This indicates that all the observed states have similar properties. If they are of the type discussed above, then they should have lifetimes which are similar.

Another prediction that comes out of this is that the group of states at 15 Mev should all have even parity. The angular distribution of the alpha particle from these states has been measured by Maxson[9] and is consistent with even parity. Also, 7.8-Mev excitation is not unreasonable for the lowest state of this configuration.

The testing of such an interpretation should not be difficult, since it makes definite predictions about many reactions. On the other hand, if the interpretation is correct, then it is possible to infer from one nucleus many of the properties of the neighboring nuclei.

ACKNOWLEDGMENTS

We wish to thank Professor Carl Levinson for his valuable discussion concerning the interpretation of these results and Professor R. Sherr who originally suggested the problem.

PHYSICAL REVIEW VOLUME 123, NUMBER 4 AUGUST 15, 1961

$O^{16}(p,\alpha)N^{13}$ Angular Distributions at 13.5–18.1 Mev*

DONALD R. MAXSON†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received April 10, 1961)

Angular distributions of alpha particles from the $O^{16}(p,\alpha)N^{13}$ ground-state reaction were measured with an ionization chamber at 10 bombarding energies from 13.5 to 18.1 Mev. The angular distributions are oscillatory but not of the form predicted by the plane wave pickup or knockon theories, and the variation with energy is more pronounced than would be expected for a simple direct reaction. The excitation curve has a minimum at $E_p \simeq 16.5$ Mev, and the angular distributions are markedly different above and below that energy. The $O^{16}(p,\alpha)N^{13*}$(2.4 Mev) reaction is also strongly energy dependent, and the $O^{16}(p,p)O^{16}$ elastic scattering cross section is quite energy sensitive at large angles. The energy dependence of the scattering cross section at 125° appears to be correlated with the $O^{16}(p,\alpha)N^{13}$ excitation function.

I. INTRODUCTION

THE activation cross section for the $O^{16}(p,\alpha)N^{13}$ reaction was first measured by Whitehead and Foster,[1] who found that the excitation function has three strong maxima below 16 Mev. Their results, which were quite unexpected and have not yet been satisfactorily explained, were confirmed and extended to 19 Mev by Rouse.[2] In the experiments to be described here, the $O^{16}(p,\alpha)N^{13}$ reaction was studied in more detail by using an ionization chamber to detect the alpha particles. Angular distributions of alphas from the reaction proceeding to the ground state of N^{13} were measured at 10 bombarding energies. Also, because of the possibility of related effects in other $(O^{16}+p)$ reactions, angular distributions and differential excitation curves were measured for $O^{16}(p,\alpha)N^{13*}$ reactions and for the elastic scattering of protons on O^{16}.

In the experiments by Whitehead and Foster and by Rouse, the excitation function was determined by bombarding a stack of Gelva or Mylar foils and measuring the N^{13} beta activity as a function of the distance through the stack. Energy resolutions of about 200 to 500 kev were obtained. Since this energy spread is at least as large as the average F^{17} level spacing in the energy range of interest, the stacked foil experiments would have been incapable of distinguishing resonances associated with individual compound nuclear levels. In order to reveal any fine structure which might have been missed in the previous experiments, Haase and Hill[3] measured the $O^{16}(p,\alpha)N^{13}$ excitation function using a magnetic spectrometer with an energy resolution of 30 kev. Their results were essentially the same as those obtained in the lower resolution experiments, and showed that, except for one narrow resonance at 14.6 Mev, the excitation curve has no fine structure between 12 and 18 Mev.

II. EXPERIMENTAL PROCEDURE

Targets were bombarded by protons from the Princeton FM cyclotron, and the scattering chamber described by Yntema and White[4] was used for all measurements. Bombarding energies were measured to an accuracy of ±0.1 Mev by means of the energy controller developed by Schrank.[5] Energies less than 15 Mev were obtained by using polystyrene absorbers in the beam collimator. No uncertainty in the average bombarding energy was introduced by this procedure,

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
† Present address: Department of Physics, Brown University, Providence 12, Rhode Island.
[1] A. B. Whitehead and J. S. Foster, Can. J. Phys. **36**, 1276 (1958).
[2] G. R. Rouse, B.S. thesis, Princeton University, Princeton, New Jersey, May, 1958 (unpublished).
[3] E. L. Haase and H. A. Hill, Bull. Am. Phys. Soc. **5**, 246 (1960).
[4] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).
[5] G. Schrank, Rev. Sci. Instr. **26**, 677 (1955).

since the energy was measured after the protons traversed the absorbers. The degradation of the beam energy did cause some uncertainty in the absolute cross section measurements, because the polystyrene foils were not at the front of the collimator, and some of the protons were scattered enough to miss the Faraday cup. The data have been corrected for such losses, but the absolute cross section measurements at energies below 15 Mev are relatively less accurate than those at the higher energies.

Alpha particles were detected with a cylindrical ionization chamber employing a Frisch grid. A commercial mixture of argon plus 10% methane was used, and the pressure was adjusted so that the range of the most energetic alphas was somewhat shorter than the length of the chamber. Singly charged particles then produced pulses not greater than about 30% as high as the highest alpha pulses. The ion chamber with its preamplifier was entirely within the evacuated scattering chamber, and the counter gas was fed in and out through flexible metal hoses, so that the pressure could be adjusted from the outside. Gas purity was maintained by flowing the gas continuously through the ion chamber. In the proton scattering measurements, the protons were detected with a conventional NaI(Tl) scintillation counter.

In all of the angular distribution measurements at bombarding energies above 15 Mev, the maximum range of angles subtended by the detector was $\pm 3.0°$ for the ion chamber and $\pm 2.1°$ for the scintillation counter. The effects of the target size and of the angular spread in the incident proton beam were included in obtaining these figures. When absorbers were used to lower the beam energy below 15 Mev, the incident protons were not so well collimated and the corresponding angular ranges were $\pm 4.7°$ for the ion chamber and $\pm 3.8°$ for the scintillation counter.

Oxygen gas was bombarded in some of the measurements. The gas cell, which was useful for angles from 45 to 135°, was a small aluminum box supported on the end of the beam collimator. The beam passed in and out through end windows of 1-mil Al foil, and the alphas and scattered protons emerged through a long side window covered with $\frac{1}{4}$ mil Mylar. An extra baffle with a vertical slot was introduced between the gas cell and the counter to define the ends of the target volume. This volume was approximately proportional to $1/\sin\theta_{\text{lab}}$, but a precise calculation would have been awkward, so the effective volume was determined experimentally. To accomplish this, the elastic scattering of protons from carbon was observed, measuring the same angular distribution with a polystyrene (CH_2) foil and with propane (C_3H_8) gas. An absolute determination of the effective volume was obtained by weighing the foil and measuring the gas pressure with a mercury manometer. The scattering cross section for carbon obtained in

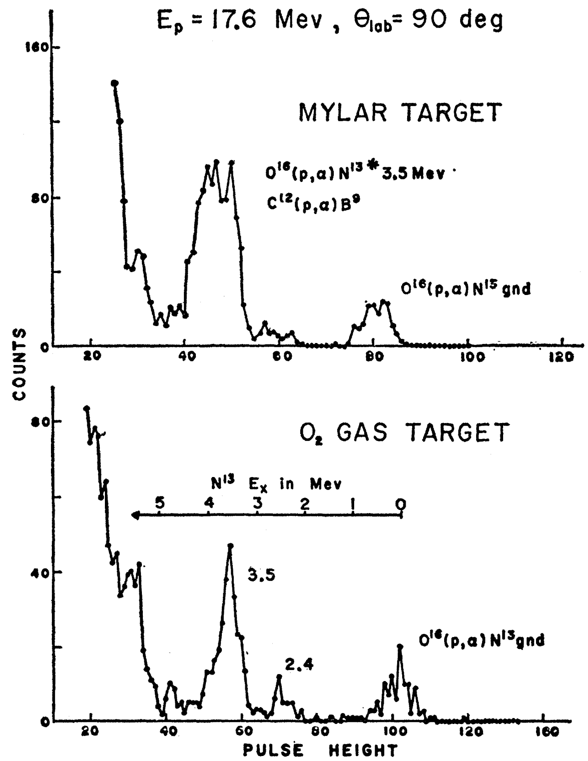

FIG. 1. Alpha-particle energy spectra from (p,α) reactions in Mylar ($C_{10}O_4H_8$) and in O_2 gas. The rise below channel 30 is the upper end of the proton pulse-height spectrum.

these measurements was in good agreement with the results of Dayton and Schrank.[6]

III. RESULTS AND DISCUSSIONS

In Fig. 1 are shown two alpha-particle pulse-height spectra, one obtained with a $\frac{1}{4}$-mil Mylar ($C_{10}O_4H_8$) target and the other with an oxygen gas target. With the Mylar target the ground-state alpha group from $C^{12}(p,\alpha)B^9$ falls on top of the alphas from the $O^{16}(p,\alpha)N^{13*}$(3.5 Mev) reaction. The spectra shown were observed at 90°; at forward angles the alphas from carbon overlap the $E_x=2.4$-Mev group from oxygen. In spite of the masking of the excited state groups, Mylar was perfectly satisfactory for use in studying the ground-state reaction, and because of its convenience it was used for most of the (p,α) measurements reported in this article. The spins and parities of the N^{13} levels which could be resolved using the O_2 gas target were $\frac{1}{2}-$ for the ground state and $\frac{1}{2}+$ for the level at 2.37 Mev.[7] The strong group at 3.5 Mev corresponds to a pair of unresolved levels, $\frac{3}{2}-$ at 3.51 Mev and $\frac{5}{2}+$ at 3.56 Mev.

Figure 2 shows the energy dependence of the $O^{16}(p,\alpha)N^{13}$ ground-state differential cross section at $\theta_{\text{lab}}=70°$, compared with a tracing of Rouse's N^{13}

[6] I. E. Dayton and G. Schrank, Phys. Rev. **101**, 1358 (1956).
[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

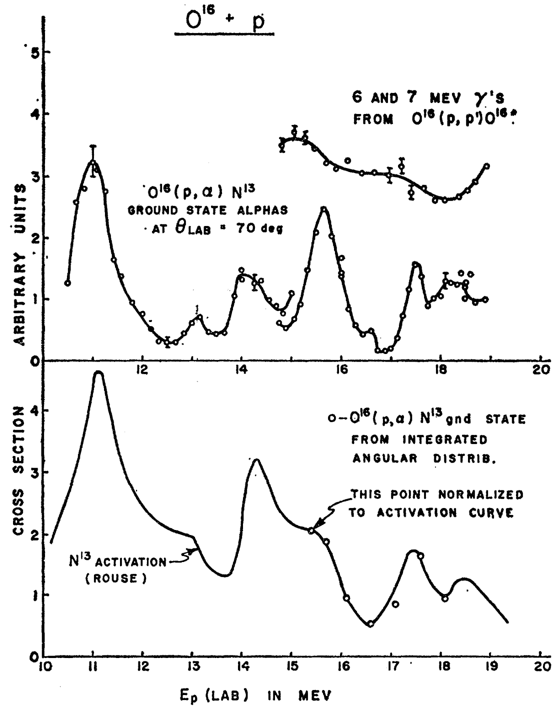

FIG. 2. The $O^{16}(p,\alpha)N^{13}$ ground-state differential excitation function at $\theta_{lab}=70°$ (upper part of figure) compared with a tracing of Rouse's N^{13} activation curve[2] (below). Total $O^{16}(p,\alpha)N^{13}$ ground-state cross sections, obtained by integrating the angular distributions of Fig. 3, are compared with the activation curve in the lower right portion of the figure. Also shown are Sherr and Yoshiki's measurements[9] of the yield of 6- and 7-Mev gamma rays from $O^{16}(p,p')O^{16*}$ inelastic scattering (smooth curve at upper right).

activation cross section.[2] The differential excitation function reproduces the main features of the activation curve. An exact correspondence would not be expected, because the differential excitation curve is sensitive to variations in the angular distribution. Although they are not shown in this figure, there is a minimum in the activation curve at about 9.3 Mev, and another maximum at 8 Mev. The complete excitation curve below 16 Mev is given by Whitehead and Foster.[1]

The minima in the $O^{16}(p,\alpha)N^{13}$ activation curve might conceivably be caused by competition from other $(O^{16}+p)$ reactions, including (p,α) reactions to excited N^{13*} levels which decay by proton emission. This conjectured interpretation was investigated by comparing the activation curve with the threshold energies of all of the common reactions induced by protons incident on O^{16}. The results were negative, in that there was no obvious correlation between the threshold energies and the structure of the excitation function.

The compound nucleus for this reaction, if one is formed, is F^{17}. Because the binding energy of a proton in F^{17} is only 0.59 Mev, the F^{17} excitation energy differs by less than 1 Mev from the laboratory bombarding energy over the entire energy range shown in Fig. 2. The levels of F^{17} within this range are not known, but an indication of the level spacing is given by the mirror nucleus O^{17}, which has about 9 levels between 8 and 9 Mev excitation energy.[7,8] Since this level spacing is small compared with the widths of the maxima in the activation curve, it may be assumed that a compound nucleus interpretation must involve groups of levels rather than individual ones.

If compound nuclear effects were responsible for the structure in the (p,α) excitation curve, related variations might be expected to occur in the excitation functions of other reactions having the same compound nucleus. One such reaction is $O^{16}(p,p)O^{16*}$ inelastic scattering. The excitation function for this process was observed by Sherr and Yoshiki,[9] who measured the yield of gammas from the de-excitation of the 6- and 7-Mev levels of O^{16}. A cellulose acetate foil was bombarded by protons, and gamma rays emitted at angles between 50 and 90° from the beam direction were detected by means of a 3×3 in. NaI(Tl) scintillator. The results, which are shown in Fig. 2, revealed no energy dependence comparable to that found for the (p,α) reaction.

In view of the strong energy dependence of the (p,α), cross section, it seemed worthwhile to measure angular distributions of alphas at several energies. The results obtained at ten bombarding energies are shown in Fig. 3. The curves were drawn to connect the points; no theoretical curves are shown. The statistical uncertainties indicated by error flags are representative for all of the data. The absolute cross sections are believed to be reliable to within ±10% for the seven curves from 15.4 to 18.1 Mev, and to within ±20% for the three curves at lower energies, which were measured using absorbers to degrade the proton beam energy.

Crude fits to some of the angular distributions of Fig. 3 could probably be obtained by using the appropriate plane wave direct reaction theories.[10,11] These theories, however, predict forward peaked oscillatory angular distributions, in which the magnitude of the cross section and the angular positions of the maxima change slowly and monotonically as functions of the proton energy. The experimental results are clearly inconsistent with these theoretical predictions. Also, except at 14.1 Mev, the angular distributions are not symmetric about 90°, implying failure of the statistical assumption and/or the continuum assumption if the reaction is interpreted in terms of a compound nuclear process. The range of 13.5–18.1 Mev in bombarding energy corresponds to 13.3–17.6 Mev in F^{17} excitation

---

[8] T. W. Bonner, Alfred A. Kraus, Jr., J. B. Marion, and J. P. Schiffer, Phys. Rev. **102**, 1348 (1956).
[9] R. Sherr and H. Yoshiki (unpublished).
[10] R. G. Thomas, Los Alamos Scientific Laboratory Report 1953 (unpublished).
[11] S. T. Butler, Phys. Rev. **106**, 272 (1957).

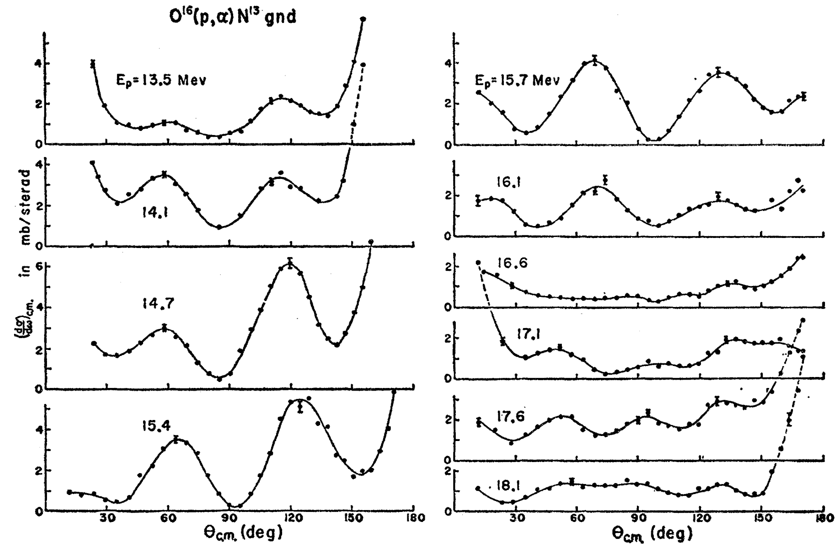

FIG. 3. Experimental angular distributions of alphas from the $O^{16}(p,\alpha)N^{13}$ ground-state reaction. The laboratory proton energy is indicated for each curve. Representative statistical uncertainties are shown for two or more points of each angular distribution.

energy. Judging from the level scheme[7,8,12–15] of O^{17}, the assumption of many overlapping levels may not be justified within this range. Between 8 and 10 Mev excitation in O^{16}, $C^{13}(\alpha,n)O^{16}$ resonances[8] indicate an average level width only about 40 per cent as great as the average level spacing, and even at bombarding energies corresponding to excitations above 15 Mev, strong gross structure maxima occur in the $N^{15}(d,n)O^{16}$ excitation function.[15] Some sort of interference phenomenon seems to be suggested by the effects shown on the right side of Fig. 3. The cross section passes through a minimum as the bombarding energy is changed through 16.6 Mev, and the phase and period of the oscillations are different above and below that energy.

The total cross section for the (p,α) reaction to the ground state of N^{13} was found by integrating the angular distributions. The energy dependence of the total cross section is compared with Rouse's activation curve in the lower part of Fig. 2. The absolute value determined from the 15.4-Mev angular distribution was 30.2 ± 3 mb, in agreement with the value 29 mb measured by Whitehead and Foster.[1] The close correspondence between the results of the different experiments indicates that the activation curve represents the excitation function for the reaction to the ground state of N^{13}. Reactions to excited levels of N^{13} would not be expected to contribute appreciably in the activation measurements, because the excited states can decay by proton emission[7] to leave stable C^{12}.

Strongly energy-dependent angular distributions at bombarding energies above 10 Mev have been observed for a few other (p,α) or (α,p) reactions. The mos-pronounced variations with small changes of bombardt ing energy have been found in the $C^{12}(\alpha,p)N^{15}$ and $Al^{27}(p,\alpha)Mg^{24}$ reactions.[16–21] These two reactions, as well as the $F^{19}(p,\alpha)O^{16}$ reaction,[22,23] also exhibit strong backward peaks at certain energies. Similar peaks, probably too sharp to be readily explained in terms of heavy particle exchange,[24,25] are seen in the 17.6- and 18.1-Mev $O^{16}(p,\alpha)N^{13}$ angular distributions of Fig. 3. In instances where the experimental results have been inconsistent with the assumption of a simple direct-reaction mechanism, it has generally not been possible to fit the angular distributions. At lower bombarding energies the compound nucleus formalism has been used with success. An analysis similar to that by Schiffer *et al.*[26] for the $C^{13}(\alpha,n)O^{16}$ reaction, or by Lee and Schiffer[27] for the $B^{11}(\alpha,p)C^{14}$ reaction, might conceivably be fruitful in the present case. An interpretation of the $O^{16}(p,\alpha)N^{13}$ excitation curve in terms of an f-wave resonance has been suggested by Kobayashi.[28]

[12] R. L. Steele and J. R. Risser, Bull. Am. Phys. Soc. **5**, 108 (1960).
[13] D. M. Worley, Jr., R. Bass, T. W. Bonner, E. A. Davis, and F. Gabbard, Bull. Am. Phys. Soc. **5**, 109 (1960).
[14] D. B. Fossan, T. H. May, R. L. Walter, and W. E. Wilson, Bull. Am. Phys. Soc. **5**, 369 (1960).
[15] J. L. Weil and K. W. Jones, Phys. Rev. **112**, 1975 (1958).

[16] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1301 (1960).
[17] I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. Japan **14**, 1260 (1959).
[18] R. Sherr, M. Rickey, and G. W. Farwell, Annual Progress Report 1957, University of Washington, Seattle, Washington (unpublished).
[19] C. E. Hunting and N. S. Wall, Bull. Am. Phys. Soc. **2**, 181 (1957).
[20] I. Kumabe, C. L. Wang, M. Kawashima, M. Yada, and H. Ogata, J. Phys. Soc. Japan **14**, 713 (1959).
[21] G. E. Fischer, V. K. Fischer, E. A. Remler, and M. D. Tatcher, Phys. Rev. **110**, 286 (1958).
[22] H. Ogata, J. Phys. Soc. Japan **14**, 707 (1959).
[23] J. G. Likely and F. P. Brady, Phys. Rev. **104**, 118 (1956).
[24] George E. Owen and L. Madansky, Phys. Rev. **105**, 1766 (1957).
[25] L. Madansky and G. E. Owen, Phys. Rev. **99**, 1608 (1955).
[26] J. P. Schiffer, Alfred A. Kraus, Jr., and J. R. Risser, Phys. Rev. **105**, 1811 (1957).
[27] L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. **115**, 160 (1959).
[28] S. Kobayashi, J. Phys. Soc. Japan **15**, 1164 (1960).

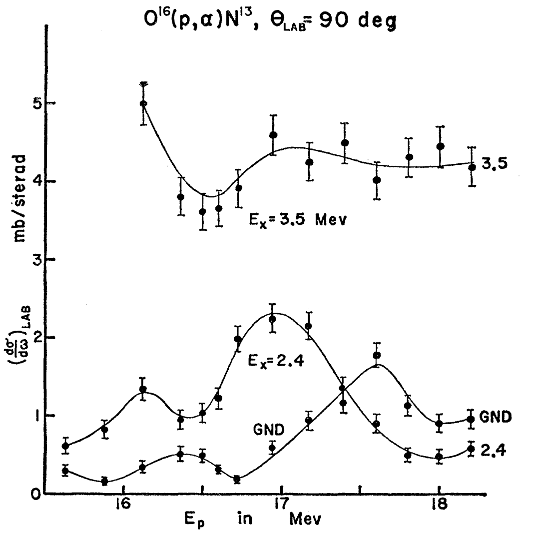

FIG. 4. Differential excitation functions at $\theta_{lab}=90°$ for the $O^{16}(p,\alpha)N^{13}$ reactions leading to the ($\frac{1}{2}-$) ground state, the ($\frac{1}{2}+$) level at 2.37 Mev, and the unresolved pair of levels ($\frac{3}{2}-$ and $\frac{5}{2}+$, respectively) at 3.51 and 3.56 Mev.

There is also some recent evidence[29] that the $O^{16}(p,\alpha)N^{13}$ results may be explained by cluster model calculations.

$O^{16}(p,\alpha)N^{13*}$ differential cross sections were measured using the O_2 gas target. Figure 4 shows differential excitation functions and Fig. 5 shows partial angular distributions of alphas from the (p,α) reactions to the ground state and 2.4-Mev levels of N^{13}, as well as from the reactions proceeding to the two unresolved levels near 3.5 Mev. From the two figures it can be seen that the reaction to the 2.4-Mev level is as strongly energy dependent as the reaction to the ground state. As the proton energy is changed from 17.0 to 17.6 Mev, the cross section for the reaction to the ground state increases, while that for the reaction to the 2.4-Mev level decreases, so that the relative magnitudes of the cross sections are interchanged. Figure 5 shows that this

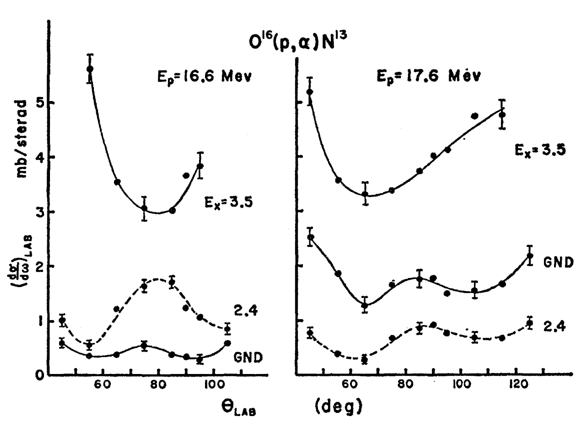

FIG. 5. Partial angular distributions of alpha particles from $O^{16}(p,\alpha)N^{13}$ reactions.

[29] H. A. Hill (private communication).

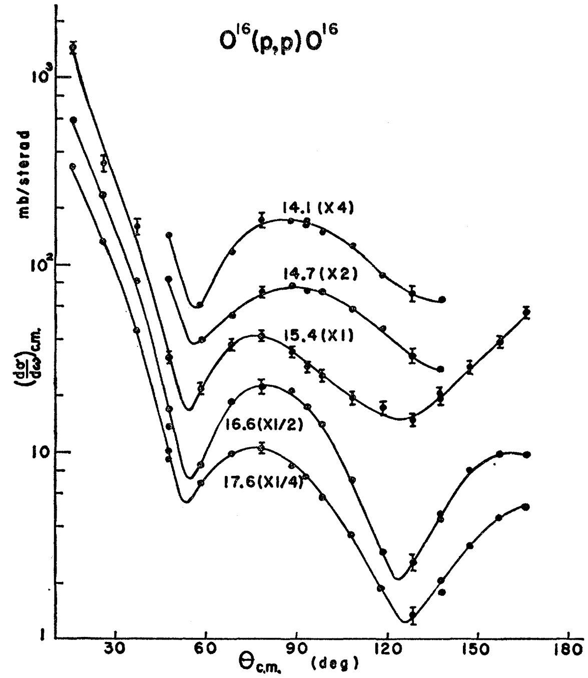

FIG. 6. $O^{16}(p,p)O^{16}$ elastic scattering angular distributions at five bombarding energies from 14.1 to 17.6 Mev (lab). The curves would overlap if plotted directly, and have been separated by multiplying the cross sections by the powers of 2 indicated in parenthesis.

interchange in the relative magnitudes occurs for the entire angular range of the measurements.

Since compound nuclear processes or effects associated with the entrance channel might lead to related energy variations in any other $(O^{16}+p)$ reaction or scattering, the elastic scattering of protons on oxygen was investigated. In order to find the most suitable angle for a detailed determination of the energy dependence, angular distributions were measured at several energies. Five elastic scattering angular distributions are shown in Fig. 6. Ordinates are indicated in mb/sr for the curve at 15.4 Mev. The other curves have been displaced vertically by multiplying by powers of 2. The actual cross sections are about the same near the central maximum (all between 34 and 43 mb/sr at 89° c.m.). An O_2 gas target was used for the runs at laboratory angles from 45 to 135°. At each angle less than 45° the elastic scattering from carbon plus oxygen was measured using a Mylar target, that from carbon was measured separately with a polystyrene target, and the contribution from oxygen was obtained by subtraction. At angles larger than 135° the carbon and oxygen peaks in the proton pulse-height spectrum were satisfactorily resolved, so that only a Mylar target was needed. The runs at 14.1 and 14.7 Mev were made with polystyrene absorbers in the beam collimator.

From Fig. 6 it can be seen that the proton angular distributions at 16.6 and 17.6 Mev are almost identical,

but that at 15.4 Mev the minimum near 125° is much shallower (by about a factor of three). Since the maximum variation with energy occurred at about 125° (lab), the energy dependence of the scattering cross section was measured at that angle. The results are shown compared with Rouse's $O^{16}(p,\alpha)N^{13}$ activation curve in Fig. 7. The three sections of the proton scattering curve were obtained with different thicknesses of polystyrene to degrade the beam energy, and were multiplied by arbitrary factors to make them join smoothly in the two regions of overlap. The number of absorbers used for each part of the curve is indicated at the top of the figure. The (p,α) tracing has been displaced upward to separate the two curves.

The (p,p) and (p,α) cross sections shown in Fig. 7 certainly do not have the same energy dependence, but every fluctuation in the (p,α) curve appears to be accompanied by a variation in the scattering cross section. If the structure in the (p,p) curve reflects the energy dependence of the compound elastic scattering, the apparent correlation between the two curves may provide some evidence favoring a compound nucleus interpretation of the (p,α) results. No definite conclusion is warranted, because similarities in the curves might arise from the common $(O^{16}+p)$ entrance channel even if no compound nucleus were formed. If compound nucleus formation is important in the $O^{16}(p,\alpha)N^{13}$ reaction, related effects might be found in $(N^{14}+He^{3})$ reactions.

Since the completion of the work described here, extensive $O^{16}(p,p)O^{16}$ elastic scattering results have been reported by Kobayashi.[28] Differential excitation functions, measured by Kobayashi at 140, 150, and 160° corroborate the existence of related energy variations in the (p,p) and (p,α) cross sections.

IV. SUMMARY

Angular distributions of alphas from the $O^{16}(p,\alpha)N^{13}$ ground state reaction were measured at 10 energies from 13.5 to 18.1 Mev. The angular distributions are oscillatory but are strongly energy dependent and qualitatively different from the predictions of the simple plane wave direct reaction theories. Compound nuclear effects are not excluded, although the maxima in the (p,α) excitation function are too broad to correspond to single F^{17} levels. The $O^{16}(p,\alpha)N^{13*}$ reaction to the 2.4-Mev level of N^{13} is also strongly energy dependent, but does not vary in the same way as the reaction to the ground state. The $O^{16}(p,p)O^{16}$ elastic scattering cross section is quite energy dependent at large angles. At 125°, the scattering cross section has fluctuations at the same energies as those in the $O^{16}(p,\alpha)N^{13}$ excitation curve, suggesting that the effects may be associated with an F^{17} compound nucleus or with the common $(O^{16}+p)$ entrance channel.

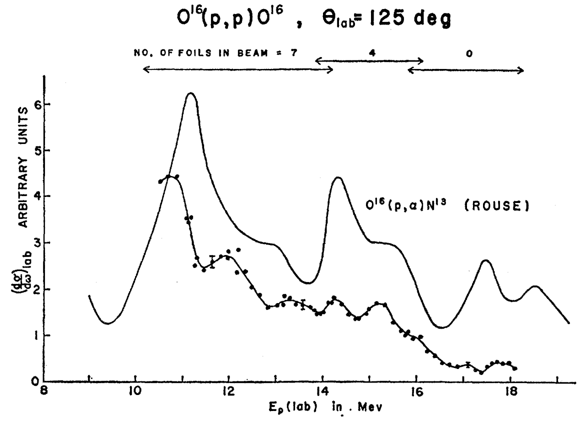

FIG. 7. Energy dependence of the $(O^{16}+p)$ elastic scattering differential cross section at 125° (lab), compared with the $O^{16}(p,\alpha)N^{13}$ excitation function.

ACKNOWLEDGMENTS

The author is indebted to Mr. G. R. Rouse and to Professor R. Sherr and Dr. H. Yoshiki for permission to reproduce their unpublished results, and especially to Professor Sherr for his continued interest and for many valuable discussions. Some of the data were taken by Mr. John H. Terrell, whose assistance is gratefully acknowledged.