was reported for the $Fe^{54}(n,t)Mn^{52m}$ (21 min) reaction.

One would expect *a priori* that (n,He^3) reactions near threshold should have cross sections somewhat smaller than similar (n,t) reactions owing to the larger Coulomb barrier against He^3 particle emission. Even with a diffuse nuclear surface and consequent lower barrier, one would not expect He^3 emission to predominate over H^3 emission near threshold. If the nuclear surface exhibited a tendency for clustering into H^2, H^3, He^3, He^4, etc. groupings,[17] then the probability for emission of tritons and He^3 particles should be about equal[18] if one neglects the Coulomb barrier effect.

[17] D. H. Wilkinson, Phil. Mag. 4, 215 (1959).
[18] B. L. Cohen and A. G. Rubin, Phys. Rev. **114**, 1143 (1959).

Thus, the fact that we have been able to show conclusively that (n,He^3) cross sections at this energy are not larger than the limits found for (n,t) reactions at this energy is in agreement with *a priori* expectations.

Work in this laboratory is continuing in an attempt to study rare reactions at 14.5 Mev; e.g., (n,t), (n,He^3), $(n,n'\alpha)$, and $(n,2p)$.

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Radiative Proton Capture in O^{18}†

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The excitation function for radiative proton capture in O^{18} has been observed at zero degrees with a 3-in.×3-in. NaI crystal. Bias adjustments were selected in order to establish the resonances for proton capture which lead to the emission of high-energy radiation. About twenty resonances were found for protons ranging in energy from 1.6 to 3.0 Mev, and there were indications for a number of weaker additional resonances. A slow-coincidence technique was used to investigate the gamma decay schemes for F^{19} for six levels of excitation from 8.56 to 10.10 Mev. Quantitative conclusions are drawn regarding the decay of these levels to the ground "triplet" of F^{19}.

I. INTRODUCTION

PRELIMINARY results on the reaction $O^{18}(p,\gamma)$ were previously reported from this laboratory.[1] The excitation function for this reaction has been measured by Butler and Holmgren[2] for protons up to 2 Mev, and the gamma-ray spectra at seven resonances have been reported.[3] The present experiment overlaps this work and extends it to 3.0 Mev. Hill and Blair[4] have studied energy levels in the same region through the $O^{18}(p,\alpha)N^{15}$ and $O^{18}(p,n)F^{18}$ reactions, and Carlson *et al.*[5] have observed elastic scattering and the yield of alpha particles in the bombardment of O^{18} by protons. Resonances established in these reactions are compared with those which we have observed through proton capture.

At six of the more prominent resonances for proton capture, we have observed the decay scheme of F^{19} to the "ground triplet," i.e., to the ground state or to one of the low-lying excited levels at 110 or 198 kev.

II. EXPERIMENT AND ANALYSIS OF DATA

A. Generator and Targets

This work was performed with the University of Texas Van de Graaff generator. The proton beam was analyzed by a 90° magnet. The magnetic field was measured and monitored with a proton resonance gaussmeter, and gaussmeter frequency was read directly on a Beckman EPUT meter. Absolute calibration of the gaussmeter-magnet system was accomplished on the $Li^7(p,n)$ threshold, which was taken to be 1.8811 Mev. In order to check this calibration, three $F^{19}(p,\alpha\gamma)$ resonances were measured at 872.7, 1346, and 1372 kev with a thin MnF_2 target.

Targets used for the $O^{18}(p,\gamma)$ studies were ZrO_2. They were prepared by heating 0.025-in. zirconium in the presence of water vapor[6] which was enriched to 85%

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* Now at Florida State University, Tallahassee, Florida.
[1] E. L. Hudspeth, I. L. Morgan, and J. T. Peoples, Phys. Rev. **99**, 643(A) (1955); J. W. Nelson and E. L. Hudspeth, Bull. Am. Phys. Soc. **5**, 109 (1960).
[2] J. W. Butler and H. D. Holmgren, Phys. Rev. **99**, 1649(A) (1955).
[3] J. W. Butler and H. D. Holmgren, Phys. Rev. **116**, 1485 (1959).
[4] H. A. Hill and J. M. Blair, Phys. Rev. **104**, 198 (1956).
[5] R. R. Carlson, C. C. Kim, J. A. Jacobs and A. C. L. Barnard, Phys. Rev. 122, 607 (1961).
[6] Enriched water produced by Weizmann Institute, Rehovoth, Israel.

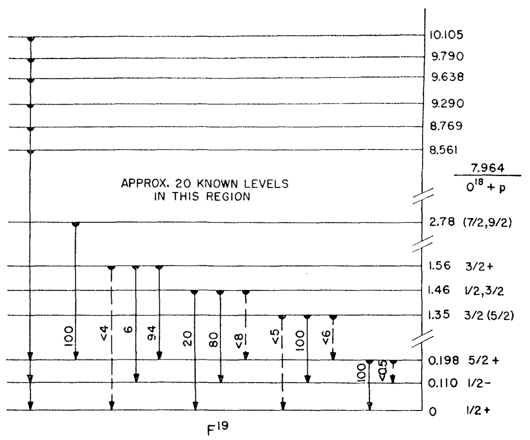

FIG. 1. Low-lying levels in F^{19} and selected higher levels (upper six in the figure) which are formed by $O^{18}(p,\gamma)$. Decay schemes investigated in the present work are indicated by a line at extreme left. Note relatively wide separation of nearly 1.15 Mev between ground "triplet" and first excited "triplet." This makes possible the observation of 0.198-Mev gamma rays and 0.110-Mev gamma rays which are in coincidence with direct decays to levels in F^{19} at those energies.

in O^{18}. Background runs were obtained by bombarding targets prepared from normal water and also blank zirconium targets.

B. Yield of Gamma Rays

The yield of gamma rays as a function of bombarding energy was measured at 0° with respect to the proton beam. Pulses produced in a 3-in.×3-in. NaI crystal mounted on a DuMont 6363 photomultiplier were analyzed in either a 20-channel analyzer or in a Penco 100-channel analyzer. Complete gamma-ray spectra were obtained at certain resonant bombarding energies, but general surveys over the bombarding interval from about 0.6 to 3.0 Mev were made by counting all pulses above some assigned value (as explained in captions and subsequent sections). The primary purpose of this part of the work was simply to locate resonances for proton capture which form F^{19} in excited states which decay directly to the ground state or to low-lying levels. We did, however, locate numerous relatively weak resonances whose decay schemes we did not study.

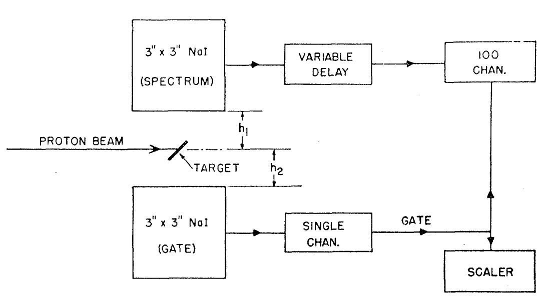

FIG. 2. Arrangement of apparatus which was used to detect coincidence between decays of highly-excited levels of F^{19} to one of the levels of the ground triplet.

C. Decay of Excited Levels of F^{19}

Coincidence Circuit

Some of the excited levels[7] of F^{19} which are of interest in this present work are shown in Fig. 1. Reference to that figure shows that the reaction $O^{18}(p,\gamma)$ may produce levels in F^{19} at 7.964 Mev or greater. Inasmuch as there are more than twenty excited levels in F^{19} below this value, the decay of F^{19} which is produced through $O^{18}(p,\gamma)$ will generally be quite complex.

In order to restrict our observations to decays which proceed directly from a specific level produced by proton capture to one of the levels of the ground triplet, the coincidence arrangement shown schematically in Fig. 2 was employed. Gate trigger pulses for the 100-channel analyzer were obtained from the differential discriminator of a Hamner non-overloading amplifier. The gate setting was checked in separate observations by feeding the output of the amplifier to the 100-channel analyzer, which was in turn gated by the differential

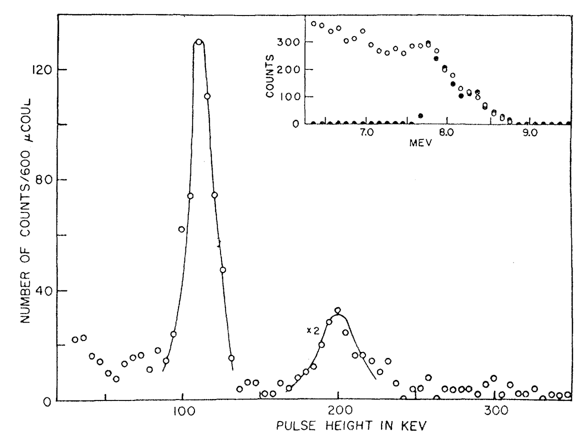

FIG. 3. Coincidence spectrum obtained at $E_p = 849$ kev with 90°–90° geometry. The inset shows the high-energy portion of the total spectrum (open circles) which was recorded in the gate counter when it was not in coincidence with the spectrum counter. (see Fig. 2). The dots in the inset show that, in coincidence operation, the spectrum counter was turned on only when the gate counter detected a pulse of approximately 7.7 Mev or more.

discriminator. Thus a visual presentation of the gate-generating portion of the total spectrum was obtained, as shown in the inset of Fig. 3. If, for example, direct decay to the ground triplet of the 8.769-Mev level of F^{19} were under observation, the gate trigger was adjusted so that the 100-channel analyzer was turned on only if the gate crystal recorded a pulse of about 7.7 Mev or more. Such a pulse could be recorded only if the decay from the 8.769 state proceeded directly to one of the levels of the ground triplet, since a decay directly to any other levels could yield at most an energy of about 7.4 Mev. In order to check our gate adjustments, the gate trigger was, on several occasions, purposely lowered

[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. 11, 1 (1959).

so that decays to the first excited "triplet" (centered about 1.46 Mev) would turn on the 100-channel analyzer. In such cases, the spectrum revealed peaks at about 1.4 Mev, in addition to those at 0.198 and 0.110 Mev. (Pursuit of such observations would of course furnish information regarding decay to the first excited triplet, since the decay scheme for levels of this triplet to the lower levels is known.)

In the early stages of this work, we also obtained coincidence data with the spectrum counter placed at 0° and the gate counter placed at 90° (instead of using the 90°–90° arrangement shown in Fig. 3). In these cases, the gate trigger pulses for the 100-channel analyzer were obtained from a 20-channel analyzer at the BNC connectors at the rear of the pulse sorter. Auxiliary electronics provided inversion, isolation, and mixing of pulses before application to the external gate connector of the 100-channel analyzer. Proper operation of the system was checked with a Co^{60} source.

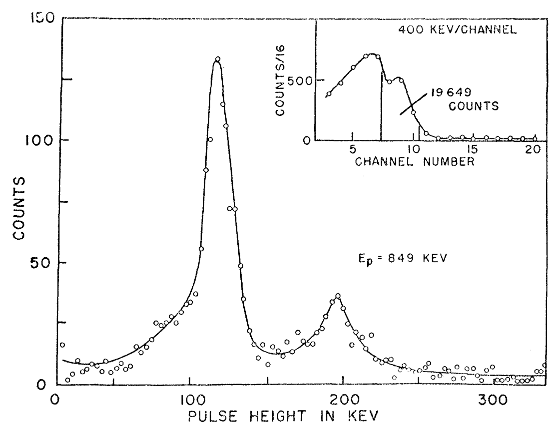

FIG. 4. Coincidence spectrum obtained at $E_p=849$ kev with 0°–90° geometry. The inset shows the high-energy portion of the total spectrum. The spectrum counter was turned on only when the gate counter received a pulse in channels 8-10 (corresponding to 7.5–8.7 Mev).

Analysis of Coincidence Data

As an example of the coincidence data, the coincidence spectrum obtained at $E_p=849$ kev ($E_x=8.769$ Mev) is shown in Fig. 3. This coincidence spectrum was analyzed as follows, using the general information on NaI crystals as reported by Heath.[8] For this particular case, $h_1=3.02$ cm and $h_2=3.18$ cm (see Fig. 2). The gate crystal recorded 5629 counts of pulse height beyond the gate setting of 7.7 Mev. The total number of counts in the 110-kev peak is 516; in the 198-kev peak there are 90 counts. The peak-to-total ratio of 110-kev radiation in a 3-in.×3-in. NaI crystal is 0.99; for 198-kev radiation this ratio is 0.93. Hence the number of 110-kev gamma rays which were incident on the crystal is about 520; the corresponding value for the 198-kev radiation is 97. For $h_1=3.02$ cm, the efficiency of the 3 in.×3 in. crystal is 0.184 for 110-kev gamma rays and 0.157 for 198-kev gamma rays. Hence the total number of 110-kev gamma rays which issued from the target (assuming isotropic emission) and which were in time coincidence with the 5629 gate counts is 520/0.184, or 2820; the corresponding figure for the 198-kev radiation is 618. Hence decay of the 8.769-Mev level of F^{19} through the ground triplet proceeds 50% through the 110 kev level and 11% through the 198-kev level; the remainder, 39%, must then represent decay directly to the ground

[8] R. L. Heath, Atomic Energy Commission Report IDO-16408, 1957 (unpublished).

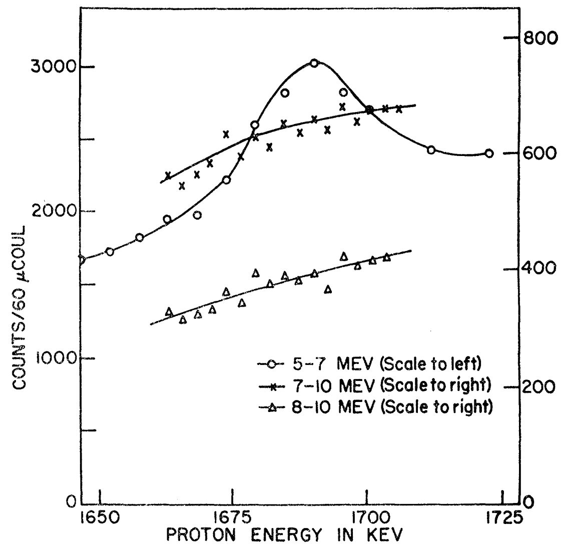

FIG. 5. Excitation curve observed in the vicinity of $E_p=1680$ kev. No resonance is apparent in the 7–10 Mev or 8–10 Mev channels; this indicates that, if $O^{18}(p,\gamma)$ is resonant in this region, there is no observable decay to the ground triplet of F^{19}. The resonance which appears in the 5–7 Mev channels is thought to arise from $F^{19}(p,\alpha\gamma)$.

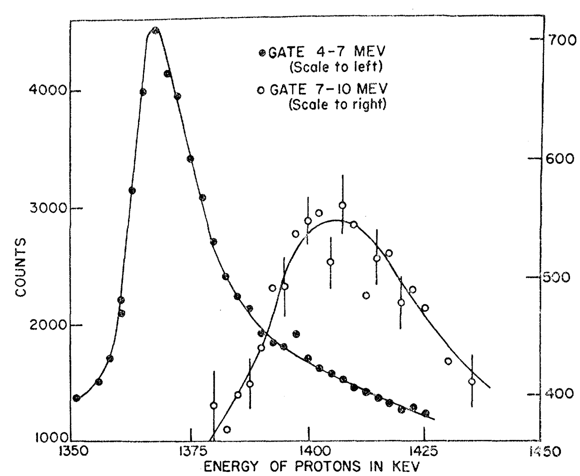

FIG. 6. Excitation curve observed in the vicinity of $E_p=1400$ kev. In contrast to the results of Fig. 5, a resonance now appears in the 7–10 Mev channels. It is ascribed to $O^{18}(p,\gamma)$. The resonance which appears at about 1370 kev is ascribed to $F^{19}(p,\alpha\gamma)$.

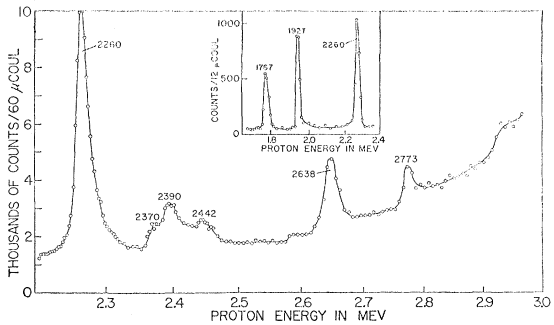

FIG. 7. Excitation curve for $O^{18}(p,\gamma)$. The inset data were obtained at 0° to the bombarding proton beam in a 3-in.×3-in. NaI crystal which was placed about 3 cm from the target. The target was about 25-kev thick for protons of energy 2.5 Mev. The inset shows data obtained with the detector bias adjusted so that only decays of F^{19} to the lowest six states were observed. The main curve was obtained with a constant window of 7–10 Mev.

level itself. Probable errors in these figures were estimated from the statistical errors and errors in estimation of background. A second run, with $h_1=5.08$ cm (and hence lowered crystal efficiencies) gave values of 52%, 13%, and 35%, respectively, for these decays; the agreement is within the estimated errors.

All of the 90°–90° coincidence spectra were analyzed in a similar manner.

A coincidence spectrum which was taken at $E_p=849$ kev with 0°–90° crystal geometry is shown in Fig. 4. The gate crystal was 3 in.×3 in. NaI and the spectrum crystal was $1\frac{1}{2}$ in.×$1\frac{1}{2}$ in. NaI. The gate counts fell into an interval of approximately 7.5 to 8.7 Mev. The data were analyzed in a manner similar to that described above.

III. RESULTS AND DISCUSSION

A. Excitation Curves

Our initial investigations of $O^{18}(p,\gamma)$ were in the energy region up to $E_p=2$ Mev. This has been previously investigated[1–3] in some detail, and excitation curves for this region have been published.[3] We observed the levels previously reported at 630, 849, 1169, 1399, 1769, and 1931 kev and at very nearly those energies. For the levels at 1767 and 1927 kev, we also observed (with thin targets) values of Γ which were, respectively, less than 5 kev and 1 kev. A detailed examination of the region beyond 1767 kev yielded evidence for two more very weak resonances located at 1778 and 1790 kev. This observation was repeated with an iron-backed target and blank.

We were not able to confirm the existence[3] of a level at 1688 kev when our observations were made with window settings of either 7–10 Mev or 8–10 Mev (see Fig. 5). A resonance did appear at about 1685 kev, however, with window settings of 5–7 Mev. This is very close to a known resonance[7] in the reaction $F^{19}(p,\alpha\gamma)O^{16}$ at $E_p=1694$ kev, $\Gamma=35$ kev. Inasmuch as fluorine is almost always observed as a contaminant of our targets, we suspect that the resonance shown in Fig. 5 near 1685 kev arises from it rather than O^{18}. This would not explain the results of Butler and Holmgren,[3] however, since their window setting was 8.4–9.6 Mev when the 1688-kev resonance was observed. In any case, they report it as very weak, and it is possible that background obscured it in our work.

These observations led us to re-examine the $O^{18}(p,\gamma)$ resonance reported at 1399 kev. We studied the region between 1350 and 1450 kev with two window settings. A resonance does appear (see Fig. 6) at $E_p=1403$ kev in the data which were taken with a 7–10 Mev window. We therefore conclude that this resonance is associated with $O^{18}(p,\gamma)$. With a window setting of 4–7 Mev, a resonance was observed at approximately 1375 kev, which is the value of a known[7] resonance for $F^{19}(p,\alpha\gamma)$. This lends support to our belief that fluorine was a target contaminant.

Figure 7 shows the excitation curve for $O^{18}(p,\gamma)$ in the region between 2.2 and nearly 3.0 Mev; the inset shows some of our lower-energy data which overlap earlier work.[3] The window settings which apply to the inset were adjusted so that only direct decays of F^{19} to levels of the ground triplet and the first excited triplet were counted. The window for the main curve of Fig. 3 was set at 7–10 Mev. Data were obtained at 0° with respect to the bombarding proton beam; the detector was a 3-in.×3-in. NaI crystal, which was placed approximately 3 cm from a target of thickness about 25 kev for 2.5-Mev protons. Figure 8 covers approximately the same energy interval, but in this case a 12-kev target was used and the detector was biased so as to record all pulses beyond those which could be produced by gamma rays from $O^{17}(p,\gamma)$, for which $Q=5.62$ Mev. The thinner target and the lower bias make possible the observation of additional resonances in $O^{18}(p,\gamma)$. The very prominant resonance at 2260 kev corresponds to

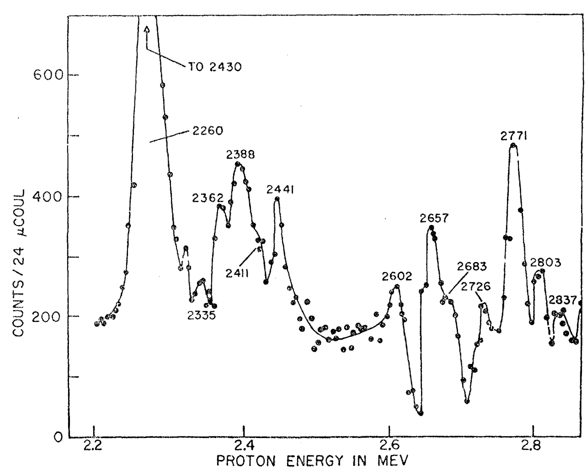

FIG. 8. These data were obtained under conditions similar to those described in caption for Fig. 7, except that the target was 12-kev thick and the detector bias was varied so that all counts above those which could arise from $O^{17}(p,\gamma)$ ($Q=5.62$ Mev) were just eliminated.

TABLE I. Resonances observed in $O^{18}(p,\gamma)$ for protons of energy 2.2–3.0 Mev.

Proton energy[a] (kev)	Particle emitted[a]	Proton energy[b] (kev) Target A	Target B	Γ (kev)
2258	α	2260	2260	7±2
2291	α,γ		?	
		2335		
			2362	
2378	α,γ	2370		
			2388	47±10
2403*	α	2399	2411	10±5
2450	α,γ	2443	2441	
2570*	α			
			2603	
2635	α	2638	?	
2655	n		2657	
			2683	
2712	α			
2729	n		2726	
2773	n,α	2773	2771	
2798	α		2803	
2824*	α		2837	
2929	α			

[a] The entries in these columns (except those marked with an asterisk) are drawn from the compilation of Azjenberg-Selove and Lauritsen (reference 7) and represent mean values for resonance energies of bombarding protons. Values marked with an asterisk represent new levels reported by Carlson *et al.* (reference 5), who observe α-emission at all resonance entries shown in the first column.

[b] Entries in these two columns are drawn from present work and represent proton resonances associated with $O^{18}(p,\gamma)$. Target A was 25 kev thick; target B, 12 kev (see Figs. 7 and 8, respectively).

the unresolved alpha resonance which Hill and Blair[4] found at 2258 kev, while their broad alpha resonance at 2378 kev corresponds to the three resonances shown in Fig. 8 at 2362, 2388, and 2411 kev. Their neutron resonance A at 2649 kev may correspond to a distortion of the 2657-kev resonance of Fig. 8. Hill and Blair's neutron resonances B (2726 kev) and C (2772 kev) correspond to the 2726 and 2771 kev resonances for $O^{18}(p,\gamma)$ shown in Fig. 8. In order to check that these were gamma-ray resonances (rather than neutron resonances which were being observed through capture of thermal neutrons by the crystal), observations were

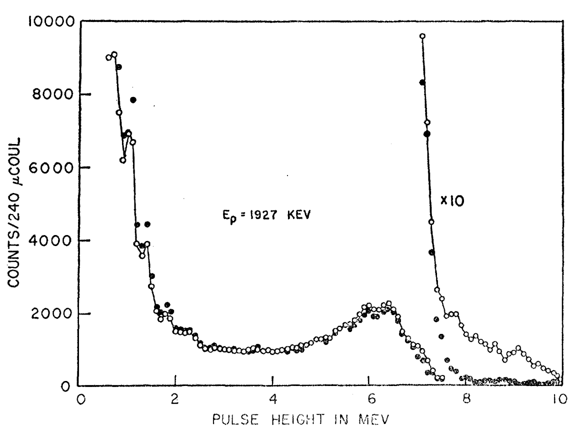

FIG. 9. Complete spectrum obtained at $E_p=1927$ kev for the gamma radiation emitted in the $O^{18}(p,\gamma)$ reaction. The data for the enriched O^{18} target (circles) and a normal target (dots) overlap almost precisely except at energies above approximately 7.5 Mev. This indicates that the 9.790-Mev level in F^{19} decays almost entirely to the lowest six levels of F^{19}.

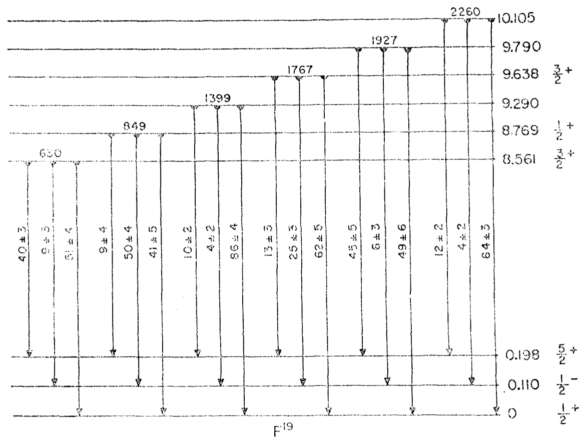

FIG. 10. Decay schemes of F^{19} from six selected levels to levels of the ground triplet. The levels are shown (in Mev) at the right, and corresponding values of E_p (in kev) are shown just above the half-dots on the arrows which indicate decay from a given level. Percentage decays are shown, with estimated errors, for the 90°–90° coincidence arrangement shown in Fig. 2.

taken with and without paraffin between the target and the crystal and no change was noted.

In the region between 2.2 and 3.0 Mev, Hill and Blair[4] found at least five $O^{18}(p,\alpha)$ resonances which are stronger than the one which they found at 2258 kev. This is, however, much the strongest resonance for gamma-ray emission in this region.

The levels which we have located in F^{19} through excitation studies of $O^{18}(p,\gamma)$ are shown in Table I, where they are compared with data which have been previously compiled.[7]

B. Gamma-Ray Spectra

Spectra were taken for each resonance which was selected for coincidence studies, but inasmuch as we are concerned only with the lower states of F^{19} they are not of importance here except in establishing the window positions for the coincidence work. The spectrum for decay from the 9.790-Mev level ($E_p=1927$ kev) is shown, however, in Fig. 9, since it reveals that the decay from this level proceeds almost enitrely to the states of the ground triplet or the first excited triplet. The following qualitative remarks apply to the spectra which were observed:

- 630 kev: predominantly to the ground triplet;
- 849 kev: complicated decay;
- 1399 kev: strong to the ground triplet;
- 1767 kev: complicated decay;
- 1927 kev: decay entirely (within limit of observation—see Fig. 9) to the ground triplet and first excited triplet;
- 2260 kev: predominantly to the ground triplet.

The background runs were taken with targets prepared from normal water; the contribution to the spectrum in the region of 6 Mev is from fluorine con-

tamination. These results agree with those of Butler and Holmgren,[3] who obtained spectra at all of these resonances except for 1399 kev and 2260 kev.

C. Decay Schemes

The decay of six excited levels of F^{19} to members of the ground triplet were observed by the coincidence method previously described. The results of these studies are shown in Fig. 10. The levels in F^{19} are indicated (in Mev) to the right of the diagram, and the proton energies (in kev) which excite these levels through bombardment of O^{18} are shown just above the half-dots which mark the beginning of each transition.

Data are shown only for the 90°–90° coincidences with apparatus arranged as shown in Fig. 2. As stated previously, the 0°–90° observations were made prior to those at 90°–90°, and in this earlier work we were not able to maintain constant values of target-crystal distance nor to use the same size crystals throughout. This means that angular resolution was not constant throughout all of the 0°–90° coincidence runs. The data for 0°–90° generally agreed within the estimated errors with those at 90°–90°, with indications of strong anisotropy only at E_p=630 kev and possibly at 2260 kev.

All 90°–90° data were taken with h_1 fixed at about 3 cm and h_2 (which does not enter into the calculation of the decay scheme) at approximately the same value.

The spins and parities shown in Fig. 10 are drawn from a general compilation,[7] except for the parities of the 8.561- and 8.769-Mev levels and for the spin and parity of the level at 9.638 Mev; these are from the work of Carlson *et al.*[5]

We also made coincidence studies of the decay of F^{19} which is formed by bombardment at two off-resonance positions. At E_p=1265 kev, the percentage decays of F^{19} to the ground level, 110-kev level, and 198-kev level were, respectively, 79±5, 10±3, and 11±4; at E_p =1565 kev, these values were 83±5, 4±2, 13±4. Hence, these two decay schemes agree within the estimated errors of measurement. Furthermore, they are very close to the values observed for the decay of states in F^{19} which are produced by resonance bombardment at E_p=1399 and 2260 kev.

The excited levels of F^{19} have been the subject of numerous theoretical studies. Elliott and Flowers[9] have, on the basis of intermediate coupling calculations, obtained results which agree with the known low-lying levels of even parity. Their lowest even-parity level for $T=\frac{3}{2}$ lies below the levels excited by proton capture in O^{18}, but it appears likely that some of the higher levels in the region 8.5 to 10 Mev could be identified with states which they predict. Redlich[10] has compared calculations based on the deformed-nucleus wave functions with those for the shell model. His two lowest $T=\frac{3}{2}$ levels correspond to excitations in F^{19} which are thought to lie at 7.40 Mev and at 9.07 Mev[3,11] (E_p=1169 kev). A third $T=\frac{3}{2}$ level is calculated[10] to lie near 10.47 Mev, which would correspond approximately to E_p=2.65 Mev. The excitation curve in this vicinity for alpha and neutron emission[4] and for gamma emission (Fig. 8) is too complex to single out a resonance which could be assigned $T=\frac{3}{2}$. A high-resolution study might yield the required information. The interpretation by Paul[12] of certain levels of F^{19} on the rotational model also leads to levels (of spins $\frac{7}{2}$ and $\frac{9}{2}$) in the region near 9.6 and 11 Mev. Assignment of spins and parities to most of the levels which have now been experimentally observed must await angular correlation experiments or other additional data.

ACKNOWLEDGMENTS

We wish to express our thanks to Joseph T. Peoples and Dr. J. D. Henderson for their cooperation in operation of the equipment and in analysis of the data.

[9] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).
[10] M. G. Redlich, Phys. Rev. **110**, 468 (1958).
[11] G. Amsel and G. R. Bishop, Phys. Rev. Letters **6**, 655 (1961); Phys. Rev. **123**, 957 (1961).
[12] E. B. Paul, Phil. Mag. **2**, 311 (1957).