explained by the much poorer energy resolution of the neutron experiments.

IV. CONCLUSION

It has been found that the inelastic scattering of 96-Mev protons results in the direct excitation of many levels in the target nucleus. Strong excitation of certain levels takes place in the light elements, and several of these have been identified with known excited states. Thus in the high-energy region, a careful separation of inelastic from elastic protons is required in experiments dealing primarily with elastic scattering. The present survey suggests the desirability of increasing the experimental energy resolution for more detailed studies with high energy protons. Such an increase in energy resolution is possible with the more nearly monoenergetic proton beams from a linear accelerator or from a cyclotron with a regenerator-type of external beam. Finally the possibility of using polarized protons, which can be easily produced at high energy, should be noted.

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Yields of the $O^{18}(p,\alpha)N^{15}$ and $O^{18}(p,n)F^{18}$ Reactions for Protons of 800 kev to 3500 kev*

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The yield of the $O^{18}(p,\alpha)N^{15}$ reaction was observed at 90° with respect to the ion beam for protons from 800 kev to 3500 kev. Resonances in the yield located fifteen energy levels in F^{19} not previously observed. Neutrons from the $O^{18}(p,n)F^{18}$ reaction were observed in the forward direction above the threshold ($E_p=2577\pm8$ kev). Simultaneous observation of alpha particles and neutrons showed that the resonance energies for the two reactions agree in some cases but not in others.

INTRODUCTION

A STUDY of the yield of the reaction $O^{18}(p,\alpha)N^{15}$ as a function of proton energy will provide information concerning the existence of energy levels in the compound nucleus F^{19}. This reaction has previously been studied by Seed,[1] Mileikowsky, and Pauli,[2] and Cohen.[3] Cohen observed resonances for proton energies of 640±5 and 850±5 kev. The present work was undertaken to extend such measurements to higher energies, since nothing was known about levels in F^{19} from the upper level found by Cohen (excitation level of 8.76 Mev in F^{19}) up to the $O^{18}(p,n)F^{18}$ threshold (excitation level of 10.47 Mev in F^{19}). The $O^{18}(p,n)$ reaction has been studied by a number of investigators.[4–6] Above the (p,n) threshold the (p,α) and (p,n) reactions were observed simultaneously so that a detailed comparison of the variation of their yields with proton energy could be made.

EQUIPMENT

The protons used in this work were accelerated by the Minnesota electrostatic generator.[7] After passing through a 90° magnet, the proton beam was refocused by means of two sets of quadrupole electrostatic lenses[8] fourteen feet apart, and then entered the target chamber. The slightly converging proton beam was defined by a tantalum collimating aperture before hitting the target foil. Particles leaving the target at 90°±1.5° with repect to the beam direction passed into a proportional counter through an aluminum window. The undeflected proton beam struck an insulated current collector cup. A magnetic field was provided around the mouth of the collector cup to eliminate current measurement errors due to secondary electrons. The beam current was measured with an integrator circuit which automatically placed a shutter in the ion beam and shorted the input lead to the scaling circuits when a condenser became charged to a predetermined potential. The neutron flux in the forward direction was intercepted by a conventional "long counter."[9] After suitable amplification, the pulses

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from the proportional counter were analyzed and counted using a 10-channel pulse-height analyzer.[10] The amplified pulses from the long counter were counted with a scale-of-64 circuit having a simple pulse-height discriminator.

The energy of the proton beam was determined by a measurement of the field in the gap of the 90° deflection magnet. The flux meter used for this measurement was of the floating-wire type similar to the one described by Cranberg.[11] However, in the instrument used here the weight which balanced the tension in the wire was maintained constant, so that the current required in the wire to produce the condition of balance was inversely proportional to the magnetic field strength. The path of the ion beam through the magnet was well defined by apertures 100 inches apart through which the beam passed before reaching the magnet, and a slit of adjustable width placed at the focal point of the magnet, 12 inches beyond the edge of the field. The slit jaws were insulated so that an electrical signal was obtained for automatic control of the potential developed by the electrostatic generator.

The target was produced by oxidizing a 0.005-mil nickel foil in an atmosphere enriched in O^{18} according to a technique described elsewhere.[12]

EXPERIMENTAL PROCEDURE

As a preliminary to the study of the O^{18} reactions, the energy scale of the magnet-flux meter combination was calibrated by use of resonances in $F^{19}(p,\alpha\gamma)$ reaction[13–15] and the $Li^7(p,n)$ threshold.[16] The fluorine targets were CaF_2 evaporated on tantalum. Targets of thickness 1, 2, and 5 kev for 1372-kev protons were used. The lithium targets were thick layers of LiF.

As a check on the linearity of the energy scale the 873.5-kev γ-ray resonance was located by using the H^+, HH^+, and HHH^+ ion beams. This test gave a calibration factor which was constant to within one part in 2000. This calibration factor was checked with the H^+ beam at the γ-ray resonance at 1372 kev and at the $Li(p,n)$ threshold at 1881.4 kev. It is believed that the energy measurements throughout the experiment where reliable to one part in 1000.

For proton energies below 900 kev, the protons scattered by the target were prevented from entering the proportional counter by the use of a 0.35-mil aluminum counter window. For higher energies, where the protons entered the counter, various window thickness and counter fillings were chosen so that the pulses from the alpha particles and protons were easily separated by the 10-channel pulse-height analyzer. The alpha-particle pulses were identified as such by comparison with pulses from polonium alpha particles under conditions where the two would lose the same energy in the counter.

The identification of the observed alpha particles and neutrons as those produced from O^{18} was checked by bombarding a target made from ordinary oxygen. The radiation observed was only that which would have been produced by the 0.2% O^{18} present in ordinary oxygen.

The preliminary investigations for this problem were done with a target which had been used previously.[17] The final data were taken with a thinner target prepared in the same fashion.[12] The energy lost by protons passing through this target was measured by determining the increases in the electrostatic generator potential necessary to reach the $Li^7(p,n)$ threshold and certain resonances in the $F^{19}(p,\alpha\gamma)$ reaction when the target was placed in the beam. For work below the $O^{18}(p,n)$ threshold the target was oriented so the normal to the target made an angle of 47° with respect to the incoming beam. In this position 2.0-Mev protons lost 26 ± 1 kev in passing through the target. Above the $O^{18}(p,n)$ threshold this angle was reduced to 32° so as to decrease the effective thickness of the target in order to improve the energy resolution.

Comparisons between the alpha-particle yields of the older, thick target (whose O^{18} content had been carefully determined previously[17]) and the thin target, indicated that the thin target contained $(2.0\pm0.3)\times10^{17}$ atoms of O^{18} per square centimeter.

From the measurements of the dimensions of the target chamber it was found that the average solid angle through which particles could leave the target and enter the counter was $(4.0\pm0.15)\times10^{-3}$ steradian. The neutron detector subtended a solid angle of 0.59 steradian at the target.

RESULTS

The observed yields of alpha particles at 90° and of neutrons at 0° as a function of incident proton energy are shown in Fig. 1. The yield scale for the neutron production is arbitrary since the sensitivity of the neutron detector was not known. The scale of the alpha particle yield curve is such that one unit is equivalent to a cross section of 1.38 millibarns per steradian. The uncertainty in this scale factor is chiefly due to the uncertainty in the number of O^{18} atoms in the target. This has been estimated at $\pm15\%$, but may be as large as $\pm25\%$.

Data on several of the peaks in the alpha-particle yield were repeated two or three times over a period

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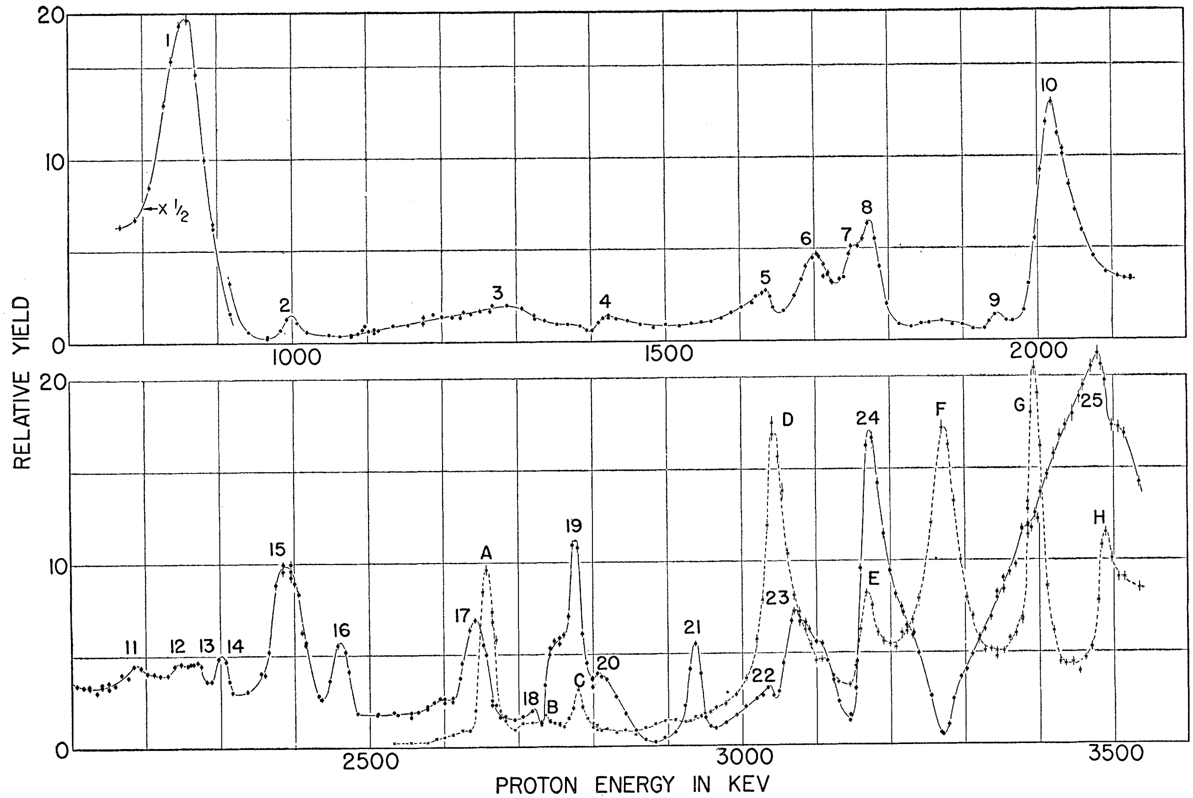

FIG. 1. Yields of the reactions $O^{18}(p,\alpha)N^{15}$ at 90° (circles and solid curve) and $O^{18}(p,n)F^{18}$ at 0° (asterisks and dashed curve). Neutron yield is on an arbitrary scale. One unit of α-particle yield is equal to 1.38 millibarns per steradian. Proton energies are uncorrected for target thickness.

of three months. The absolute yield was found to be reproducible to within the counting statistics, as indicated by the vertical extent of some of the data points on the graphs, and the energy scale was reproducible to within $\pm 0.1\%$.

Table I lists the proton energies in the laboratory system of coordinates which produced the most prominent maxima in the yield of alpha particles. The errors quoted for the energies are largely due to the uncertainty in the exact location of the top of the peaks due to the asymmetries of the peaks or an unfortunate spacing of the data points. The proton energies, in the tabulated data, have been corrected for target thickness.

Table II lists the proton energies which produced the most prominent maxima in the yields of neutrons and the observed widths of some of the peaks at half-maximum height. The peaks for which no widths are listed had shapes which made it difficult to give a valid estimate of their widths. For comparison purposes there are also listed some previously published data.[6]

The threshold energy for the $O^{18}(p,n)$ reaction was found to be 2577 ± 8 kev as compared with 2590 ± 4 kev determined at Wisconsin[4] and 2584 ± 10 kev recently published by Mark and Goodman.[6]

The production of γ rays was observed simultaneously with the $O^{18}(p,\alpha)$ reaction in the neighborhood of the peak at 1934 ± 4 kev. The maxima in both yields occurred at the same energy. This is comparable with the strong resonance in the γ-ray yield reported at 1931 ± 2 kev by Butler and Holmgren.[18]

DISCUSSION OF RESULTS

The resonances observed in the yield of alpha particles below the $O^{18}(p,n)$ threshold serve to locate fifteen energy levels in F^{19} which have not been previously reported. The position of the lowest level observed differs from the previously reported value by slightly more than the sum of the uncertainties quoted. The difference may be due to an underestimate of target thickness. A similar degree of agreement appears between the present values of the neutron resonances and those previously published. However, it is worth noting that the widths of the peaks at half-maximum observed here are consistently less than the earlier values.

The neutron threshold obtained here is consistent with both previously published values,[4,6] although

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TABLE I. $O^{18}(p,\alpha)N^{15}$ resonances. Energies of protons (E_p) which produced maxima in the yield of alpha particles at 90°. Energies have been corrected for target thickness. The resonances are numbered as shown in Fig. 1. Column 3 gives the excitation energy (E_x) of the compound nucleus, F^{19}.

Resonance	E_p (kev)	E_x (Mev)
1	838±6	8.749
2	980±4	8.883
3	1271±10	9.159
4	1406±4	9.287
5	1621±4	9.491
6	1688±4	9.554
7	1736±5	9.600
8	1761±4	9.623
9	1934±4	9.787
10	2007±4	9.856
11	2175±4	10.016
12	2232±5	10.070
13	2258±5	10.094
14	2291±5	10.125
15	2378±5	10.208
16	2450±5	10.276
17	2635±5	10.451
18	2712±5	10.524
19	2767±5	10.576
20	2798±6	10.606
21	2929±5	10.730
22	3029±6	10.825
23	3064±6	10.858
24	3165±6	10.953
25	3473±6	11.245

lower than either. The position of the one γ-ray resonance observed agrees well with the previously reported value.[18]

A comparison of the curves in Fig. 1 as well as the proton energies given in Tables I and II shows that the peaks in the yields of neutrons and alpha particles do not, in general, occur at the same proton energies. This cannot be due to shifts in the energy scale since the two reactions were observed simultaneously. At 2929±5 kev an alpha-particle peak has no corresponding neutron peak at all. At 3264±6 kev a strong neutron peak coincides with a deep minimum in the alpha particle yield. In contrast, a neutron peak at 3163±6 kev agrees well with an alpha-particle peak at 3165±6 kev, and there are several other cases where there is a slight shift between the two. The significance of these variations might be much more apparent when angular distribution and total cross-section data for both reactions become available.

Butler and Holmgren[18] have made a search for gamma-ray emitting levels of F^{19} by a study of the $O^{18}(p,\gamma)$ reaction. They proposed that the 9.062-Mev level (E_p=1169 kev) which they observed was a member of an isotopic spin quartet. If this were a $T=\frac{3}{2}$ level of F^{19}, then the $O^{18}(p,\alpha)N^{15}$ reaction via this state would be forbidden. The experimental

TABLE II. $O^{18}(p,n)F^{18}$ resonances. Energies of protons (E_p) which produced maxima in the yield of neutrons in the forward direction. Energies have been corrected for target thickness. The resonances are designated by letters corresponding to those on Fig. 1. Column 3 gives, for comparison, the values of E_p previously published (reference 6); column 4 gives the values of resonance width at half-maximum (Γ) observed here, after correction for target thickness; and column 5 gives the values of Γ previously published.

Resonance	E_p (kev)	Previous E_p (kev)	Γ (kev)	Previous Γ (kev)
A	2649±5	2657±2	10±3	40±2
B	2726±5	2732±6		
C	2772±5	2778±2	<20	35±5
D	3037±5	3045±2	33±3	60±2
E	3163±6	3170±2	18±6	45±10
F	3264±6	3268±2	29±3	65±2
G	3387±6	3386±2	15±3	45±2
H	3483±6	3495±4		

results in Fig. 1 for the $O^{18}(p,\alpha)N^{15}$ reaction seem to agree with this hypothesis. The closest observed maximum in the yield is at E_p=1277 kev and is 200 kev wide.

One striking feature of the excitation functions is the appearance of more structure in the $O^{18}(p,\alpha)N^{15}$ excitation function than in the $O^{18}(p,n)F^{18}$ function. This cannot be accounted for by isotopic spin selection rules operating between nuclear states which are eigenfunctions of the isotopic spin operator since the conventional isotopic spin assignments for the ground states of N^{15} and F^{18} are $\frac{1}{2}$ and 0, respectively. Impurities in the states in F^{19} will not operate to preferentially inhibit one of the reactions. On the other hand, if the isotopic spin impurities of the ground states of F^{18} and N^{15} are the causes for the observed differences, then the admixture of $T=\frac{3}{2}$ into the ground state of N^{15} must be significantly larger than the admixture of $T=1$ into the ground state of F^{18}. It seems more likely that the differences in the excitation functions for the two reactions are attributable to large values of J for the excited states of F^{19}. Large values of J imply large values for the orbital angular momenta (L) taken off by the α particle and neutron. Since the α particles are emitted with approximately 5 Mev and the neutrons with 0.5 Mev or less, the large values of L would strongly inhibit neutron emission.

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