the separation of the two hyperfine lines is directly equal to $2W_{1,2}$. In the case of $I=2$ the separation of the two outermost hyperfine lines is always equal to $2W_{1,2}$ (see Fig. 2 in Ref. 17).

From the data of Wagner *et al.*[17] we take the separation of the two outermost lines ($M=0, 2, -2$) in the hyperfine spectrum of Yb^{170} in Yb_2O_3 and get

$$\tfrac{1}{4}e^2qQ_2{}^{170}(1+\tfrac{1}{3}\eta^2)^{1/2}=3.3\times10^{-6}\text{ eV},$$

and from the present measurement

$$\tfrac{1}{4}e^2qQ_{3/2}{}^{171}(1+\tfrac{1}{3}\eta^2)^{1/2}=2.4\times10^{-6}\text{ eV}.$$

By using the expression

$$Q_0=\frac{(I+1)(2I+3)}{3K^2-I(I+1)}Q_I,$$

one obtains a ratio of the intrinsic quadrupole moments:

$$Q_0{}^{171}/Q_0{}^{170}=2.4\times5\times2\times10^{-6}/3.3\times7\times10^{-6}=1.04.$$

By Coulomb excitation[2] in Yb^{170} and Yb^{171}, the quadrupole moments were determined to be

$$Q_0{}^{171}=8.0\text{ b},^{18}$$

$$Q_0{}^{170}=7.5\text{ b},^{19}$$

leading to a ratio of

$$Q_0{}^{171}/Q_0{}^{170}=8.0/7.5=1.07,$$

which agrees very well with our data.

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[18] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

[19] B. Elbeck, K. O. Nielsen, and M. C. Olesen, Phys. Rev. **108**, 406 (1957).

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Gamma Rays from the Low-Lying Levels of F^{18}†

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A 5-mm-thick lithium-drifted germanium counter was used to detect the low-energy gamma rays ($E\gamma<1.8$ MeV) emitted at 90° to the beam following bombardment of an O^{16} gas target with He^3 ions with a mean energy of 1.8 MeV. The excitation energies of the first seven levels of F^{18} were determined to ±2 keV or better from energy measurements of the de-excitation gamma rays from these levels. The decay of the F^{18} 2.10-MeV level to the 0.94- and 1.08-MeV levels was confirmed, and an upper limit of 6% was placed on the branch to the 1.045-MeV level.

INTRODUCTION

The sixth excited state of F^{18} at an excitation energy of 2.10 MeV has been reported[1] to have a mean lifetime of $(0.7\pm0.2)\times10^{-12}$ sec and decays to the F^{18} ground state and first excited state at 0.94 MeV with branching ratios of $38\pm3\%$ and $28\pm5\%$, respectively.[2,3] The remaining 34% is made up of branches to one or both of the 1.045- and 1.082-MeV levels so that gamma rays with energies of 0.94, 1.02, 1.045, 1.055, 1.082, and 1.16 MeV are possible from the decay of the 2.10-MeV level. Both of the previous investigations[2,3] of the decay of the F^{18} 2.10-MeV level were done with NaI (Tl) gamma-ray detectors which do not have adequate resolution to separate these gamma-ray lines. The work of Poletti and Warburton[3] indicated that the branch to the 1.082-MeV level was more intense than that to the 1.045-MeV level, but this was not absolutely certain and no sharp limit was placed on the intensity of the 2.10 → 1.045 transition.

The F^{18} 0.94- and 1.045-MeV levels have $J^\pi=3^+$ and 0^+, respectively; while the 1.082-MeV level has $J=0$, 1, or 2 with 0 preferred.[3] The F^{18} 2.10-MeV level has $J=1$ or 2.[3] Thus, either the $2.10\rightarrow0.94$ or the $2.10\rightarrow1.045$ transition must be quadrupole and the $2.10\rightarrow1.082$ transition may be also. Combining the lifetime measurement for the 2.10-MeV level with the branching ratios gives a strength of 54 ± 18 Weisskopf units for the $2.10\rightarrow0.94$ transition if it is $E2$ and 128 ± 42 Weisskopf units to be divided between the $2.10\rightarrow1.082$ and $2.10\rightarrow1.045$ transitions if they are both $E2$.[3] These transition strengths are strong enough to be quite startling and so it is of interest to check on the decay modes of the 2.10-MeV level and in particular to find the rela-

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[1] A. E. Litherland, M. J. Yates, B. M. Hinds, and D. Eccleshall, Nucl. Phys. **44**, 220 (1963).

[2] J. A. Kuehner, E. Almqvist, and D. A. Bromley, Phys. Rev. **122**, 908 (1961).

[3] A. R. Poletti and E. K. Warburton, Phys. Rev. **137**, B595 (1965).

tive intensities of the 2.10 → 1.082 and 2.10 → 1.045 branches. This was the motivation for the present work.

EXPERIMENTAL PROCEDURES

The F^{18} levels were populated by means of the $O^{16}(He^3,p)F^{18}$ reaction. A 3-MeV He^3 beam from the Brookhaven National Laboratory electrostatic accelerator was used to bombard an oxygen gas target 2.6 cm long. The target cell was constructed from 0.025-cm stainless-steel tubing with a nickel entrance foil 1.27×10^{-4} cm thick. The energy loss of the He^3 beam in the nickel foil was about 600 keV and the loss in the O^{16} gas was about 950 keV. The beam energy at the center of the chamber was 1.8 MeV.

The gamma rays produced in the target were detected with a lithium-drifted germanium detector. The detector was 5 mm thick with a cross-sectional area of 6 cm^2. The detector, at liquid-nitrogen temperature, was placed in an aluminum container[4] with a 0.1-cm entrance window and was centered at 90° to the incident He^3 beam. The distance from the beam to the front face of the counter was 3.2 cm. The counter thus detected gamma rays from the target emitted at angles from roughly 45 to 135° with respect to the incident beam.

Pulses from the counter were amplified with a standard commercial low-noise preamplifier and post-bias amplifier and displayed on a 1024-channel pulse-height analyzer. The electronic line width obtained with this system was about 4.2-keV full width at half-maximum and the width for the 662-keV line from Cs^{137} was about 5.0 keV. The spectra which were recorded covered the energy region up to 2.1 MeV.

A partial pulse-height spectrum obtained for the gamma rays produced in the $O^{16}(He^3,p)F^{18}$ reaction is shown in Fig. 1. The energies of the various lines were determined from a separate run with a mixed source of Bi^{207} and F^{18}. The counting rate in the calibration run was adjusted to be roughly the same as for the run shown in Fig. 1 in order to minimize the effects of gain shifts. The procedures used for extracting energies relative to the 1063.9-keV Bi^{207} line were similar to those described previously by Alburger *et al.*[5]

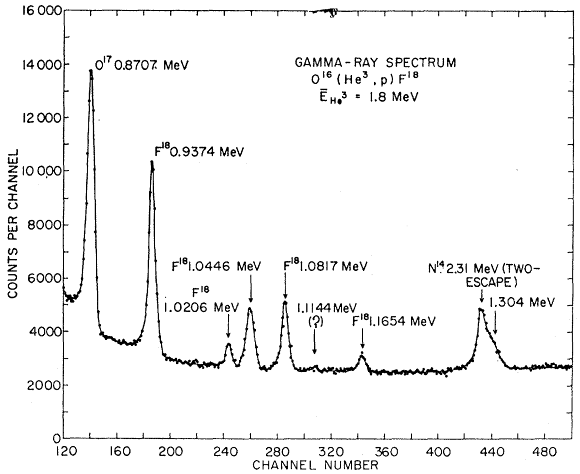

FIG. 1. Partial pulse-height spectrum for the $O^{16}(He^3,p)F^{18}$ gamma rays. The energy calibration is about 1.45 keV per channel.

THE $O^{16}(He^3,p)F^{18}$ GAMMA RAYS

The Q value of the $O^{16}(He^3,p)F^{18}$ reaction is 2.021 MeV,[6] and the energy of the He^3 beam after passing through the nickel entrance window was about 2.2 MeV. Thus, gamma rays from the F^{18} levels above the 10th excited state at 3.35-MeV excitation were not expected.

The He^3 beam had a small $(HD)^+$ contamination and carbon deposits built up on the entrance foil during the measurement. Thus gamma rays from reactions of ~2-MeV deuterons and ~1-MeV protons with carbon, nickel, and oxygen were expected as well as those from He^3-induced reactions in oxygen, carbon, and nickel. However, only three gamma-ray peaks and a possible fourth from reactions other than $O^{16}(He^3,p)F^{18}$ were evident in the pulse-height region of major interest (Fig. 1). These were gamma-ray peaks with energies of 870.7±1.5, 1290, 1304, and possibly 1114.4±2 keV. The 870.7-keV line is assigned to O^{17} and presumably arose from the $O^{16}(d,p)O^{17}$ reaction. The 1290-keV line is thought to be a two-escape peak of a 2.31-MeV gamma ray since an intense Compton edge was seen at the right energy to be associated with this gamma ray. This line is assigned to the decay of the first excited state of N^{14} populated by the $C^{12}(He^3,p)N^{14}$ reaction. The origin of the 1304-keV peak is not known. It cannot be fitted into the decay schemes of N^{14}, O^{17}, or F^{18}. The 1114-keV line has been seen in previous work. It is thought to arise from the decay of Zn^{65} produced by activation of the beam tube.

The observed gamma rays which were believed to originate from the $O^{16}(He^3,p)F^{18}$ reaction are listed in Table I. The list includes two lower energy gamma rays and four higher energy gamma rays in addition to those identified in Fig. 1. The peaks at 658.9 and 1703 keV had the right relative intensities and energies to be associated with the decay of the F^{18} 1.70-MeV level. The two-escape peak of the 2529-keV gamma ray was seen, its full-energy-loss peak was not. It was identified by its energy and by its intensity relative to the 1592.8-keV line. The identification of the 1647-keV line is not certain; in fact, the peak at this energy may have been the two-escape peak of a 2669-keV gamma ray. The

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[4] C. Chasman and R. A. Ristinen (to be published).

[5] D. E. Alburger, C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. **136**, B913 (1964).

[6] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959). T. Lauritsen and F. Ajzenberg-Selove, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1962), NRC 61-5,6.

TABLE I. Gamma rays from O^{16}(He^{3},p)F^{18}.

E_γ (keV)	Assignment[a]
(182.2±1.0)	1.125 → 0.940
658.9±1.5	1.70 → 1.045
937.4±1.5	0.940 → 0
1020.6±1.5	2.10 → 1.082
1044.6±1.5	1.045 → 0
1081.7±1.5	1.082 → 0
1165.4±1.5	2.10 → 0.940
1592.8±2	2.52 → 0.940
1647 ±3	(3.35 → 1.70)
1703 ±3	1.70 → 0
2529.2±2	2.52 → 0

[a] Reference 6.

TABLE II. Excitation energies of the low-lying levels of F^{18}.

Level	Present work (keV)	Ajzenberg-Selove and Lauritsen[a] (keV)[b]
1	937.4±1.5	940
2	1044.6±1.5	1045
3	1081.7±1.5	1082
4	(1119.7±2)	1125
5	1703.5±2	1700
6	2102.6±2	2104
7	2529.7±2	2525
10	(3350.5±3)	3354

[a] Reference 6.
[b] All ±10 keV.

energy of the 182.2-keV line was obtained using annihilation radiation and a 170-keV peak to provide an energy calibration. The 170-keV line was assigned to the C^{13} 3.85 → 3.68-MeV transition, in which case it has an energy of 169.5±0.4 keV.[6] If the identification of the 170-keV line is wrong, the quoted energy of the 182.2-keV line is wrong also.

The errors assigned to the gamma-ray energies in Table I are due almost entirely to uncertainties associated with possible Doppler shift and Doppler-broadening effects. All of the gamma rays listed in Table I except the 182.2-keV line originate from levels with lifetimes which are known or expected to be less than 10^{-10} sec.[1–3] Since the stopping time of the recoiling F^{18} nuclei in the gas target is of the order of 10^{-9} sec, all these gamma rays should show Doppler effects. Three effects are expected. First, there is a Doppler broadening due to the angular distribution of the recoiling F^{18} nuclei which is roughly 3 keV for a 1-MeV gamma ray in the present case. Second, there is a broadening of the gamma-ray lines due to the approximately 90° acceptance angle of the gamma-ray detector. This effect is about 4 keV for a 1-MeV gamma ray, so that the total linewidth due to Doppler effects should be about 5 keV. Combining this with the natural linewidth of the detecting system gives 7 keV which is to be compared to the observed linewidth which was 7–9 keV for the peaks shown in Fig. 1. This agreement is quite satisfactory.

The third Doppler effect is a possible Doppler shift of the gamma-ray energy due to the detector being at an average angle to the beam different than 90°. The uncertainties assigned to the gamma-ray energies are mostly due to this source.

The excitation energies of the F^{18} levels in Table II result from the gamma-ray energies and assignments of Table I. The agreement between the present results and earlier work is surprisingly good, the only serious disagreement outside of *our* uncertainties is with the fourth excited state and this energy involves the uncertain measurement of the 1.12 → 0.94-MeV transition.

THE F^{18} 2.10-MeV LEVEL

The 1.16- and 1.02-MeV gamma rays expected from the F^{18} 2.10 → 0.94 and 2.10 → 1.08 transitions are evident in Fig. 1. (The two-escape peak of the 2.10 → 0 transition[1] has an expected energy of 1080.6±2 keV and thus is unresolved from the 1081.7-keV peak identified in Fig. 1.) The intensities are in the ratio (1.07±0.1):1 which is to be compared to the ratio (0.82±0.18):1 obtained by Poletti and Warburton[3] assuming a negligible 2.10 → 1.045 branch. We average these two values to obtain revised branching ratios of (30±4)% and (32±4)% for the 2.10 → 0.94 and 2.10 → 1.08 transitions. The 2.10 → 1.045 transition would give rise to a gamma ray of 1058±2 keV. There is a slight excess of counts at the expected position of this line in Fig. 1, which could be due to a 2.10 → 1.045 branch of ≈3%; however, it is just barely statistically significant, so we quote a limit of 6% on the branching ratio of the 2.10 → 1.045 transition.

The present results confirm the conclusion[3] that the 2.10 → 1.08 transition has a branching ratio of about 30%. The consequences of this have been discussed in some detail by Poletti and Warburton.[3] Briefly, combining the lifetime measurement[1] with the branching ratios to the 0.94- and 1.08-MeV levels leads to the conclusion that the 2.10 → 1.08 transition must be predominantly dipole and it would be very surprising if the 2.10 → 0.94 transition were not dipole also. This is in conflict with the suspected assignment of $J=0$ to the 1.08-MeV level.[7] We conclude that the lifetime measurement[1] of the F^{18} 2.10-MeV level may be in error and should certainly be checked.

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[7] E. Almqvist, D. A. Bromley, and J. A. Kuehner, Bull. Am. Phys. Soc. 3, 27 (1958).