)$ and $\sigma_c(E_C)$ are known values. At 76 Mev we obtain $G_\alpha>0.01$. If the alpha particle is evaporated in a later step, $\bar{G}$ for the neutron-level width becomes smaller and thus G_α becomes larger. If the alpha particle is evaporated after the neutrons, we obtain $G_\alpha>0.04$.

The sharp-peak component could also be explained if in the electric disintegration the alpha particles carry off one-third of the kinetic, internal, and potential energy of the carbon ions.†

ACKNOWLEDGMENTS

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† *Note added in proof.*—Preliminary measurements indicate that the maximum energy of the C^{12} ions was 125 Mev rather than 120 Mev [John R. Walton, University of California (private communication, 1958)]. This will make a better agreement with helium induced reactions. In some recent experiments Flerov *et al.* [Academy of Atomic Energy, Moscow, USSR (private communication, 1958)] have measured excitation functions for C^{12} induced reactions in U^{238} and found the peak for the $(C,4n)$ reaction to be at 69 Mev. The cross section for the reaction was twice as high as found in our experiments. The discrepancy can be ascribed to uncertainties in the beam intensities.

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Energy Levels in F^{18} from the $N^{14}(\alpha,\alpha)N^{14}$ and $N^{14}(\alpha,p)O^{17}$ Reactions*

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Elastically scattered alpha particles from N^{14} and ground-state protons from the $N^{14}(\alpha,p)O^{17}$ reaction show resonances at 2.88-, 3.09-, 3.60-, 3.67-, 3.72-, 4.00-, 4.05-, 4.11-, 4.28-, 4.50-, and 4.55-Mev bombarding energies, corresponding to excited states of the F^{18} nucleus at 6.65, 6.82, 7.21, 7.27, 7.30, 7.52, 7.56, 7.61, 7.74, 7.91, and 7.95 Mev. Scattering-matrix analysis of the elastically scattered alpha particles, together with angular distributions of the reaction protons, indicate that the 6.65-, 6.82-, 7.21-, 7.27-, 7.30-, 7.52-, 7.91-, and 7.95-Mev states in F^{18} probably have angular momenta and parities of 1^-, 2^-, 4^+, 1^+, 3^-, 3^-, 2^-, and 1^+, respectively.

INTRODUCTION

OBSERVATIONS on scattered α particles and reaction protons from accelerated helium ions incident on nitrogen gas have been extended to 4.7 Mev. A number of narrow resonances have been observed in the energy range from 3.5 to 4.7 Mev. Phase-shift analysis of the elastic scattering was not attempted because of the complexity associated with spin 1.[1] Instead, an attempt has been made to determine angular momenta and parities of the corresponding excited states of F^{18} from excitation curves at several angles in the immediate neighborhood of the resonances, using the scattering-matrix analysis as described by Blatt and Biedenharn.[2]

The reaction $N^{14}(\alpha,p)O^{17}$ was the first α-induced nuclear transmutation observed by Rutherford.[3] This reaction figured prominently in the early investigations

* Supported in part by the U. S. Atomic Energy Commission.
† Now at Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[1] J. M. Blatt and L. C. Biedenharn, Phys. Rev. **86**, 399 (1952).
[2] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. **24**, 258 (1952).
[3] E. Rutherford, Phil. Mag. **37**, 581 (1919).

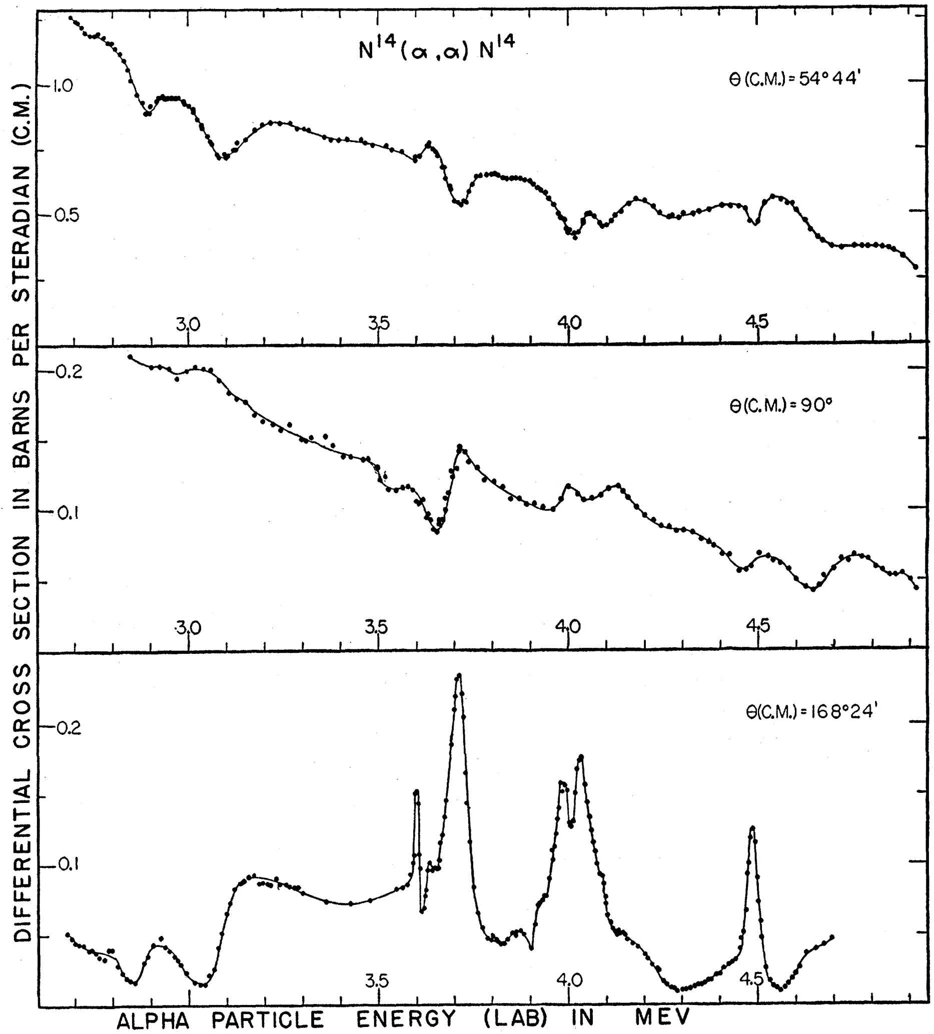

FIG. 1. Center-of-mass differential cross section for the elastic scattering of α particles by N^{14}.

of nuclear reactions.[4] The first cloud chamber observation of a nuclear collision resulting in transmutation was of this reaction,[5] and it was among the first for which evidence of resonance penetration of the nuclear potential barrier was obtained.[6,7] Using natural α particles, Champion and Roy[8] and Roy,[9] confirmed the fact that resonances existed in the neighborhood of 3.6 and 4.2 Mev and showed that the protons to the ground state of O^{17} exhibited an energy-dependent anisotropy with angle of emission. Devons[10] and Brubaker[11] first studied the elastic scattering of natural α particles from nitrogen gas and observed resonance effects in the region of 4 to 7 Mev. Using thin gas targets in a large precisely constructed gas scattering chamber, with monoenergetic helium ions from a Van de Graaff electrostatic accelerator, Heydenburg and Temmer[12] took excitation curves and angular distributions of elastically scattered alphas and excitation curves of the ground-state protons in the energy range up to 3.5 Mev. The present work is essentially an extension of theirs, using similar equipment and methods. Similar work from 2 to 3.8 Mev has been done concurrently by Herring.[13]

[4] E. Rutherford and J. Chadwick, Phil. Mag. **42**, 809 (1921) and **44**, 417 (1922); P. M. S. Blackett, Proc. Roy. Soc. (London) **A107**, 349 (1925); Chadwick, Constable, and Pollard, Proc. Roy. Soc. (London) **A130**, 463 (1931).
[5] P. M. S. Blackett, reference 4.
[6] E. C. Pollard, Proc. Roy. Soc. (London) **A141**, 375 (1933).
[7] H. Stegmann, Z. Physik **95**, 72 (1935).
[8] F. C. Champion and R. R. Roy, Proc. Roy. Soc. (London) **A191**, 269 (1947).
[9] R. R. Roy, Phys. Rev. **82**, 227 (1951).
[10] S. Devons, Proc. Roy. Soc. (London) **A172**, 127 (1939).
[11] G. Brubaker, Phys. Rev. **56**, 1181 (1939).

EXPERIMENTAL PROCEDURE

The Rice Institute 5-Mev Van de Graaff accelerator was used to accelerate singly ionized helium ions. The slit settings of the 90° analyzing magnet were such that

[12] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **92**, 89 (1953).
[13] D. Herring (private communication). See also Bull. Am. Phys. Soc. Sec. II, **2**, 303 (1957).

the energy spread was 0.2% at the entrance to the differential pumping tube of the scattering chamber. Calibration of the field of the analyzing magnet was in terms of the frequency of a Li^7 moment detector. The large-volume scattering chamber has been described in the literature.[14] It consists of a cylindrical volume about 75 cm diameter and 35 cm high, filled with gas at low pressure. It has two detectors which can be positioned from the outside of the chamber to an accuracy in angle of 6 minutes. The detectors are scintillation counters, using thin thallium-activated cesium iodide crystals mounted on Du Mont 6291 photomultiplier tubes.

The chamber is equipped with two butyl pthalate manometers which give the pressures of the scattering gas in the chamber and at the first stage in the differential pumping tube. One side of each manometer is at high vacuum and the other open to the chamber and first stage in the differential pumping tube, respectively. The difference of levels is read with a cathetometer, and the accuracy of the readings is 0.4%. The difference of levels, when multiplied by the density of the butyl pthalate, gives the respective pressures.

We have tried to take most of our data at a gas pressure of 0.25 cm of Hg. This pressure corresponds to a target thickness varying from 4 kilovolts at a laboratory angle of 90° to 14 kilovolts at our most backward angle. The high stopping power of N^{14} results in energy losses to our incident α particles of from 75 to 130 kilovolts in the scattering gas up to the center of the chamber. This energy loss was computed from tabulated values of the stopping power for α particles in N^{14} and is believed to be good to within 10%. The number of α particles incident upon the gas target was determined by charge integration in the Faraday cup. On the assumption of gas stripping, a charge of $2e$ per particle was used. Before entering the Faraday cup, the α particles passed through an aluminum foil of 0.76 cm air equivalent thickness. Due to electron capture near the end of the range, at the lower energies some of the particles reaching the Faraday cup are singly ionized, or even have zero charge. To correct this, the average charge state as a function of energy was determined by measuring the cross section for Rutherford scattering in argon at a pressure for which the total energy loss in the gas was approximately the same as for N_2. From the ratio of the expected value of the cross section assuming the charge of the α particles to be $2e$ to the value obtained experimentally, the average charge at each bombarding energy could be calculated. The scattering and reaction cross sections of nitrogen were corrected accordingly. At energies above 3.5 Mev, no charge state corrections were necessary.

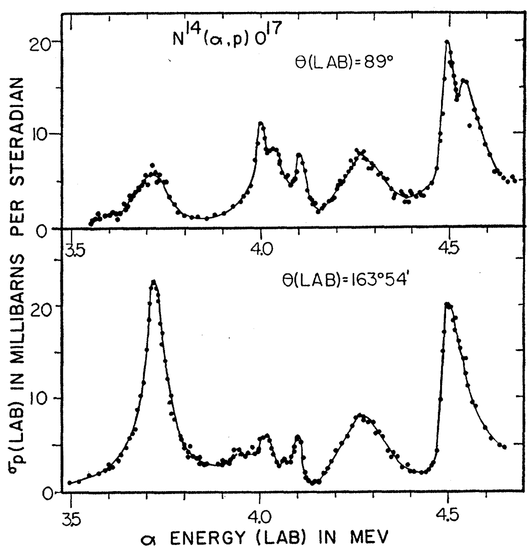

FIG. 2. Laboratory differential cross section of the protons from the $N^{14}(\alpha,p)O^{17}$ reaction. The protons are to the ground state of O^{17}.

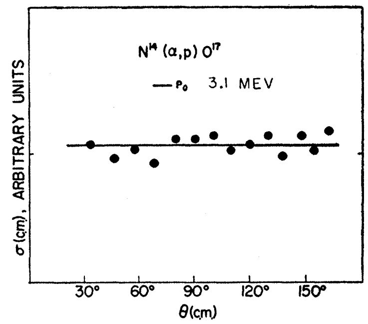

FIG. 3. Angular distribution of the O^{17} ground-state protons at 3.11 Mev.

EXPERIMENTAL RESULTS

We have taken excitation curves of the elastically scattered α particles at center-of-mass angles of 54° 44′, 90°, and 168° 24′, from approximately 2.8 to 4.7 Mev. The curves are shown in Fig. 1. We have also measured the $N^{14}(\alpha,p)O^{17}$ cross section at laboratory angles of 89° and 163° 54′ from 3.5 to 4.6 Mev (Fig. 2). Three angular distributions of the protons to the ground state of O^{17} were taken, at energies of 3.11, 3.72, and 4.26 Mev. These are plotted in Figs. 3, 4, and 5.

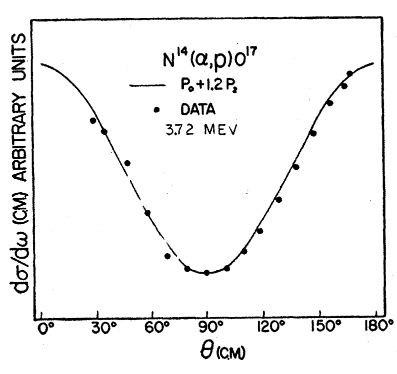

FIG. 4. Angular distribution of the O^{17} ground-state protons at 3.72 Mev.

[14] Russell, Phillips, and Reich, Phys. Rev. **104**, 135 (1956).

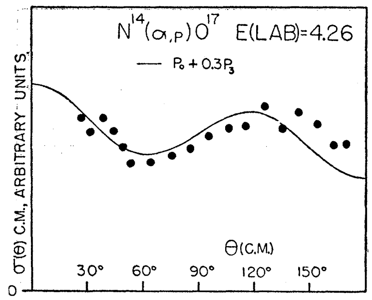

FIG. 5. Angular distribution of the O^{17} ground-state protons at 4.26 Mev.

The uncertainty in the elastic scattering cross section due to counting statistics was less than 1% for the 54° 44′ curve and of the order of 3% for the 168° 24′ and 90° curves. For the proton data this uncertainty varies from 30% for the smallest cross sections to 3% for the largest. If we include the error from gas density, current integration, and solid angle measurements, we estimate the error in the absolute value of the cross section, excluding the statistical error of counting, to be ±5%. The error in the energy scale, which is due to the uncertainty of the energy loss of the α particles in the nitrogen, to the spread in energy due to the size of the defining slits of the 90° analyzing magnet, and to the inhomogeneity of the magnetic field at the higher energies, is estimated to be 20 kev, while the relative accuracy of the energy between points is probably of the order of 3 kev.

In taking the proton data we were able to resolve the elastically scattered α-particle group from the proton group to the ground state of O^{17}. Figure 6 shows the two groups at a bombarding energy of 3.11 Mev and at a laboratory angle of 163° 54′. For the more forward angles, i.e., for the 89° excitation curve and the angular distributions, thin foil absorbers were used to separate the protons from the α particles. We did not observe any of the O^{17} first excited state proton group,[9,15] because of the small yield and lower energy of that group.

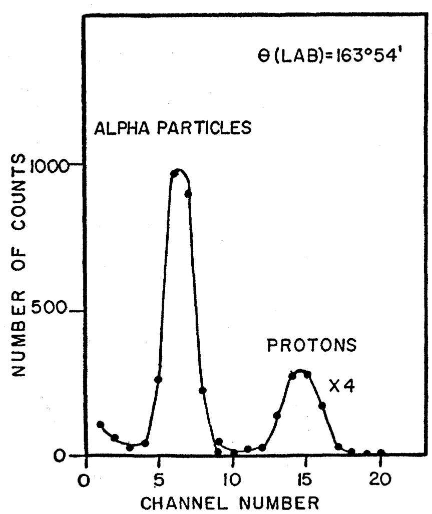

FIG. 6. Pulse-height distribution of the resolved α particles and protons at 3.11 Mev.

ANALYSIS

The analysis of scattering data for channel spin unity (the nitrogen ground state being 1^+) is considerably more complicated than for spin 0 or $\frac{1}{2}$. This results from the fact that the angular momentum selection rule permits three l values for a given J value, i.e., $l=J$, $J\pm1$. Of the three, two are always associated with the same parity. Thus, those states whose parity π is $(-)^J$ can be made with only one l, while states whose parity π is $-(-)^J$ can be made with two. Scattering by a nuclear state of the latter type may result in change of

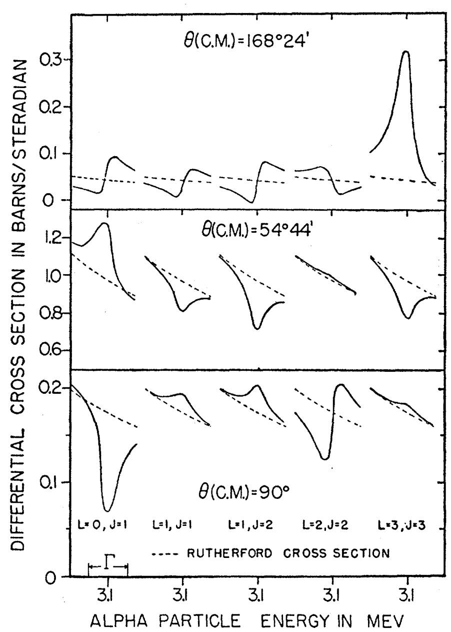

FIG. 7. Theoretical curves for the elastic scattering cross section of α particles by N^{14}. The resonant energy was taken to be 3.1 Mev, and the width 100 kev. Note that ordinates of the 54° 44′ curves do not start at zero. The nonresonant components of the cross section are not included.

l, i.e., the scattering matrix may have a nonzero element connecting the two possible l values. A discussion of the scattering matrix for this case is given by Blatt and Biedenharn.[1] For a given value of J there are in all four parameters to be determined in order to describe the scattering completely: one for the parity $(-)^J$ and three for the parity $-(-)^J$. This is in contrast with two parameters for a given J in the case of channel spin $\frac{1}{2}$.

To achieve the limited objective of assigning J and π values to the states, however, an analysis using only one l value appeared to be a reasonable approximation, since quite possibly only one l value was of practical importance by virtue of relative penetrabilities or some feature of the nuclear interaction. It seemed plausible

[15] E. Pollard and P. W. Davison, Phys. Rev. 72, 736 (1947).

TABLE I. $N^{14}(\alpha,\alpha)N^{14}$ and $N^{14}(\alpha,p)O^{17}$ resonances and corresponding excited states in F^{18*} with angular momentum and parity assignments.

E_α (Mev)	Γ_{lab} (kev)	l_α	J	π	Excitation energy in F^{18} (Mev) Present work	Heydenburg and Temmer[a]	Ahnlund[b]
2.88	76±10	1	1	−	6.65	6.69	6.666
3.09	95±10	1	2	−	6.82	6.85	6.820
3.60	<10	4	4	+	7.21	···	···
3.67	55±10	0,2	1	+	7.27	···	···
3.72	68±7	3	3	−	7.30	···	7.304
4.00	45±15	3	(3)	−	7.52	···	7.527
4.05	80±20	⩾3	⩾2	···	7.56	···	7.552
4.11	50±15	···	···	···	7.61	···	···
···	···	···	···	···	···	···	7.713
4.28	150±25	···	···	···	7.74	···	7.728
···	···	···	···	···	···	···	7.889
4.50	38±5	(1,3)	(2)	(−)	7.91	···	7.917
4.55	90±20	(0,2)	(1)	(+)	7.95	···	···

[a] See reference 12.
[b] See reference 18.

also that assignments might be obtained more simply from the expression (7.12) of Blatt and Biedenharn[2] than from a phase shift analysis. This expression for the elastic scattering cross section is based on assumptions about the form of the scattering matrix and contains explicitly the resonance contribution from an isolated nuclear state, the contributions from Coulomb and hard-sphere potentials, and from interference between them. The resonance term and the two terms describing interference between resonance and potential scattering vary rapidly with energy in the immediate neighborhood of the resonance. Resonances from states with different l and J values show quite contrasting behavior, as shown in Fig. 7, where the calculated elastic scattering cross section is plotted for different combinations of J and l (and hence π) over one energy interval, and at the three c.m. angles, 54° 44′, 90°, and 168° 24′, at which experimental data were taken. States with $\pi=-(-)^J$ occur twice, once for each possible l value. Thus 2^- is shown for $l=1$ and $l=3$. Of the states $0^\pm$, only 0^- can be formed because of the positive parity of the N^{14} ground state. At the more forward angles, where the Rutherford cross section is large, the term describing interference between resonance and Rutherford scattering is the largest of those that show resonant behavior. At 54° 44′, where the Legendre polynomial of order two is zero, this term vanishes for an $l=2$ resonance. The fact that $l=2$ resonances showed small or no effect at this angle proved an aid in the analysis. Similarly, the resonance-Rutherford interference term vanishes for odd l at 90°.

To obtain the curves of Fig. 7 and similar curves at other energies, the expression (7.12) of reference 2, with the stated simplifying assumptions, was programmed for an IBM-650 computer. An additional assumption made in computing the curves of Fig. 7 was that only the incident channel was open. This is not altogether unrealistic, since the experimental data show that $\Gamma_\alpha \gg \Gamma_p$ everywhere. The hard-sphere phase shifts used in the calculation were obtained by graphical interpolation from the curves of Fig. 8. These curves were fixed by three points each taken from the tabulated values of Bloch *et al.*[16]

An aid to the assignment of angular momentum and parity values was the angular distributions of the protons to the ground state of O^{17}. A complicating factor was the high value of the O^{17} ground state spin, i.e., $\frac{5}{2}$, resulting in two outgoing channel spin values, 2 and 3. However, the restriction on J imposed by the order of the Legendre polynomial needed to fit a proton angular distribution, and the practical restriction on the proton orbital angular momentum from penetrability due to the negative Q did, in fact, contribute information.

We now consider the assignments to the individual resonances. The results are listed in Table I. From the features of the elastic scattering cross section, the resonance just below 3 Mev appears due to a 1^- state. If this assignment is correct, our value for the resonance energy is 2.88 Mev.[17,18] A 1^- state can be formed only with $l_\alpha=1$. The low proton production cross section[12] at this resonance is consistent with the assignment, in view of the low J and of the fact that $l_p=3$ for protons of

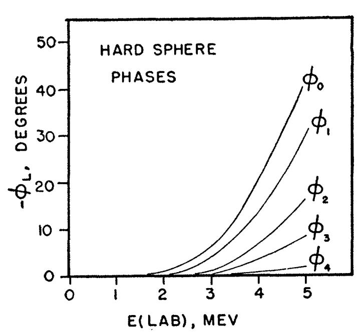

FIG. 8. Hard-sphere phases used in calculating the theoretical curves for the elastically scattered α particles.

[16] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).
[17] The value for this energy in reference 12 falls outside our estimated error limits, even when we add a reasonable increment for shape uncertainty; the value of the energy of the corresponding state, as given by Ahnlund,[18] who did the $O^{17}(p,\alpha)N^{14}$ experiment, falls inside that uncertainty.
[18] K. Ahnlund, Phys. Rev. **106**, 124 (1957).

channel spin 3. At 3.09 Mev,[19] the elastic scattering cross section indicates a 2^- state formed mainly by α particles with $l_\alpha=1$. For both proton channel spins, $l_p=1$ is allowed. Because of this fact and of the larger statistical weight for $J=2$, the assignment is consistent with the relatively higher proton production cross section at 3.09 than at 2.88 Mev. At first sight the 2^- assignment is contradicted by the nearly isotropic angular distribution of the protons (Fig. 3), but when the expected distribution is calculated for a 2^- state neglecting the higher l_p values 3 and 5, it is nearly enough isotropic to fit the data within experimental error. The elastic scattering cross section at 168° indicates that α particles with $l_\alpha=3$ contribute very little to the formation of this state.

In the region 3.5 to 3.8 Mev, the elastic scattering cross section shows a complicated behavior which indicates the presence of three resonances. Only one of these, the resonance at 3.72 Mev, shows an appreciable yield of protons. A 3^- assignment for the corresponding state clearly fits the elastic scattering data at 168° and 54°. This state can be formed only with $l_\alpha=3$. The maximum in the calculated elastic cross section for a 3^- state lies at lower energy than the resonance energy E_0, consistent with the relative positions of elastic scattering and proton production peaks in the experimental data. E_0 and Γ in Table I were obtained from the proton data. For both proton channel spins, $l_p=1$ is allowed, consistent with the high proton production cross section and the fact that the highest power of $\cos\theta$ required to fit the proton angular distribution (Fig. 4) is two. The 90° curves for the elastic scattering between 3.65 and 3.70 Mev can only be explained by the presence of a resonance formed by α particles with $l_\alpha=0$ or $l_\alpha=2$. The best fit at all angles is obtained from a 1^+ state, 45–65 kev wide, with E_0 from 3.66 to 3.67 Mev, formed predominantly with $l_\alpha=2$. The curves do not rule out the possibility that α particles with $l_\alpha=0$ contribute to the formation of this state, but the contribution to the cross section from $l_\alpha=0$ is probably restricted to less than half that from $l_\alpha=2$. The fact that $l_p\geqslant 2$ for protons of both channel spins, together with the low J, probably explains the low yield of protons from this resonance. The narrow resonance at 3.60 Mev undoubtedly has $J\geqslant 3$ and is formed by α particles of high l_α. A 4^+ assignment fits the elastic scattering data well, provided the width is so small (<10 kev) that target thickness makes the observed value of the cross section lower than the calculated. Target thickness and penetrability then explain failure to see the resonance for the proton reaction.

[19] This value depends on the assignment, as at 2.88 Mev.

For the 4.00-Mev resonance, a 3^- assignment is not quite as firm as the others, although we are reasonably sure that $l_\alpha=3$. Due to interference, we were not able to make assignments at 4.05, 4.11, and 4.28 Mev. The broad resonance at 4.28 Mev may actually be due to several states, possibly including the 7.889- and 7.713-Mev states of F^{18*} listed in reference 18. The asymmetry about 90° of the proton angular distributions (Fig. 5) makes this reasonable.

Finally, elastic scattering and proton production data are indicative of two overlapping resonances at 4.50 and 4.55 Mev. The 4.50-Mev resonance is probably due to a 2^- state made with a mixture of $l_\alpha=1$ and $l_\alpha=3$, and the 4.55-Mev resonance is probably due to a 1^+ state formed with both $l_\alpha=0$ and $l_\alpha=2$.

ACKNOWLEDGMENTS

We are greatly indebted to the computing group of the Shell Oil Company for the use of their computer. We would like to thank Professor L. C. Biedenharn for helpful discussions, and Professor G. C. Phillips for suggesting and initiating the problem. Finally, we wish to thank R. R. Perry and J. H. Johnson for their help in checking the IBM-650 program and P. N. Dean for his help in obtaining some of the experimental data.