The term which has the form of the interaction of an excited j' nucleon with the closed shells can be written down in a close form. We have to add contributions from the appropriate shells and only from nucleons identical to the excited one. We get for a closed shell with $2j+1$ identical nucleons, by using the technique of Sec. II,

$$\langle j^{2j+1}(0)j' | (\sum_{i=1}^{2j+1} \mathbf{r}_i)\cdot\mathbf{r}' | j^{2j+1}(0)j'\rangle$$
$$=(2j+1)\langle j^{2j+1}(0)j' | \mathbf{r}_1\cdot\mathbf{r}' | j^{2j+1}(0)j'\rangle$$
$$=(2j+1)\,\langle j^{2j}(j)j_1(0)j' | \mathbf{r}_1\cdot\mathbf{r}' | j^{2j}(j)j_1(0)j'\rangle$$
$$=(2j+1)\sum_J (2J+1)W^2(jjj'j';0J)V_J'$$
$$=\frac{1}{2j'+1}\sum_J (2J+1)V_J'. \quad \text{(A11)}$$

Inserting the values of V_J' from (A6) and (A7), we obtain

$$-\frac{1}{2j'+1}\sum_J (2J+1)(nl\|r\|n'l')^2(2j+1)(2j'+1)$$
$$\times W^2(ljl'j';\tfrac{1}{2}1)W(jj'j'j;J1)$$
$$=-(2j+1)(nl\|r\|n'l')^2W^2(ljl'j';\tfrac{1}{2}1)$$
$$\times\sum_J (2J+1)W(jj'j'j;J1). \quad \text{(A12)}$$

Using Eq. (43) reference 16, we can carry out the summation over J:

$$\sum_J(2J+1)W(jj'j'j;J1)=-[(2j+1)(2j'+1)]^{\frac{1}{2}}$$
$$\times(-1)^{j+j'}\sum_J(-1)^{J+1}W(jjj'j';0J)$$
$$\times W(jj'j'j;J1)=-(-1)^{j+j'}[(2j+1)(2j'+1)]^{\frac{1}{2}}$$
$$\times W(jjj'j';01)=1. \quad \text{(A13)}$$

Thus the interaction of a $n'l'j'$ nucleon with the closed nlj shell is

$$-(2j+1)(nl\|r\|n'l')^2W^2(ljl'j';\tfrac{1}{2}1). \quad \text{(A14)}$$

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Gamma-Ray Threshold Method and the $O^{18}(d,n\gamma)F^{19}$ Reaction

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A neutron threshold technique involving observations of the gamma rays from the de-excitation of the residual excited states is described. A study of the $O^{18}(d,n\gamma)F^{19}$ reaction with this technique has resulted in the observation of neutron thresholds at bombarding energies of 346±8, 525±8, and 584±10 kev. These thresholds correspond to states at 6.048±0.014, 6.210±0.014, and 6.262±0.015 Mev in the F^{19} nucleus, respectively. A detailed gamma-ray spectrum was obtained at a bombarding energy of 1.00 Mev using a single-crystal spectrometer, and another detailed spectrum was obtained at 1.40 Mev using a three-crystal pair spectrometer. Coincidence measurements were made for several of the cascade gamma rays.

I. INTRODUCTION

NEUTRON threshold techniques have been used to observe a number of nuclear reactions[1] in order to determine the energies of excited states in the residual nuclides. The essence of the neutron threshold method is the use of a detector which discriminates against the "fast" neutrons in favor of the "slow" neutrons (a few kev of energy) which are emitted just above their threshold. Since these techniques generally have utilized enriched BF_3 or boron-lined proportional counters surrounded by a small amount of paraffin moderator, this discrimination against the faster neutrons is purely a statistical matter involving the B^{10} neutron-capture cross section as a function of neutron energy and the scattering cross section of hydrogen, also as a function of neutron energy. In addition, the fractional energy loss of the neutron per collision in the paraffin is also a statistical function, but is independent of neutron energy. Thus the ratio of "slow" to "fast" efficiencies is never large, as contrasted with electronic pulse-height discrimination employed in modern scintillation detectors. A further complication in the above method of threshold detection is that a neutron which leaves the target as a fast neutron might enter the detector as a slow neutron because of degradation of its energy by the floor and walls of the laboratory, or by the target assembly and the detector equipment.

A technique which involves the observation of the resulting gamma rays instead of the neutrons obviates many of the inherent disadvantages of neutron detec-

[1] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951). T. W. Bonner and C. F. Cook, Phys. Rev. **96**, 122 (1954). Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955). Butler, Dunning, and Bondelid, Phys. Rev. **106**, 1224 (1957).

tion. A new threshold may[2] result in the emission of a quantum of higher energy than any previously available, avoiding the necessity of detecting low-energy particles with a background of high-energy particles. Another advantage of gamma-ray detection is that modern scintillation techniques can be used, and therefore electronic pulse-height discrimination can be employed. If the $(d,n\gamma)$ Q-value is higher than those for the competing reactions, as in the case of O^{18}, and if the new threshold involves an excited state which decays primarily to the ground state, the "background" of pulses in the highest energy region due to lower energy gamma rays is usually negligible. Even when these two conditions are not met, the appearance of a new gamma ray can frequently be detected with the aid of multichannel pulse-height discriminators.

Still another advantage of this "gamma-ray threshold" technique over the neutron threshold technique is that quite often information can be obtained concerning the decay schemes of the excited states corresponding to the thresholds. Since two closely spaced states in the nucleus might decay by different schemes, they can sometimes be resolved by determining different thresholds for gamma rays of different energies.

For the reasons stated above, a gamma-ray threshold technique was used to investigate the $F^{19}(d,n\gamma)Ne^{20}$ reaction, and several thresholds were found and reported[3] in preliminary form. The present experiment concerns the application of the gamma-ray threshold technique to the $O^{18}(d,n\gamma)Fe^{19}$ reaction.

Before the present experiment was performed, the region of excitation between 5.5 Mev and 8.5 Mev in F^{19} was completely unexplored. With the use of threshold techniques and deuterons up to 1.8 Mev in energy, one can investigate the region of excitation from 6.0 to 7.3 Mev. That has been done and is reported herein. A preliminary account of a part of the present work has been published.[4]

II. THRESHOLD DETERMINATIONS

A. Experimental Procedure

Targets of O^{18} were prepared from the enriched gas[5] by oxidation of thin nickel foils (ten microinches thick). The deuterons were supplied by the NRL Nucleonics Division 2-Mv Van de Graaff accelerator. The gamma-ray spectrometer consisted of a 3-in. diam×3-in. NaI(Tl) crystal, a DuMont K 1197 three-in. multiplier phototube, a 20-channel differential pulse-height analyzer, and associated electronic equipment.

The crystal was placed about 2 in. from the target at 90° with respect to the deuteron beam. A liquid nitrogen cold trap was placed about one foot from the target, between the target and the magnetic beam analyzer, to deter the formation of carbon films or other contaminants on the target. This trap was not nearly so effective as later adaptations,[6] but did help considerably in keeping target contamination to a reasonably low value.

The gamma-ray spectrum was displayed on the 20-channel analyzer at each bombarding energy used. For most of the spectra, the analyzer calibration was about 166 kev per channel, and the 20 channels covered the region between about 3.3 and 6.6 Mev. Because the yield from the reaction rose rapidly as a function of deuteron energy, and because the gain of the phototube was observed to be a function of counting rate (or phototube current), precautions were taken to insure gain stability from one bombarding energy to another. For bombarding energies below 500 kev, where the yield was low, a Cs^{137} source was taped to the side of the NaI crystal to provide a calibration check. The source remained in position continuously to keep the total counting rate the same during calibration checks as during the data-taking periods. Before and after the spectrum was obtained at each different bombarding energy, the coarse (but precise) gain switch of the amplifier was changed by a factor of 8 to put the Cs^{137} 0.662-Mev gamma-ray peak at about the same position as that of a 5-Mev gamma ray. If the Cs^{137} peak had

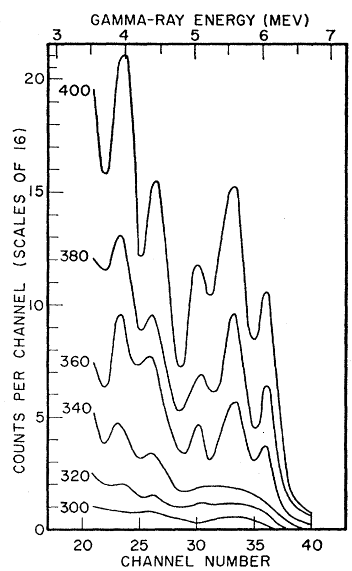

FIG. 1. Gamma-ray spectra recorded for bombarding energies from 300 kev to 400 kev in 20-kev intervals. Note the appearance of a new gamma ray of 6.1 Mev between 340 and 360 kev.

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[2] The word "may" is used because (1) the new state might not decay by emission of a single gamma ray to the ground state, and (2) the Q-values for the $(d,n\gamma)$ reaction and competing reactions, such as proton or alpha-particle emission, might be such that higher energy gamma rays are emitted in connection with such competing reactions.

[3] J. W. Butler, Phys. Rev. **98**, 241(A) (1955). Thresholds at 0.51, 0.60, 0.76, 0.85, 1.15, 1.35, 1.79, and 2.06 Mev of bombarding energy were reported verbally and also in a complete written account in an NRL progress report not generally available. A complete account is to be published.

[4] H. D. Holmgren and J. W. Butler, Phys. Rev. **99**, 655(A) (1955).

[5] The enriched O^{18} gas was kindly supplied by Professor A. O. C. Nier. The isotopic composition was as follows: O^{16}, 59.8%; O^{17}, 0.89%; and O^{18}, 39.3%.

[6] J. W. Butler and C. R. Gossett, Phys. Rev. **108**, 1473 (1957).

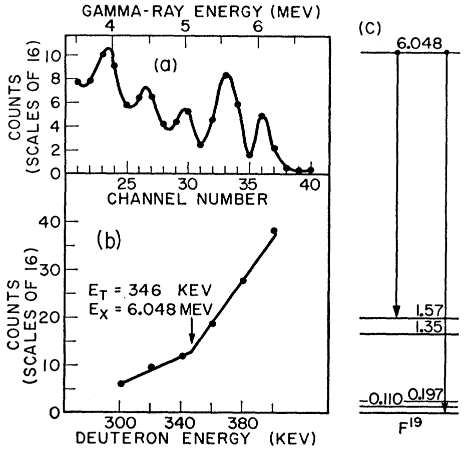

FIG. 2. (a) The sum of the individual channels at bombarding energies of 360 and 380 kev minus the sum of the individual channels at bombarding energies of 300, 320, and 340 kev. (b) The sum of the three peak channels—30, 33, and 36—as a function of bombarding energy. The position of the break determines the threshold energy. (c) The decay scheme of the residual state associated with the neutron threshold.

shifted slightly between bombarding energies, the phototube high voltage was changed slightly to bring the peak back into the same channel as before. The beam was on the target continuously. Above 500 kev of bombarding energy, the 1.37-Mev gamma ray from the reaction (de-excitation of the 1.57-Mev state by stop-over transition through the 0.197-Mev state) was used for a calibration check, and the Cs^{137} source was removed.

B. Results

Since the yield from the reaction was very low below about 250 kev of bombarding energy, data were not taken below this energy. Figure 1 illustrates the gamma-ray spectra at bombarding energies of 300, 320, 340, 360, 380, and 400 kev. Note the sudden appearance of a gamma ray of about 6.1 Mev of energy between bombarding energies of 340 and 360 kev. The three peaks at 6.1, 5.6, and 5.1 Mev are the total-capture, single-escape, and double-escape peaks, respectively, for a gamma ray of 6.1 Mev. Since the Q value of the reaction is 5.737 Mev,[7] the energy of a F^{19} state corresponding to a threshold in the vicinity of 350 kev would be about 6.1 Mev. Therefore, the gamma ray appearing at this threshold has the proper energy for a ground-state transition from the new excited state.

If one sums the individual channels for bombarding energies of 300, 320, and 340 kev and subtracts this spectrum, channel by channel, from the sum of the individual channels for bombarding energies of 360 and 380 kev, the spectrum shown in Fig. 2(a) is obtained. (The summing process is employed to obtain better statistics than were available from the spectrum obtained at a single bombarding energy.) Then if one sums the three peak channels—30, 33, and 36—at each bombarding energy and plots this sum as a function of deuteron energy, the curve shown in Fig. 2(b) is the result. The threshold energy is thus fixed by the break in the curve at 346±8 kev. From this threshold energy, one computes that the corresponding excited state in F^{19} is at 6.048±0.014 Mev. Part of the uncertainty in the energy of the state comes from the uncertainty in the masses.

A 4.4-Mev gamma ray exhibits the same threshold and therefore probably represents a transition from the 6.048-Mev state to the 1.57-Mev state. The decay scheme is illustrated in Fig. 2(c).

In the preliminary account of the present experiment, the 6.048-Mev state was given as 6.04 Mev because the mass tables of Ajzenberg and Lauritsen[8] were used, whereas in the present account the mass tables of Wapstra[7] were used. The threshold energy has not changed.

There was some evidence for another break in the vicinity of 370-380 kev, but such evidence was inconclusive and is therefore not illustrated. The excitation curve between 300 and 460 kev was obtained several times. On two of the curves, the possible break at about 370 kev was more pronounced than on the others. The gamma-ray energy appeared to be essentially the same as the one exhibiting a threshold at 346 kev. If there is another threshold about 370 kev, it corresponds to an excited state at 6.07 Mev in F^{19}.

The excitation curve was measured at 20-kev intervals up to a bombarding energy of 1.80 Mev. Two other thresholds were found and are illustrated in Figs. 3 and 4. Figure 3(a) was obtained by summing the individual

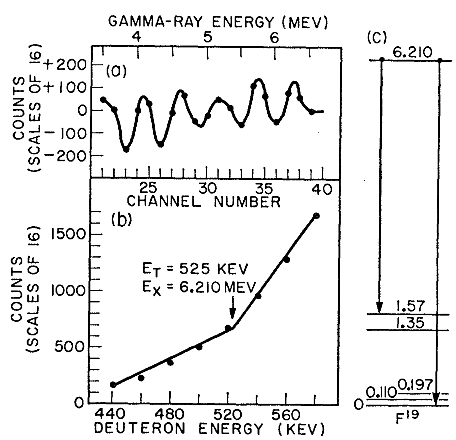

FIG. 3. (a) The sum of the individual channels at bombarding energies of 540, 560, and 580 kev minus the normalized sum of the individual channels at bombarding energies of 440, 460, 480, 500, and 520 kev. The normalization process makes the algebraic sum of the counts in all 20 channels equal to zero. (b) The sum of the peak channels—25, 28, 31, 34, 35, 37, and 38—as a function of bombarding energy. (c) The decay scheme of the residual state associated with the neutron threshold.

[7] Calculated from the mass tables of A. H. Wapstra, Physica **21**, 367 (1955).

[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

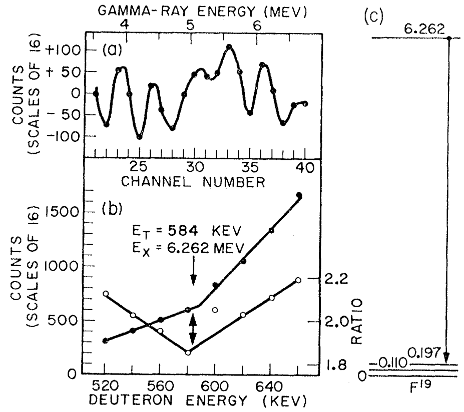

FIG. 4. (a) The sum of the individual channels at bombarding energies of 600, 620, and 640 kev minus the normalized sum of the individual channels at bombarding energies of 540, 560, and 580 kev. (b) The sum of the peak channels—30, 33, and 36—as a function of bombarding energy (solid circles); and the ratio of this sum to the sum of all 20 channels as a function of bombarding energy (open circles). Note the displaced zero on the "Ratio" scale, which is in arbitrary units. (c) The decay scheme of the residual state associated with the neutron threshold.

channels at bombarding energies of 540, 560, and 580 kev, and subtracting from this sum the normalized[9] sum of the channels obtained at bombarding energies of 440, 460, 480, 500, and 520 kev.

Note that the energy of the gamma ray shown in Fig. 3(a) is slightly higher than the one shown in Fig. 2(a), and that some evidence exists for a gamma ray in the region of 4.6 Mev, again representing a cascade transition to the 1.57-Mev state. The sum of the peak channels—25, 28, 31, 34, 35, 37, and 38—is plotted as a function of bombarding energy in Fig. 3(b), indicating a threshold break at 525±8 kev corresponding to an excited state at 6.210±0.014 Mev in F^{19}. The decay scheme is shown in Fig. 3(c).

Figure 4(a) shows the sum of the individual channels for bombarding energies of 600, 620, and 640 kev minus the normalized sum for bombarding energies of 540, 560, and 580 kev. In this case, the normalization number was 2.49. The range 540 to 580 kev was chosen because it represents the interval above the lower threshold (at 525 kev) but below the present threshold. Since the spectrum below about 5 Mev is primarily in the negative region of the graph, there is probably no new gamma ray appearing in this region at this threshold.

The solid circles in Fig. 4(b) show the sum of channels 30, 33, and 36 as a function of bombarding energy. Sometimes, when the over-all yield is rising rapidly or fluctuating as a function of bombarding energy, it is useful to "normalize" the yield by dividing the counts in each channel by the total counts in all 20 channels. This type of normalization was not necessary for the thresholds of the present experiment, but to illustrate the method, this type of normalization was used to obtain the open circles in Fig. 4(b). These open circles show the ratio of the sum of channels 30, 33, and 36 to the sum of all 20 channels as a function of deuteron energy. The threshold break is at slightly different points on the two curves, so the average value of 584±10 kev is adopted. This threshold energy corresponds to an excited state at 6.262±0.015 Mev in F^{19}. Figure 4(c) shows the decay scheme.

No other thresholds were observed up to the maximum deuteron energy used, 1.80 Mev. Table I lists a summary of all the thresholds observed, Q values, excited states, and gamma-ray energies.

III. GAMMA-RAY SPECTRA

A. Single Crystal

A detailed spectrum of the gamma rays emitted at a bombarding energy of 1.00 Mev was obtained by making six consecutive "sweeps" with the 20-channel analyzer. The resulting spectrum is shown in Fig. 5. The three peaks of the 6.1-Mev gamma ray are evident, with some slight indication of a 5.2-Mev gamma ray. This indication is very weak, however, because the other two peaks of such a gamma ray are not evident. There is some evidence[10] for a 5.2-Mev state in F^{19}, but the data of Fig. 5 are not considered to be additional evidence for such a state. The three peaks of the 4.4-Mev gamma ray are also evident. As suggested before, the 4.4-Mev gamma-ray peak is primarily from a cascade from the states at 6 Mev to the 1.57-Mev state, although it could also include a ground-state transition from a state of that energy or possibly some other cascade. The three peaks of a 3.09-Mev gamma ray are quite evident. This gamma ray comes from the $C^{12}(d,p\gamma)C^{13}$ reaction as the result of a contaminant film of carbon on the target. The 1.35-Mev gamma ray is the cascade from the 1.57-Mev state to the 0.197-Mev state. Its great intensity is an indication that most of the upper states decay to the 1.57-Mev state a great deal of the time, unless the neutron group corresponding to this state also has a very high relative intensity. Seale[10] measured

TABLE I. Summary of neutron thresholds observed in the $O^{18}(d,n\gamma)F^{19}$ reaction.

Deuteron energy (kev)	Q-Value (kev)	Energy of excited state in F^{19} (Mev)	Gamma-ray energies (Mev)
346± 8	−311±7	6.048±14	4.4 and 6.0
525± 8	−472±7	6.210±14	4.6 and 6.2
584±10	−525±9	6.262±15	6.1

[9] The normalization process consists of multiplying the latter sum by a constant (in this case 1.46) to make the 20-channel sums equal. It would be unrealistic to subtract one peaked spectrum from another peaked spectrum of higher over-all intensity and expect to find other peaks in the difference. The normalization process meant that if the only difference between the two spectra was one of over-all intensity, because of the higher cross section, a straight line along the abscissa would be the result, with statistical deviations, of course.

[10] R. L. Seale, Phys. Rev. 92, 389 (1953).

the neutron spectrum of the $O^{18}(d,n)F^{19}$ reaction for a deuteron energy of 2 Mev, and in his spectrum the neutron group leaving the F^{19} nucleus in the 1.57-Mev state was of average intensity. The lowest energy gamma-ray peak (which goes off the top of the graph) represents the 0.875-Mev gamma ray from the $O^{16}(d,p\gamma)O^{17}$ reaction.

B. Pair Spectrometer

In order to search for other gamma rays which might be present, but obscured under on of the "escape" peaks of the more intense gamma rays, a three-crystal pair spectrometer was built and used to obtain the spectrum at a bombarding energy of 1.4 Mev. The nature of the spectrometer was relatively conventional and therefore will not be described (or shown) in detail. The center crystal was 1-in. diam×$1\frac{1}{2}$-in. long and the two wing crystals were $1\frac{1}{2}$-in. diam×1-in. long. The windows for the wing crystals were set for the range 460–560 kev, and a resolving time of 1 μsec was used.

Figure 6 illustrates the spectrum at a deuteron energy of 1.40 Mev. In addition to the 6.1- and 4.4-Mev peaks (labeled "6.0" and "4.3" Mev, respectively, in Fig. 6—the independent values from these data), there is weak evidence for the peaks at 4.8 and 3.4 Mev, and strong evidence for peaks at 3.9 and 2.6 Mev. Another spectrum obtained with twice the amplifier gain (and therefore channels half as wide) confirmed the 3.4-Mev peak and gave weak evidence for another peak at 2.3 Mev. In the single-crystal spectrum of Fig. 5, the peaks at 3.9 and 3.4 Mev appeared too intense with respect to the 4.4-Mev peak for them to be due to a single gamma ray but such evidence in a single-crystal spectrum is not conclusive. The 3-crystal pair spectrum confirms the presence of the 3.4- and 3.9-Mev gamma rays.

Another pair spectrum obtained at a deuteron energy of 2.00 Mev (not illustrated) indicated a low intensity gamma ray of about 7.0-Mev energy. Also in this spectrum, the peak at about 4.3 Mev was almost twice as high as the 6.1-Mev peak.

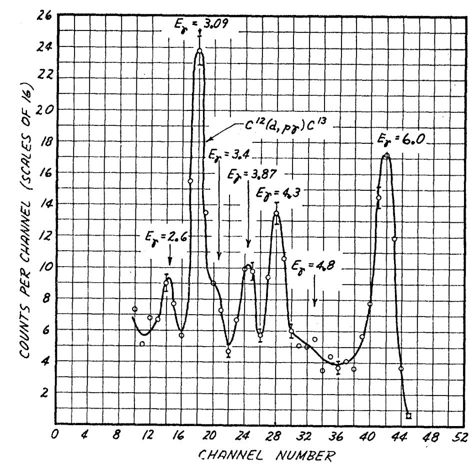

FIG. 6. Gamma-ray spectrum obtained with a three-crystal pair spectrometer at a deuteron energy of 1.40 Mev. Uncertainty bars are shown at representative points to indicate the statistical uncertainties.

IV. COINCIDENCE MEASUREMENTS

In order to observe the decay schemes of the states excited in the reaction, coincidence measurements were performed. The two crystals employed were 3-in. diam×3-in. long and $1\frac{1}{2}$-in. diam×1-in. long, respectively. In all cases the smaller crystal was used for the lower energy gamma rays and the larger crystal for the higher energy gamma rays. A Pb brick was placed between the crystals, and a resolving time of 1 μsec was used.

Figure 7 shows the low-energy gamma rays in co-

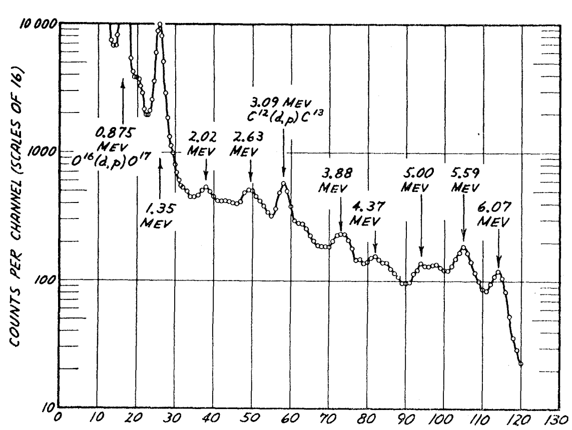

FIG. 5. Gamma-ray spectrum obtained with a 3-in.×3-in. NaI crystal at a deuteron energy of 1.00 Mev. The peaks at 3.09 and 0.875 Mev are due to the (d,p) reaction on C^{12} and O^{16}, respectively.

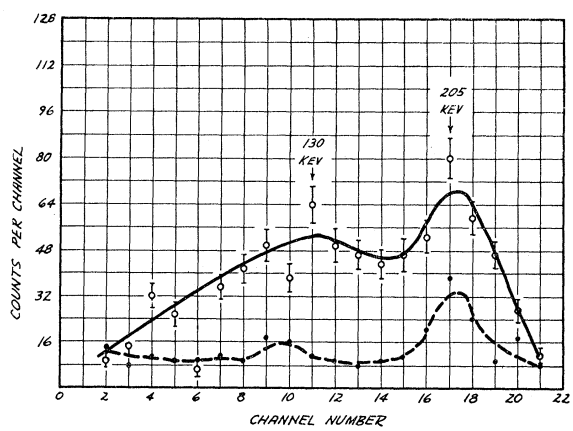

FIG. 7. Low-energy gamma-ray spectrum in coincidence with pulses in the larger crystal between 5.25 and 7.00 Mev, at a deuteron energy of 1.40 Mev. The solid circles are the accidental coincidences. The open circles are the total coincidences, true plus accidental. The total coincidence count in channel 6 is apparently spurious. The 205-kev peak represents the ground-state transition from the 197-kev state. The 130-kev peak is probably a ground-state transition from the 109-kev state even though the energy agreement is not good. A $1\frac{1}{2}$-in. diam×1-in. long crystal was used to obtain this low-energy spectrum.

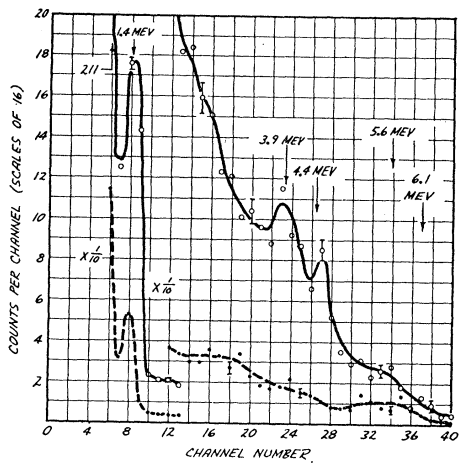

FIG. 8. High-energy gamma-ray spectrum in coincidence with pulses in the smaller crystal between 150 and 250 kev. The solid circles are the accidental coincidences. The open circles are the total coincidences, true plus accidental. A 3-in.×3-in. crystal was used.

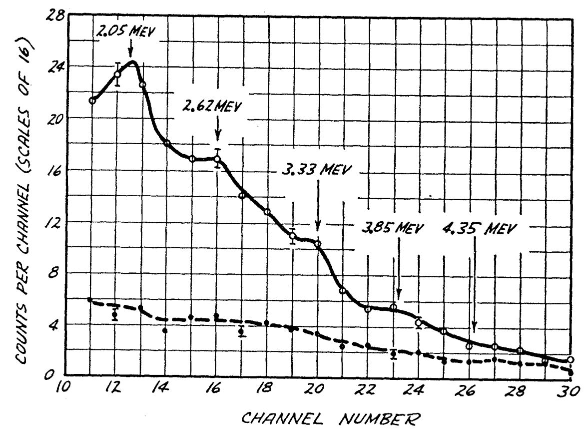

FIG. 9. Gamma-ray spectrum in coincidence with pulses in the smaller crystal between 1.20 and 1.60 Mev. The solid circles are the accidental coincidences. The open circles are the total coincidences, true plus accidental.

incidence with pulses in the larger crystal between 5.25 and 7.00 Mev, at a bombarding energy of 1.4 Mev. The 0.197-Mev state is clearly involved in cascades with the high-energy states, and the 0.110-Mev state is probably also involved although here the identification of the peak at 130 kev with the 110 kev transition is rather nubilous. The time intervals required to obtain the coincidence data were relatively long compared to the ungated spectra, and gain shifts could have occurred. The 0.197-Mev state cascades through the 0.110-Mev state less than 1% of the time,[11] so if the 110-kev gamma ray does appear here, it is excited by a transition whose energy appears in the window, that is, 5.25 to 7.00 Mev.

Figure 8 shows the complementary spectrum—the high-energy gamma rays in coincidence with pulses in the smaller crystal between 150 and 250 kev. The experimental arrangement here is less advantageous than the previous arrangement because (1) the high-energy pulses are spread out over a larger energy region (and therefore good statistics with good energy resolution are more difficult to obtain), and (2) some of the pulses in the 150–250 kev interval arise from gamma rays of any higher energy (and therefore true coincidences could be obtained without a 0.197-Mev gamma ray being involved).

The 4.4-Mev gamma ray appears strong in the coincidence spectrum and therefore probably represents, as suggested before, a cascade from the 6-Mev states to the 1.57-Mev state, which decays by emission of a 1.35-Mev gamma ray cascading through the 0.197-Mev state.

One final coincidence spectrum was obtained by setting a window about the 1.35-Mev gamma ray and using the resulting pulses to gate the analyzer recording the output of the larger crystal. The resulting spectrum is shown in Fig. 9. Although the 4.4-Mev gamma ray might be present in the coincidence spectrum, it is not so prominent as gamma rays of 3.3, 2.6, and 2.0 Mev. Perhaps the levels in the region of 4.9, 4.2, and 3.6 Mev (excited by neutron emission) also decay through the 1.57-Mev state, and thus tend to obscure the cascade contribution from the 6-Mev states.

V. DISCUSSION

Of the various reactions possible when O^{18} and O^{16} are bombarded with deuterons, the (d,n) reaction on O^{18} has the highest Q value, 5.7 Mev. The (d,α) reaction on O^{18} has the second highest Q-value, 4.2 Mev, but is not expected to produce gamma rays higher than about 3 Mev of an intensity at all comparable with the (d,n) reaction, due to the energy dependence of the alpha and neutron partial widths. The (d,p) reaction on C^{12} produces an intense 3.09-Mev gamma ray, and can produce gamma rays of 3.68 and 3.86 Mev above their thresholds at about 1.1 and 1.3 Mev, respectively. But these higher energy gamma rays are not expected to be of appreciable intensity until at least 0.5 Mev above their thresholds because of the Coulomb barrier to proton emission.

The spectrum of Fig. 6 has therefore been interpreted to arise from the $O^{18}(d,n\gamma)F^{19}$ reaction, except for the 3.09-Mev peak, which comes from the $C^{12}(d,p\gamma)C^{13}$ reaction, but this peak includes some contribution from the 3.06-Mev gamma ray from the $O^{16}(d,p\gamma)O^{17}$ reaction.

When F^{19} is left excited by the $O^{18}(d,n)F^{19}$ reaction, it can decay by both alpha-particle and gamma-ray emission if the residual state is above 4 Mev of excitation (as are all the states associated with neutron thresholds in the present experiment). Therefore, one might expect that above about 5 Mev of excitation the predominant mode of decay would be by alpha emission, and that gamma-ray emission would be unobservable. (This situation is reversed, however, if the residual excited state has an isobaric spin of $\frac{3}{2}$.) The states which

[11] C. A. Barnes, Phys. Rev. 97, 1226 (1955).

are observed (by means of their gamma-ray emission) in the present experiment are therefore expected to have relatively narrow alpha-particle widths.

In a recent experiment performed by Smotrich, Jones, McDermott, and Benenson,[12] observations were made on the alpha particles scattered by N^{15}, and in their results confirmation of all the levels found in the present experiment can be found. In the region of interest to the present experiment, they found states at 6.05, 6.07, 6.22, 6.26, 6.31, 6.51, and 6.53 Mev. The states at 6.05, 6.22, and 6.26 Mev are in excellent agreement with the states found in the present experiment at 6.048 ± 0.014, 6.210 ± 0.014, and 6.262 ± 0.015 Mev, respectively. In addition, the indication mentioned previously (in Sec. IIIB) for a threshold at 6.07 Mev was probably a real effect, although the existence of the state on the basis of the present experiment is still open to question.

No "gamma-ray thresholds" corresponding to the higher states were observed in the present experiment. Several possible reasons may be stated. (1) Selection rules inhibit low-energy neutron emission leaving these residual states. (2) These states have relatively small reduced proton widths. (3) These states have relatively small gamma-ray widths. (4) These states decay predominantly by cascade through one or more of the lower states. (5) The gamma-ray energies involved in the decay of these states are essentially the same as those associated with the lower states, and their appearance therefore makes only a very small increase in the yield of these gamma rays (or in other words, the sensitivity of the experimental technique has decreased).

One outstanding feature of the spectra of Figs. 5 and 6 is the relative intensity of the 6-Mev gamma ray with respect to the others. If most of this intensity is due to the 6.048-Mev state, as the spectra of Fig. 1 seem to suggest, then this state must have (1) a relatively large reduced proton width, (2) a relatively large gamma-ray width, (3) a relatively small alpha-particle width, or (4) a wave function having a relatively large overlap with the compound nucleus.

The first three possibilities mentioned above would be expected to hold if the 6.048-Mev state has an isobaric spin of $\frac{3}{2}$. On the basis of the O^{19}-F^{19} mass difference and the F^{17}-O^{17} decay energy, one would expect the first $T=\frac{3}{2}$ state in F^{19} to be at an excitation energy of about 7.5 Mev. Therefore, it appears unlikely that the 6.05-Mev state is a $T=\frac{3}{2}$ state, even though the reasons given in the previous paragraph to explain the intensity of the gamma ray from this state are consistent with a $T=\frac{3}{2}$ state. The 6.05-Mev state was formed by alpha-particle bombardment of N^{15}, and neglecting mixing and impurity of the isobaric spins, this fact would indicate that the isobaric spin of this state, as well as all the others found in the present experiment, is $\frac{1}{2}$. Thus it is not clear which of the possibilities mentioned above is primarily responsible for the relative intensity of the 6-Mev gamma ray.

Harlow *et al.*[13] observed the neutrons from the $O^{18}(d,n)F^{19}$ reaction, using the "ratio method"[1] and found a neutron threshold at 0.497 ± 0.015 Mev indicating an excited state in F^{19} at 6.184 ± 0.018 Mev. They did not extend their data below 400 kev, and therefore could not have observed the lowest threshold found in the present experiment, 346 kev. Their threshold at 497 ± 15 kev probably corresponds to the one at 525 ± 8 kev found in the present experiment, although the agreement of the measurements is not good. They did not observe the threshold found in the present experiment at 584 kev, and this is probably due to the greater sensitivity of the "gamma-ray threshold" method over the neutron threshold method with present-day detection techniques.

Another experiment relating to the same region of excitation in F^{19} was performed by Hossain and Kamal.[14] Using 9.5-Mev bombarding protons, they observed the inelastically scattered protons from the $F^{19}(p,p')^*F^{19}$ reaction, using photographic emulsions to measure the energies of the protons. They found a state at 6.07 ± 0.02 Mev and a possible state at 6.50 ± 0.09 Mev. They identified their state at 6.07 ± 0.02 Mev with the 6.05-Mev state reported in the preliminary account of the present experiment.[4] However, since Smotrich *et al.*[12] found states at both 6.05 and 6.07 Mev, it seems probable that the 6.07-Mev excited-state proton group of Hossain and Kamal was an unresolved doublet due to both states.

[12] Smotrich, Jones, McDermott, and Benenson, Bull. Am. Phys. Soc. Ser. II, 3, 26 (1958), and private communication from K. Jones.

[13] Harlow, Marion, Chapman, and Bonner, Phys. Rev. **101**, 214 (1956).

[14] A. Hossain and A. N. Kamal, Phys. Rev. **108**, 390 (1957).