[8] J. Konijn, R. van Lieshout, J. P. Deutsch, and L. Grenacs, Nucl. Phys. A91, 439 (1967).

[9] L. G. Mann, K. G. Tirsell, and S. D. Bloom, Nucl. Phys. A97, 425 (1967).

[10] C. N. Davids, A. Boudreaux, R. C. Pardo, L. A. Parks, and D. P. Whitmire, private communication.

[11] G. G. J. Boswell and T. McGee, J. Inorg. Nucl. Chem. 30, 2571 (1968).

[12] C. E. Moss, C. Détraz, C. S. Zaidins, and I. J. Frantsvog, Phys. Rev. C 5, 1122 (1972).

[13] A. Gallmann, F. Jundt, E. Aslanides, and D. E. Alburger, Phys. Rev. 179, 921 (1969).

[14] C. E. Moss, C. Détraz, and C. S. Zaidins, Nucl. Phys. A170, 111 (1971).

[15] C. N. Davids, D. L. Matthews, and D. P. Whitmire, Bull. Am. Phys. Soc. 17, 71 (1972); and to be published.

[16] W. D. Arnett and S. E. Woosley, private communication.

PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Study of Some ^{20}F Excited States*

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(Received 11 September 1972)

Excited states of ^{20}F which deexcite via γ-ray cascades through the 823-keV state were studied using the ^{18}O(^{3}He, p) reaction at a beam energy of $E_{^3\text{He}} = 2.88$ MeV. Particle γ-ray angular correlations in a standard collinear geometry were obtained using NaI detectors for observing those γ rays which were in coincidence with proton groups representing excited states up to 4.3 MeV excitation. The analysis of these data involved the simultaneous fitting of the correlations of all possible cascading γ rays from the state under study and resulted in the measurement of spins, branching, and multipole mixing ratios for some excited states and their subsequent electromagnetic deexcitations. Coincident γ-ray spectra were also obtained with a Ge(Li) detector which provided additional information regarding the more complex decay schemes. Previously unreported lifetime information for the 1824- and 1972-keV states was obtained using the Doppler-shift-attenuation method and the ^{18}O($t, n\gamma$)^{20}F reaction at a beam energy of $E_t \simeq 2.85$ MeV. These mean lifetimes are ≤ 65 fsec and ≥ 1.1 psec, respectively. The combined data for the 1824-keV state, as well as recently reported two-particle transfer data, suggest that the 823- and 1824-keV states are the $J^\pi = 4^+$ and 5^+ members, respectively, of the ground-state rotational band. Data obtained regarding the 1972-keV state suggest that this state has a $J^\pi = 3^-$ assignment, while those for the 2195-keV state imply a $J^\pi = 3^+$ assignment. The results of this experiment are compared with recently reported shell-model calculations.

I. INTRODUCTION

The nuclear spectroscopy of the excited states of ^{20}F is not well understood despite a large number of completed experimental investigations. This is due in part to the fact that many of the combinations of targets and reactions normally used with conventional standard investigative techniques do not always yield unambiguous spin assignments. One recent study[1] reviews the available spectroscopic information and compares this information with the results of the Oak Ridge shell-model calculations.[2] These shell-model calculations have been very successful in describing nuclear properties of many nuclei in this mass region and should, as a consequence, be just as successful with the nucleus ^{20}F. One of the resulting features of these calculations (independent of the Hamiltonians used) is a set of rotational-band-like states starting with the $J^\pi = 2^+$ ground state. The predicted $J^\pi = 4^+$ state is consistently positioned in the region of excitation equivalent to 1 MeV, while the $J^\pi = 5^+$ state is generally predicted to be at an excitation energy of about 2 MeV. A recent report[3] points out the consistency between experiment and theory if it is assumed that the 656- and 823-keV states are the $J^\pi = 3^+$ and 4^+ members of this rotational band, although the 823-keV state was known to have spin $J = 2$ or 4. In addition to positive-parity states generated by the presence of the active nucleons in sd-shell orbits as calculated by the Oak Ridge shell-model group,[2] it is expected[4] that there should be some low-lying negative-parity states whose origins are outside of the sd shell.

The present investigation consisted of a study of the excited states of ^{20}F using the ^{18}O(^{3}He, $p\gamma$)-^{20}F and ^{18}O($t, n\gamma$)^{20}F reactions at bombarding energies of $E_{^3\text{He}} = 2.88$ and $E_t = 3.0$ MeV. The investigation was undertaken in an effort to better understand the possible existence of a ground-state rotational band. As a consequence, the states of most interest were those which deexcite via γ-ray cascades through the 823-keV state which is suspected of being the $J^{\pi}=4^{+}$ member of this band. Aside from attempting to obtain spin assignments for these and other states, another motive for the investigation was to obtain a more accurate set of branching and multipole mixing ratios for the γ-ray transitions. The partial radiative widths derived using the above ratios are sensitive indicators of the validity of the wave functions obtained from the various Hamiltonians used in the shell-model calculations. The principal mode of investigation relied on particle–γ-ray angular correlations obtained in a standard collinear geometry using NaI(Tl) counters for detection of the cascading γ rays. A Ge(Li) detector was also used to obtain coincident γ-ray spectra. The above studies yielded spin assignments for excited states as well as yielding branching and multipole mixing ratios for the subsequent electromagnetic deexcitations of these states. Since there existed no lifetime information for the 1824- and 1972-keV states, Doppler-shift-attenuation measurements were attempted using both the $^{18}O(^{3}He, p\gamma)^{20}F$ and $^{18}O(t, n\gamma)^{20}F$ reactions with a Ge(Li) detector, in a singles mode, for observing the γ rays. The attenuated shifts were compared to the full shifts observed when the excited ions recoiled into vacuum.

II. EXPERIMENTAL PROCEDURE

The angular-correlation studies consisted of particle-γ-ray correlations obtained in a standard collinear geometry.[5] The coincident γ rays for these measurements were observed simultaneously in a 4-in. × 4-in. and a $1\frac{1}{2}$-in. × 4-mm NaI(Tl) detector. The latter counter was used to observe the 167-keV γ ray originating from the deexcitation of the 823- to the 656-keV state. The γ rays in both counters were observed in time coincidence with protons detected in an annular silicon surface-barrier detector positioned at 173 ± 4° to the beam axis. The Lockheed 3-MV Van de Graaff accelerator was used with the $^{18}O(^{3}He, p\gamma)$-^{20}F reaction at bombarding energy of $E=2.88$ MeV. An investigation of the excitation function indicated that the 823-keV state was weakly populated at all beam energies below 3 MeV. The above beam energy was chosen on the basis of an optimum yield to all other excited states of interest. Beam currents of ~100 nA were used on a target consisting of $H_2{}^{18}O$ anodized (~200 μg/cm^2 in areal density) onto a 1-mil tantalum backing. Approximately eight hours of data collection time were needed at each of the five angles corresponding to the positions of the two NaI(Tl) detectors. The data from each detector combination were identified by an appropriate flag pulse. The data collection system consisted of conventional modular electronics and a SEL 810A computer interfaced to one 128- and two 8192-channel analog-to-digital converters. This arrangement allowed a three-parameter collection of data onto magnetic tape with simultaneous on-line and/or subsequent off-line data analysis. The coincident γ-ray data obtained using the Ge(Li) detector were taken under similar conditions to the above except data were collected only at $\theta_{\gamma}=90°$. The data collection time for this run was ~48 h at a beam current of ~60 nA. No effort was made to obtain accurate excitation energies from the Ge(Li) data, and throughout this report the excitation energies quoted are those reported by Rollefson, Jones, and Shea.[6] The coincident Ge(Li) data were used mainly for obtaining accurate branching ratios of closely spaced states whose corresponding particle groups could not be resolved in the annular detector. For those states whose corresponding particle groups could be fully resolved, the branching ratio data were taken from both the NaI(Tl) and Ge(Li) γ-ray spectra.

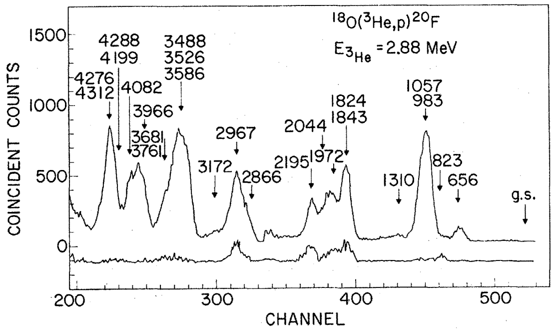

FIG. 1. The upper curve is a proton spectrum obtained in coincidence with all γ rays observed at 45° in the 4-in. × 4-in. NaI(Tl) detector. The lower curve is a proton spectrum in coincidence with the 167-keV line in the $1\frac{1}{2}$-in. × 4-mm NaI(Tl) detector. Random coincidence events have been subtracted.

With the $^{18}O(^{3}He, p\gamma)^{20}F$ reaction, the γ-ray angular correlations associated with a given particle group and collected in a collinear geometry are a function of the relative populations of the $m=0$ and ±1 magnetic substates, as well as the usual angular-momentum parameters of spin and electromagnetic multipole radiation. The large number of parameters in this kind of situation usually results in ambiguous spin assignments for most cases if the angular correlation of only one γ ray is obtained. This is particularly true in the cases where the correlation can only be described by Legendre polynomial terms with $K \leqslant 2$. In order to overcome this situation, one should include in a single analysis the angular correlations of all of the cascading γ rays which are in coincidence with a particular proton group. In this kind of analysis the relative population of the two magnetic substates in the description of the angular correlation of each γ ray is a common parameter. This in effect increases the number of degrees of freedom in the subsequent least-squares fit and improves the chance of a unique spin assignment. In general the value of the multipole mixing ratio for any spin combination is usually known for all of the γ-ray transitions except the initial cascade. Because the angular correlation of a secondary γ ray is a function of the mixing ratio of the transitions feeding it, the above analysis can in general provide for a more sensitive method in restricting the spin of the primary state and/or the value of the mixing ratio of the primary transition. In the analysis of the present data all of the cascade correlations involved the deexcitation of a state through the 823-keV state whose spin is known to be $J = 2$ or 4 and which in turn decays to the 656-keV and ground states. The value and associated error of the mixing ratio of all transitions associated with the decay of the 823-keV state have been measured[3] for the two spin possibilities. This leaves the multipole mixing ratio of the primary transition and the relative population of the $m = 0$ and ± 1 substates of the initial state as the only parameters necessary to describe the angular correlations aside from a separate normalization for each of the individual correlations. The data for all of the angular correlation experiments were analyzed by comparing, for a given spin combination, the predicted and measured correlations in a least-squares fit and χ^2 analysis. These analyses include the proper corrections for the finite solid angle of the NaI(Tl) detectors and maintained the phase convention of Rose and Brink[7] for the multipole mixing ratios. The angular correlations were fitted to a Legendre polynomial expansion and the resulting coefficients are given in Table II. The measured mixing ratios for some of the relevant transitions are given in Table III. The results of the present analysis will be compared with those of Quin, Bissinger, and Chagnon.[8]

III. LIFETIME MEASUREMENTS

The mean lifetimes of most of the low-lying excited states in ^{20}F have been measured[9, 10] using the Doppler-shift-attenuation method in conjunction with the $^{19}F(d, p\gamma)^{20}F$ reaction. Two states which were not populated in these studies and for which lifetime measurements have not been made are the 1824- and 1972-keV states. These states are formed with enough strength in the $^{18}O(^3He, p\gamma)^{20}F$ and $^{18}O(t, n\gamma)^{20}F$ reactions that an attempt was made to measure the lifetimes of these states in the present experiment. Because of the small cross section of these states, it was decided not to use a particle-coincident mode in the data collection (which would limit the cone of the recoiling ^{20}F ions) but rather to observe the lines in a "singles" ungated mode at $\theta_\gamma = 0°$ and 90° and compare these shifts to that observed at $\theta_\gamma = 0°$ when the ^{20}F ions recoiled into vacuum. In order to do this, a target assembly was constructed which consisted of 40 $\mu g/cm^2$ of $Ta_2{}^{18}O_5$ (deposited through anodization of $H_2{}^{18}O$) on a 0.05-mil Ta foil. A second tantalum foil of the same thickness was spaced 0.04 in. in front of the target surface such that bombardment of the target material through either of these two foils would result in the ^{20}F ions recoiling into vacuum or tantalum, respectively, under the same kinematic conditions. The $^{18}O(t, n\gamma)^{20}F$ reaction was chosen for this portion of the study, because the tritons lose significantly less energy (~150 keV) in one of the Ta foils than does a ^3He beam (~500 keV), thus maintaining a reasonable yield to the states of interest. A beam energy of $E_t = 3.0$ MeV was used such that the tritons striking the target material had an energy of $E_t \simeq 2.85$ MeV. The beam current was ~100 nA and was stopped approximately 1 in. beyond the target assembly in a Faraday cup. The face of the 20-cm^3 Ge(Li) detector was positioned approximately $2\frac{1}{2}$ in. from the center of the target on a rotatable arm which allowed the detector to be positioned at $\theta_\gamma = 0°$ or 90° with respect to the beam. The spectra were collected with an 8192-channel analog-to-digital converter at a dispersion of 0.561 keV/channel. The data collected consisted of spectra obtained at $\theta_\gamma = 0°$ and 90° with the ^{20}F ions recoiling into the Ta and into vacuum. The Ge(Li) spectra were gain stabilized during data acquisition through the use of software stabilization on the 1.28-MeV γ ray emanating from a ^{22}Na source placed near the detector.

The 1001-keV γ ray resulting from the decay of the 1824-keV state to the 823-keV state had nearly a full Doppler shift when recoiling into Ta. The centroid of the peak associated with recoils into vacuum corresponds to $V/c = 0.005$ and is equivalent to an average value for the direction of motion of the ^{20}F recoils and associated neutrons of 48 and 75°, respectively. The measured attenuated shift was found to be $F(\tau) = 0.86 \pm 0.10$ where the quoted error reflects the uncertainty arising from the background subtraction, as well as the statistical error. This factor, when corrected for the target thickness according to the method described by Paul, Thomas, and Hanna,[11] becomes $F(\tau) = 0.82 \pm 0.11$. Since this value is approximately 1.6 standard deviations from a full shift, it is assumed for the lifetime derivation that $F(\tau) \geq 0.71$.

The 1149-keV γ-ray line resulting from the decay of the 1972-keV state to the 823-keV state displayed no discernible attenuated shift for recoils into Ta between the angles $\theta_\gamma = 0$ and 90°. A full shift was observed between these angles for recoils into vacuum, and an attenuation factor of $F(\tau) = 0.03 \pm 0.07$ was calculated. To within 1 standard deviation the limit was then set at $F(\tau) \leq 0.1$; no correction for target thickness was made, since the time required for a recoil to traverse the $Ta_2{}^{18}O_5$ layer is short compared to the lifetime of the state. A thicker target (~200 $\mu g/cm^2$ on a 0.001-in.-thick Ta backing) was used with both the $(^3He, p)$ and (t, n) reactions at beam energies of 3 MeV in order to collect spectra with better statistics for this 1149-keV line. No discernible attenuated shift could be found between $\theta_\gamma = 0$ and 90°, thus confirming the $F(\tau) \leq 0.1$ measured with the "sandwich" target array.

In order to obtain lifetimes from these attenuated shift factors, a value of $K_e = 0.72$ keV cm$^2/\mu$g ($\alpha = 0.38$ psec) was used to describe the electronic slowing down of ^{20}F ions in Ta. This was obtained from an extrapolation, using the Lindhard and Sharff[12] equations, of the data by Porat and Ramavataram[13] for Ne ions stopping in gold. The universal stopping-power equation of Lindhard, Scharff, and Schiott[14] was used to calculate the characteristic nuclear stopping parameters. The method of analysis described by Blaugrund[15] was used to calculate curves representing the nuclear lifetimes in terms of the attenuation factor $F(\tau)$. The resulting lifetimes for the 1824- and 1972-keV states are ≤65 fsec and ≥1.1 psec, respectively. Recent measurements at Queen's University[16] have found lifetimes consistent with those measured in this experiment.

IV. ANGULAR-CORRELATION MEASUREMENTS

The upper spectrum in Fig. 1 represents the protons in coincidence with all γ rays observed at $\theta_\gamma = 45°$ in the 4-in.×4-in. NaI(Tl) detector. The lower spectrum represents those protons observed in coincidence with the 167-keV line detected with the $1\frac{1}{2}$-in.×4-mm NaI(Tl) counter. Random coincidence events have been subtracted in both cases. From this lower spectrum, as well as by the observation of the 167-keV line in the coincident Ge(Li) spectra, the states which decayed through the 823-keV state were readily identified. There were a few states above 3 MeV excitation which did decay via this route, but this mode of deexcitation was in general too weak to establish which states were involved. Aside from these, no new states other than those reported in Ref. 8 were found to decay through the 823-keV state. It is those states which have a mode of deexcitation through the 823-keV state upon which the effort reported in this paper was concentrated.

A. States Below 1.31 MeV Excitation

The 656-keV state has been experimentally established as a $J^\pi = 3^+$ state. (See Ref. 1 for the latest review.) The data collected in the present experiment agree with past work of their kind[8] and introduce no new information.

The 823-keV state was populated very weakly in this work, and it was impossible to extract information from the angular correlations of the γ rays cascading from this state due to the poor statistics associated with the γ-ray spectra. It has previously been established[3, 8] that this state has a $J = 2$ or 4 spin assignment, and all pertinent information regarding partial transition rates has been ascertained.[3]

The proton group leading to the 983- and 1057-keV states could not be fully resolved from each other in the particle detector nor could the γ-ray lines deexciting these states be resolved in the NaI detectors. It was impossible to obtain any useful information from the composite angular correlations. The coincident Ge(Li) data indicated that these states decayed entirely to the ground state with branches to the 823- and 656-keV state being ≤2% of the total decay. The coincident NaI(Tl) data also concurred with this conclusion. This would then eliminate the previous 10±10% branch assigned by Quin, Bissinger, and Chagnon[8] for the decay of the 983-keV state to the 656-keV state. Previous spin and parity assignments[8] for the 983-keV state are $J = 1$, 2, or 3, while that for the 1057-keV state[1, 8] is $J^\pi = 1^+$.

The 1309-keV state was very weakly populated at the beam energy used in this experiment, and consequently no information could be obtained. Previous measurements[8] using this reaction fix the spin as $J = 1$, 2, or 3. The final section of this paper deals with the possibility that the 983- and 1309-keV states may have negative parity.

B. 1824- and 1843-keV States

The decay schemes of the states in this closely spaced doublet were established from the coincident Ge(Li) spectra, and the relative branching ratios thereof are given in Table I. An upper limit of 3% for a possible decay of the 1824-keV state to ground state was established[17] and is a tighter restriction than the previous assignment[8] of ≤20%. This is rather significant in that the 1824-keV state is the first state which could possibly be a candidate for the $J^\pi = 5^+$ member of the ground-state rotational band. Fortunately, the two states have entirely different decay schemes, thereby allowing the use of NaI(Tl) detectors in the measuring of angular correlations. Figure 2 illustrates NaI(Tl) γ-ray spectra obtained in coincidence with this unresolved particle group. Angular correlations were extracted from the four γ-ray lines associated with the decay of the 1824-keV state. Since the 823-keV state presently has an assignment of $J = 2$ or 4, two sets of χ^2 analyses were performed and are illustrated in Fig. 3. The upper analysis illustrated assumes a spin $J = 4$ for the 823-keV state, and one obtains the best fit for $J = 5$ with $J = 3$ and 4 giving poorer but acceptable fits for the 1824-keV state. On the basis of the lifetime, octupole radiation was not included in the analysis. The heavy bar illustrates the region of restriction for the mixing ratio assuming that any quadrupole strength would not exceed 100 W.u. This would reject the spin $J = 4$. The measured values for the mixing ratios can be found in Table III. The lower analysis illustrated in Fig. 3 features the χ^2 plot assuming a spin $J = 2$ for the 823-keV state; one obtains acceptable fits for $J = 1$ and 3 for the 1824-keV state. Recent two-particle-transfer analysis[18] of ^{18}O(^{3}He, p)^{20}F direct reaction data for the formation of the 1824-keV state indicates that an $l = 4$ can be associated with the formation of this state. If this is so, then the spin and parity of the 1824-keV state must be $J^\pi = 4^+$ or 5^+. It is assumed that the $J^\pi = 3^+$ assignment [which is also allowed for an $l = 4$ transfer in a (^{3}He, p) direct reaction] can be eliminated on the basis that the state should have been populated by an $l = 2$ transfer. Since no such component is observed, the only way that this can be compatible with the results of the analysis of the present data is if the 823- and 1824-keV states had spin assignments of $J = 4$ and 5, respectively. A comparison with the shell-model calculations will be made in the final section of this paper in

TABLE I. A summary of branching ratios measured in this experiment for states which have relevance in regard to the present discussion.

Initial state (keV)	Final state (keV)	Present results
983	0	≥96
	656	≤2
	823	≤2
1057	0	≥96
	656	≤2
	823	≤2
1824	0	<3
	656	≤5
	823	≥95
1843	0	≥94
	656	≤6
	823	<4
	983	<4
	1309	<4
1972	0	16 ± 4
	656	<3
	823	55 ± 3
	983	<3
	1309	29 ± 3
2044	0	8 ± 4
	656	92 ± 4
	823	<5
2195	0	58 ± 4
	656	<5
	823	42 ± 4
2967	0	19 ± 5
	656	17 ± 5
	823	35 ± 4
	1972	29 ± 4
3966	983	22 ± 7
	1309	78 ± 7
4082	0	45 ± 7
	1057	55 ± 7

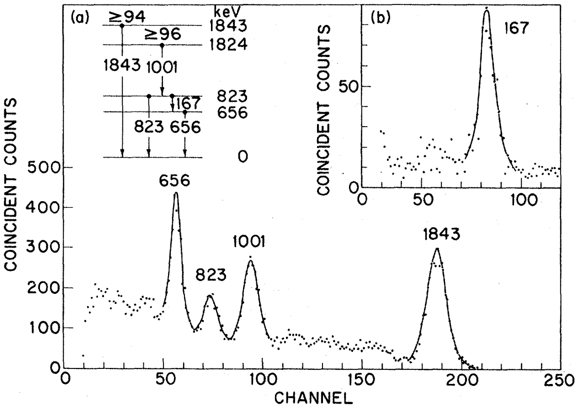

FIG. 2. (a) The γ-ray spectrum observed with the 4-in.× 4-in. NaI(Tl) detector in coincidence with the proton group representing the 1824- and 1843-keV states; (b) the γ-ray spectrum observed in the $1\frac{1}{2}$-in. × 4-mm-thick NaI(Tl) detector for the same coincidence conditions as above. Random coincidence events have been subtracted from these spectra. The photopeaks of the cascading γ rays are labeled by their associated energy in keV.

regards to these two states being the $J^\pi = 4^+$ and 5^+ members of the ground-state rotational band.

The analysis of the angular correlations for the 1843 → 0 transition yielded no new information beyond that found by previous investigations.[8]

C. 1972- and 2044-keV States

The particle groups associated with the formation of these two states could not be resolved. The decay schemes of these states were obtained from the coincident Ge(Li) γ-ray spectra, and the relative branching is given in Table I. The decay of each state is such that the angular correlation of four cascading γ rays could be used in the analysis of the 1972-keV state. These were the 1972-, 1149-, 823-, and 167-keV γ rays. The least-squares fit and χ^2 analysis of the 1972 → 0 transition limits the spin of this state to $J = 1$, 2, or 3. Assuming that the 823-keV state is $J = 4$, the analysis of the combined angular correlations of the remaining 3 γ rays allows a spin of $J = 2$ or 3 for this state with the corresponding value of the mixing ratio given in Table III. The possibility of this state being a $J^\pi = 3^-$ state predicted by recent calculations[4] will be discussed in the final section. The angular correlation of the 2044 → 656-keV transition yielded no new information beyond that already published.[8]

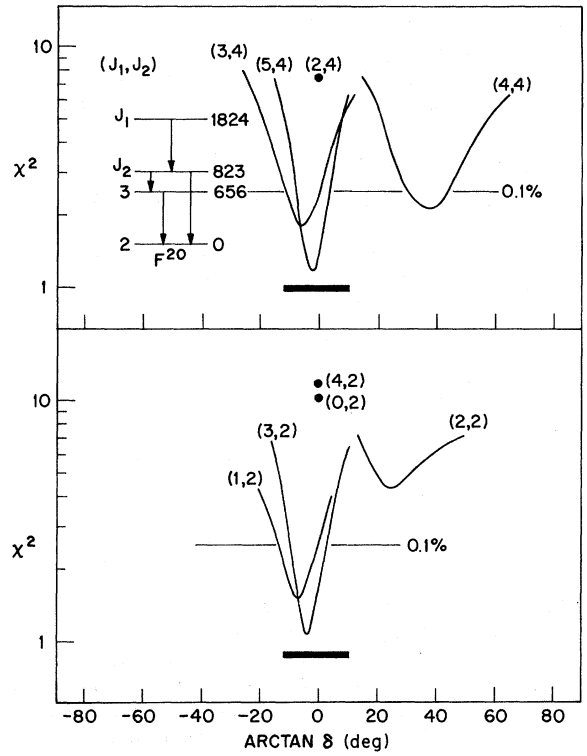

FIG. 3. The upper portion illustrates the results of the least-squares fit (in terms of χ^2) as a function of the mixing ratio of the 1001-keV γ-ray transition assuming a spin of $J = 4$ for the 823-keV state. The solid bar represents the region in which the minimum must occur if the quadrupole strength is not to exceed 100 W.u. On the basis of the measured lifetime octupole radiation is not considered in the analysis. The lower portion illustrates the χ^2 analysis for an assumed spin of $J = 2$ for the 823-keV state.

D. 2195-keV State

The decay scheme for this state is given in Table I. Angular correlations were obtained for all five of the γ rays cascading from this state. The least-squares fit and χ^2 analysis of the 2195 → 0 transition limits the spin of this state to $J = 1$, 2, or 3. On the assumption that any quadrupole radiation in this transition would not exceed 100 W.u., the spin $J = 2$ could be eliminated on the basis of the measured mixing ratio. In addition to this, the simultaneous analysis of the angular correlations of the remaining four γ rays rejects all spins but $J = 3$ for the 2195-keV state if the spin of the 823-keV state is assigned $J = 4$. The formation of this state was found[1] to be associated with $l = 2$ in the stripping reaction $^{19}F(d, p)^{20}F$. This implies a positive-parity assignment for the 2195-keV state. This state is discussed in the final section in terms of its being the second $J^\pi = 3^+$ state predicted by recent shell-model calculations.[2]

TABLE II. The Legendre-polynomial expansion coefficients for the angular correlations obtained with the $^{18}O(^3He, p\gamma)^{20}F$ reaction at a beam energy of $E_{^3He} = 2.88$ MeV. The analysis included the appropriate correction for the solid angle of the γ-ray detector.

State (keV)	Transition (keV)	a_2/a_0	a_4/a_0
1824	1824 → 823	−0.27 ± 0.04	+0.05 ± 0.05
	823 → 656	−0.13 ± 0.03	−0.07 ± 0.03
	823 → 0	+0.33 ± 0.13	−0.16 ± 0.15
	656 → 0	−0.41 ± 0.04	+0.02 ± 0.05
1843	1843 → 0	+0.19 ± 0.07	−0.21 ± 0.08
1972	1972 → 823	+0.19 ± 0.06	−0.10 ± 0.06
	823 → 656	−0.32 ± 0.07	−0.07 ± 0.07
	823 → 0	+0.25 ± 0.14	+0.14 ± 0.16
2195	2195 → 823	−0.06 ± 0.07	−0.08 ± 0.09
	823 → 656	−0.13 ± 0.10	−0.05 ± 0.11
	823 → 0	+0.38 ± 0.10	−0.08 ± 0.13
	656 → 0	−0.27 ± 0.06	−0.13 ± 0.06
	2195 → 0	−0.26 ± 0.02	−0.10 ± 0.04
4082	4082 → 0	−0.13 ± 0.05	+0.01 ± 0.05
	4082 → 1057	−0.30 ± 0.10	−0.01 ± 0.11

E. 2866- and 2967-keV States

The particle groups representing these states could not be resolved, and consequently the respective decay schemes had to be obtained from the coincident Ge(Li) data. The 2866-keV state was found to decay mainly to the ground state. Limits on the decay of this state to other excited states could not be set because the state was very weakly populated. The decay scheme is given in Table I for the 2967-keV state, and two branches not previously reported[8] were observed: these are transitions to the 656- and 1972-keV states. Unfortunately, angular correlations could not be reliably obtained or analyzed for any single transition because of either (1) energy degeneracies in the photopeaks as observed by a NaI detector or (2) the difficulty involved in interpreting the angular correlations of multiply fed γ rays. The spin of this state has previously been limited[8] to $J=2$, 3, and Fortune *et al.*[1] report the formation of the state to be associated with $l=2$ implying $J^\pi=1^+$, 2^+, 3^+. If the state were $J^\pi=2^+$, the 35% branch in the decay of this state to the $J=4$, 823-keV state implies an $E2$ strength of $\geqslant 25$ W.u. with respect to the measured lifetime.[9, 10] Although this limit is not prohibitively large, an enhancement of this magnitude would indicate the $J^\pi=3^+$ assignment to be more likely for this state.

F. States Between 3488 and 3761 keV Excitation

The protons leading to these five states could not be resolved in the particle detector. The γ rays corresponding to the main decay modes of the 3488-, 3526-, 3586-, and 3681-keV states as given in Refs. 19–22 were observed, but no attempt was made to retrieve absolute branching ratios. Relevant to the discussion in the final section is the non-observance of a ground-state transition from the 3586-keV state. This state is found to decay mainly to the 1057-keV, $J^\pi=1^+$ state. A γ-ray line of 3108 ± 5 keV was observed and would correspond to a transition from the 3761- to the 656-keV state. The decay of this state had not been previously reported.

TABLE III. Multipole mixing ratios for various γ-ray transitions in ^{20}F as observed in the present studies. The phase convention is that of Ref. 7.

E_i (keV)	E_f (keV)	J_i	J_f	Multipole mixing ratio^a
1824	823	5	4	-0.03 ± 0.07
1972	823	2	4	0 ± 0.10^b
	823	3	4	$+0.27 \pm 0.30^b$
	0	2	2	$\geq +0.17$
	0	3	2	-0.06 ± 0.14
2195	823	3	4	$+0.07 \pm 0.10$
	0	3	2	0 ± 0.09

^{a} The mixing ratio is defined in terms of $\langle L+1\rangle/\langle L\rangle$.

^{b} This value agrees well with earlier unreported work using the ^{18}O$(t, n\gamma)^{20}$F reaction in conjunction with the experiment of Ref. 3.

G. 3966- and 4082-keV States

The proton groups representing these two states could not be resolved in the particle detector, and the coincident Ge(Li) data were used to extract

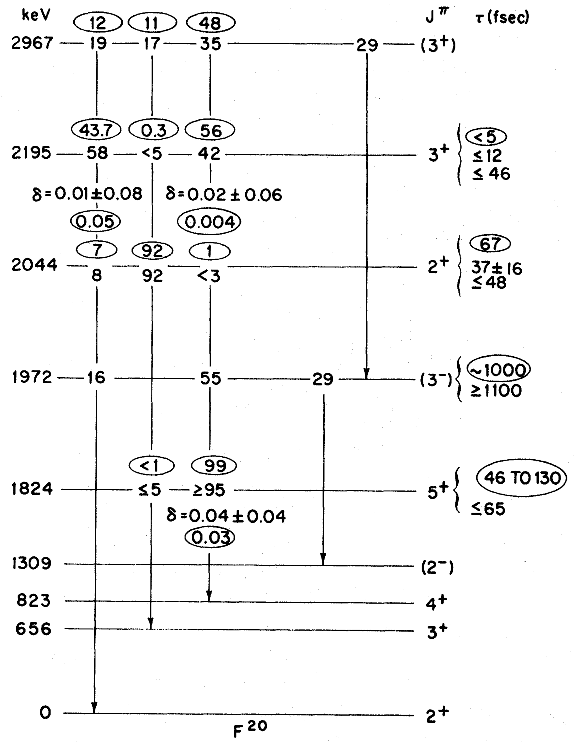

FIG. 4. The decay schemes of some of the ^{20}F states as measured in the present experiment. The numbers encircled represent the calculated branching and mixing ratios, and lifetimes taken from the work of Halbert *et al.*[2] In general all of the Hamiltonians used in those calculations yield results similar to those presented here. Where this is not the case, the range of the calculated values are shown. The calculated lifetime for the 1972-keV state is from Ref. 4. The experimental values for the lifetimes of the 2044-, 2195-, and 2967-keV states were taken from Refs. 9 and 10 while that for the 1824- and 1972-keV states are the results of the present experiment. In the case of the branching ratios for the 2967-keV state, a comparison between theory and experiment is made only for the $M1/E2$ transitions. See the text for further discussion regarding the comparison of theoretical and experimental results for these states.

the relative branching ratios of their respective deexcitations which are given in Table I. It was possible to extract reliable angular correlation data for both transitions from the 4082-keV state. The least-squares fit and χ^2 analysis of this data restricted the spin of this state to $J=1$ or 2. The formation of this state in the $^{19}F(d,p)^{20}F$ reaction[1] was found to be associated with a combination of $l=0$ and 2, thus implying a spin-parity assignment of $J^\pi=1^+$. Unfortunately, it was not possible to place tight restrictions on the mixing ratios for either of the transitions from this state for $J=1$. Further discussion regarding this state can be found in the next section of this paper.

V. DISCUSSION

A. Positive-Parity States

In the shell-model calculations of Halbert *et al.*,[2] all $1d_{5/2}$, $2s_{1/2}$, and $1d_{3/2}$ orbitals are considered for the active valence particles. They use a number of realistic effective Hamiltonians, all of which produce somewhat the same ordering of positive-parity states. The first four of these states are predicted to be in the order of $J=2$, 3, 4, and 1 starting with the ground state (see Refs. 1 and 2). These can be readily identified with the 0-, 656-, 823-, and 1057-keV states. The first three of these states are associated with the same nuclear configuration and, in terms of the rotational model, would be considered[3] members of the ground-state rotational band based on the coupling of an $\Omega=\frac{1}{2}$ proton and an $\Omega=\frac{3}{2}$ neutron. The next higher-spin member of this band is predicted to be at approximately 2 MeV excitation. The logical candidate for this state is the 1824-keV state; it has all of the properties necessary for such an identification. Figure 4 illustrates some of the measured nuclear properties of this state in comparison with those predicted by the shell model.[2] The calculations predict that the $E2$ branch to the $J^\pi=3^+$ state is less than 1% regardless of which Hamiltonian is used. That is consistent with the results of this experiment. There is also good agreement with the predicted mean lifetime and multipole mixing ratio of the transition to the $J^\pi=4^+$ state.

Two more positive-parity states having $J=2$ and 3 are predicted in the general region of 2 MeV excitation. Fortune *et al.*[1] associate the known $J^\pi=2^+$ state at 2044 keV with one of these predicted states on the basis of the large $l=2$ spectroscopic factor measured in the $^{19}F(d,p)^{20}F$ reaction. This identification is further strengthened by the remaining measured nuclear properties as shown in Fig. 4. Both the predicted branching ratio and mean lifetime are in reasonable agreement with the experimental results. The 2195-keV state is the logical candidate for the $J^\pi=3^+$ state, and Fortune *et al.*[2] attempt to make this identification on the basis of the $l=2$ spectroscopic factor associated with its formation. This idenfication is confirmed by the spin assignment of $J=3$ in the present experiment and by the comparison of measured and nuclear properties illustrated in Fig. 4.

The identification of the two remaining states experimentally found in the region of 2 MeV excitation will be considered in the next subsection. The next predicted positive-parity state is a $J^\pi=3^+$ state at 3.1 MeV excitation. On the basis of the $l=2$ spectroscopic factor[1] associated with the formation of this state, it might be identified with the 2967-keV state. As pointed out in an earlier section this state is most likely a $J^\pi=3^+$ state, although at this time $J^\pi=2^+$ cannot be rigorously excluded as a possibility. Figure 4 illustrates some of the measured nuclear properties in comparison to those predicted,[23] and there is, in general, very good agreement, thus strengthening the tentative identification.

The next two positive-parity states are predicted at an excitation of approximately 3.3 MeV. These states are $J^\pi=1^+$ and 0^+ states based on couplings of a $2s_{1/2}$ neutron to the ^{19}F ground state. States at 3488 and 3526 keV were found[1] to have $l=0$ spectroscopic strengths which correspond to those predicted for the $J^\pi=1^+$ and 0^+ states, respectively. The fact that the 3526-keV state decays only to the 1057-keV $J^\pi=1^+$ state lends added support to the interpretation that it is the $J^\pi=0^+$ state.

There is a large density of states found in the region above 3 MeV excitation, and consequently their identification with model states is difficult to make. One state which has been tentatively identified on the basis of its $l=0$ spectroscopic strength as the third predicted $J^\pi=1^+$ state is the 4082-keV state. The observed transitions to the $J^\pi=2^+$ ground state and $J^\pi=1^+$, 1057-keV state, as well as the spin limitations of $J=1$ or 2 found in this experiment, lend added weight to such an interpretation.

B. Negative-Parity States

As shown in the previous section, all of the positive-parity states predicted below 3 MeV excitation can be accounted for. It is expected that a number of the low-lying states in ^{20}F should be associated with configurations based outside of the *sd* shell. Calculations in this regard have been made[4, 24] with the resulting level scheme containing a spin sequence of $J^\pi=1^-$, 2^-, 2^-, and 3^-. All of these states are predicted to lie below 2 MeV excitation. There are four states observed experimentally which lie below this excitation and for which no correspondence can be made with the predicted positive-parity states. All of these states are very weakly populated in particle-transfer reaction studies[1,18] which suggests that these states might well be states whose origins are proton holes in the $1p$ shell. The lowest two states, at 983 and 1309 keV excitation, have been shown to be of negative parity through a recent linear-polarization experiment[25] and have been assigned $J^\pi = 1^-$ and 2^-, respectively. The previous decay branch of $\leq 20\%$ for the decay of the 983- to the 656-keV state has been reduced to $\leq 2\%$ by the present experiment and as a consequence removes a previous difficulty regarding the interpretation of the 983-keV state as a $J^\pi = 1^-$ state. The $E1$ transitions from both of these negative-parity states to the ground state represent strengths of about 7.5×10^{-4} W.u.

Of the remaining two states which could possibly have negative parity, only the 1972-keV state has a decay to one of the two lowest-lying negative-parity states mentioned above. Using the lifetime limit of ≥ 1.1 psec, the 29% branch to the 1309-keV state represents an $M1$ strength of ≤ 0.04 W.u. The predicted[4] $M1$ strength for a 3_1^- to 2_1^- or 2_2^- to 2_1^- transition is 0.11 to 0.05 W.u. for reasonable values of the $p_{3/2}p_{1/2}$ energy gap. Although there is good agreement with theory for a $J^\pi = 3^-$ or 2^- assignment, the spin assignment for the 1972-keV state is more likely $J = 3$ because of the large quadrupole enhancement involved in the transition to the 823, $J^\pi = 4^+$ state if one assumes $J = 2$ for the 1972-keV state. Based on all of the above, this state is tentatively given a $J^\pi = 3^-$ assignment. Assuming the remaining transitions from this state are pure $E1$ transitions one finds strengths of $\leq 2.5 \times 10^{-5}$ and $\leq 5.8 \times 10^{-4}$ W.u. for the decays to the ground and 823-keV states, respectively. The decay scheme for this state is illustrated in Fig. 4.

The remaining candidate for consideration as having negative parity is the 1843-keV state. This state was previously[8] given an assignment of $J^\pi = 2, (1^+, 3^+)$, which is based on the decay of the $J^\pi = 1^+$, 3488-keV state to this state. The arguments stemming from the present data for both of these states would corroborate this. The main decay mode of this state is to the ground state with a relative branch from Table I of $\geq 96\%$. The lifetime of the state is known,[9,10,22] and such a branch would imply an $E1$ strength equivalent to $\sim 6 \times 10^{-3}$ W.u. This is relatively strong but not unreasonable. If this state is the second $J^\pi = 2^-$ state, then the widths for the $M1$ transitions to the 1309- and 983-keV states, calculated from the predicted[4] $B(M1)$ values, are $\leq 2\%$ of the total measured width of this state. This would be in accord with the limits set in Table I for such transitions. On the basis of the systematics presented above, the 1843-keV state is tentatively assigned $J^\pi = 2^-$.

ACKNOWLEDGMENTS

The author wishes to thank his colleagues at Lockheed for constructive comments and suggestions regarding this experiment and the subsequent manuscript. The author is also indebted to Dr. H. T. Fortune, Dr. K. A. Hardy, Dr. I. P. Johnstone, and Dr. B. H. Wildenthal for valuable discussions on various aspects of this work.

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[*] Work supported in part by the Lockheed Independent Research Program.

[1] H. T. Fortune, G. C. Morrison, R. C. Bearse, J. L. Yntema, and B. H. Wildenthal, Phys. Rev. C 6, 21 (1972).

[2] E. C. Halbert, J. B. McGrory, B. H. Wildenthal, and S. P. Pandya, in *Advances in Nuclear Physics* (Plenum, New York, 1971), Vol. 4.

[3] J. G. Pronko and R. W. Nightingale, Phys. Rev. C 4, 1023 (1971).

[4] I. P. Johnstone, B. Castel, and P. Sostegno, Phys. Letters 34B, 34 (1971); and private communication.

[5] A. E. Litherland and A. J. Ferguson, Can. J. Phys. 39, 788 (1961).

[6] A. A. Rollefson, P. F. Jones, and R. J. Shea, Phys. Rev. C 1, 1761 (1970).

[7] H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

[8] P. A. Quin, G. A. Bissinger, and P. R. Chagnon, Nucl. Phys. A155, 495 (1970).

[9] T. Holtebekk, R. Stromme, and S. Tryti, Nucl. Phys. A142, 251 (1970).

[10] R. L. Hershberger, M. J. Wozniak, Jr., and D. J. Donahue, Phys. Rev. 186, 1167 (1969).

[11] P. Paul, J. B. Thomas, and S. S. Hanna, Phys. Rev. 147, 774 (1966).

[12] J. Lindhard and M. Scharff, Phys. Rev. 124, 128 (1961).

[13] D. I. Porat and K. Ramavataram, Proc. Roy. Soc. (London) 78, 1135 (1961).

[14] J. Lindhard, M. Scharff, and H. E. Schiott, Kgl. Danske Videnskab. Selskab, Mat.– Fys. Medd. 33, No. 14 (1963).

[15] A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).

[16] G. F. Millington and J. R. Leslie, private communication.

[17] A similar branching was obtained by a group at Notre Dame, L. A. Alexander *et al.*, Phys. Rev. C 6, 817 (1972).

[18] H. T. Fortune and D. J. Crozier, Bull. Am. Phys. Soc. 17, 444 (1972).

[19] I. Bergquist, J. A. Biggerstaff, J. H. Gibbons, and W. M. Good, Phys. Rev. 158, 1049 (1967).

[20] P. Spilling, H. Gruppelaar, H. F. De Vries, and A. J. J. Spits, Nucl. Phys. A113, 395 (1968).

[21] T. Holtebekk, S. Tryti, and G. Vamraak, Nucl. Phys. A134, 353 (1969).

[22] R. Hardell and A. Hasselgren, Nucl. Phys. A123, 215 (1969).

[23] The partial radiative widths for these transitions cannot be found in Ref. 2. They were calculated and passed on to the author by B. H. Wildenthal in a private communication.

[24] J. B. McGrory and B. H. Wildenthal, private communication.

[25] K. A. Hardy, A. H. Lumpkin, and Y. K. Lee, Bull. Am. Phys. Soc. 17, 90 (1972); and private communication (to be published).

PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Structure of the 8.65-8.69-MeV Doublet in ^{11}C[†]

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(Received 19 September 1972)

The 8.65- and 8.69-MeV states in ^{11}C have been studied with the ^{10}B(^{3}He,*d*)^{11}C reaction, with a resolution of 9 keV (full width at half maximum). Comparison of absolute spectroscopic strengths for this reaction and for the ^{10}B(*d*,*p*)^{11}B reaction to the 9.19-MeV ($J^\pi = \frac{7}{2}^+$) and 9.27-MeV ($J^\pi = \frac{5}{2}^+$) states in ^{11}B shows unambiguously that the spin sequence in ^{11}C is the same as in ^{11}B. An additional outcome of the present experiment is a measurement of the width of the 8.69-MeV state: $\Gamma_{\text{TOTAL}} = 15 \pm 1$ keV. The natural width of the 8.65-MeV state is considerably less than the experimental resolution width of 9 keV.

I. INTRODUCTION

The mirror nuclei ^{11}B and ^{11}C have been extensively studied by a number of different experimental techniques,[1] and a great deal is known[1] about their level structure and mirror correspondences below 10 MeV in excitation. However, there do persist a few unanswered questions concerning states in this excitation region. In particular, the 8.65-8.69-MeV doublet in ^{11}C has been identified as the mirror of the 9.19-9.27-MeV doublet in ^{11}B (see Fig. 1), but the spin sequence, which is known[1] to be $\frac{7}{2}^+$, $\frac{5}{2}^+$ in ^{11}B, has not been definitively established in ^{11}C. An earlier study of the ^{10}B(^{3}He, *d*)^{11}C reaction[2] suggested that the ordering in ^{11}C was the same as in ^{11}B, but in that study the ^{11}C states were not completely resolved. Further studies[3] have not clarified the issue. We have performed a high-resolution study of the ^{10}B(^{3}He, *d*) reaction in order to establish the spin sequence in ^{11}C, by comparison of these data with those of the analog reaction[4] ^{10}B(*d*,*p*) leading to the 9.19-9.27-MeV states in ^{11}B.

II. EXPERIMENTAL PROCEDURE

The reaction was induced by an 18-MeV ^{3}He^{++} beam produced by the University of Pennsylvania tandem Van de Graaff accelerator. The reaction products were momentum-analyzed in a multiangle magnetic spectrograph and were recorded in nuclear emulsions. The emulsions were discriminately scanned to produce composite deuteron energy spectra at 18 laboratory angles from 3.75 to 67.5° in 3.75° intervals. The yields were converted to cross sections taking into account proper solid angle, target thickness, and incident-charge-integration-normalization factors. The target was a self-supporting isotopically enriched (97%) ^{10}B foil having a thickness of 15 μg/cm^2, representing an energy loss of 4 keV for 18-MeV ^{3}He^{++} ions.

A deuteron energy spectrum showing the region of interest is shown in Fig. 2. The peaks labeled ^{17}F and ^{12}C$_{12}$ indicate the relatively small amounts of ^{16}O and ^{11}B contamination present in the ^{10}B target. No ^{12}C contamination was detectable. The good resolution [9 keV full width at half maximum (FWHM)] allowed a determination of the natural width of the 8.69-MeV state. The width was calculated assuming that the measured width is quadratically related to the sum of the natural width Γ and the resolution width (9 keV FWHM). The average value of the width extracted at four forward angles is $\Gamma = 15 \pm 1$ keV. The 8.69-MeV state is slightly unbound[1] (by ~1 keV) to proton decay,