was changed in steps of a few volts and the $L\alpha_1$ x-ray intensity, recorded by a Geiger counter, was measured as a function of the voltage. This intensity is a measure of the electronic excitation of the L_{III} state. Figures 1–3 show the L_{III} excitation curves of the 5*d* elements Ta, W, and Pt, revealing a structure very similar to that recorded by Nilsson for the 3*d* elements.

One of the major difficulties in obtaining the excitation curve is the contamination of the target. This factor limited the number of runs which could be averaged. Figure 1 is the average of four runs with 4096 counts per point. Figure 2 is the average of five runs with 5120 counts per point, and Fig. 3 is the average of five runs with 10 240 counts per point. The structure shown in the excitation curves is reproducible under "clean" target conditions. We have chosen to draw the curves with straight line segments in that future careful work will probably reveal more detailed structure for the 5*d* elements similar to that found by Nilsson in some of the 3*d* elements.

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Energy Levels in F^{18} from Alpha-Particle Reactions in Nitrogen*

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We have examined both the elastic scattering of alpha particles in nitrogen as a function of the energy between 1.5 and 3.5 Mev at 90°, 125°16′, 137°43′ and 156°20′ (center of mass), and the cross section for the $N^{14}(\alpha,p)O^{17}$ reaction at 90° (lab) in the same energy region. Two new resonances at $E_\alpha=2.935$ Mev and $E_\alpha=3.140$ Mev correspond to levels in F^{18} at excitation energies of 6.69 Mev and 6.85 Mev, respectively. These same levels were found to emit protons as well, leading to the ground state of O^{17}. The (α,p) reaction has a relative probability of about 5 percent for the upper level and 0.3 percent for the lower level, compared to the elastic scattering.

1. INTRODUCTION

THE availability of high currents of singly charged helium ions from our pressurized Van de Graaff generator using a radio-frequency ion source makes it possible to re-examine most of the alpha-particle reactions which were carried out with natural alpha emitters in the past. Since we had a gas scattering system available from our alpha-helium scattering experiments,[1] we decided to investigate the historically important nitrogen nucleus, first disintegrated by Rutherford in 1919.[2] The elastic scattering of alpha particles on nitrogen had previously been studied at higher energies by Devons[3] and Brubaker,[4] yielding broad resonances in F^{18} at 8.0-Mev and 8.5-Mev excitation ($E_\alpha=4.6$ Mev and 5.2 Mev, respectively). Champion and Roy,[5] using cloud-chamber technique, and Roy,[6] employing nuclear emulsions, have studied the $N^{14}(\alpha,p)O^{17}$ reaction. They reported resonances distinct from those giving rise to elastic scattering anomalies at about 5.6-, 7.1-, and 7.6-Mev excitation in F^{18} corresponding to alpha energies of 1.7, 3.5, and 4.2 Mev, respectively. Angular distributions of the proton groups leading to the ground state and the 0.875-Mev excited state of O^{17} were obtained by Roy[6] for the two highest levels.

* A preliminary account of this work was given at the 1953 Washington Meeting of the American Physical Society [Bull. Am. Phys. Soc., 28, No. 3, 15 (1953)].

1 G. M. Temmer and N. P. Heydenburg, Phys. Rev. **90**, 340 (1953).

2 E. Rutherford, Phil. Mag. **37**, 581 (1919).

3 S. Devons, Proc. Roy. Soc. (London) **A172**, 127 (1939).

4 G. Brubaker, Phys. Rev. **56**, 1181 (1939).

5 F. C. Champion and R. R. Roy, Proc. Roy. Soc. (London) **A191**, 269 (1947).

6 R. R. Roy, Phys. Rev. **82**, 227 (1951).

2. EXPERIMENTAL

(a) $N^{14}(\alpha,\alpha)N^{14}$

A beam of singly charged helium ions collimated to a circular area of 1 mm diameter entered our scattering chamber through a differential pumping system. The scattering gas pressure was kept around 3 mm Hg. A movable proportional counter filled with nitrogen to 7 cm Hg subtended an angle of about two degrees at the scattering volume and could be set accurately at angles up to 147.5° in the laboratory. A very thin window of Formvar some 6–8 μg/cm^2 thick allowed us to efficiently detect alpha particles down to about 40 kev.

A Faraday cup separated from the scattering chamber by a 0.00002-inch nickel foil was used to integrate the beam current. The normalization of the entire system was achieved by scattering from argon gas, for which pure Rutherford scattering behavior in both angular and energy dependence was ascertained over the ranges of interest.

Our elastic scattering data consist of two types of measurements: scattering yields as a function of energy at four fixed angles, and angular distributions at three different energies. Figures 1, 2, and 3 summarize the former, while Fig. 4 shows the angular distributions. The ordinate plotted in all cases is the ratio of observed to Rutherford scattering. For orientation purposes we have plotted the absolute differential scattering cross section at 156°20′ in Fig. 5. The arrows along the energy axis locate the actual positions of the two new

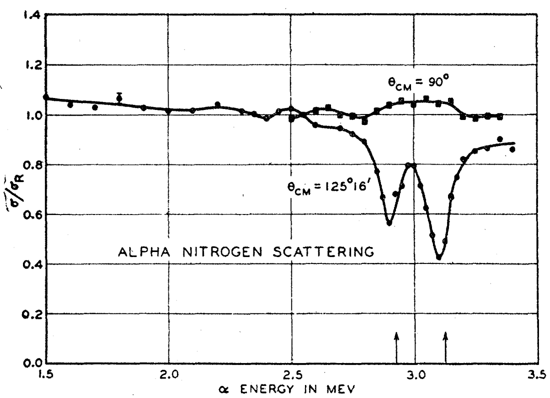

FIG. 1. Elastic alpha-nitrogen scattering at $\theta_{c.m.}=90°$ (squares) and $\theta_{c.m.}=125°16'$ (circles). Ratio of observed to Rutherford scattering *vs* alpha energy. Arrows indicate positions of two new resonances.

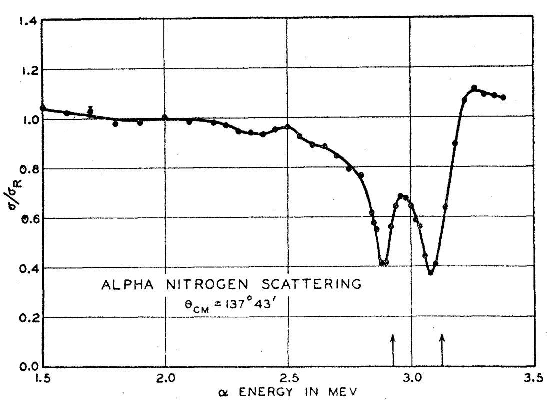

FIG. 2. Elastic alpha-nitrogen scattering at $\theta_{c.m.}=137°43'$. Ratio of observed to Rutherford scattering *vs* alpha energy. Arrows indicate positions of two new resonances.

resonances as determined from the location of the peaks in the (α,p) reaction (see below). Only a complete theoretical analysis of the elastic scattering resonances would allow us to find the exact locations from the scattering data alone.

The effective target thickness in this experiment was of the order of 400 ev and is therefore completely negligible. The statistical accuracy of most points is of the order of two percent. The energy of our generator was calibrated against the known neutron thresholds of the reactions $Be^9(p,n)B^9$ (2.059 Mev) and $B^{11}(p,n)C^{11}$ (3.015 Mev).[7] Some of the smaller irregularities in our scattering yield curves may be due to the small amount of N^{15} present in ordinary nitrogen (0.38 percent).

It should be remarked that inelastic scattering to the first excited state at 2.31 Mev in N^{14} becomes energetically possible at an alpha energy of 3.23 Mev but could not have been observed because of the low energy of the inelastically scattered particles. Furthermore, this group does not seem to appear[8] because of the self-conjugate nature of the nuclei involved and the consequent applicability of charge parity conservation.[9]

(b) $N^{14}(\alpha,p)O^{17}$

Because of the low relative yield of protons it turned out to be necessary to interpose an appropriate thickness of nickel absorber foil in front of the proportional

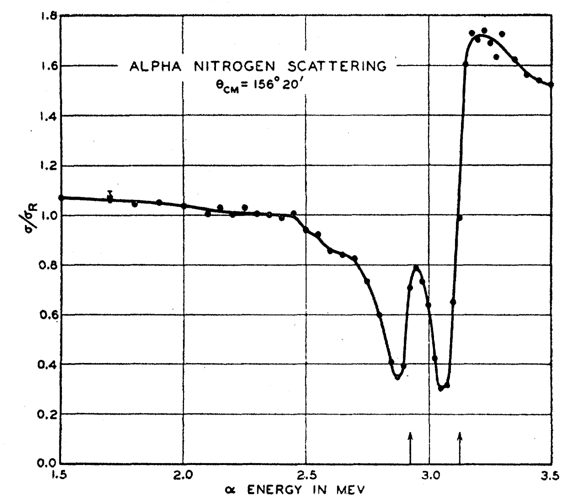

FIG. 3. Elastic alpha-nitrogen scattering at $\theta_{c.m.}=156°20'$. Ratio of observed to Rutherford scattering *vs* alpha energy. Arrows indicate position of two new resonances.

counter in order to stop all alpha particles and permit protons to be detected. Also, the solid angle subtended by the counter was increased by a factor of 20. A thickness of 0.00015 in. Ni foil allowed us to observe protons at angles greater than 90° (lab). The yield of ground state protons as a function of alpha energy is shown in Fig. 6. The energy of the protons leading to the ground state of O^{17} is about 1 Mev at an alpha energy of 3 Mev. We have checked the pulse height in our counter corresponding to these protons by scattering 1-Mev protons elastically from nitrogen. Protons leading to the 0.875-Mev excited state in O^{17} would not have been detected.

The proton emission cross section is seen to be very

[7] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[8] Carmichael, Sampson, and Johnson, Bull. Am. Phys. Soc. **28**, No. 3, 49 (1953).
[9] N. M. Kroll and L. L. Foldy, Phys. Rev. **88**, 1177 (1952).

small compared to the elastic scattering cross section at these energies, being about 5 percent of Rutherford for the larger peak and 0.3 percent for the small peak. Evidence of a third, very broad proton-emitting resonance around 3.5 Mev can be seen at the higher energies when a single level resonance expression for the 3.14-Mev resonance is subtracted from the observed results. The locations and widths of the three proton-emitting resonances and the corresponding excitation energies in F^{18} are summarized in Table I.

3. INTERPRETATION

Because of the rather close spacing of the observed resonances compared to their widths it is not possible to interpret our results on the basis of a single level expression. Table II shows a summary of the possible

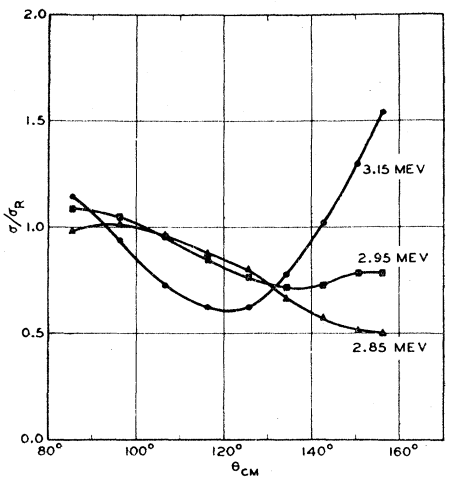

FIG. 4. Angular distributions of elastic alpha-nitrogen scattering at 2.85 Mev (triangles), 2.95 Mev (squares) and 3.15 Mev (circles). Ratio of observed to Rutherford scattering *vs* center-of-mass angle.

contributing alpha-particle orbital angular momenta for a number of assumed spins and parities of the compound nucleus F^{18}, along with possible angular momenta of emitted protons leading to either the ground state or first excited state of the residual nucleus O^{17}. It should be noted that because of the fact that the incident channel spin is unity (spin of $N^{14}=1$) it is possible to have up to *two* orbital momenta contribute to a given fluorine resonance of specified spin and parity. Hence, if more than one resonance has to be considered at once, spin and parity assignments become rather complex. The most complete treatment of general nuclear reactions involving spins has recently been given by Blatt and Biedenharn.[10] Figure 7 shows a collection of theoretical angular distributions for elastic scattering of alpha particles by nitrogen

[10] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 24, 258 (1952).

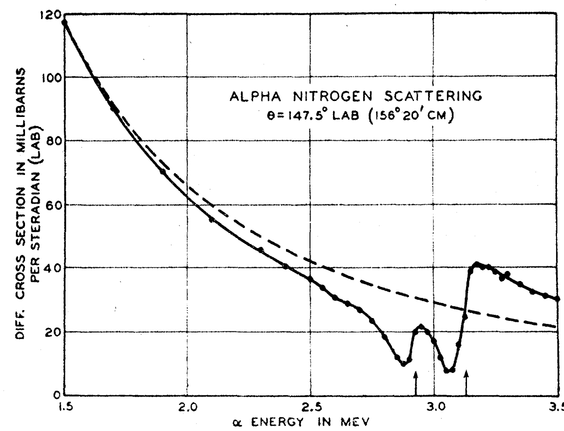

FIG. 5. Elastic alpha-nitrogen scattering at $\theta_{c.m.}=156°20'$. Absolute differential cross section in millibarns/steradian *vs* alpha energy. Dashed curve shows pure Rutherford scattering cross section.

calculated from their expression for various assumed states in F^{18} and incident angular momenta. Phase shifts of $\pi/2$ were used throughout. Effects of finite nuclear size have been justifiably neglected (see below). In addition, the evidently unrealistic assumption of only *one* contributing compound level was made here. Our hope was that some conclusions might be drawn from our angular distribution at 3.15 Mev where contributions might be expected to come predominantly from only one resonance level. The experimental points for our angular distribution have been

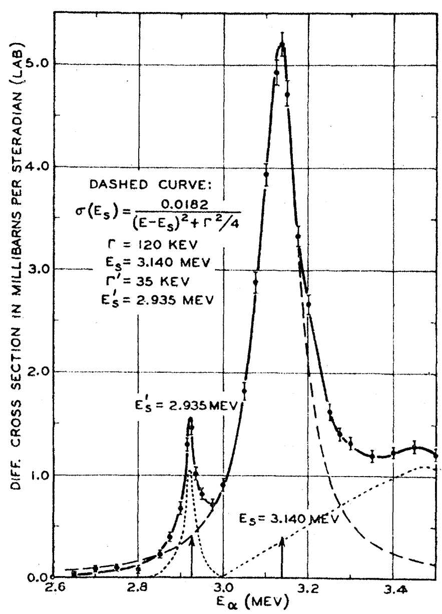

FIG. 6. Differential cross section for the $N^{14}(\alpha,p)O^{17}$ reaction *vs* alpha energy at $\theta_{lab}=90°$. Solid curve goes through experimental points. Dashed curve shows single level expression fitted to large resonance. Dotted curves represent difference between observed and dashed curve values. $E_s=3.140$ Mev has a lab width $\Gamma_{lab}=120$ kev, $E_s'=2.935$ Mev has a lab width $\Gamma_{lab}'=35$ kev.

inserted in Fig. 7 mainly to show that two and possibly three levels must undoubtedly be taken into account even at 3.15 Mev. No spin or parity assignments have been made to date. Some rough results on the angular distribution of protons from the 3.14-Mev resonance are compatible with isotropy in the center-of-mass system. The only assignment for the 6.85-Mev level in F^{18} which can definitely be ruled out on the basis of line shape is $J=1^+$, $l_\alpha=2$. The rise in the angular distribution at 3.15 Mev at the backward angles seems to favor $l_\alpha=0$ for this level.

4. CONCLUSIONS

In contrast to previous work on nitrogen we have found two levels in F^{18} giving rise to both anomalous elastic scattering and proton emission. Figure 8 shows the location of the new levels and their characteristics on an energy level diagram. The reported proton-emitting level at 1.7 Mev was not observed in the elastic scattering and seems somewhat doubtful in view of the nearby threshold of the reaction ($E_{th}=1.54$ Mev). Another level reported at 3.5 Mev[6] might actually be a conglomeration of the two new levels plus the broad one near 3.5 Mev.

It is noteworthy that the elastic scattering does not depart appreciably from Rutherford scattering even at the largest angle up to 2.5 Mev and the deviations are attributable to the onset of the resonances. This fact justifies our neglect of phase shifts due to nuclear size in the theoretical curves of Fig. 7.

TABLE I. New energy levels in F^{18}.

E(Mev)	E_c(Mev)[a]	Γ_{lab}(kev)	Γ(kev)
2.935	6.694	35±5	27±4
3.140	6.854	120±10	93±8
~3.5	~7.1	~600	~460

[a] Excitation energy of the compound nucleus F^{18}.

TABLE II. Possible angular momenta for $N^{14}(\alpha,\alpha)N^{14}$ and $N^{14}(\alpha,p)O^{17}$ for various assumed spins and parities of F^{18}.

J of F^{18}	Parity	l_α	l_{p0}[a]	l_{p1}[b]
0	+	—	—	—
0	−	1	3	1
1	+	0,2	2,4	0,2
1	−	1	1,3	1
2	+	2	0,2,4	2
2	−	1,3	1,3,5	1,3
3	+	2,4	0,2,4,6	2,4
3	−	3	1,3,5	3

[a] Orbital angular momentum of proton group to ground state of O^{17} ($I=5/2+$).
[b] Orbital angular momentum of proton group of 0.875-Mev state of O^{17}($I=1/2+$).

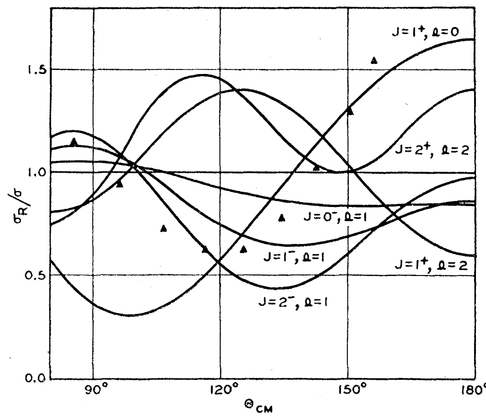

FIG. 7. Theoretical angular distributions for $N^{14}(\alpha,\alpha)N^{14}$ at $E_\alpha=3.15$ Mev, after Blatt and Biedenharn (see reference 10). J=assumed spin of level in F^{18}, l=alpha-particle orbital angular momentum. Nuclear size effects and other resonances neglected. Triangles indicate experimental points obtained at 3.15 Mev.

Spin and parity assignments of two levels in F^{18} seem possible in principle from existing results but have to await the outcome of a very complete theoretical analysis of our elastic scattering data and proton angular distributions.

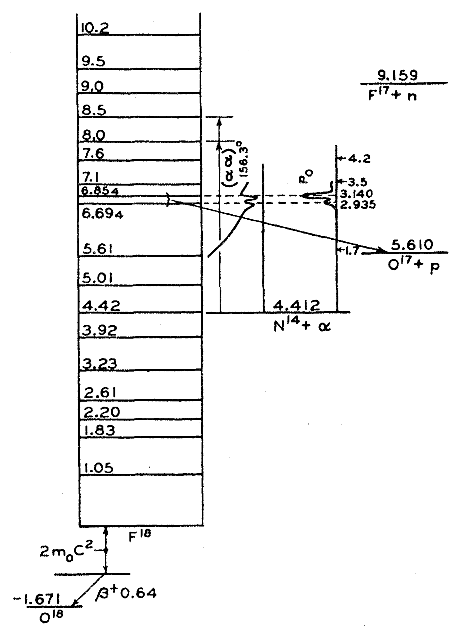

FIG. 8. Energy levels in F^{18}. Levels in bracket are new.

The one of us from a neighboring institution would like to express his appreciation for the kind hospitality extended to him by the Department of Terrestrial Magnetism and its director, Merle A. Tuve.