High-Resolution Measurements of the $O^{16}(p,\alpha)N^{13}$ Excitation Function*

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The $O^{16}(p,\alpha)N^{13}$ activation cross section was measured from 12 to 18 Mev with an energy resolution of 30 kev. The results are essentially the same as obtained by Whitehead and Foster and Rouse, using poorer resolution except for one very narrow resonance. As the proton energy increases through this resonance, the cross section first rises 7% to a maximum, then drops 33% to a minimum, and finally rises 6%. The peak and valley have a width at half-maximum of 30 kev and the peak and valley are separated by 60 kev. The proton energy at halfway down the drop was determined, using the limp-wire technique, to be 14.600±0.020 Mev. This resonance is well suited for calibration purposes. A qualitative interpretation of the results is made using the "cluster model."

INTRODUCTION

The activation cross section for the $O^{16}(p,\alpha)N^{13}$ reaction has been measured by Whitehead and Foster[1] from 6 to 15 Mev and extended by Rouse[2] to 19 Mev with resolutions ≥ 200 kev. Their excitation functions exhibit four large peaks placed approximately 3 Mev apart. The following higher-resolution measurements were undertaken to try to determine whether these large peaks were a number of narrow resonances or were some sort of "giant" resonances.

Since the excited states of N^{13} can all decay by proton emission,[3] the N^{13} activity produced by the proton bombardment of O^{16} is to a very good approximation produced by the $O^{16}(p,\alpha)N^{13}$ reaction. Therefore, the interpretation of the results is not complicated by the possibility of $O^{16}(p,\alpha\gamma)N^{13}$ reactions, and this is one of the few cases where the cross section for a ground-state reaction has been measured over such a large energy range and with good resolution.

EXPERIMENTAL PROCEDURE

The proton beam from the Princeton FM cyclotron was sent directly into a double-focusing magnetic spectrometer with the targets and Faraday cup behind the spectrometer. At 14.5 Mev, the spectrometer was operated with slit widths of 1.5 mm which corresponded to a beam energy spread of 26 kev (full width at half-height). Above or below this energy, the slit widths were adjusted so that the ratio of the energy loss in the target and the beam energy spread allowed by the spectrometer was always a constant and the same as that at 14.5 Mev. Targets were $\frac{1}{4}$-mil (0.00025-in.) thick Mylar and the calculated energy loss in these targets for 14.5-Mev protons is 30 kev using the data of Aron *et al.*[4] for the dE/dx. This energy loss together with the 26-kev beam energy spread leads to a calculated resolution of 27 kev for very narrow resonances. The results obtained on the sharp resonance at 14.6 Mev are consistent with this.

The procedure was to bombard a Mylar foil for 10 min (one half-life of N^{13}), wait 5 min for any short-lived activity to die, and measure the activity with two Geiger tubes for 10 min. The short-lived activity could be either the 20-sec activity of C^{10} or the activity in the Al backing on the Mylar targets. It was found that with the $\frac{1}{4}$-mil targets and a proton energy of 15.5 Mev, 54% of the N^{13} recoils escaped from the target in the forward direction and about 6% escaped in the backward direction. For this reason a 0.3-mil Al foil was placed behind each Mylar target to stop the N^{13} recoils in the forward direction. The maximum half-life of the activity produced in the Al was about 7 sec, and so after the 5-min delay between bombardment and counting the Al activity was less than background.

There were actually five Mylar targets used, with one always at the bombarding station, one at the counting station, and three waiting for the N^{13} activity to die down. This meant that there was a 75-min interval between the times a particular target was counted, or in other words, only 0.5% of the N^{13} activity of one counting would be present at the next counting of that target. The positrons from the N^{13} decay were detected by two Geiger tubes which together subtended a solid angle of 7.3 sr at the target.

The activation measurements in references 1 and 2 were performed using a stacked-foil technique. That was tried here but did not work well for these higher-resolution measurements. This was because (a) if there were a 5-stack cycle, and each stack contained 5 targets, there would be 25 Mylar targets whose thicknesses had to be known to 1%; (b) the 0.3-mil Al behind the Mylar targets used to stop N^{13} recoils made it necessary to know the energy loss in the 25 Al foils to 1%; and (c) the calibration of 5 Geiger tubes had to be known to 1%. For these reasons it took less time to use a 5-stack cycle but with a single target in each stack.

The proton beam was stopped in a Faraday cup and the charge collected by a leaky integrator. The charge was collected on a condenser with capacity C. A re-

* This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.

[1] A. B. Whitehead and J. S. Foster, Can. J. Phys. 36, 1276 (1958).
[2] G. R. Rouse, B.S. thesis, Princeton University, May, 1958 (unpublished).
[3] F. Ajzenburg-Selove and T. Lauritsen, Nuclear Phys. 11, (1959).
[4] W. A. Aron, B. G. Hoffman, and F. C. Williams, Atomic Energy Commission Report AECU-663, 1951 (unpublished).

sistor of resistance R was connected from the condenser to ground, with R chosen so that $RC=t_{\frac{1}{2}}/\ln 2$, where $t_{\frac{1}{2}}$ is the half-life of N^{13}. Under these conditions, the voltage V on the condenser satisfies the same differential equation as the number N of N^{13} atoms produced in the target. Therefore, the voltage on the condenser at any time is proportional to the number of N^{13} atoms at that time. In practice, the RC is made equal to $t_{\frac{1}{2}}/\ln 2$ to within 1% where $t_{\frac{1}{2}}=10.08\pm0.04$ min.[5] With the beam current being constant within a factor of 2, this was more than adequate to keep the normalized activity N/V reproducible to 1%.

In order to correct for the N^{13} activity produced by the proton bombardment of the carbon in the Mylar targets ($C_{10}O_4H_8$), the activation cross section was measured from 12 to 18 Mev using polyethylene targets.

RESULTS AND CONCLUSIONS

The results obtained for the $O^{16}(p,\alpha)N^{13}$ reaction and $C^{13}(p,n)N^{13}$ and $C^{12}(p,\gamma)N^{13}$ reactions are shown in Fig. 1. The results for these reactions are essentially the same as obtained by Whitehead and Foster[1] and Rouse.[2] The relative errors in Fig. 1 are indicated by the scatter of the data and are statistical errors. The uncertainty in the absolute cross section is $\pm30\%$, mostly because of the uncertainty in the solid angle subtended by the Geiger tube. These measured absolute cross sections agree with those of Whitehead and Foster.[1]

In the $O^{16}(p,\alpha)N^{13}$ reaction, there is a very narrow resonance at 14.6 Mev which did not appear in references 1 and 2. This resonance is shown in detail in Fig. 2 and is well suited for calibration purposes. The proton energy at halfway down the drop was determined, using the limp-wire technique, to be 14.600 ±0.020 Mev. The data obtained from the Mylar targets were corrected above 16 Mev for the activity from the $O^{16}(p,d)O^{15}$ reaction. The data of Tocher[6] were used for this.

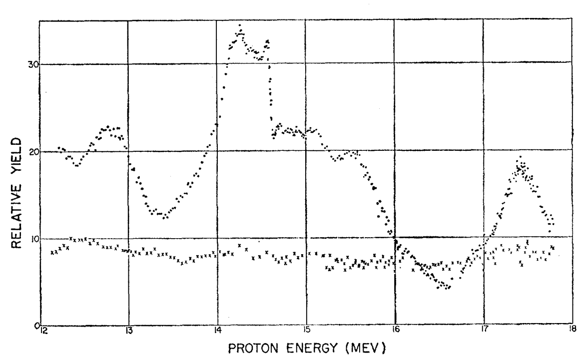

FIG. 1. The dots are the experimental points for the $O^{16}(p,\alpha)N^{13}$ reaction. To obtain the cross section in mb, multiply the vertical scale by 1.15 ± 0.35. The crosses are the experimental points for the $C^{12}(p,\gamma)N^{13}$ and $C^{12}(p,n)N^{13}$ reactions with targets not enriched in C^{12} or C^{13}. The energy scale has been corrected for target thickness.

[5] D. H. Wilkinson, Phys. Rev. **100**, 32 (1955).
[6] D. A. Tocher, Princeton University, 1959 (unpublished).

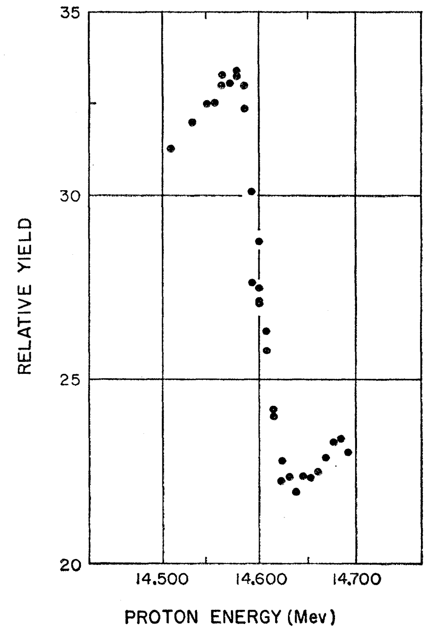

FIG. 2. The 14.6-Mev resonance in the $O^{16}(p,\alpha)N^{13}$ reaction. The energy scale has been corrected for target thickness.

The activation cross section for the proton bombardment of carbon is shown in Fig. 1. Both the $C^{13}(p,n)N^{13}$ and $C^{12}(p,\gamma)N^{13}$ reactions contribute in an unknown ratio. Assuming the N^{13} activity is produced solely by the $C^{13}(p,n)$ reaction, then the cross section in mb is obtained by multiplying the vertical scale by 5.2 ± 1.5. Assuming the N^{13} activity is produced by the $C^{12}(p,\gamma)N^{13}$ reaction, the cross section is obtained by dividing the above factor by 99. The $C^{12}(p,\gamma)N^{13}$ reaction cross section was measured by Cohen[7] at 11 Mev, and he obtained 1.8 mb. This is considerably larger than the upper limit of 0.50 ± 0.15 mb which we would obtain using the results of reference 1.

The attempts which have been made to understand the structure in the $O^{16}(p,\alpha)N^{13}$ reaction have not been very fruitful. First, it was thought that there might be a correlation between the structure of the $O^{16}(p,\alpha)N^{13}$ reaction and the threshold energies of other $(O^{16}+p)$ reactions. But there was no obvious correlation. Another possibility is that compound nuclear effects are responsible for the structure in the (p,α) excitation curve. If this is so, there might be similar variations in the excitation functions of other reactions having the same compound nucleus. To check this, Sherr and Yoshiki[8] measured the yield of gammas from the de-excitation of the 6- and 7-Mev levels of O^{16}. Their results are shown in reference 9, and they found no energy dependence comparable to that found in the (p,α) reaction. Furthermore, the angular distributions measured by Maxson[9] are clearly inconsistent with the predictions

[7] B. Cohen, Phys. Rev. **100**, 206 (1955).
[8] R. Sherr and H. Yoshiki (unpublished).
[9] D. R. Maxson, following paper [Phys. Rev. **123**, 1304 (1961)].

of the appropriate plane-wave direct-reaction theories.

There is another way in which to look at this, using the "cluster model."[10] In the "cluster model" the existence of two or more clusters is assumed. Here it is assumed that the particles in different shell model configurations (p states or s-d states) are decoupled. Thus, in Ne^{20} there are four s-d nucleons outside an O^{16} core, and the core properties are assumed to be essentially independent of the coupling of the four s-d nucleons. The spins and parities of the four s-d nucleon structure is 0^+, 2^+, 4^+, 6^+, and 8^+. From the variational calculations of Watanabe, Levinson, and Hill,[11] using the same model, the 0^+–2^+ splitting was calculated to be 1.33 Mev and a 0^+–4^+ splitting of 3.9 Mev. In Ne^{20} there is a 2^+ state at 1.63 Mev and another of unknown spin and parity of 4.25 Mev.[3] We shall now classify these two states as the 2^+ and 4^+ states in the above model.

In the case of F^{19} there should exist an analogous set of states. But here the core will be N^{15} with a spin of $\frac{1}{2}^-$, instead of O^{16} with spin 0^+. Therefore, the analog to the 0^+ state in Ne^{20} will be a $\frac{1}{2}^-$ in F^{19}; the analog to the 2^+ state in Ne^{20} will be a $\frac{3}{2}^-$, $\frac{5}{2}^-$ doublet; and the analog of the 4^+ in Ne^{20} will be a $7/2^-$, $9/2^-$ doublet in F^{19}. In F^{19} a $\frac{1}{2}^-$ state exists at 0.110 Mev, and doublets exist at 1.35 and 1.46 Mev with spins $(\frac{3}{2},\frac{5}{2})$ and $(\frac{1}{2},\frac{3}{2})$, respectively.[3] We shall classify this doublet as the analog to the above 2^+ state in Ne^{20}. Thus, the splitting of the 0^+–2^+ states in Ne^{20} at 1.63 Mev has gone to 1.3 Mev in F^{19}. Hence, one might expect this splitting to further decrease as the size of the core is decreased.

There is one other assumption that is made. This is that the wave function for a core and four s-d particles has a large overlap with the wave function of a core and an alpha particle. This assumption is quite plausible, since it has been verified by Watanabe that the four s-d particles are only weakly coupled to the rest of the core. Since we are studying alpha particle emission, we are then selecting those states which are formed by a core and four s-d particles.

In Ne^{20} there is another state which has a very large reduced width for alpha-particle emission. This is a

TABLE I. "Cluster model" levels of O^{16} with a C^{12} core.

E_x (Mev)	J^π	θ_α^2
6.06	0^+	
6.92	2^+	
9.58	1^-	0.85
10.36	4^+	0.26
11.25	0^+	0.76
11.62	3^-	0.73
12.43	1^-	
13.09	1^-	
13.25	3^-	

[10] K. Wildermuth and Th. Kanellopoulos, Nuclear Phys. 1, 150 (1958).
[11] S. Watanabe, C. Levinson, and H. A. Hill, Bull. Am. Phys. Soc. 4, 256 (1958).

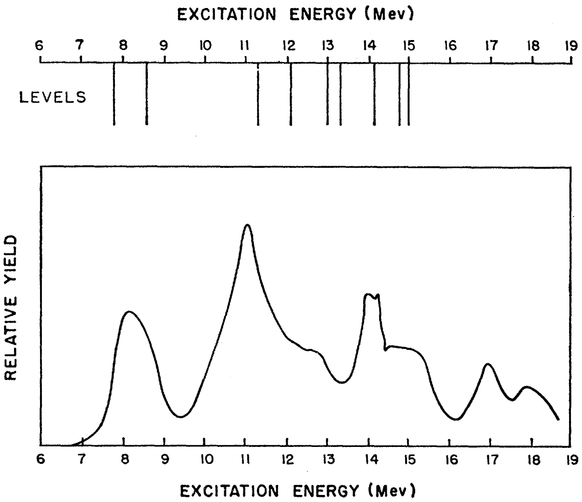

FIG. 3. At the top are the "cluster model" states of O^{16} drawn with the lowest state at an excitation of 7.8 Mev. Below is shown the total cross section of the $O^{16}(p,\alpha)N^{13}$ reaction plotted against the excitation energy of F^{17}.

$3-$ state at 7.2 Mev. Hence, there must also be some $f_{7/2}$ configuration mixing in with the s-d configurations of the four nucleons outside the O^{16} core.

In O^{16} with a C^{12} core, there should be an analogous set of states to those discussed in Ne^{20} and F^{19}. These states are found by selecting those states which have a large reduced width for alpha-particle emission and are shown in Table I.[3] The first 0^+ and 2^+ states shown cannot decay by alpha-particle emission and were put on the list because they fit the pattern determined by F^{19} and Ne^{20}.

In F^{17} there should exist a set of states analogous to the set just selected in O^{16} except for F^{17} the core is N^{13} with a spin of $\frac{1}{2}^-$ instead of a core of C^{12} with spin 0^+. We shall assume that the spacing of the states selected with the C^{12} core in O^{16} does not change appreciably in going to N^{13} core in F^{17}. The only thing that will change is the excitation energy at which this series of states start. This is used as a parameter and is chosen as 7.8 Mev for F^{17}, whereas it is 6.06 Mev, 0.110 Mev, and the ground state for O^{16}, F^{19}, and Ne^{20}, respectively. At the top of Fig. 3 are drawn these "cluster model" states of O^{16} started at an excitation of 7.8 Mev. In the lower part of Fig. 3 is plotted the total cross section for the $O^{16}(p,\alpha)N^{13}$ reaction as a function of the excitation of F^{17}. Thus, with this model one is able to obtain qualitative agreement with the experimental results except for the 14.6-Mev resonance. If this interpretation is correct, then this resonance cannot be described this way, since its lifetime is so much longer than the rest of the states.

One point which should be noticed from the $O^{16}(p,\alpha)N^{13}$ data is that each state has apparently the same lifetime, which follows from the width of each resonance.

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.

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

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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,

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