Energy Levels in F^{19} from the $O^{18}(d,n\gamma)F^{19}$ Reaction

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The gamma-ray threshold technique has been applied to the $O^{18}(d,n\gamma)F^{19}$ reaction in the range of deuteron bombarding energies from 1.55 to 3.36 Mev. Four gamma-ray thresholds have been observed: 1.85±0.05, 2.15±0.05, 2.64±0.03, and 3.16±0.03 Mev, corresponding to excited states in F^{19} at 7.40±0.05, 7.67±0.05, 8.11±0.03, and 8.58±0.03 Mev, respectively.

I. INTRODUCTION

ABOVE 8.5 Mev, the $O^{18}(p,\gamma)F^{19}$ reaction[1] and the $O^{18}(p,\alpha)N^{15}$ reaction[2–4] have been used to determine the energies of excited states in the compound nucleus, F^{19}, by measurement of the bombarding energies of resonances. Between 6.0 and 7.3 Mev, the gamma-ray threshold method[5] has been applied to the $O^{18}(d,n\gamma)F^{19}$ reaction to determine the excited states in the residual F^{19} nucleus corresponding to deuteron bombarding energies from 0.25 to 1.80 Mev. In the present experiment, the use of this technique has been extended to cover the gap between 7.3 and 8.6 Mev corresponding to deuteron bombarding energies between 1.55 and 3.36 Mev, respectively.

II. EXPERIMENTAL PROCEDURE

The NRL 5-Mv Van de Graaff accelerator was used to furnish bombarding deuterons to the target chamber shown in Fig. 1. The targets were prepared by oxidation of thin nickel foils, 10 microinches thick, in an atmosphere enriched[6] in O^{18}. The thickness to 3-Mev incident deuterons was about 30 kev. A disk of pure tin, about 0.020-in. thick, was used to stop the deuterons after they had traversed the target. In order to check on the background yield the natural nickel oxide target (NiO^{16}) could be inserted into the path of the beam by means of the push rod, operating through an O-ring seal. The double target holder could be placed in the rear, since the two target holders were interchangeable. This permitted the use of an optional stopping disk, such as gold. The brass absorber between the target and the crystal was used to attenuate the intense low-energy gamma rays, such as the 0.875-Mev gamma ray from the $O^{16}(d,p)O^{17}$ reaction, and to scatter some of the neutrons out of the target-crystal path. The heater element (helical wire shown in Fig. 1) was used to prevent the buildup of carbon and other contaminants on the target.

The gamma-ray threshold technique has been described in a previous communication.[5] Basically, it involves the observation of the gamma rays emitted by the residual excited nucleus, instead of the observation of the neutrons emitted in the reaction. Thus the method has the advantage of dealing usually with a higher energy gamma ray at a new threshold, instead of a lower energy neutron. Consequently, modern scintillation techniques including electronic pulse-height discrimination, can be employed conveniently.

The NaI crystal, 1-in. diam×$1\frac{1}{2}$-in. long, was optically coupled to a 6292 multiplier phototube. (This particular crystal-tube combination has 7.5% resolution for the Cs^{137} 0.662-Mev gamma ray.) The yield of gamma rays for the reaction was relatively high, so the small size of the crystal was not a disadvantage from a counting rate point of view, but instead offered two advantages. (1) The ratio of neutron to gamma-ray sensitivity of the small crystal was less than for a larger crystal, and (2) the interpretation of the spectra of high-energy gamma rays was simpler than for a crystal of intermediate size because each gamma ray gave rise to essentially only one peak, namely, the double-escape peak in the response spectrum of the

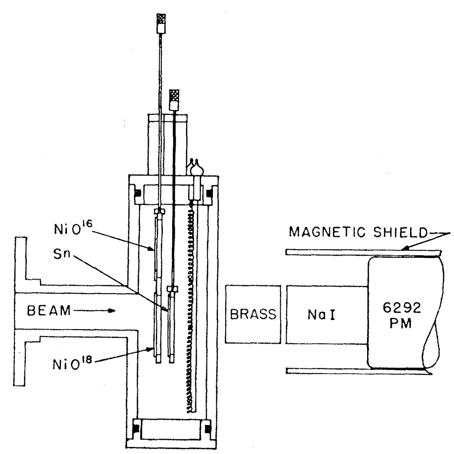

FIG. 1. Semischematic representation of the target chamber and crystal geometry. The brass absorber reduced the counting rate of low-energy gamma rays and neutrons. The beam stopper could be heated to diminish the background yield due to carbon buildup.

[1] J. W. Butler and H. D. Holmgren, Phys. Rev. 99, 1649(A) (1955).
[2] J. Seed, Phil. Mag. 42, 566 (1951).
[3] C. Mileikowsky and R. T. Pauli, Arkiv Fysik 4, 299 (1952).
[4] A. V. Cohen, Phil. Mag. 44, 583 (1953).
[5] H. D. Holmgren and J. W. Butler, Phys. Rev. 99, 655(A) (1955); J. W. Butler and H. D. Holmgren, Phys. Rev. 112, 461 (1958).
[6] 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%

crystal to pair production. The pulses from the scintillation counter were analyzed by a 20-channel pulse-height analyzer.

III. RESULTS

Four gamma-ray thresholds were found. The first three of these indicate new energy levels in F^{19}, while the fourth corresponds to the 0.630-Mev resonance in the $O^{18}(p,\gamma)F^{19}$ reaction.[1] Figure 2(a) shows the gamma-ray spectra below and above the first threshold found, the one at 1.85 Mev. The 5-Mev peak is the double-escape peak for a 6-Mev gamma ray. This prominent gamma ray was found in a previous experiment[5] to have a threshold at a bombarding energy of about 0.346 Mev, and corresponds to a state in F^{19} at 6.05 Mev. In order to make a detailed comparison of the two spectra possible, they have been normalized to the same total number of counts in the 20 channels. It is because of this normalization process that the counts per channel in the lower energy channels are greater below threshold than above. Thus, the apparent drop in the yield of the 6-Mev gamma ray is not real, and indicates only a relative drop with respect to the yield in all 20 channels.

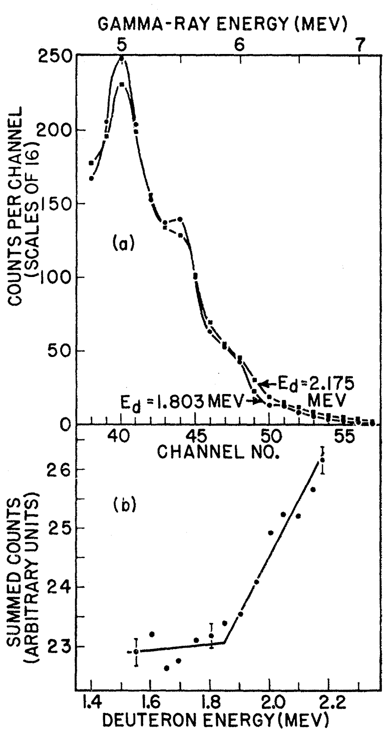

FIG. 2. (a) Gamma-ray spectra above (solid squares) and below (solid circles) the 1.85-Mev threshold. The two spectra have been normalized to the same total area. It is the combination of this normalizing process and the relative increase of high-energy gamma-ray counts above threshold that causes the apparent decrease in yield of the 6-Mev gamma ray (5-Mev double-escape peak). (b) The sum of the normalized channels 45–54 inclusive as a function of bombarding energy. The break at 1.85 Mev is considered to be the threshold. Standard statistical deviations are shown on representative datum points. The "Channel No." abscissa refers only to the curve in (a).

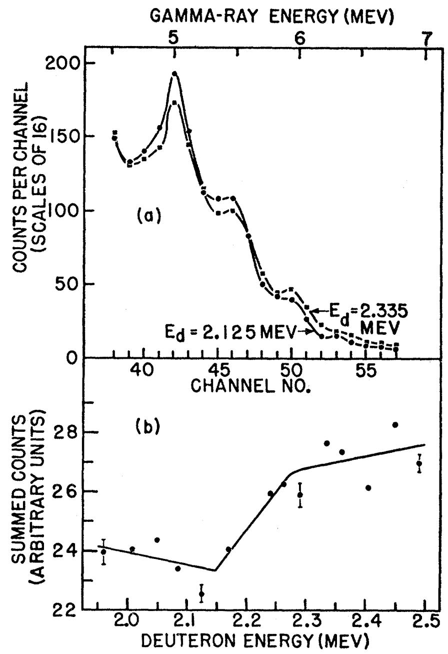

FIG. 3. (a) Gamma-ray spectra above (solid squares) and below (solid circles) the 2.15-Mev threshold. The two spectra have been normalized to the same total area. (b) The sum of the normalized channels 48 through 57 as a function of bombarding energy. Standard statistical deviations are shown on representative datum points. The "Channel No." abscissa refers only to the curve in (a).

In Fig. 2(a), the "threshold" gamma ray seems to be mainly in channels 46 to 54, inclusive. There is no peak corresponding to the typical spectrum of a single gamma ray, but this could be due to a number of factors: fairly large statistical uncertainties, high background, and multiplicity of gamma rays. In order to determine the position of the threshold, the sum of these normalized channels was plotted as a function of deuteron energy, and is shown in Fig. 2(b). The "break" indicating the position of the threshold occurs at a bombarding energy of 1.85±0.05 Mev, corresponding to a Q value for formation of this particular state in the residual F^{19} nucleus of -1.66 ± 0.05 Mev and corresponding to an excitation energy in F^{19} of 7.40±0.05 Mev. (This last value was computed using Wapstra's table of masses.[7]) The zero on the ordinate scale is displaced in order to magnify the region close to the threshold. This helps in determining the position of the threshold, even though the scatter of the datum points appears larger due to the magnification of their uncertainties.

Figure 3(a) shows the normalized gamma-ray spectra below and above the second threshold. Since the new gamma ray seems to be concentrated mainly in channels 48 to 57, inclusive, the sum of these channels is plotted in Fig. 3(b) as a function of deuteron energy. This curve indicates a threshold at a bombarding energy of 2.15±0.05 Mev, and thus a Q value of -1.93 ± 0.05

[7] A. H. Wapstra, Physica **21**, 367 (1955).

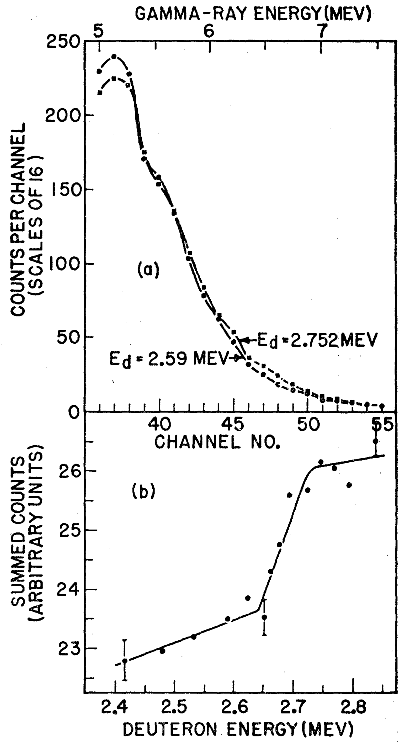

FIG. 4. (a) Gamma-ray spectra above (solid squares) and below (solid circles) the 2.64-Mev threshold, the two-spectra having been normalized to the same total area. (b) The sum of normalized channels 43 and 45 through 51 as a function of bombarding energy. Standard statistical deviations are shown on representative datum points. The "Channel No." abscissa refers only to the curve in (*a*).

Mev and a residual excited state in F^{19} at 7.67 ± 0.05 Mev.

The third threshold observed is illustrated in Fig. 4, where (a) depicts the normalized spectra below and above threshold, and (b) shows the sum of channels 43 and 45 through 51 as a function of deuteron energy. The threshold is thus indicated to be 2.64 ± 0.03 Mev, corresponding to a Q value of -2.38 ± 0.03 Mev, and an excited state in F^{19} at 8.11 ± 0.03 Mev. The fact that the resolution of the spectra in Fig. 4(a) appears to be poorer than in the previous two figures is primarily due to the increased intensity of the new gamma rays associated with the previous two thresholds.

The gamma-ray spectra associated with the fourth threshold observed are shown in Fig. 5(a). It can be seen that the predominance of the 6-Mev gamma ray is beginning to disappear. The sum of channels 43 through 49 inclusive are plotted in (b), indicating a threshold at 3.16 ± 0.03 Mev, a Q value of -2.84 ± 0.03 Mev, and an excited state in F^{19} at 8.58 ± 0.03 Mev. This threshold was observed on four different occasions giving values of 3.15, 3.15, 3.16, and 3.17 Mev, respectively. The adopted value is the one given above.

The results of all four threshold observations are presented in Table I which gives the deuteron bombarding energy, the Q value, and the energy of the residual F^{19} excited state.

IV. DISCUSSION

The above results give the excited states in F^{19} found by means of the gamma-ray threshold technique applied to the region of excitation energies between 7.3 and 8.6 Mev. Previous experiments by others have covered the adjacent regions of excitation. Seed,[2] using the $O^{18}(p,\alpha)F^{19}$ reaction, found resonances indicating energy levels at about 8.56 and 8.76 Mev. Mileikowsky and Pauli,[3] and Cohen[4] also investigated the $O^{18}(p,\alpha)F^{19}$ reaction with results in essential agreement with Seed. Butler and Holmgren[1] found the same two levels by means of the $O^{18}(p,\gamma)F^{19}$ reaction. The region between 6.0 and 7.4 Mev was investigated by Butler and Holmgren,[5] applying the gamma-ray threshold technique to the $O^{18}(d,n\gamma)F^{19}$ reaction. They found three excited states in this region, 6.05, 6.21, and 6.26 Mev. All of these results, including those of the present experiment, are shown in the energy level diagram of Fig. 6.

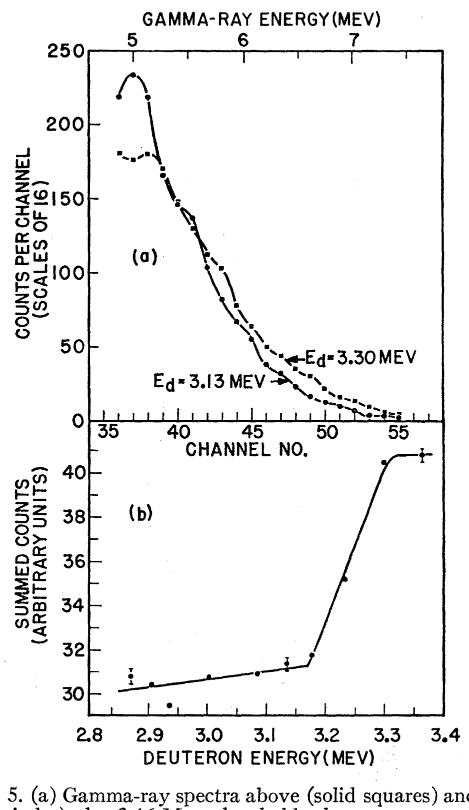

FIG. 5. (a) Gamma-ray spectra above (solid squares) and below (solid circles) the 3.16-Mev threshold, the two spectra having been normalized to the same total area. (b) The sum of normalized channels 43 through 49 as a function of bombarding energy. The threshold energy at 3.17 Mev obtained from this curve is averaged with energies obtained from curves of three other runs to yield a value of 3.16 Mev. Standard statistical deviations are shown on representative datum points. The "Channel No." abscissa refers only to the curve in (a).

In a recent experiment which is of interest to the present discussion, Smotrich *et al.*[8] observed the scattering of alpha particles from N^{15}. In the region of excitation covered by the present experiment, they observed many energy levels as resonances in their excitation function. The ones which have a direct bearing on levels found in the present experiment are discussed below in connection with those levels. Wherever a clear identification could be made between a resonance observed by Smotrich *et al.* and a threshold observed in the $O^{18}(d,n\gamma)F^{19}$ reaction, the position of the resonance is indicated also in Fig. 6.

Smotrich *et al.* observed no resonance corresponding to the threshold at 1.85 Mev. As a corollary of this result, one can say that the state corresponding to this threshold does not emit alpha particles, or at least has a very small alpha partial width. The operation of the isobaric spin selection rules offers one possible explanation for such a state showing a negligibly small alpha width even though many lower alpha-emitting states are observed. Applying the rules in their simplest form, one would expect that a $T=\frac{3}{2}$ state in F^{19} would not break up by alpha emission, and thus could not be formed by alpha bombardment of N^{15}.

However, a $T=\frac{3}{2}$ state could be produced by the (d,n) reaction on O^{18} used in the present experiment. From the O^{19}-F^{19} and F^{17}-O^{17} disintegration energies, one can calculate that the lowest isobaric spin quartet state in F^{19} should occur at an energy of about 7.5 Mev. Thus there exists the possibility that the state corresponding to the 1.85-Mev threshold (7.40 Mev) is the first $T=\frac{3}{2}$ state in F^{19}.

One further observation which supports this hypothesis is the fact that the 1.85-Mev threshold has a rise occurring over a bombarding energy interval about twice as long as the other thresholds. The ground state of O^{19} is believed to be $\frac{5}{2}+$. Since only *s*-wave neutrons can be emitted with observable intensity near threshold (assuming the compund nucleus model), a final state in F^{19} of $\frac{5}{2}+$ would require *d*-wave incoming deuterons. At higher energies above threshold, *p*-wave neutrons could be emitted with *p*-wave bombarding deuterons. This effect would tend to increase the energy interval over which the threshold effect is observable. Thus, the long rise of the 1.85-Mev threshold is consistent with

TABLE I. Neutron gamma-ray thresholds found in the $O^{18}(d,n\gamma)F^{19}$ reaction.

Deuteron energy (Mev)	Q value (Mev)	Energy of excited state in F^{19} (Mev)
1.85±0.05	−1.66±0.05	7.40±0.05
2.15±0.05	−1.93±0.05	7.67±0.05
2.64±0.03	−2.38±0.03	8.11±0.03
3.16±0.03	−2.84±0.03	8.58±0.03

[8] Smotrich, Jones, McDermott, and Bennenson, Bull. Am. Phys. Soc. Ser. II, 3, 26 (1958); and K. Jones (private communication).

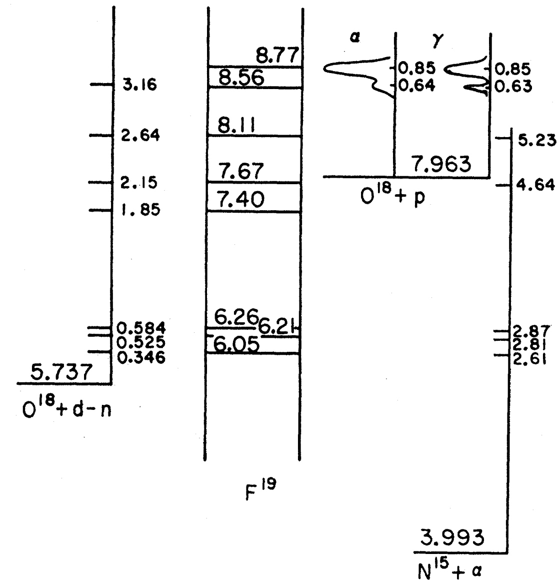

FIG. 6. The energy level diagram of F^{19} over the interval of interest to the present experiment. The three lowest states were found as thresholds in reference 5. The four thresholds of the present experiment are indicated on the $O^{18}+d$-n diagram, with their corresponding levels in F^{19}. The resonances in the alpha bombardment of N^{15} are indicated where they correspond to states found in the present experiment. Resonances in the proton bombardment of O^{18} are also shown in the region of interest here.

the 7.40-Mev state having a spin of $\frac{5}{2}$ and being the first $T=\frac{3}{2}$ state in F^{19}, although it should be re-emphasized that the present evidence is not sufficient to preclude other interpretations.

It is possible that the break at 1.85±0.05 Mev is actually due to the $O^{16}(d,n)F^{17}$ reaction threshold, which is about 1.836±0.003 Mev, since the "O^{18}" target contained 50% more O^{16} than O^{18}. However, this possibility was tested with a natural CaO target and similar data processing, and there was no upward break in the region of interest. In fact there was a slight downward slope of the curve corresponding to Fig. 2(b). Furthermore the counts in channels 45–54 were more than a factor of 20 lower than with the O^{18} target. Therefore, it is considered unlikely that the 1.85-Mev threshold is due to O^{16}.

The second threshold of the present experiment (E_d=2.15 Mev, E_x=7.67 Mev) might correspond to the state in F^{19} at 7.70 Mev observed by Smotrich *et al.* From alpha-particle width considerations, it is more likely that it corresponds to their state at 7.76 Mev, because the lower state has a width of 30 kev and the upper, a width of 8 kev. Another possibility is that the state corresponding to the second threshold (7.67 Mev) is an isobaric spin quartet state, and therefore not observed by Smotrich *et al.*

The third threshold (8.11 Mev in F^{19}) very probably corresponds to the 8.12-Mev state of Smotrich *et al.* because their 8.12-Mev state is fairly narrow, 6 kev.

The fourth threshold (8.58±0.03 Mev in F^{19}) corresponds to the 8.56-Mev state observed as a resonance at 0.630 Mev in the $O^{18}(p,\gamma)F^{19}$ reaction.[1] The data of Smotrich *et al.* did not go beyond excitation energies of 8.4 Mev, and therefore did not include the 8.56-Mev state.

Harlow *et al.*[9] have used the "counter ratio" method to look for neutron thresholds in the $O^{18}(d,n)F^{19}$ reaction. In the region of interest to the present experiment, they found a weak indication for a threshold at a bombarding energy of 3.05±0.02 Mev. Although one might at first be inclined to identify this threshold with the fourth threshold found in the present experiment, 3.16±0.03 Mev, the discrepancy in the energies is well outside the stated uncertainties in the measurements.

Harlow *et al.* did not observe the first three thresholds listed in Table I. Their failure to do so is probably due to the greater sensitivity of the "gamma-ray threshold" technique as compared with the "counter ratio" technique.

The same state in F^{19} (8.56 Mev) has been excited by both the (p,γ) and the $(d,n\gamma)$ reactions on the same initial nuclide, O^{18}. It is useful to conceive of both reactions as being basically similar (in terms of the direct process model) since they both result in the addition of a proton to form the same excited state which then decays with the emission of a gamma ray. However, in the (p,γ) case, the entering proton is free and has a well-defined energy, whereas in the $(d,n\gamma)$ case, the proton is bound and has a continuum of energies up to a well-defined maximum (this maximum being the total kinetic energy in the center-of-mass system minus the binding energy of the deuteron). Thus, the difference in bombarding energies (in the c.m. system) between the *threshold* in the $(d,n\gamma)$ case, and the *resonance* in the (p,γ) case should be precisely the binding energy of the deuteron. For the 8.56-Mev state in F^{19}, the c.m. kinetic energies are 0.596±0.002 and 2.84±0.03 Mev for the (p,γ) resonance and the $(d,n\gamma)$ threshold, respectively. The difference, therefore, is 2.24±0.03 Mev, which is in good agreement with the deuteron binding energy of 2.227±0.003 Mev measured from the $H^2(\gamma,n)H^1$ reaction by Noyes *et al.*[10]

This procedure is potentially one of the most precise methods of measuring the binding energy of the deuteron. In the present experiment, such precision was not achieved, of course, partly because such was not its purpose. It is conceivable that the 3.16-Mev $(d,n\gamma)$ threshold could be measured within an uncertainty of 2 kev or less and it is quite certain that the 0.630-Mev (p,γ) resonance could be measured within a fraction of a kev. Thus a direct experimental measurement of the deuteron binding energy could be made with an experimental uncertainty of about 2 kev or less.

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

[10] Noyes, Van Hoomissen, Miller, and Waldman, Phys. Rev. **95**, 396 (1954).