Mean Lives, Branching Ratios, and Excitation Energies of Levels in ^{20}F below 4 MeV†

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The ^{19}F$(d, p)^{20}$F reaction has been used to study the mean lives, branching ratios, and excitation energies of several of the levels of ^{20}F. The Doppler-shift attenuation method was used to obtain the following information concerning the mean lives of the low-lying levels in ^{20}F: $\tau(0.66\text{ MeV}) = (3.6\pm0.7)\times10^{-13}$ sec, $\tau(0.82\text{ MeV}) \geq 4.4\times10^{-12}$ sec, $\tau(0.98\text{ MeV}) = (1.3_{-0.4}^{+0.6})\times10^{-12}$ sec, $\tau(1.06\text{ MeV}) \leq 9.2\times10^{-14}$ sec, and $\tau(1.31\text{ MeV}) = (1.1_{-0.3}^{+0.4})\times10^{-12}$ sec. In addition, upper limits were found for levels at 2.04, 2.19, 2.96, 3.49, and 3.53 MeV. A previously unreported branching ratio of the 2.96-MeV level was found to be ($2.96\to0.0$ MeV) 0.24 ± 0.03, ($2.96\to0.66$ MeV) 0.14 ± 0.02, and ($2.96\to0.82$ MeV) 0.62 ± 0.06. A value of 3^+ is suggested for the spin and parity of the 0.66-MeV level.

I. INTRODUCTION

INFORMATION about the properties of the low-lying energy levels of ^{20}F has been obtained mainly from angular distributions of protons produced in the ^{19}F$(d, p)^{20}$F reaction,[1–3] from γ-ray spectra produced by neutron caputure in ^{19}F,[4,5] and from particle–γ-ray correlations of radiations from the reactions ^{19}F$(d, p)^{20}$F and ^{18}O$(^3$He$, p)^{20}$F.[6,7] The latter reference contains a summary of most of the previous experimental information concerning ^{20}F. However, as discussed in detail by Bissinger *et al.*,[7] the interpretations of these experiments are sufficiently ambiguous that spin and parity assignments for some of these states cannot be made with confidence. Attempts at theoretical interpretations of the structure of ^{20}F are rare, and have not been strikingly successful. Kurath[8] concluded that, in order to explain the magnetic moment of its ground state, the low-lying levels of ^{20}F must be rotational states which have a mixture of $K=1$ and $K=2$ rotational quantum numbers. More recently, Gunye and Warke,[9] using a Hartree-Fock calculation, predict a low-lying rotational band of states with spins of $J=2$, 3, 4, and 5. Halbert *et al.*[10] have estimated the quadrupole transition probability for the $0.66\to0.0$-MeV transition from a shell-model calculation with effective interactions. Their result is approximately the same as obtained from the Nilsson rotational model.

The work described in this paper was undertaken with the hope that additional information about the electromagnetic transitions among the states in ^{20}F would help to clear up some of the ambiguities in spin and parity assignments for these states, and in addition would perhaps indicate the type of model which is most appropriate for calculating the properties of this nucleus. We have used the Doppler-shift attenuation method to obtain mean lives, or limits thereto, for states in ^{20}F up to 3.5 MeV. Branching ratios for some of these states have also been measured.

II. EXPERIMENTAL METHOD

A. General

The method we use to measure Doppler shifts has been described in a previous paper.[11] The reaction ^{19}F$(d, p)^{20}$F was used to produce recoiling ^{20}F nuclei in excited states. The initial velocities of these nuclei were defined by detecting protons from the reaction and recording only those γ rays from the decay of ^{20}F which were in time coincidence with protons of appropriate energy. Average energies of γ rays emitted approximately in and opposite to the direction of recoil were measured and used to obtain the numerator of the ratio

$$F=\frac{\langle E_{\gamma1}\rangle-\langle E_{\gamma2}\rangle}{(E_0/c)\langle\mathbf{v}_0\rangle_p\cdot\{\langle\hat{r}\rangle_{\gamma1}-\langle\hat{r}\rangle_{\gamma2}\}}\,. \qquad (1)$$

The denominator of this ratio is the unattenuated Doppler shift, where $\langle\mathbf{v}_0\rangle_p$ is the space average of the initial velocities of the recoil ions allowed by the finite size of the particle detector. The unit vector $\hat{r}$ is in the direction of an emitted γ ray, and $\langle\hat{r}\rangle_{\gamma i}$ is its average over the dimensions of the γ-ray detector located at position i with respect to the recoil ions. The quantity E_0 is the energy difference of the initial and final states of the transition. The unattenuated Doppler shift has been calculated from the known geometry of our arrange-

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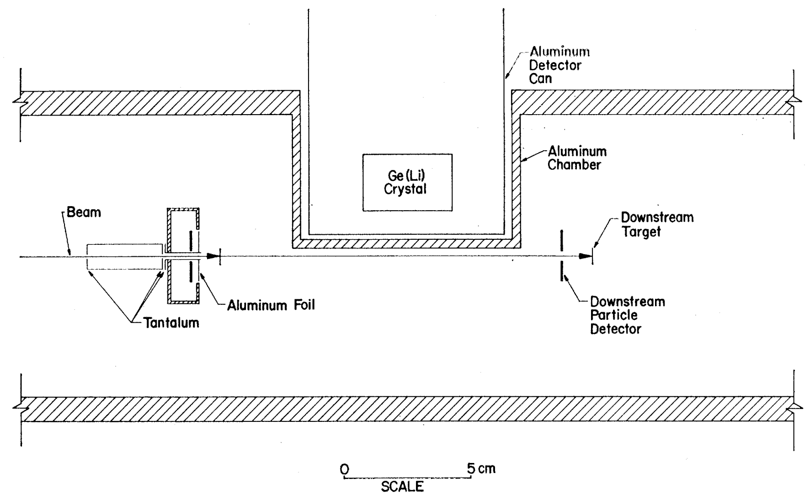

FIG. 1. Experimental arrangement of the collinear target chamber. The collimator arrangement for the downstream detector is identical to that shown for the upstream detector. The aluminum foil is 0.001 in. thick.

ment and kinematics of the reaction. This calculation and experimental checks of the calculation are described in detail in Ref. 11.

To obtain the mean life τ of a state from the Doppler-shift attenuation factor F and the slowing-down properties of the medium through which the excited nuclei recoil we use essentially the method of Blaugrund.[12] In practice a calculated curve of F versus τ is plotted, and experimental measurements of F are read into the curve to obtain τ. In these calculations we use stopping powers obtained from the theory of Lindhard *et al.*[13] Slowing down in both the target material and the backing are included.

B. Details

Targets of natural calcium fluoride approximately 250 μg/cm^2 thick evaporated on copper backings were bombarded with a 10–50-nA beam of 1.90–2.25-MeV deuterons. Protons from the ^{19}F$(d, p)^{20}$F reaction were detected in a silicon surface-barrier detector covered with 0.001-in. aluminum foil to keep elastically scattered deuterons from being detected. γ rays in coincidence with protons from a given state in ^{20}F were detected with a 20-cm^3 Ge(Li) crystal.

Two different experimental arrangements were used in this work. In the old method, described in Ref. 11, protons were detected with a 150-mm^2 detector located at 125° to the beam. The γ rays in coincidence with these protons were detected alternately at 0° and 155° to the recoiling nuclei by rotating the γ-ray detector about the target. This procedure has the disadvantages that it changes the background seen by the detector and enhances the possibility of mechanical and electrical changes during the course of a given measurement. The new arrangement is shown in Fig. 1. The γ-ray detector was placed as close to the beam as possible between two target-and-particle-detector sets. The beam passed through the upstream detector, was split by the upstream target, passed through the downstream detector, and was stopped by the downstream target. Two identical 300-mm^2 annular detectors were placed equal distances, 11.4 mm upstream for their respective targets. Both of these particle detectors subtended angles at the target of from 170° to 140° with the incident beam, and produced identical average initial recoil velocities of the ions in each target. The targets were placed at equal distances on either side of the γ-ray detector. The geometry was such that the γ-ray detector was located at 24° from the beam direction for the upstream target and 156° from the beam direction for the downstream target. γ rays in coincidence with protons detected by the upstream detector were routed to one-half of the memory of the pulse-height analyzer, while, simultaneously, those in coincidence with protons detected in the downstream detector were routed to the other half. Thus, $\langle E_{\gamma 1}\rangle$ and $\langle E_{\gamma 2}\rangle$ in the numerator of Eq. (1) were measured simultaneously, greatly reducing the possibility of systematic errors in the measurement. The γ-ray coincidence rates from both targets were made equal by adjusting the proton counting rates from single-channel analyzers which analyzed pulses from the two particle detectors. This adjustment was accomplished by moving the upstream target into or out of the beam while monitoring the respective counting rates. The gain of all the electronics and the zero level of the analog-to-digital converter (ADC) were digitally stabilized.

Coincidences were obtained using low-level leading-edge timing in the γ-ray leg and the zero crossover from a timing single-channel analyzer in the proton leg. These two timing signals were used to start and stop a time-to-amplitude converter. The output of this con-

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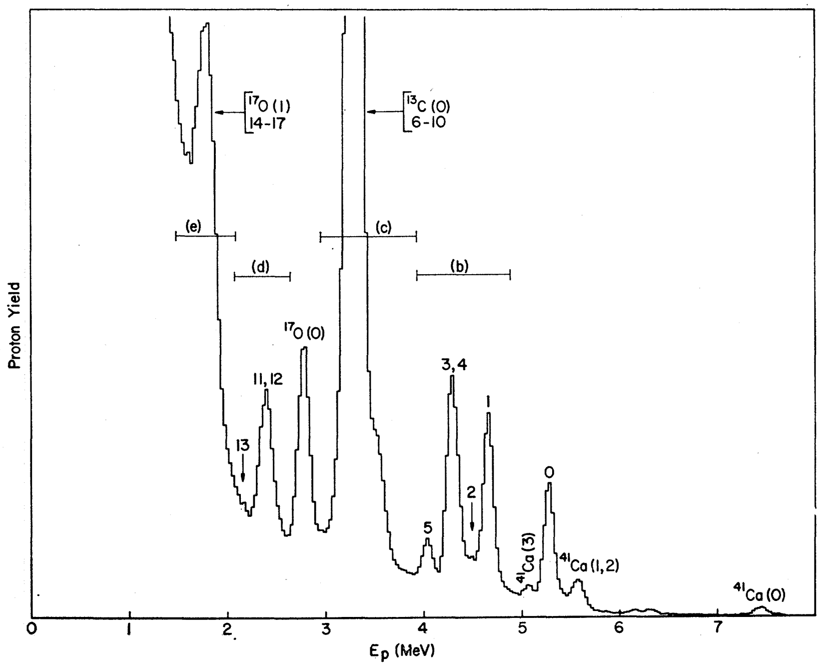

FIG. 2. Proton spectrum from the reaction ^{19}F$(d, p)^{20}$F obtained with the experimental arrangement of Fig. 1. Numbering of the proton peaks corresponds to the known levels of ^{20}F where the doublet reported in Ref. 14 is taken as two levels. Those proton groups resulting from calcium and from carbon and oxygen impurities in the target are also shown.

verter was passed through a single-channel analyzer and used to open a gate through which the linear signal from the γ-ray detector, if in time coincidence with a proton of appropriate energy, passed to the pulse-height analyzer. The over-all time resolution of the system was about $2\tau = 30$ nsec. The beam current and target thickness were chosen to give a small chance rate. The chance rate was measured by comparing the ratios of the yields of the γ rays of interest to those of 0.511- and 1.632-MeV γ rays in the coincidence and in the singles spectra. The 1.632-MeV γ rays followed the β decay of ^{20}F. Pulse pileup was reduced by rejecting any two γ-ray pulses which were closer together in time than 8 μsec.

Average γ-ray energies used in the numerator of Eq. (1) were obtained from pulse-height spectra by subtracting a quadratic background function and computing the centroid of the remainder. The statistical uncertainties in locating the centroid were used as errors in the average γ-ray energies quoted. In addition, several measurements of each average γ-ray energy were made, and standard deviations of individual measurements from the over-all average were computed. In almost all cases, errors obtained in this way agreed with the computed uncertainties. Where discrepancies between the two methods for computing errors did occur, the larger of the two errors was used. In addition to statistical errors in the γ-ray energies, the error in the Doppler-shift attenuation factor F includes an uncertainty of 2.0% in the calculation of the unattenuated Doppler shift; 1% to allow for errors in positioning the various components in the experimental arrangement and 1% to allow for the angular distribution of protons across our particle detector.

III. RESULTS

A. Energies

A spectrum of protons obtained with a 2.25-MeV deuteron beam incident on a 250-μg/cm^2 CaF_2 target is shown in Fig. 2. Numbering of proton peaks corresponds to the known levels in ^{20}F, where the recently reported doublet[14] is taken as two levels. We have studied γ rays in coincidence with protons to the 0.66-, 0.82-, 0.98-, 1.06-, 1.31-, 2.04-, 2.19-, 2.96-, 3.49-, and 3.53-MeV states in ^{20}F. The energies of these states are known to about ± 10 keV from magnetic analyses of proton spectra from (d, p) reactions. Recently the energies of some of the γ-ray transitions among these states have been measured with uncertainties of less than 1 keV.[5] Protons to all of these states could not be resolved individually, and in fact γ rays in coincidence with protons to a cluster of states were usually observed. However, the good resolution of the γ-ray detector enabled us to identify the individual states from which the γ rays originate. The requirement that γ rays be in time coincidence with protons to a given state or a given cluster of states greatly simplifies the resulting spectrum, so that identification of γ rays with a given transition is relatively easy. For example, Fig. 3(a) shows the very complex singles γ-ray spec-

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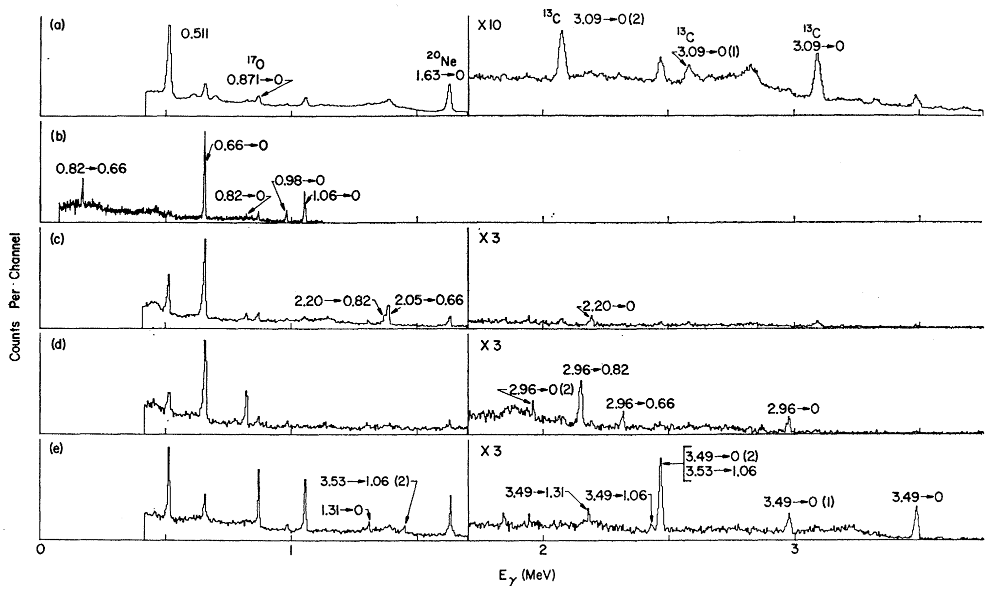

FIG. 3. γ-ray spectra from the $^{19}F(d, p)^{20}F$ reaction. (a) γ-ray singles spectrum with labeled impurity transitions. (b)–(e) γ-ray coincidence spectra corresponding to the proton windows shown in Fig. 2. The observed transitions in ^{20}F are labeled when they first appear. Each ordinate scale is from zero to an arbitrary number of counts.

trum obtained with 2-MeV deuterons on CaF_2 and Figs. 3(b)–3(e) show spectra in coincidence with protons in windows labeled (b)–(e), respectively, in Fig. 2. From spectra such as those in Fig. 3, the energies of some of the states in ^{20}F have been obtained with precision of 0.5–2.0 keV. The γ-ray energies were obtained from measurements made at 90° to the moving nuclei, and from the average of γ-ray energies measured at forward and backward direction with respect to the moving nuclei, so that no Doppler-shift correction is necessary in going from γ-ray energy to the energy difference between states of the transition. Also, in all cases, the decrease in γ-ray energy due to the recoil of the ^{20}F nucleus on emission of the γ-ray was small compared to experimental errors, and was neglected. Energies of some states in ^{20}F are listed in Table I.

TABLE I. Energies of some levels in ^{20}F.

Level (MeV)	Energy (keV) This work	Energy (keV) Reference[a]
0.66	655.4±0.5	656.3±0.5
0.82	822.6±0.7	
0.98	983.4±0.7	983.5±0.7
1.06	1055.2±0.6	1056.9±1.0
1.31	1308.0±0.9	1309.1±0.7
2.96	2964.5±2.0	2966.0±2.0

[a] Reference 5.

The energy calibration of our system was obtained by locating the peaks from ^{22}Na and ^{60}Co sources in the singles spectrum. To check the accuracy of the energy calibration, the energies of annihilation radiation and of the 0.871-MeV γ rays from ^{17}O were determined from peaks which appeared as chance counts in the coincidence spectrum. From a number of such measurements we conclude that the energy calibration could be in error by as much as 0.3 keV for a γ ray with an energy 900 keV. We have added this uncertainty directly to the statistical errors in determining centroids in order to obtain the errors quoted in Table I.

TABLE II. Branching ratios of some levels in ^{20}F.

Level (MeV)	Branch	Present work	Previous results
0.82	0.82→0	0.42±0.04	0.37[a] 0.25[b]
	0.82→0.66	0.58±0.06	0.63[a] 0.75[b]
0.98	0.98→0	≥0.95	≥0.90[c]
	0.98→0.66	≤0.05	≤0.10[c]
1.31	1.31→0	≥0.86	
	1.31→0.66	≤0.14	
2.96	2.96→0	0.24±0.03	
	2.96→0.66	0.14±0.02	
	2.96→0.82	0.62±0.06	

[a] Reference 6.
[b] Reference 4.
[c] Reference 7.

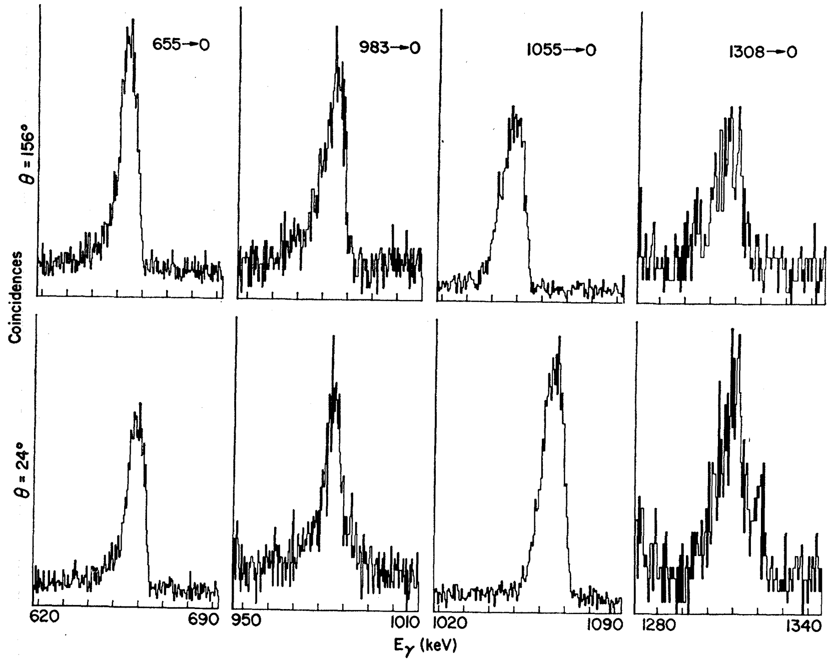

FIG. 4. Coincidence spectra from the ^{19}F$(d, p)^{20}$F reaction showing the Doppler shifts of several transitions. Shifts such as these were used to determine the mean lives of the various levels in ^{20}F. Each ordinate scale is from zero to an arbitrary number of counts. Spectra for the same transition have the same scale.

B. Branching Ratios

Table II shows our results for the branching in the decay of several states in ^{20}F. These results were obtained at only two or three angles, with respect to the recoiling nuclei, and are not true angular averages. However, none of the results quoted appeared to be sensitive to angle. The uncertainties are simply calculated standard deviations in the areas under individual peaks. The spectrum in coincidence with protons to the 1.31-MeV state showed a peak at 0.66 MeV which seems to indicate that a small fraction of the time this state may decay through the 0.66-MeV state. However, as indicated in Table II, this conclusion is quite uncertain.

C. Mean Lives

Figure 4 illustrates the spectra measured at about 24° and 156° with respect to recoiling ^{20}F nuclei of γ rays in coincidence with protons to the 0.66-, 0.98, 1.06-, and 1.31-MeV states in ^{20}F. These spectra were obtained with the collinear arrangement described in Sec. II above. Doppler shifts of γ rays from those states were deduced directly from these and similar spectra. However, the direct yield of the 0.82-MeV state in the (d, p) reaction with 2-MeV deuterons was so low that for this state Doppler shifts were measured for γ rays from the cascade 2.96→0.82→0.0 MeV. The Doppler-shift attenuation factors so measured were then related to mean lives of the 0.82- and 2.96-MeV states by

$$F_{\text{meas}}=\frac{\tau_{0.82}F(\tau_{0.82})-\tau_{2.96}F(\tau_{2.96})}{\tau_{0.82}-\tau_{2.96}}. \tag{2}$$

As can be seen, to obtain information about the 0.82-MeV state from this equation it was necessary for us first to measure the Doppler-shift attenuation factor for the γ-rays emitted in the 2.96→0.82-MeV transition. For the particular case considered, $\tau_{2.96}/\tau_{0.82}<10^{-2}$, so that the application of Eq. (2) is trivial.

Since Doppler-shift measurements on the five lowest states were made with the proton window over all five states, a small correction was made to the results for the 0.66-MeV γ rays to account for cascades from the 0.82-MeV level. This correction was made using Eq. (2), and its magnitude was determined from the area under the 0.82-MeV peak in the coincidence spectrum, the measured branching ratio of that state, and the variation with energy of the efficiency of the Ge(Li) crystal. The correction was about 4% of the attenuation factor of the 0.66-MeV peak. In addition, the Doppler shifts of 0.66-MeV γ rays were measured in the case where they were produced in the cascade 2.04→0.66→0.0 MeV. This measurement was subject to a 12% correction similar to the one described above because γ rays from the cascade 2.19→0.82→0.66→0.00 MeV were also present.

Results of the Doppler-shift measurements are presented in Table III. The initial average speeds of recoiling ^{20}F nuclei are listed in column 3; column 4 shows the measured energy differences between γ rays emitted in and opposite to the direction of these recoiling nuclei, and column 5, the Doppler-shift attenuation factor, is the ratio of column 4 to the calculated unattenuated shift. The errors in column 5 include both the statistical errors in column 4 and a 2.0% uncertainty

TABLE III. Doppler shifts and mean lives in ^{20}F.

Energy level (MeV)	Method of population	$\langle \| \mathbf{v}_0 \| \rangle_p/c$	ΔE (keV)	F	τ_1[a] (10^{-13} sec)	τ_2[b] (10^{-13} sec)
0.66	Direct	0.00850	4.50±0.15	0.448±0.021	$3.59_{-0.39}^{+0.51}$	
	Direct	0.00951	4.95±0.11	0.473±0.017	$3.40_{-0.35}^{+0.35}$	
	2.04	0.00784	3.29±0.17	0.406±0.026	$4.10_{-0.55}^{+0.70}$	
				Average	$3.57_{-0.24}^{+0.27}$	$3.57_{-0.78}^{+0.73}$
0.82	2.96	0.00859	0.17±0.18	0.014±0.016	≥50	≥44
0.98	Direct	0.00834	3.02±0.73	0.204±0.051	$10.3_{-2.8}^{+4.2}$	
	Direct	0.00936	1.65±0.38	0.102±0.024	$22.5_{-5.0}^{+8.5}$	
				Average	$12.8_{-2.4}^{+3.8}$	$12.8_{-4.1}^{+6.2}$
1.06	Direct	0.00831	16.52±0.23	1.046±0.028		
	Direct	0.00932	15.32±0.26	0.888±0.029		
	Direct	0.00959	17.33±0.30	0.993±0.030		
			Value used	$F \geq 0.83$	≤0.86	≤0.92
1.31	Direct	0.00819	3.76±0.54	0.195±0.029	$10.6_{-2.0}^{+2.9}$	
	Direct	0.00946	2.74±0.58	0.128±0.028	$17.7_{-4.2}^{+6.3}$	
	3.49	0.00704	3.27±0.62	0.201±0.040	$10.0_{-2.3}^{+3.3}$	
				Average	$11.1_{-1.4}^{+2.0}$	$11.1_{-2.9}^{+4.1}$
2.04→0.66	Direct	0.00784	19.40±0.22	0.992±0.028	≤0.32	≤0.38
2.19→0.82	Direct	0.00776	19.09±0.50	1.007±0.040	≤0.39	≤0.46
2.96	Direct	0.00859	42.8 ±1.6	0.967±0.048		
2.96→0.82	Direct	0.00859	30.27±0.70	0.946±0.033		
			Average	0.952±0.027	≤0.51	≤0.62
3.49	Direct	0.00704	>40	>0.92	<0.38	<0.47
3.53→1.06	Direct	0.00702	31.35±0.48	1.024±0.029	≤0.28	≤0.32

[a] The errors in the column marked τ_1 are the sum of uncertainties in τ due to errors in the measurement of F and the measurement of the target thickness.

[b] The errors in this column include *assumed* uncertainties of 20% in the atomic and nuclear slowing-down powers of the targets and backings.

in the calculated full shift. Each of the values of F listed is the average of several individual measurements. Column 6 shows the mean lives or limits, and their errors, obtained from our values for F. These errors result from the errors in F and from an uncertainty of $\pm 50\ \mu g/cm^2$ in the target thickness. Column 7 shows the increased errors which include a 20% uncertainty in the calculated electronic and nuclear stopping powers used to obtain the mean lives from the F values. Where limits are quoted, they correspond to an F value 2 standard deviations away from our measured value. For the three measurements on the 1.06-MeV level, the spread in results is much greater than the errors on the individual measurements. Since we do not understand this large spread, the limit to the mean life to this state was deduced by using a value of F 2 standard deviations below the *lowest* of these measurements.

IV. DISCUSSION

A. 0.66-MeV Level

According to Bissinger *et al.*,[7] particle–γ-ray correlations and (d, p) angular distributions limit the choice of quantum numbers for this state to 1^+, 2^+, and 3^+. A recent, and as yet unpublished, measurement[15] of the vector-analyzing power of $^{19}F(d, p)$ reaction leaving ^{20}F in its first excited state shows that the transferred neutron has $j_n = \frac{5}{2}$, and therefore that the spin of the

[15] P. Quin (private communication).

0.66-MeV state is 2 or 3. From the angular correlation data, the most probable values of multipole mixing ratios are $-1 \geq \delta \geq -3$ for $J=2$, and $\delta=-0.05$ for $J=3$. Combining our measured mean life for the 0.66-MeV state with a value of $\delta \leq -1$ yields an experimental $E2$ radiation width for which

$$\Gamma_{\mathrm{exptl}}(E2)/\Gamma_W(E2) \equiv |M(E2)|^2 \geq 3000,$$

where Γ_W is the single-particle width calculated from the equations tabulated by Wilkinson.[16] This ratio is clearly unrealistic, and leaves only the choice $J^\pi(0.66 \text{ MeV}) = 3^+$. The transition 0.66 MeV→ground state is then nearly pure $M1$, and $|M(M1)|^2=0.3$.

Bergqvist *et al.*[4] found some indication that the 1^- state in ^{20}F at 6.6 MeV decays through the 0.66-MeV state. The observation of this transition would be in contradiction with the conclusion that the 0.66-MeV state is 3^+. However, the γ rays from transitions from the 1^- state to several low excited states in ^{20}F were not resolved, leaving the possibility that the spectrum produced by neutron capture in this state could be interpreted in another way.

B. 0.82-MeV Level

From previous work[7] and from recent, as yet unpublished, extensions of that work[17] the most likely assignments for the spin of this level and the multipole mixture of its transition to ground are $J=2$, $\delta=2.1$, or $J=4$. An assignment of $J=4$ to this level is not consistent with the (d, p) data.[1] These (d, p) data also favor a positive parity for this state. For $J=2^+$, $\delta=2$, our limit to the mean life gives $|M(E2)|^2 \leq 100$ and $|M(M1)|^2 \leq 2\times10^{-3}$. For $J=4^+$ the ground-state transition is pure $E2$ and $|M(E2)|^2 \leq 120$.

C. 0.98-MeV Level

As indicated in Table II, we were unable to observe a previously reported transition from this level to that at 0.66 MeV. We find the limit for this transition to be $\leq 5\%$. The spin of this level and the multipolarity mixture of the transition to the ground state in order of preference[7] are $J=2$, $\delta=+14.3$; $J=3$, $\delta=-11.4$; and $J=1$ with a wide range of possible mixing ratios. If $J=2$ or 3 and if the parity of the state is positive, the transition would be nearly pure $E2$ and $|M(E2)|^2 \simeq 200$. This is a very large enhancement. If the quantum numbers of the 0.98-MeV state were 1^+, we could obtain $|M(E2)|^2 \leq 200$, or $|M(M1)|^2 \leq 2.5\times10^{-2}$. If it were 1^-, $|M(E1)|^2 \simeq 10^{-2}$ could be obtained. No definitive conclusions can be reached.

D. 1.06-MeV Level

The quantum numbers of this level are most probably 1^+,[7] and a wide range of multipole mixtures are possible for its transition to the ground state. If the transition were all $M1$, $|M(M1)|^2 \geq \frac{1}{3}$, and if it were all $E2$, $|M(E2)|^2 \geq 2.5\times10^3$. The latter number is huge, and indicates that the multipolarity of the transiton is predominantly $M1$.

E. 1.31-MeV Level

Again in order of preference,[7] for this level, (a) $J=2$, $\delta=0.04$ or 1.9, (b) $J=1$, $\delta=-0.7$, or (c) $J=3$, $\delta=0.42$. A strong transition observed to this state following thermal-neutron capture rules out choice (c). Results of (d, p) angular distributions agree and show that the parity of this state is positive. Alternative (a) gives $|M(M1)|^2=1.3\times10^{-2}$ or $|M(E2)|^2=47$ and $|M(M1)|^2=2.8\times10^{-3}$. For alternative (b), $|M(E2)|^2=20$ and $|M(M1)|^2=9\times10^{-3}$.

To summarize, our results on transition probabilities are not in disagreement with the spin assignments or multipole-mixture measurements of Bissinger *et al.*[7] In addition, our measurements, combined with appropriate multipole mixtures, indicate that the spin quantum number of the 0.66-MeV state is 3 and that its parity is positive. Our results and their analysis strikingly illustrate the difficulty encountered in obtaining unambiguous information about the properties of levels in ^{20}F.

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