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Study of F^{20} Using the $O^{18}(t, n\gamma)$ Reaction*

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Some of the low-lying excited states of F^{20} were studied using the $O^{18}(t, n\gamma)F^{20}$ reaction at a bombarding energy of $E_t = 2.7$ MeV. The methods of n-γ and γ-γ angular correlations were used to obtain information concerning the spins of the 823- and 656-keV states and the multipole mixing ratios of the subsequent electromagnetic deexcitations of these states. The mean lifetime of the 823-keV state was measured with the recoil-distance technique to be 79± 6 psec. The results of the experiment are discussed in terms of current nuclear models.

INTRODUCTION

The nucleus F^{20} is an odd-odd nucleus situated in a region of mass number where large nuclear (prolate) deformations have been observed. The coupling of the odd neutron and odd proton to the deformed core results in a possibility of two rotational bands at low excitations.[1] These are the $K = 1$ and 2 bands formed in the antiparallel and parallel coupling of the last neutron ($\Omega = \frac{3}{2}$) and proton ($\Omega = \frac{1}{2}$). Of these two possible bands it is expected[2] that the $K = 2$ band would be at a lower excitation and form the ground-state rotational band. The Oak Ridge shell-model group[3-6] has made calculations for F^{20} using realistic interactions and predicts a rotational-like set of states with a spin sequence of $J^\pi = 2^+, 3^+, 4^+, 5^+$ commencing with the ground state. The ground state is known[7] to be $J^\pi = 2^+$ and the first excited state has recently been shown[8] to have a spin and parity of 3^+. It would appear that these two states are the anticipated members predicted by both models. Of vital importance, of course, is the location and confirmation of these and higher-spin members in order to further test the validity of the application of the above models to nuclei in this mass region. A state at 823 keV is known[7] to be $J^\pi = 2^+, 4^+$ and consequently is a very good candidate for a low-lying $J^\pi = 4^+$ state whose predicted position is at about 1.0 MeV.[6]

Despite the efforts of a large number of experimental investigations into the structure of F^{20}, the resulting data have generally led to ambiguous and uncertain spectroscopic information. One of the latest published investigations is that of Quin, Bissinger, and Chagnon[7] where information on spin assignments, multipole mixing, and branching ratios has been accumulated using the $O^{18}(He^3, p)$ reaction. The mean lives of some of the low-lying F^{20} excited states have been measured as well by a number of experimental groups with reported values for the 823-keV state of $0.9^{+0.9}_{-0.4}$ psec,[9] >4.4 psec,[10] and 76 ± 20 psec[11]. In view of the obvious discrepancy in these reported mean lifetimes it was felt that the lifetime of this state should be remeasured. The methods of n-γ and γ-γ angular correlations were used to obtain additional information concerning the spins of the 823- and 656-keV states and the multipole mixing ratios of the subsequent electromagnetic deexcitations of these states.

LIFETIME MEASUREMENT OF THE 823-keV STATE

Preliminary measurements using the reaction reported herein indicated that this state had a mean lifetime greater than that which could be measured using the Doppler-shift-attenuation method. Consequently, the lifetime of this state was measured by observing the recoil effects of the excited F^{20} ions in the line shape of the deexcitation γ rays with the plunger technique.[12, 13] The plunger stopping material consisted of polished tantalum metal mounted on a micrometer screw which could adjust to within an accuracy of 0.1 mil (1 mil = 0.001 in.) the distance between target material and stopper. The target consisted of a thin layer of H_2O^{18} anodized (~45-V anodizing potential) on the plunger side of a 0.1-mil tantalum window. The experiment was performed using the Lockheed 3-MV Van de Graaff accelerator at a beam energy of $E_t = 3.0$ MeV; the tantalum window degraded the beam energy to ~2.7 MeV before striking the target material. The resulting reaction γ rays were observed at 0° to the beam axis in a 20-cc Ge(Li) detector positioned about 3.5 cm from the target. This detector had a resolving power equivalent to a full width at half maximum of ~2.9 keV for the unshifted 823-keV line. The Doppler-shift recoil effects attributed to the lifetime of the 823-keV state were observable in the 823- and 656-keV line shapes. Since the 656-keV state has a reported mean life[9, 10] of 0.36 psec and is much shorter than what could be measured with the present method, the lifetime effects observed in the latter line shape resulted from cascade feeding via the 167-keV transition. The other two states which feed the 656-keV state have also been reported[9, 10] to have very short mean lives. The shifted and unshifted portions of the observed line shapes could be individually well represented by Gaussian curves with their respective dimensions. The ratio of the unshifted peak areas to the total areas for the various plunger distances is illustrated in Fig. 1. These two curves were fitted with the function $Y = e^{-D/D_m} + b$, where $D_m = V\tau_m$. The velocity V is the average ion velocity and was readily obtained from the difference in centroids of the shifted and unshifted portions of the line shapes. The value of V obtained from both transitions agreed well within experimental error, and an average velocity factor of $V/c = (495 \pm 5) \times 10^{-5}$ was used in extracting the lifetime. This factor corresponds to an average center-of-mass angle of ~78° for an emission of the associated neutrons. The values of D_m obtained from the curves are listed in Fig. 1 and have a weighted mean value of 4.63 ± 0.22 mils. Using the relationship $\tau_m = D_m/V$, a value of 79 ± 6 psec is obtained for the mean life of the 823-keV state, where the quoted error includes an additional 1% uncertainty representing an upper limit on possible sources of error not explicitly considered above (see for example Ref. 13). The above result agrees well with the value of 76 ± 20 psec reported by Nickles.[11]

ANGULAR-CORRELATION MEASUREMENTS

The angular-correlation studies consisted of γ-γ and n-γ coincident correlations obtained with Meth-

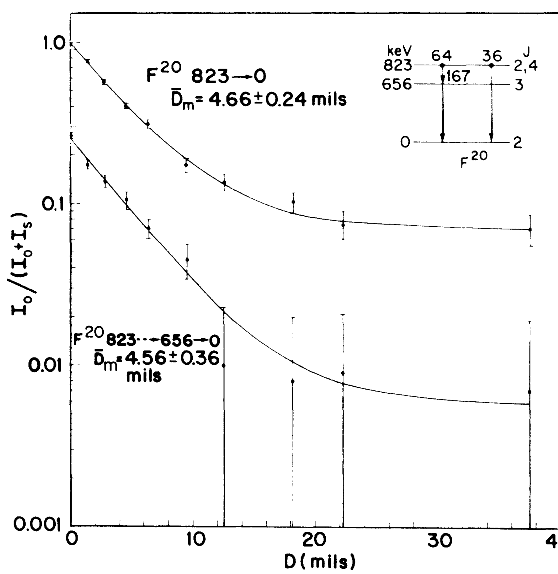

FIG. 1. The decay curves for the 823-keV state of F^{20} as obtained from the 823- and 656-keV transitions. The area of the unshifted portion of the line is represented by I_0 while that of the shifted portion is represented by I_s. The parameter D is the plunger distance and D_m is the mean displacement having a direct relationship to the mean lifetime as indicated in the text.

ods I and II as described by Litherland and Ferguson.[14] Three groups of n-γ angular correlations were obtained; these consisted of the γ-ray spectra measured (in time-coincidence with neutrons) with a 20-cc Ge(Li) detector, a 4-in.×4-in. NaI(Tl) detector, and a 4-mm×$1\frac{1}{2}$-in. NaI(Tl) detector. With the use of the Ge(Li) detector n-γ angular correlations for 13 lines corresponding to various transitions in F^{20} were obtained. Some of these transitions were also resolved in the 4-in.×4-in. NaI detector such that the accumulation of data containing greater statistical accuracy was possible for these states. The 4-mm-thick NaI detector was used only to observe the 167-keV transition connecting the 823- and 656-keV states. The analysis of some of the correlations obtained with the above detectors did not result in significantly new information beyond that which is presently published (see Ref. 7) and consequently will not be presented in this paper. A few of the lines observed in this reaction and not reported by other authors correspond to decays to states whose spin assignments are yet ambiguous, and for this reason the data for these states will not be presented until a further understanding of the spectroscopy of the F^{20} excited states is accomplished. The γ-γ angular correlations were obtained with 4-in.×4-in. and 4-mm×$1\frac{1}{2}$-in. NaI(Tl) counters which were specifically used to observe the correlations of γ rays in coincidence with the 167-keV transition. The Lockheed 3-MV Van de Graaff accelerator was used to produce the reaction $O^{18}(t, n)F^{20}$ at a triton beam energy of 2.7 MeV. This beam energy was chosen because of the relatively large cross section for population of the 823-keV state. Beam currents in the range of 50 to 100 nA were used on a target consisting of H_2O^{18} anodized (~300-V anodizing potential) onto a 1-mil tantalum backing. 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 neutrons for the n-γ angular correlations were observed using an annular NE 213 liquid scintillator located about the beam axis at 180° Pulse-shape discrimination was used to identify pulses corresponding to neutrons. In the analysis of the n-γ data it is assumed that the multipole mixing ratio and the relative population of the $m=0$ and ±1 substates are unknown quantities. In addition to these variables, an upper limit to the population of higher substates due to the solid angle of the neutron detector[14] and to the γ-ray feeding of a state of interest from higher excited states must be included. This latter correction comes about since, in the system used, no separation of the neutron groups leading to the individual states is possible. If it is assumed that dipole radiation is the predominant mode of feeding from upper states, then only the population of the $m=\pm2$ substates needs to be considered beyond the already unknown relative population of the $m=0$ and ±1 substates. An upper limit for the contribution of the relative population of the $m=\pm2$ substates for the correlation data dealt with in this paper was calculated from Eq. 28 of the work of Harris, Hennecke, and Watson[15] to be such that $P(\pm2) \leq 0.25$. In the analysis of the γ-γ angular correlations the relative populations of all the substates are considered as unknown parameters to be determined in the analysis. The data for all of the angular-correlation experiments were analyzed by comparing, for a given spin combination, the predicted and measured correlation in a least-squares fit and χ^2 test. These analyses included the proper corrections for the finite solid angle of the NaI detectors and maintained the phase convention of Smith[16]

TABLE I. A summary of the mixing-ratio values for transitions observed in the present experiment. The sign convention is that of Rose and Brink (Ref. 17). For the values quoted from Ref. 7 the sign convention was changed to conform to that given herein.

Transition (keV)	J^{π}_i	J^{π}_f	Present experiment	Ref. 7	Av.
656→0	3^+	2^+	$+0.03\pm0.04$ $(n$-$\gamma)$ [a]	$+0.05\pm0.05$	$+0.04\pm0.03$
823→656	4^+	3^+	$+0.02\pm0.05$ $(\gamma$-$\gamma)$		
			-0.01 ± 0.03 $(n$-$\gamma)$	0 ± 0.37	0 ± 0.03
	2^+	3^+	0 ± 0.05 $(\gamma$-$\gamma)$		
			-0.08 ± 0.08 $(n$-$\gamma)$	0 ± 0.37	-0.02 ± 0.05
823→0	4^+	2^+	$+0.01\pm0.04$ $(n$-$\gamma)$ [a]	0 ± 0.035	0 ± 0.03
	2^+	2^+	-2.5 ± 1.2 $(n$-$\gamma)$ [a]	$-2.3^{+9.1}_{-1.1}$	-2.4 ± 1.0

[a] This is an average taken from the results of the NaI(Tl) and Ge(Li) runs.

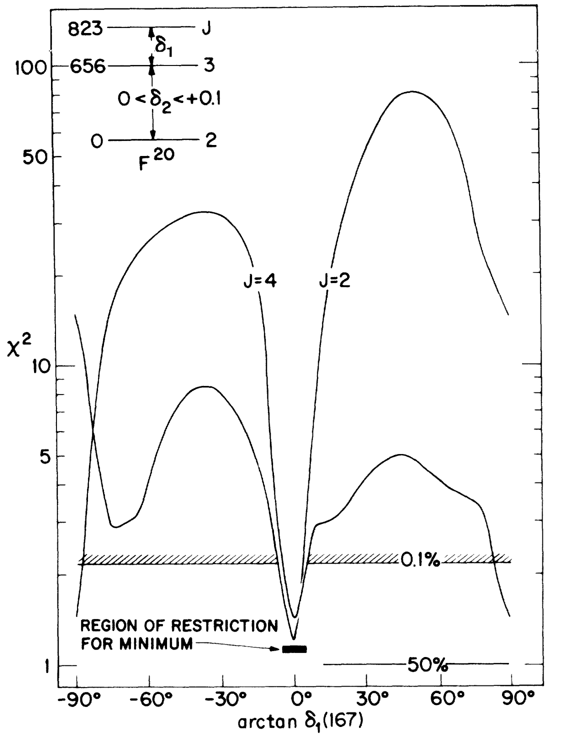

FIG. 2. The χ^2 analysis of the γ-γ angular-correlation data for the $823 \rightarrow 656 \rightarrow 0$-keV transitions. The solid bar represents the region to which a minimum must be restricted in order to be an acceptable solution based on an $E2$ transition strength of ≤ 30 W.u.

and Rose and Brink[17] for the electromagnetic multipole mixing ratio.

The χ^2 analysis of the n-γ angular correlation for the 167-keV transition yielded minima for possible assignments $1 \leq J \leq 5$. However, the minima for $J=1$, 3, and 5 involve unreasonably large quadrupole or octupole components, thus restricting the spin of the 823-keV state to $J=2$ or 4. Table I lists the mixing ratios obtained from the analysis of the above correlation, as well as the mixing ratios for the two other transitions obtained from the n-γ correlations in the present experiment, which could possibly be associated with a ground-state rotational band.

Although a number of γ rays were observed to be in coincidence with the 167-keV transition, only the 656-keV line provided sufficient statistics to allow the retrieval of reliable correlation data. In the analysis of these correlations the mixing ratio of the 656-keV transition was assumed to have a value of $0 \leq \delta \leq +0.1$. This is consistent with the data obtained in this experiment (see Table I) and previous reports.[7] The γ-γ angular correlations consisted of a total of 30 independent data points and Fig. 2 illustrates the associated χ^2 analyses for spins $J=2$ and 4. Again, as in the case of the n-γ correlation, the minima for spins $J=1$, 3, and 5 are above the 0.01% limit or indicate unreasonable amounts of quadrupole or octupole radiation. The minima for spins $J=2$ and 4 both fall within the indicated limits of restriction for a maximum quadrupole enhancement of 30 Weisskopf units (W.u.) and the associated values of the mixing ratios are listed in Table I.

DISCUSSION

The angular-correlation experiments could not restrict the spin of the 823-keV state beyond the $J=2$ or 4 possibilities. They did, however, restrict the assigned value of the electromagnetic mixing ratios for each spin possibility well enough so that this state might be examined in terms of its partial transition strengths based on the measured lifetime discussed above. Assuming a $J^{\pi}=2^+$ assignment and using the measured mixing ratios and lifetime, the $M1$ transition strengths for the 823- and 167-keV transitions were calculated to be 4×10^{-5} and 0.06 W.u., respectively. The latter value is a typical $M1$ strength, while the former appears to be rather inhibited unless there is some isospin forbiddeness involved. On the other hand, if the 823-keV state is assumed to be $J^{\pi}=4^+$, one finds that the transition strengths are rather typical. Table II lists these strengths as well as other parameters based on the assumption that the

TABLE II. Parameters calculated on the assumption that the states listed are members of the ground-state rotational band with the 823-keV state being the $J^{\pi}=4^+$ member.

State (keV)	Transition $J^{\pi}_i \rightarrow J^{\pi}_f$	$\lvert M(E2)\rvert^2$	$B(E2)$ (e^2 fm^4) Exp	Theo [a]	$\lvert Q_0\rvert$ (b)	$\lvert M(M1)\rvert^2$	$B(M1)$ (μ_N^2) Exp	Theo [a]
656 [b]	$3^+ \rightarrow 2^+$	9.2 ± 7.9	29 ± 25	27.2	0.28 ± 0.19	0.31 ± 0.04	0.56 ± 0.07	0.06
823	$(4^+)\rightarrow 2^+$	3.2 ± 0.3	10 ± 1	11.4	0.29 ± 0.02	...	...	...
	$(4^+)\rightarrow 3^+$	≤ 17	≤ 51	21.2	≤ 0.43	0.054 ± 0.004	0.10 ± 0.01	0.1

[a] These theoretical values are the results of the shell-model calculations of Halbert *et al.* (Ref. 6) and are taken from Tables XIX and XXIV of their work.

[b] A mean lifetime of $\tau=0.36\pm0.05$ psec was used for this state and is the average value of the lifetimes given in Refs. 9, 10.

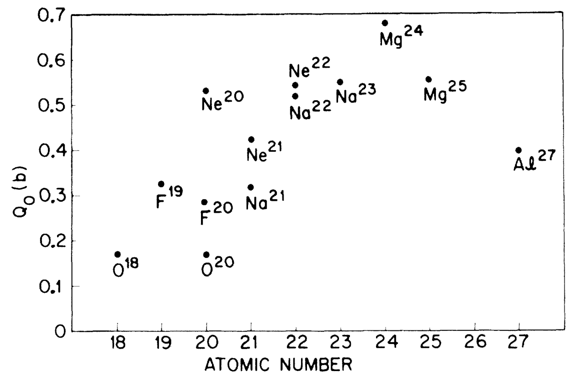

FIG. 3. A plot of the atomic number of the indicated nuclei versus the intrinsic quadrupole moment, Q_0, obtained from the $B(E2)$ values of the first-excited-state transitions of the ground-state rotational band of these same nuclei.

two states listed are members of the expected ground-state rotational band. The intrinsic quadrupole moment Q_0 as defined by the simple rotational model was calculated from the $E2$ partial widths. The values given in Table II for the three transitions are consistent with each other and those expected for the ground-state rotational band. Figure 3 illustrates a plot of Q_0 taken from the first-excited to ground-state transition of the ground-state rotational band for various nuclei in the s-d shell. The F^{20} value falls in line with the general increase of nuclear deformation as one goes from mass 16 to 24.

The Oak Ridge shell-model group[6] has predicted a rotational-band-like set of states commencing with the $J^\pi = 2^+$ ground state. Their efforts include a calculation of transition strengths based on a number of Hamiltonians. Listed in Table II are the $B(M1)$ and $B(E2)$ values calculated by them using a realistic, effective Hamiltonian labeled as $K + O^{17}$ in their tables. Again, on the assumption that the 823-keV state is the third member of the ground-state rotational band, a comparison can be made between their calculations and the experimental transition strengths presented in Table II. There is excellent agreement between their predictions and the experimental values for all cases except the $B(M1)$ value for the $656 \rightarrow 0$-keV transition. This difference could possibly be understood in terms of the sensitivity of the effective $M1$ operator to small wave-function admixtures as well as to the assumed simplification in the form of the $M1$ operator as explained in their paper. It should also be pointed out that their $B(M1)$ value for the transition from their second $J = 2$ $(T = 1)$ state to the $J^\pi = 3^+$ state is $4.3\mu_N{}^2$ and is also greatly different from the experimental value listed in Table II for the $823 \rightarrow 656$-keV transition.

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