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Excited Levels in F^{20} at 1.82 and 1.84 MeV*

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Examination of the γ-ray spectrum from $O^{18}(He^3,p\gamma)F^{20}$ in the region near 1.85-MeV excitation has indicated the existence of a new level in addition to the one previously reported. With a magnetic spectrograph, this doublet structure has been confirmed, and the excitation energies of the two levels have been measured as 1824.4 ± 2.1 and 1843.0 ± 2.2 keV. The separation is 18.6 ± 0.7 keV. Directional correlations of γ rays from these levels have been studied in an axially symmetric arrangement. Based on these correlations, the spins of both levels are restricted to the values 1, 2, or 3; a probable assignment of spin 2 or 3 is made for the 1.84-MeV level. Branching ratios and multipole mixtures are reported.

INTRODUCTION

The low-lying excited levels of F^{20} have been studied mainly with the reaction $F^{19}(d,p)F^{20}$. Watson and Buechner[1] reported nineteen levels up to 4.31 MeV in excitation. None of these fell between 1.31 and 1.97 MeV. Later, Rickards[2] identified two additional levels including one at approximately 1.85 MeV. In other investigations[3–7] using deuteron energies from 0.5 to 4.3 MeV, no levels near 1.8 MeV were reported.

A study of the $O^{18}(He^3,p\gamma)F^{20}$ reaction, including directional correlations, through F^{20} levels up to 1.85 MeV in excitation, has been previously reported by some of the present authors.[8] Upon further investigation, it has been found that what was believed to be a single level, at a nominal energy of 1.85 MeV, exhibits large variations in apparent branching ratio with different bombarding energies. It has been deduced that this apparent level is in fact a doublet which was not resolved in the earlier work.

Subsequent study of the $O^{18}(He^3,p)$ reaction with the broad-range magnetic spectrograph, as described below, has confirmed the existence of the doublet with excitation energies of 1.824 and 1.843 MeV. The reinvestigation of the decay scheme and the γ-ray angular correlations is also reported below.

EXPERIMENTAL PROCEDURES

Energy Measurements

The broad-range magnetic spectrograph used in these measurements has been previously described in detail.[9,10] Targets of $Ta_2O^{18}{}_5$ on 0.005-in. Ta backings were used for this part of the work. These were produced by anodizing one side of the tantalum foils in a solution of $Na_2B_4O^{18}{}_7$ in D_2O^{18} to a potential of 30 V. The resulting oxide coatings were approximately 300-Å thick, corresponding to an energy loss of 13 keV for 4-MeV He^3 ions.

The incident beam energy was determined by measuring the energy of the He^3 particles elastically scattered from the tantalum backing with the target reversed so that the beam struck the uncoated side. For some of the measurements, the beam energy was determined by substituting a thin gold target and measuring the elastically scattered He^3 particles.

An absorber foil was placed over that portion of the plates used for recording proton tracks in order to remove the large background of He^{3+} ions elastically scattered from the thick tantalum backing.

Directional Correlations

In this part of the work, self-supporting targets of $Al_2O^{18}{}_3$ were used, as previously described.[8] Protons emerging within 0.1 rad of the beam axis were detected with an annular silicon surface-barrier detector which could be placed in either the 0° or 180° position, establishing the axial reaction symmetry required for analysis of the γ-ray angular distributions according to method 2 of Litherland and Ferguson.[11] The small acceptance angle of the proton detector limited the contributions of orbital angular momentum components $m_l>0$ along the beam axis to the order of 1%.

Gamma rays were detected with four 4×4 in. NaI(Tl) scintillation counters placed at different angles to the beam axis, operated simultaneously, each in

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coincidence with the proton detector. Coincident events were recorded as four two-parameter spectra in quadrants of a 4096-channel pulse-height analyzer, as were periodic samples of the singles spectra from all detectors. The angular correlations were interpreted by direct least-squares fitting of the coincidence-peak intensities to Eq. (23) of Litherland and Ferguson,[11] which is in the form of a Legendre polynomial series, the coefficients of which may be expressed[12,13] as

$$A_k=Q_kF_k(J,\delta)G_k(J,Z)\,,\quad k\text{ even}\,, \tag{1}$$

where Q_k is the correction factor for finite solid angle, F_k is the usual γ-ray angular correlation factor for mixed transitions, and G_k is the particle factor. G_k depends only on the assumed spin J of the excited level and on a single parameter Z characterizing its alignment. For each assumed spin, a sequence of values of the multipole mixing ratio δ is generated and a least-squares fit of the experimental data to the computed correlation function is carried out. A goodness-of-fit index

$$\chi^2=\frac{1}{n}\sum\left(\frac{w-w_{\text{exp}}}{\sigma_{\text{exp}}}\right)^2 \tag{2}$$

is then tabulated. The number of degrees of freedom, n, was approximately 30 for each transition studied in this experiment.

Through the alignment parameter Z, the angular correlation usually varies with beam energy and with orientation of the particle detector. In order to exploit these variations, data have been taken under a variety of conditions as listed in Table I.

RESULTS

Energy Measurements

Portions of spectra of the $O^{18}(He^3,p)F^{20}$ reaction taken with the magnetic spectrograph are shown in Fig. 1. Each spectrum includes the doublet as well as an isolated group to illustrate the group shape obtained with the 13-keV thick target. The weighted mean energy difference between the two levels is 18.6±0.7 keV. In this mean, the measurement at 130° was given twice the weight of the others, since at this angle the two groups were most clearly resolved and had the best group shape. The error quoted is the internal error of the measurements, defined as

$$e_{\text{int}}=\left[\sum_j\frac{1}{(\Delta E^j)^2}\right]^{-1/2}\,, \tag{3}$$

where ΔE_j is the uncertainty in an individual measurement. For the spacing between the two levels, the uncertainty in the measurement of the groups on the plate was used to obtain ΔE_j. The principal source of uncertainty was the indeterminacy in group shape due to the small numbers of tracks. An additional source of error is that the two groups were not completely resolved in the 70° spectrum.

TABLE I. Coefficients of Legendre-polynomial fits to the directional correlations of the 1.82 → 0.83-MeV transition, corrected for the finite solid angle of the γ-ray detectors.

Beam energy (MeV)	Proton angle	A_2	A_4
3.30	180°	-0.57 ± 0.07	-0.16 ± 0.13
3.60	180°	-0.43 ± 0.06	
3.70	180°	-0.58 ± 0.06	
3.80	180°	-0.53 ± 0.03	$+0.17\pm0.05$
3.80	0°	-0.50 ± 0.12	
3.90	180°	-0.31 ± 0.05	-0.15 ± 0.07
4.10	180°	-0.30 ± 0.04	

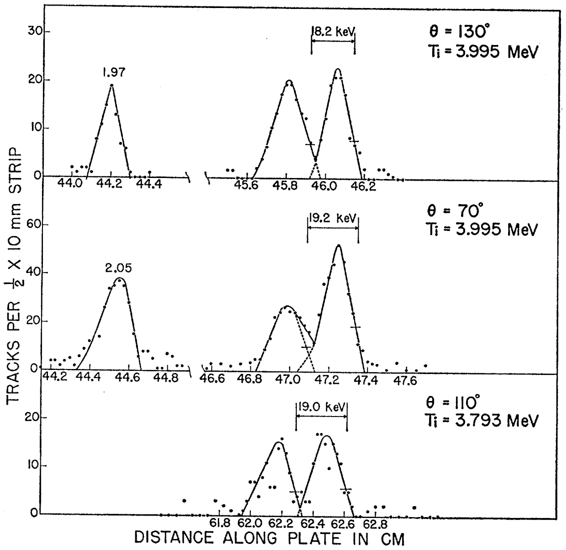

FIG. 1. Spectra of $O^{18}(He^3,p)F^{20}$ showing the levels at excitation energies of 1824.4±2.1 and 1843.0±2.2 keV. In each case another isolated group of comparable intensity is also shown.

The assignment of both groups to excitation of F^{20} is based on the observed shift in kinetic energy of the proton group with angle. As the angle of observation is changed from 70–130°, the spacing between the groups remains constant as seen in Fig. 1, and the Q values remain constant within 5 keV. If the mass number of the recoil nucleus were one unit greater or less than 20, the calculated Q values at 70° and 130° would differ by 39 or 52 keV, respectively.

Six spectra were taken to obtain the excitation energy of the lower level of the doublet. The average of these values is 1824.4±2.1 keV. As a somewhat thicker target, with approximately 20-keV energy loss for 4-MeV He^3 ions, was used in four of these measurements, the upper excitation energy was not obtained from these spectra. Rather the separation given above was added

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to the lower value, yielding an excitation energy of 1843.0±2.2 keV.

The stated errors are obtained by combining the statistical uncertainty, which is taken as the larger of the standard deviation of the mean and the internal error, with the spectrograph calibration uncertainty.

The standard deviation of the mean for the energy of the lower excited state is 1.6 keV, whereas the internal error is 2.0 keV. An uncertainty of 0.03% of the excitation energy has been adopted for the error in the shape of the spectrograph calibration curve.

The errors which are assumed to exist in an individual measurement and which are used to calculate the internal error for the excitation energy of the lower state, are obtained as follows.

Random errors include errors in setting the spectrograph magnetic field and observation angle, counting and plotting errors, part of the differential hysteresis effect, and field drift between recording the elastically scattered He^3 particles and recording the reaction protons. For three of the measurements, the He^{3+} ions which had been elastically scattered from tantalum were used to give the input energy, and then the spectrograph field was changed to record the reaction products. This introduces an additional uncertainty in determining the Q values but has little effect on the excitation energies. For the remaining three measurements, the He^{3+} ions which had been elastically scattered from a thin gold target were used to obtain the input energy and the same spectrograph field was used to record the proton groups. In all measurements which were used to obtain excitation energies both the ground state and the excited state groups were obtained at a single field setting.

Systematic errors include surface layers on the targets and hysteresis and saturation effects in the magnetic field which cause uncertainties in the shape of the calibration curve. A surface layer on the $Ta_2O^{18}{}_5$ targets would make all the Q values too low but would have very little effect on the excitation energies.

An error of 0.1% of the excitation energy has been assumed for each run, owing to a combination of the above possible errors. An additional error ranging from 2 to 5 keV has been assumed for each run because of poor statistics which give rise to an uncertainty in determining the one-third height of a peak.

The error for the higher excited state is obtained by combining the error in the lower state with the internal error from the measurements of the separation of the two levels.

Decay Scheme

In the two-parameter ($p\gamma$) coincidence spectra, in the region of proton energy corresponding to approximately 1.83-MeV excitation in F^{20}, prominent coincidence peaks at γ-ray energies $E_\gamma \approx 1.83$, 1.00, and 0.66 MeV were observed, with a weaker peak at $E_\gamma \approx 0.83$ MeV. This would be consistent with one transition from the doublet to the ground state, and one from the doublet to the 0.83-MeV level with subsequent deexcitation of this level.[8] The coincidence peak at $E_\gamma \approx 1.83$ MeV is slightly displaced in particle energy from the cascade peaks, making it possible to identify the ground-state transition primarily with the 1.84-MeV level and the cascade primarily with the 1.82-MeV level. At a beam energy of 3.50 MeV and with the proton detector at 0°, the cascade peaks nearly vanish, permitting an upper limit of 5% cascade transition intensity to be placed on the 1.84-MeV level. While no reaction condition has been found where the ground-state peak vanishes, the relative intensities measured with 4.10-MeV beam energy and 180° proton angle indicate an upper limit of 40% for ground-state transitions from the 1.82-MeV level. These results are shown in Fig. 2 together with the decay scheme[8] for the lower-lying levels.

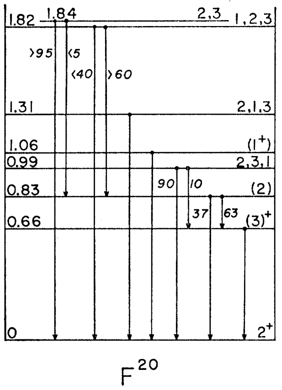

FIG. 2. The low-lying levels of F^{20} with energies, branching ratios, and probable spin assignments from this and earlier work.

Use of relatively thick targets and a large proton detector in the coincidence experiments resulted in a coincidence peak profile width of the order of 100 keV in proton energy. Throughout the experiments, the displacement in excitation energy of the coincidence peaks was consistently about 14 keV. In view of the linewidth, this value is reasonably consistent with the value obtained with the magnetic spectrograph. Its constancy, in spite of the large variations in relative intensity of the cascade and ground-state peaks, indicates that the fractional intensity of the 1.82 ⟶ 0-MeV transition is probably much less than the 40% limit.

Angular Correlations

Coefficients of Legendre-polynomial fits to the intensities of the $E_\gamma \approx 1.0$ and 1.83 MeV coincidence peaks are listed in Tables I and II. In the interpretation given below, it has been assumed that these correspond entirely to the 1.82 ⟶ 0.83- and 1.84 ⟶ 0-MeV transitions, respectively. It has also been assumed that the spin of the 0.83-MeV level is 2, as strongly indicated by prior experiments.[8]

The 1.82-MeV Level

The 1.82 → 0.83-MeV transition is essentially uncontaminated by a possible 1.84 → 0.83-MeV transition, as indicated above. The large anisotropy (see Table I) rules out any possibility of spin 0 for this level. A spin of 5 or larger would imply at least an octupole transition; the attendant long lifetime would, with the recoil velocity of the F^{20} ions, lead to an asymmetry about 90°, which was not observed. Results of the analysis of the angular correlations in terms of spin and multipole mixing ratio are illustrated in Fig. 3. The choice $J=4$ may be completely excluded. The remaining possibilities, $J=1$, 2, or 3, all give acceptable fits to the data for certain values of the multipole mixing ratio.

The analysis has been repeated with the less likely assumption that the spin of the 0.83-MeV level is 4. These results, not illustrated, would be consistent with spin assignments of 2 or 3 only for the 1.82-MeV level.

The 1.84-MeV Level

Angular correlations of the ground-state radiation have been measured under several reaction conditions. The coefficients of least-squares fits to Legendre polynomial series are given in Table II. Figure 4 shows the χ^2 graph for all of the data, analyzed in terms of the spin of the 1.84-MeV level and the multipole mixing ratio. Spin assignments of 0 or 4 are directly excluded by these angular correlations, while spins of 5 or greater can be rejected on the basis of lifetime, as above. While the best fit is obtained with $J=2$, the possibilities $J=1$ or 3 are also in good agreement with the data.

TABLE II. Coefficients of Legendre-polynomial fits to the directional correlations of the 1.84 → 0-MeV transition, corrected for the finite solid angle of the γ-ray detectors.

Beam energy (MeV)	Proton angle	A_2	A_4
3.30	180°	$+0.39\pm0.04$	
3.50	0°	$+0.39\pm0.05$	
3.60	180°	$+0.37\pm0.02$	
3.70	180°	$+0.33\pm0.02$	$+0.10\pm0.03$
3.80	180°	$+0.26\pm0.03$	
3.80	0°	$+0.27\pm0.02$	-0.05 ± 0.04
3.90	180°	$+0.31\pm0.05$	$+0.12\pm0.07$
4.10	180°	$+0.30\pm0.03$	

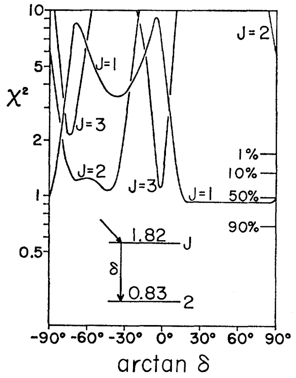

FIG. 3. Plot of χ^2 versus arctan δ for the 1.82 → 0.83-MeV transition. For $J=0$ or 4, all values of χ^2 exceed 10.

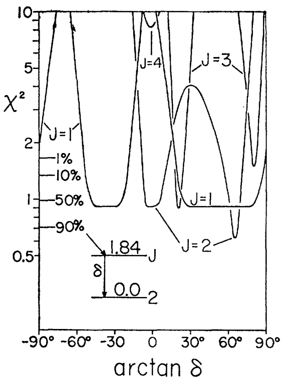

FIG. 4. Plot of χ^2 versus arctan δ for the 1.84 → 0-MeV transition, encompassing all of the data. The χ^2 value for $J=0$ is greater than 10.

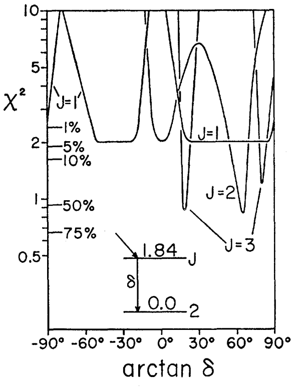

FIG. 5. Plot of χ^2 versus arctan δ for the 1.84 → 0-MeV transition, for the data taken at 3.70- and 3.90-MeV beam energy with the proton detector at 180°. There are 9 degrees of freedom in the fits.

Of the several sets of data, those measured with beam energies of 3.70 and 3.90 MeV, with the proton detector at 180°, have been analyzed separately from the rest. The result of this analysis is shown in Fig. 5, where it may be seen that the possibility $J=1$ is very much less probable than $J=2$ or 3. It may be noted that at 3.70 MeV, the intensity of the cascade 1.82 → 0.83 → 0.66 → 0 MeV is less than 15% of the ground-state radiation; this combined with the branching-ratio limits for the 1.82-MeV level implies that, at worst, less than 10% of the ground-state coincidence peak is due to a possible 1.82 → 0-MeV transition. Thus the significant A_4 coefficient observed at this energy cannot arise from this possible interference.

These results indicate a probable spin assignment of 2 or 3 to the 1.84-MeV level, without positively excluding spin 1. The corresponding multipole mixing ratios may be read from Figs. 4 and 5.

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