B. Li^7

Angular distributions at 200, 256, and 600 kev are shown in Fig. 5. Agreement at 200 and 600 kev is quite good. In order to compare the on resonance results with the theoretical curve, shown solid, a correction was made for the 20-kev resolution used, shown dotted. Again agreement is quite good.

Thomas *et al.*[9] have shown from the thermal scattering data that the potential scattering must be either all channel spin 1, or all channel spin 2. Extrapolating to the energies under consideration, this would lead in the case of $s=2$ to a much stronger interference term than that obtained using a statistical mixture. If the potential scattering were all channel spin 1, there would be no interference term. Accordingly, asymmetry ratios were measured with 5-kev resolution for bombarding energies of 200, 220, 255, 287, 400, and 510 kev as shown in Fig. 6. The dotted curve is theoretical for a statistical mixture. All channel spin 1 would produce no asymmetry; all channel spin 2 would have a ratio of 5 at 220 kev. Multiple-scattering corrections would tend to raise the experimental values below 260 kev but not enough to agree with all $s=2$ potential scattering. It is concluded that $J=3^+$ is correct, the s-wave scattering phase shift is positive, and a statistical channel spin potential scattering mixture gives the best fit to the data.

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Angular Distribution of Neutrons from $O^{18}(p,n)F^{18}$†

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The reaction $O^{18}(p,n)F^{18}$ has been studied using monoenergetic protons from the Rockefeller electrostatic generator. Resonances in the neutron yield in the forward direction are found at proton energies $E_p=2.657$, 2.732, 2.778, 3.045, 3.170, 3.268. 3.386, 3.495, 3.600, and 3.755 Mev. The angular distribution of neutrons from this reaction at proton energies $E_p=3.045$, 3.170, 3.268, and 3.386 Mev has been measured with a proton recoil counter. The most probable values of the spins of the excited states in F^{19} corresponding to these resonances are $J=\frac{3}{2}^{\pm}$, $\frac{1}{2}^{\pm}$, $\frac{3}{2}^{\pm}$, and $\frac{1}{2}^{\pm}$ respectively.

I. INTRODUCTION

ANGULAR distribution experiments may be used in several ways to study the dynamics of a nuclear reaction. If the reaction goes through a compound system with well-defined energy levels, it may be possible to determine the angular momentum quantum numbers of these levels.[1,2] On the other hand, if the compound system has broad, overlapping energy levels, then a knowledge of the angular distribution of the reaction products as a function of energy may lead to information regarding the competing states by which the reaction may take place.[3,4]

The reaction $O^{18}(p,n)F^{18}$ has been studied previously by several workers. Blaser *et al.*[5] measured the neutron yield between proton energies of 2.5 and 7.0 Mev with relatively poor resolution and found seven broad resonances in this region. Richards *et al.*[6] measured the neutron yield with much better resolution between 2.5 and 3.75 Mev and were able to show that some of the broad resonances observed by Blaser *et al.* are actually due to the superposition of several sharp, well-defined resonances in the yield. These authors also made an accurate determination of the $O^{18}(p,n)F^{18}$ threshold. The sharp resonances in the yield and the relatively large cross section make this reaction well suited for a more detailed study.

II. TARGETS

The target used in the experiment was obtained by oxidizing a 10-mil tantalum disk in an atmosphere of enriched (20% O^{18}) oxygen. It was found that the amount of oxygen deposited could be varied by controlling the pressure of oxygen in the chamber. In this manner it was possible to obtain targets with a surface layer containing a known amount of oxygen. The target used in this experiment had roughly 10^{19} atoms of O^{18} per square centimeter.

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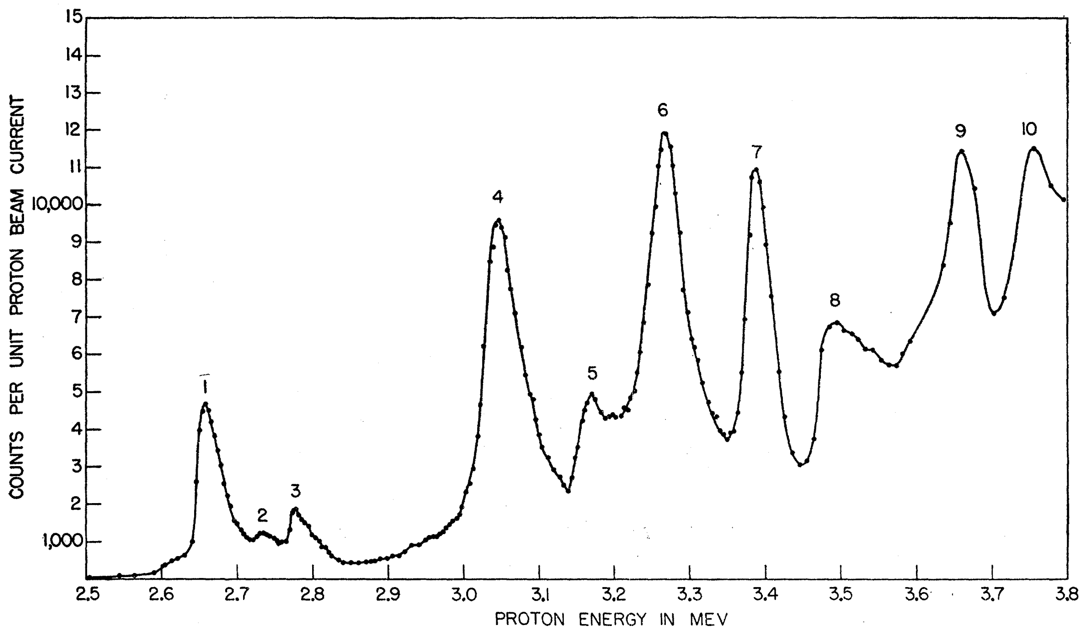

FIG. 1. Neutron yield from $O^{18}(p,n)F^{18}$ in the forward direction obtained with the BF_3 counter. The observed resonances are numbered in order of increasing energy and the observed properties are listed in Table I.

III. TOTAL NEUTRON YIELD

Monoenergetic protons (0.1% resolution) from the Massachusetts Institute of Technology—Rockefeller electrostatic generator were used to bombard the enriched O^{18} targets described above. The total yield of neutrons in the forward direction from the reaction $O^{18}(p,n)F^{18}$ was measured as a function of proton energy in 5-kev intervals between threshold and 3.8 Mev. A BF_3 counter of the type described by Hansen and McKibben[7] was used to detect the neutrons. The machine was calibrated by using the $Li^7(p,n)Be^7$ reaction threshold[8] at $E_p=1881.4\pm1.1$ kev. The yield curve is shown in Fig. 1. Ten resonances are observed in the neutron yield which correspond to excited energy levels in the compound nucleus F^{19}. The threshold of the reaction $O^{18}(p,n)F^{18}$ was determined as $E_t=2.584\pm0.010$ Mev, in good agreement with the value $E_t=2.590\pm0.004$ Mev reported by Richards *et al.*[6] The energies of resonances 1, 3, 4, 5, 6, 7, and 8 are also in reasonably good agreement with the results obtained by these workers. Table I summarizes the data obtained. The half-widths Γ quoted in column 3 are the experimental half-widths obtained directly from Fig. 1. No attempt has been made to correct these values for the finite thickness of the target since the thickness of the oxide layer was not known.

IV. ANGULAR DISTRIBUTIONS

A hydrogen-filled (65 psi) proton recoil counter was used to measure the angular distribution of neutrons. The response of this counter relative to that of the BF_3 counter as a function of neutron energy is shown in Fig. 2. Since the response of the BF_3 counter is roughly independent of neutron energy in this region,[9] the curve shown in Fig. 2 closely approximates the actual response of the recoil counter over this energy region. The output from the counter was biased so that pulses corresponding to neutrons with energies less than 100 kev were not counted. Above 300 kev, the response varies roughly as the total neutron scattering cross section of hydrogen. The pronounced dip in the response curve at roughly 450 kev is probably due to the oxygen in the glass cap

TABLE I. Summary of data. The resonances are numbered as shown in Fig. 1. Column 2 shows the proton energy in kev at which the peak of the resonance appears. Column 3 lists the experimental widths at half-maximum; column 4 gives the neutron yield, Y_R, relative to resonance 6; column 5 gives the excitation energy E_x, compound nucleus, F^{19}, for each resonance; and column 6 indicates the most probable spin, J, assigned to the excited levels in F^{19} obtained from the angular distribution data.

Resonance	E_p (kev)	Γ (kev)	Y_R	E_x (Mev)	J
1	2657±2	40±2	0.399	10.471	···
2	2732±6	···	0.109	10.542	···
3	2778±2	35±5	0.160	10.586	···
4	3045±2	60±2	0.807	10.839	$\frac{3}{2}$
5	3170±2	45±10	0.420	10.957	$\frac{1}{2}$(?)
6	3268±2	65±2	1.000	11.050	$\frac{3}{2}$
7	3386±2	45±2	0.932	11.162	$\frac{1}{2}$(?)
8	3495±4	···	0.580	11.265	···
9	3600±20	85±20	0.966	11.365	···
10	3755±20	···	0.966	11.511	···

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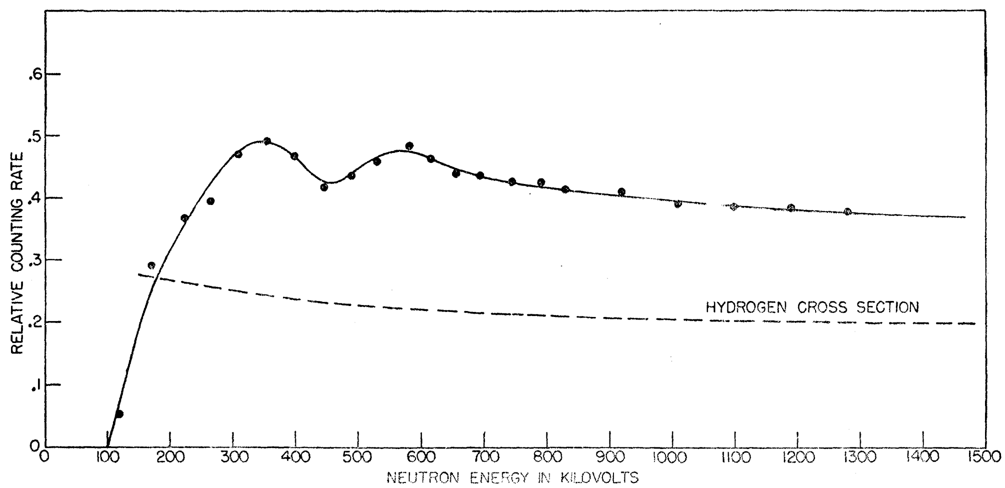

FIG. 2. Sensitivity of the proton recoil counter as a function of neutron energy. This curve was obtained by comparing the response of the recoil counter with that of the BF_3 counter at various neutron energies.

of the counter tube. Oxygen has a large resonance in the scattering cross section at this neutron energy. The recoil counter was used as a neutron detector because it is insensitive to the background of scattered slow neutrons and because its response is relatively independent of neutron energy over the region of interest. For a given bombarding-proton energy, the energy of the outgoing neutrons will be a function of angle because of center-of-mass motion. The experimental results must therefore be corrected for this effect by using the curve shown in Fig. 2.

The angular distribution measurements were made by mounting the proton recoil counter on a goniometer which made it possible to swing the counter in a horizontal arc around the direction of the proton beam from 0° to 140° in the laboratory system. The experimental geometry is shown in Fig. 3. At each angle, the number of neutron counts for a constant number of microcoulombs of protons on the target was determined. A BF_3 monitor was used to make certain that the number of neutrons per unit proton current remained constant throughout each run.

The curves shown in Fig. 4 are the angular distributions of neutrons in the center-of-mass system at proton energies corresponding to resonances 4, 5, 6, and 7.

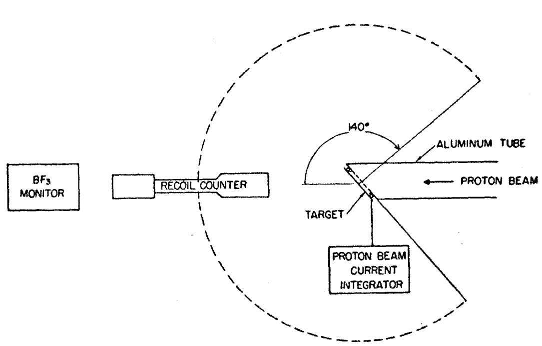

FIG. 3. Experimental geometry. The recoil counter is mounted on a goniometer which permitted measurements on either side of the beam axis.

These results have been corrected for the changing sensitivity of the recoil counter to neutrons emitted from the target at various angles. It was not possible to measure angular distributions from resonances 1, 2, and 3 because the neutron energy is too low and from resonances 8, 9, and 10 because the machine could not be held steady at these energies for the rather long time required for each run. Measurements were made on both sides of the target in order to eliminate systematic errors in alignment.

The results were analyzed using the statistical methods given by Rose.[10] The highest order of $P_L(\cos\theta)$ necessary to fit the data was determined by calculating all coefficients and errors up to $L=4$ and then discarding all those with errors equal to or larger than the coefficient itself. The solid curves in Fig. 4 are drawn from the best fit (calculated for $L_{\max}=2$ for resonances 4 and 6) obtained from the experimental points which are shown. Table II summarizes the results. The large errors in the coefficients are a result of the inefficiency of the recoil counter which makes the counting time for good statistics prohibitively long.

V. INTERPRETATION OF RESULTS

The results described in the previous section may be used to obtain information regarding the angular momentum quantum numbers of the excited levels in F^{19} which correspond to the resonances in the neutron yield. The methods of Blatt and Biedenharn[11] have been used to make the analysis. The quantum numbers of the ground states of O^{18} and F^{18} are $J=0^+$ and $J=1^+$ respectively.[12] The zero ground-state spin of O^{18} simplifies the calculation since only one incoming channel spin ($s=\frac{1}{2}$) need be considered. Two outgoing channel spins are possible and hence the angular distribution will be

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the incoherent sum of the contributions from each channel. In all calculations, only the neutron group going to the ground state of F^{18} need be considered since the first excited state of F^{18} is at 1.05 Mev.[12]

The distributions obtained from resonances 5 and 7 are isotropic within the experimental uncertainty. The excited levels in $F^{19}(E_x=10.957$ and 11.162 Mev) corresponding to these resonances should therefore have angular momentum $J=\frac{1}{2}^+$ or $\frac{1}{2}^-$. It should be pointed out that these results are not entirely trustworthy. As can be seen from Fig. 4, both of these distributions actually have a small systematic anisotropy. However, no coefficients can be calculated because of the large experimental errors. No parities can be determined from these data.

The anisotropic distributions obtained from resonances 4 and 6 indicate that for these levels ($E_x=10.839$ and 11.050 Mev) $J>\frac{1}{2}$. Resonances 4 and 6 both also exhibit angular distributions which are not symmetric about 90°. Odd orders of $P_L(\cos\theta)$ appear in angular distributions if the reaction proceeds through two states of the compound nucleus which have opposite parities. It is probably, therefore, that the angular distributions at these resonances is influenced by a broad energy level of opposite parity on which these resonances seem to be superposed (see Fig. 1).

Since the highest order of $P_L(\cos\theta)$ necessary to fit the data for these angular distributions is $L=2$, the probable value of the spin for the states in F^{19} corresponding to these resonances is $J=\frac{3}{2}^+$ or $\frac{3}{2}^-$. A more detailed analysis of the data does not seem fruitful in view of the large experimental uncertainties and the large number of unknown parameters in the theoretical formulas.

TABLE II. Angular distributions. The best fit of the experimental data to a series of Legendre polynomials, $W(\theta)=P_0+(a_1/a_0)P_1+(a_2/a_0)P_2$. The errors in the coefficients include only the statistical deviations in the counting rate and the statistical errors made in the corrections for the sensitivity of the recoil counter.

Resonance	$W(\theta)$
4	$P_0+(0.12\pm0.02)P_1-(0.52\pm0.03)P_2$
5	P_0
6	$P_0+(0.33\pm0.02)P_1-(0.14\pm0.03)P_2$
7	P_0

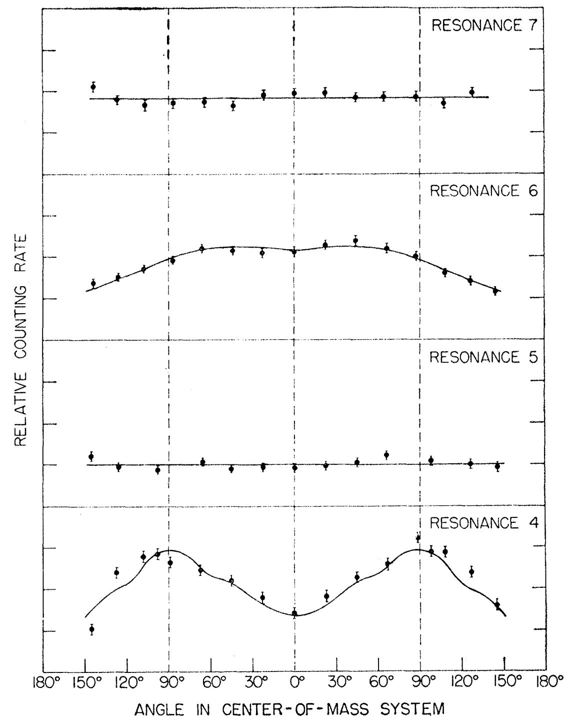

FIG. 4. Angular distributions. This figure shows the angular distribution of neutrons in the center of mass system at proton energies $Ep=3.045$, 3.170, 3.268, and 3.386 Mev, corresponding to resonances 4, 5, 6, and 7 respectively. These results have been corrected for the change in sensitivity of the counter for neutrons emitted from the target at various angles.

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