known polarizabilities[5] and scaling the atomic size according to the Thomas-Fermi model of the atom as the cube root of the atomic number ($r_0 \propto Z^{\frac{1}{3}}$), we find the zero energy cross sections given in Table I. Because of a faster increase of polarizability than atomic size the zero energy cross section increases with atomic number.

In Fig. 1 the cross section values from Table I are compared with the experimental results of Ramsauer and Kollath. With the exception of He, our values are seen to fit smoothly to their measurements. In the case of He a low value is substantiated by swarm measurements of Townsend and Bailey,[6] which indicate a strong decrease in cross section as the mean electron energy approaches zero.

[5] J. H. Van Vleck, *Electric and Magnetic Susceptibilities* (Oxford University Press, London, 1932), p. 225.

[6] H. S. W. Massey and E. H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Oxford University Press, London, 1952), p. 28.

The conclusion drawn from this agreement is that the polarization force does indeed determine the elastic scattering of electrons in the neighborhood of zero energy. As a corollary electrons in the limit of zero energy are not scattered within the closed shells of the noble gas atoms. This is viewed as a consequence of the Pauli exclusion principle. It appears then that the occurrence of the Ramsauer-Townsend minimum for the noble gas atoms is not fortuitous but rather a result of their closed shells.

*Note added in proof.*—The predicted elastic cross sections are contradicted by measurements of spectral line shifts. The line shift depends on the interaction between the bound electron and a neighbor atom. This work, which is summarized by Massey and Burhop,[6] on page 178, was brought to our attention by A. V. Phelps. The cross section for argon is in agreement with our calculation using conventional methods.[1]

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# Radiative Proton Capture by $O^{18}$

J. W. Butler and H. D. Holmgren
*Nucleonics Division, United States Naval Research Laboratory, Washington, D. C.*

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A search for gamma-emitting levels in $F^{19}$ between 8.3 and 9.8 Mev of excitation energy has been made by bombarding a NiO target (39% $O^{18}$) with protons over the energy range 360 to 1960 kev. Resonances in the gamma-ray yield were observed with the use of a 3-in. diam×3-in. sodium iodide crystal and a 20-channel pulse-height analyzer. The results are as follows:

| Resonance energy (kev) | Resonance width (kev) | γ-ray energies (Mev) |
|---|---|---|
| 630±2 | 2.6±1.0 | 8.5 ±0.2 |
| 849±3 | 40±5 | 8.5 ±0.3, 7.2±0.2, 4.8±0.2, 4.3 ±0.2(?), 2.4±0.2(?) |
| 1169±2 | ≤0.9 | 8.8 ±0.2, 7.7±0.2, 6.27±0.05, 3.67±0.05, 2.59±0.05, 1.24±0.05 |
| 1399±5 | <15 | ··· |
| 1685±5 | <15 | ··· |
| 1769±2 | 4.0±1.0 | 9.4 ±0.3 |
| 1931±2 | 1.5±1.0 | 9.8 ±0.2, 8.45±0.10 |

The angular distribution of the 6.27-Mev gamma ray from the 1169-kev resonance was measured, and the results are listed in tabular form. The results of the present experiment are compared with other experiments using the $O^{18}(p,\gamma)F^{19}$, $O^{18}(p,\alpha)N^{15}$, and the $O^{18}(d,n)F^{19}$ reactions.

## I. INTRODUCTION

THE region of excitation in $F^{19}$ from about 6 Mev to about 10 Mev is conveniently accessible only by means of nuclear reactions on the target nuclide, $O^{18}$. Accordingly, a program was begun at this laboratory to investigate this region from about 6 Mev to about 9 Mev by means of the $O^{18}(d,n\gamma)F^{19}$ reaction, and the region from about 8 Mev to about 10 Mev by means of the $O^{18}(p,\gamma)F^{19}$ reaction. The results of the experiments using the $O^{18}(d,n\gamma)F^{19}$ reaction have been reported in abstract[1] and final[2,3] form. The results of the $O^{18}(p,\gamma)F^{19}$ reaction have been reported as an abstract account[4] and are herein presented in complete form.

In the region of interest to the present experiment, two states are known from previous experiments with

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

[2] J. W. Butler and H. D. Holmgren, Phys. Rev. **112**, 461 (1958).

[3] Butler, Fagg, and Holmgren, Phys. Rev. **113**, 268 (1959).

[4] J. W. Butler and H. D. Holmgren, Phys. Rev. **99**, 1649(A) (1955).

the $O^{18}(p,\alpha)N^{15}$ reaction. They are the 8.56- and 8.76-Mev states, corresponding to resonances at bombarding energies of 640 and 850 kev, observed by Cohen[5] and Seed,[6] their bombarding energy ranges being 430–890 and 490–960 kev, respectively. Mileikowsky and Pauli[7] had previously found the lower resonance using the same reaction and a bombarding energy range from 400 to 750 kev. Between the preliminary report and final report of the present experiment, the excitation curve for the $O^{18}(p,\alpha)N^{15}$ reaction has been measured to higher energies, 800–3500 kev, by Hill and Blair,[8] indicating more energy levels in the region of interest to the present experiment. The results from the $O^{18}(p,\alpha)N^{15}$ reaction and previous measurements by Hudspeth *et al.*[9] with the $O^{18}(p,\gamma)F^{19}$ reaction will be discussed along with the results of the present experiment.

## II. EXPERIMENTAL PROCEDURE

The experimental techniques and procedure were similar to those described previously.[2,10] Targets of $O^{18}$ were prepared from the enriched gas[11] by oxidation of thin nickel foils[12] of various thicknesses. Most of the data were taken with 5-microinch thick foils. The protons were supplied by the NRL Nucleonics Division 2-Mv Van de Graaff accelerator, whose beam-analyzing magnet was controlled by proton magnetic moment apparatus and calibrated by the 993.3-kev resonance in the $Al^{27}(p,\gamma)Si^{28}$ reaction. The gamma-ray spectrometer consisted of a 3-in. diam×3-in. NaI(Tl) crystal, a DuMont K 1197 3-in. multiplier phototube, a 20-channel differential pulse-height analyzer, and associated electronic equipment.

A liquid-nitrogen trap was placed about one foot from the target, between the target and the magnetic beam analyzer, in order to deter the formation of carbon films or other contaminants on the target. (This trap was not nearly so effective as later adaptations,[10] but did help considerably in keeping target contamination to a reasonably low value.)

In order to determine with certainty that an observed resonance was actually due to $O^{18}$, a similar target of NiO made from normal oxygen and the enriched $O^{18}$ target were bombarded alternately. A number of resonances were observed to be common to both targets. Some of these were later identified as being due to the nickel of the foil[10] and others were determined to be due to a small fluorine contamination on the target. The net $O^{18}$ yield was determined by taking the difference between the $O^{18}$ and normal oxygen targets. Thus the "background" due to the Ni, $F^{19}$, and $O^{16}$ was subtracted out along with room background.

## III. RESULTS AND DISCUSSION

The gamma-ray counting rates (in arbitrary units) as a function of bombarding energy are shown in Figs. 1 and 2. Figure 1 covers the proton energy range from 360 to 1250 kev, and Fig. 2 covers the range from 1210 to 1960 kev. The counts corresponding to energy losses in the crystal between 7.7 and 9.3 Mev are represented by the dots in Fig. 1; the crosses represent energy losses between 5.3 and 6.5 Mev. The dots in Fig. 2 give the gamma-ray counting rate for energy losses from 8.4 to 9.6 Mev.

Seven resonances were observed, and are listed in Table I, along with the measurements of resonance widths, gamma-ray energies, and the energies of excitation of the compound states in $F^{19}$. The values of the energies of excitation were calculated using the mass table of Wapstra.[13] Estimated uncertainties in the measured values are also listed in Table I. The stated uncertainty in the value of the energy of excitation includes the uncertainties in mass values given by Wapstra.

The resonances will be individually discussed below in order of increasing proton energy.

### 560 Kev

There are several reports indicating a level in $F^{19}$ at about 8.49 Mev, corresponding to a resonance in the $O^{18}(p,\alpha)$ and $O^{18}(p,\gamma)$ reactions at a bombarding energy of 560 kev. Mileikowsky and Pauli[7] observed an "anomaly" in the $O^{18}(p,\alpha)$ reaction at 600 kev. Their energy scale was 40 kev higher than that of other experimenters; thus their "anomaly" was at 560 kev on the present energy scale. Cohen[5] confirmed the existence of

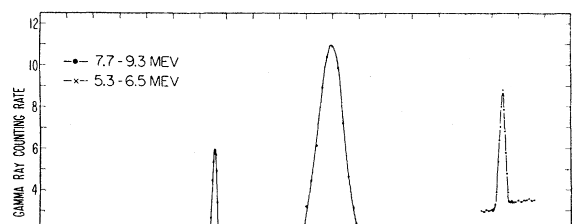


FIG. 1. Yield of gamma rays from the $O^{18}(p,\gamma)F^{19}$ reaction as a function of proton bombarding energy from 360 kev to 1250 kev. Yield is in arbitrary units. The dots represent the counts corresponding to energy losses in the crystal between 7.7 and 9.3 Mev. The crosses represent the counts corresponding to energy losses in the crystal between 5.3 and 6.5 Mev.

[5] A. V. Cohen, Phil. Mag. **44**, 583 (1953).
[6] J. Seed, Phil. Mag. **42**, 566 (1951).
[7] C. Mileikowsky and R. T. Pauli, Nature **166**, 602 (1950); Arkiv Fysik **4**, 299 (1952).
[8] H. A. Hill and J. M. Blair, Phys. Rev. **104**, 198 (1956).
[9] Hudspeth, Morgan, and Peoples, Phys. Rev. **99**, 643(A) (1955); and E. L. Hudspeth (private communication).
[10] J. W. Butler and C. R. Gossett, Phys. Rev. **108**, 1473 (1957).
[11] 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%; $O^{18}$, 39.3%.
[12] Holmgren, Blair, Famularo, Stratton, and Stuart, Rev. Sci. Instr. **25**, 1026 (1954).
[13] A. H. Wapstra, Physica **21**, 367 (1955).

TABLE I. Resonances observed in the $O^{18}(p,\gamma)F^{19}$ reaction. The uncertainties in the values of the energies of excitation include the uncertainties in the mass values given by Wapstra.

| Proton energy (kev) | Resonance width (kev) | Energy of excitation in $F^{19}$ (Mev) | Gamma-ray energies (Mev) | Observed in $O^{18}(p,\alpha)N^{15}$ reaction ? |
|---|---|---|---|---|
| 630±2 | 2.6±1.0 | 8.561±0.011 | 8.5 ±0.2, others | Yes |
| 849±3 | 40±5 | 8.768±0.011 | 8.5 ±0.3, 7.2±0.2, 4.8 ±0.2, 4.3±0.2(?), 2.4 ±0.2(?) | Yes |
| 1169±2 | ≤0.9 | 9.071±0.011 | 8.8 ±0.2, 7.7±0.2, 6.27±0.05, 3.67±0.05, 2.59±0.05, 1.24±0.05 | No |
| 1399±5 | <15 | 9.289±0.012 | | Yes |
| 1685±5 | <15 | 9.560±0.012 | | Yes |
| 1769±2 | 4.0±1.0 | 9.639±0.011 | 9.4 ±0.3, others | Yes |
| 1931±2 | 1.5±1.0 | 9.793±0.011 | 9.8 ±0.2, 8.45±0.10, others | Yes |

the anomaly, or probable resonance, at 560 kev; and Harlow *et al.*[14] detected a neutron threshold in the $O^{18}(d,n)F^{19}$ reaction at 3.05±0.02 Mev, corresponding to a resonance in the $(p,\gamma)$ or $(p,\alpha)$ reactions at 560 kev.

The data of Fig. 1 give no indication of such a resonance in the $(p,\gamma)$ reaction, at least as far as ground-state gamma-ray transitions are concerned. An examination of the counting rates in other energy channels likewise gave essentially no indication of such a resonance. The evidence against such a resonance, or state, comes (in addition to the present experiment) from the work of Seed,[6] who did not observe the $(p,\alpha)$ anomaly or resonance at 560 kev, and from Butler *et al.*[3] who did not observe a gamma-ray threshold in the $O^{18}(d,n\gamma)F^{19}$ reaction corresponding to a resonance at 560 kev, but did observe a gamma-ray threshold corresponding to the 630-kev resonance.

## 630 Kev

The lowest-energy resonance observed in the present experiment was at 630±2 kev, width 2.6±1.0 kev, corresponding to a state in $F^{19}$ at 8.561±0.011 Mev. This state is the same as the alpha-emitting state observed by Seed,[6] and Cohen[5] in the $O^{18}(p,\alpha)N^{15}$ reaction. Their measurements of the resonance bombarding energy were both 640 kev, and Cohen's measurement of the resonance width was 15 kev. The small discrepancy in the resonance energy between the present experiment and those of Seed[6] and Cohen[5] can be explained by the nature of the alpha-yield curve. The 640-kev resonance in the $(p,\alpha)$ experiments was superimposed on a steeply rising yield (as suggested by Cohen,[5] probably due to a very wide resonance overlapping the two resonances at 640 and 850 kev). This steeply rising "background" could make the resonance peak appear at somewhat higher energy, and cause the width measurement to be unreliable.

The gamma-ray spectrum from the 630-kev resonance is complex, but includes a reasonably strong gamma ray of 8.5±0.2 Mev, which is a transition to the ground-state "triplet," probably the ground state itself, since the measured energy of the gamma ray is essentially the same as the total excitation energy of the compound state. However, since the uncertainty in measurement includes transitions to the other two states of the ground-state "triplet," these transitions cannot be excluded by the present data.

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

## 849 Kev

The next resonance observed, 849±3 kev, corresponds to the resonance observed by Seed[6] at 850 kev, by Cohen[5] at 850 kev, by Hudspeth *et al.*[9] at 850 kev, and by Hill and Blair[8] at 838±6 kev. Cohen[5] measured the width to be about 45 kev, in good agreement with the present value of 40±5 kev.

The gamma-ray spectrum from the 849-kev resonance indicates the existence of gamma rays of the following energies: 8.5±0.3, 7.2±0.2, 4.8±0.2, 4.3±0.2(?), and 2.4±0.2(?) Mev. The 8.5-Mev gamma ray has a low intensity, and corresponds to a transition to the ground-state triplet, probably the 0.198-Mev state, based on the energy measurement, since the energy of the excited state is 8.768±0.011 Mev. The 7.2-Mev gamma ray is relatively strong, and corresponds to a transition to the "triplet" at about 1.5 Mev, probably the 1.56-Mev state. The 4.8-Mev gamma ray is also relatively strong and probably corresponds to a transition to one of the levels at about 4 Mev. The total-capture peak of a possible 4.3-Mev gamma ray occupies the same energy channels as the single-escape peak of the 4.8-Mev gamma ray, and therefore the existence of the 4.3-Mev gamma ray is somewhat uncertain. There is also evidence for a possible 2.4-Mev gamma ray.

No special significance is attached to the small anomaly above the 849-kev resonance. The reason for the yield curve not returning to about zero above this resonance is not quite clear; but the method of directly subtracting the yield of the normal NiO target from the

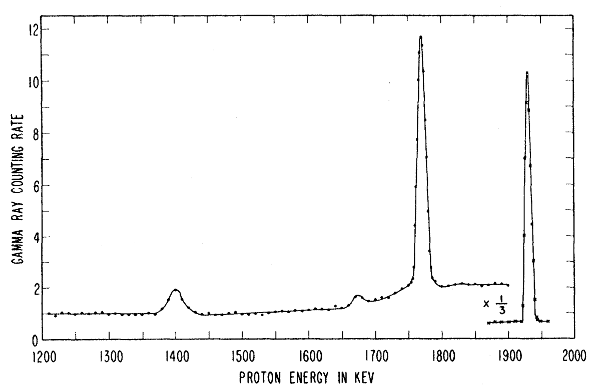


FIG. 2. Yield of gamma rays from the $O^{18}(p,\gamma)F^{19}$ reaction as a function of proton bombarding energy from 1210 kev to 1960 kev. Yield is in arbitrary units. The energy window used was from 8.4 to 9.6 Mev. The numbers represented by the crosses have been reduced by a factor of three to keep them from going off scale.

$NiO^{18}$ target was probably not a precisely quantitative way of removing background effects because of the unknown degree of oxidation of the two different targets, possible small differences in the nickel foil thicknesses, and the fact that $O^{16}$ was contained in different amounts in both targets, etc. In addition, the relative amounts of other contaminants, such as fluorine, may have been different in the two targets. Therefore, again no special significance is attached to the absolute level of the excitation curve in the vicinity of 1 Mev.

### 1169 Kev

At 1169±2 kev, another resonance was observed, having a width of ≤0.9 kev and corresponding to an excited state of 9.071±0.011 Mev in $F^{19}$. This resonance was observed to decay predominantly to the 2.78-Mev state and only very slightly to the ground-state triplet; therefore it appears in the crosses of Fig. 1 rather than in the dots (the energy region represented by the crosses includes the energy of a transition to the 2.78-Mev state).

Since the isobaric spin of $O^{18}$ is one, and that of the proton is $\frac{1}{2}$, it is possible to form isobaric spin quartet (or $T=3/2$) states in the $O^{18}(p,\gamma)F^{19}$ reaction. If one calculates empirically the energy of excitation in $F^{19}$ corresponding to the ground state of $O^{19}$, the value obtained is about 7.56 Mev. (This calculation is based on the difference in masses between $O^{19}$ and $F^{19}$, and the beta-decay energy of $F^{17}$.) The state in $F^{19}$ corresponding to the 1.47-Mev state in $O^{19}$ should therefore be about 9.03 Mev. This suggests the possibility that the compound state responsible for the 1169-kev resonance (9.071 Mev of excitation) is the analog of the 1.47-Mev state in $O^{19}$.

Since alpha-emitting compound states usually have relatively large widths (usually much larger than 1 kev if several Mev are available), the narrowness of the 1169-kev resonance implies that a selection rule forbids the emission of alpha particles. Approximately 5 Mev of energy are available for breakup of the compound state into an alpha particle and $N^{15}$ in the ground state. On the basis of simple application of the isobaric-spin selection rules, a $T=3/2$ state in $F^{19}$ could not emit alpha particles to the ground state of $N^{15}$ because the isobaric spin of $N^{15}$, $\frac{1}{2}$, and that of an alpha particle, zero, cannot add up to 3/2. Hill and Blair[8] searched the region about the 1169-kev resonance, and found no evidence for an alpha-particle resonance in the $O^{18}(p,\alpha)N^{15}$ reaction, thus confirming that this state does indeed have a negligible partial alpha-particle width. It does not seem likely that spin or parity could forbid alpha-particle emission because of the energy available to the alpha particle and the fact that the state was formed by approximately 1-Mev protons impinging on $O^{18}$. (That is, one would expect that the outgoing alpha particle could take away as much, or more, angular momentum as was brought in by the incoming proton.)

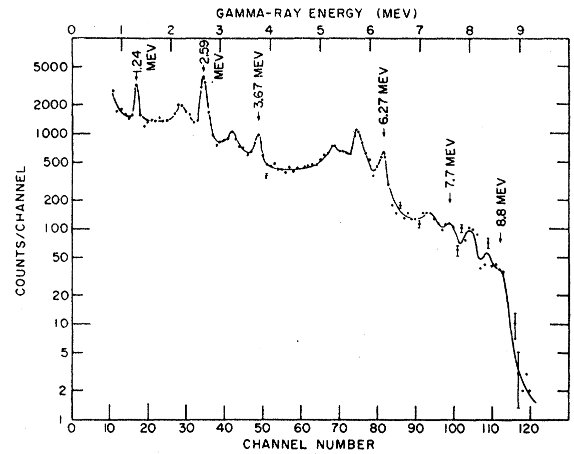


Fig. 3. The detailed spectrum of gamma rays from the 1169-kev resonance. Six sets of spectra were made over successive channel intervals with the 20-channel pulse-height analyzer in order to obtain the data for this spectrum. Background was subtracted by taking the difference between "on resonance" and "off resonance" spectra, the difference between the two bombarding energies being 5 kev. Representative standard statistical deviations are shown on the datum points. The assignments of the various gamma rays are discussed in the text.

Because the 1169-kev resonance appeared to be intrinsically more interesting than the other resonances, the spectrum of emitted gamma rays was determined in more detail than for the other resonances. The results are shown in Fig. 3. Six successive (in energy) spectra were made with a 20-channel pulse-height analyzer in order to obtain the spectrum of Fig. 3. The weak 8.8±0.2 Mev gamma ray corresponds to a transition to the ground-state triplet, probably the 0.198-Mev state. The weak indication for a 7.7±0.2 Mev gamma ray is consistent with a transition to the triplet at about 1.5 Mev, probably the 1.35-Mev state. The strong 6.27±0.05 Mev gamma ray corresponds to a transition to the 2.78-Mev state. It is not clear where the 3.67-Mev gamma ray fits into the decay scheme, but it probably represents a double stop-over transition involving the 1.35-Mev state, since the 7.7-Mev gamma ray is too low in intensity to account completely for the relatively strong 1.24-Mev peak. One possible assignment for the 3.67-Mev gamma ray is to the transition from the 9.07-Mev resonant state to the 5.46-Mev state, which then cascades through the 2.78- and 1.35-Mev states. Figure 4 illustrates the decay scheme from the 1169-kev resonance state, including the placement of the two lower energy gamma rays, 2.59 and 1.24 Mev.

Since the 1.47-Mev state[15] in $O^{19}$ is $\frac{1}{2}^{+}$, the angular distribution of the gamma radiation from its analog state in $F^{19}$ would have to be isotropic, regardless of the spin and parity of the final state. A measurement of the angular distribution of the gamma rays from the 1169-kev resonance was therefore made to check the hypoth-

[15] Stratton, Blair, Famularo, and Stuart, Phys. Rev. **98**, 629 (1955).

TABLE II. Angular distribution of gamma-ray counts between 5 and 7 Mev for the 1169-kev resonance.

| Angle | Relative counting rate |
|---|---|
| 0° | 63±3 |
| 30° | 77±4 |
| 60° | 86±5 |
| 90° | 102±5 |

esis that these two states are members of the same isobaric spin quartet.

The experimental procedure was similar to that described in a previous communication.[10] The energy window used for the angular distribution was 5–7 Mev. The results are given in Table II. Since the gamma radiation was not isotropic (the yield at 0° being 38±6% less than at 90°), the 9.07-Mev state does not have a spin of $\frac{1}{2}$ and therefore probably does not correspond to the 1.47-Mev state in $O^{19}$, but could possibly correspond to another state in $O^{19}$. Since the primary gamma ray from the 1169-kev resonance represented a transition to the 2.78-Mev state, whose spin is not known, it is not possible to determine the spin of the state corresponding to the 1169-kev resonance from the angular distribution. Furthermore, angular intervals were chosen rather large (30°) since the primary purpose of the distribution measurement was to determine whether or not the distribution was isotropic.

The dimensionless reduced proton width of the 1169-kev resonance has been calculated in a manner previously described,[10] assuming that all of the observed width is due to protons, and that the width of the state is near the upper limit indicated by the measurements. Under these conditions, the dimensionless reduced proton width, $\theta^2$, is 0.001. This value appears rather small for the proton to correspond to the last neutron in a low-lying state of $O^{19}$, since one would expect a relatively large dimensionless reduced neutron width for such low-lying states. (This is because the low-lying levels of such a nucleus, a doubly-closed shell plus three nucleons, are expected, on the basis of the shell model, to involve rearrangement of the extra-core nucleons with the core remaining intact. This implies fairly similar configurations and fairly large fractional parentage coefficients between the ground state and such low-lying states.) However, this generalization is not always valid, as demonstrated by the negative-parity state in $F^{19}$ at 0.110 Mev. So it is not completely unreasonable that a $T=3/2$ state in $F^{19}$ could exhibit a fairly small reduced proton width.

## 1399 and 1685 Kev

The next two resonances, 1399±5 and 1685±5 kev, corresponding to excited states of 9.289±0.012 and 9.560±0.012 Mev, respectively, were very weak, but repeatable. They were therefore reported with all the other resonances in the abstract account[4] of the present experiment. They were later confirmed as alpha-emitting resonances in the $O^{18}(p,\alpha)N^{15}$ reaction by Hill and Blair,[8] whose measured resonance bombarding energies were 1406±4 and 1688±4 kev, respectively. Because of the weakness of gamma-ray emission from these resonances, it was not feasible to measure the gamma-ray energies. The resonance widths could likewise not be measured, but an upper limit was determined to be 15 kev in both cases.

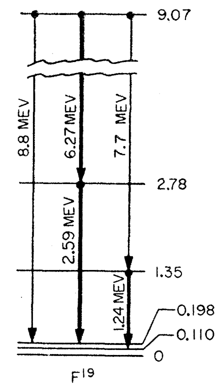


FIG. 4. De-excitation cascade scheme for the 1169-kev resonance. Another gamma ray, of 3.67 Mev, was observed, but it is not clear where it fits into the cascade scheme. Possible assignments are discussed in the text. For the sake of clarity, only those states of $F^{19}$ which enter into the decay scheme are shown.

## 1769 Kev

The 1769±2 kev resonance corresponds to the 1767-kev resonance reported by Hudspeth *et al.*[9] for the same reaction. This excited state has also been observed as an alpha-emitting resonance by Hill and Blair[8] at 1761±4 kev. The gamma-ray spectrum from this resonance was fairly flat (and therefore somewhat complex) out to a cutoff point in the vicinity of 9.5 Mev. There was evidence of a gamma ray of about 9.4±0.3 Mev and also others. The resonance width was measured to be 4.0±1.0 kev and the corresponding excited state in $F^{19}$ is 9.639±0.011 Mev.

## 1931 Kev

The highest-energy resonance observed was at 1931±2 kev. It is the same as the gamma-ray resonance observed by Hudspeth *et al.*[9] at 1927 kev. Hill and Blair[8] observed both alpha particles and gamma rays from this resonance, whose energy they measured as 1934±4 kev. The gamma-ray energies measured in the present experiment for this resonance were 9.8±0.2 and 8.45±0.10 Mev, corresponding to a transition to a member of the ground-state triplet, probably the ground state itself, and a transition to the 1.5-Mev triplet, probably the 1.35-Mev state. The 1931-kev resonance was the second narrowest observed in the excitation function, being 1.5±1.0 kev in width, and corresponds to a state in $F^{19}$ at 9.793±0.011 Mev.