for these three cases as a result of the present work.

The author is indebted to John C. Hardy for suggesting this problem.

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Linear-Polarization Measurements of the Gamma-Ray Transitions in ^{20}F†

K. A. Hardy
Florida International University, Miami, Florida 33144,
and Johns Hopkins University, Baltimore, Maryland 21218
and
Y. K. Lee
Department of Physics, Johns Hopkins University, Baltimore, Maryland 21218

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Linear-polarization and angular-distribution measurements are reported for the γ rays from the decay of the 636-, 823-, 984-, 1057-, 1309-, and 2044-keV levels in ^{20}F. Using our data, in addition to that of previous workers, the levels at 984 and 1309 keV were found to have negative parity, as opposed to the previous assumption of positive parity. Spins and parities of the other levels are discussed, as well as the mixing ratios of the decay γ rays.

I. INTRODUCTION

The odd-odd nucleus ^{20}F has been treated with detailed shell-model calculations using a number of different Hamiltonians,[1, 2] and as a deformed core, to which the odd neutron and odd proton are coupled.[3] Four odd-parity states below 2 MeV are predicted by a model which couples a $p_{1/2}$ and a $p_{3/2}$ proton hole to the ground state of ^{21}Ne.[4] All of these calculations suffer from a lack of experimental information about ^{20}F, even though the nucleus has been the subject of many experimental investigations in the last several years.[5, 6] In particular, the spins and parities of the levels at excitation energies of 823, 984, and 1309 keV are not known. The levels at 984 and 1309 keV are good candidates for the predicted odd-parity states, since there are four states below 2 MeV that are not accounted for by shell-model calculations. These states are the states at 984, 1309, 1840, and 1971 keV. Up to the present time linear-polarization measurements on the γ-ray decay of these states have not been possible, as NaI polarimeters do not have the resolution necessary to separate the decay γ rays from each other. The development of high-resolution polarimeters has made these polarization measurements possible. A measurement of the linear polarizations of the γ-ray transitions from the low-lying levels can give information about the spins and parities of these levels, as well as the mixing ratio of the transitions themselves. These measurements were undertaken to obtain additional information about these low-lying levels.

II. EXPERIMENTAL

The ^{19}F$(d, p)^{20}$F reaction was used to populate the levels in ^{20}F. A thin CaF$_2$ target was bombarded with deutron beams of 0.9, 1.1, and 1.2 MeV. It was found that a deutron energy of 1.2 MeV gave slightly better alignment to the states in ^{20}F; therefore all the measurements discussed were carried out at this energy. The angular distributions and the linear polarizations of the γ transitions from the levels in ^{20}F were measured simultaneously. The 1632-keV state in ^{20}Ne is populated by the β decay of ^{20}F, as well as the competing ^{19}F$(d, n)^{20}$Ne reaction. The 1632-keV transition in ^{20}Ne is known to be a pure $E2$ transition and can be used to check the polarization measurements; therefore the angular distribution and linear polarization of this transition was measured also. The angular distributions were measured with a 32-cm^3 Ge(Li) detector at angles between 0 and 90° to the beam direction. A 40-cm^3 Ge(Li) detector, held at a fixed position was used as a monitor.

The linear polarizations were measured with a two-section Ge(Li) polarimeter similar to the one described by Hardy *et al.*[7] The polarimeter used in these experiments differed from the one described in Ref. 7 in that larger crystals are used, the crystals having an active volume of 4 cm^3. Also, the use of constant-fraction timing techniques has improved the time resolution from 100 to 20 nsec. The efficiency calculations were carried out as dsecribed in Ref. 7 and checked by using the highly-polarized radiation from the ^{24}Mg$(p, p'\gamma)^{24}$Mg and the ^{28}Si$(p, p'\gamma)^{28}$Si reactions. The polarimeter was located 16 cm from the target making solid-angle corrections to the polarization data unnecessary. The angular-distribution detector was kept 60 cm from the target to keep the dead-time cor-

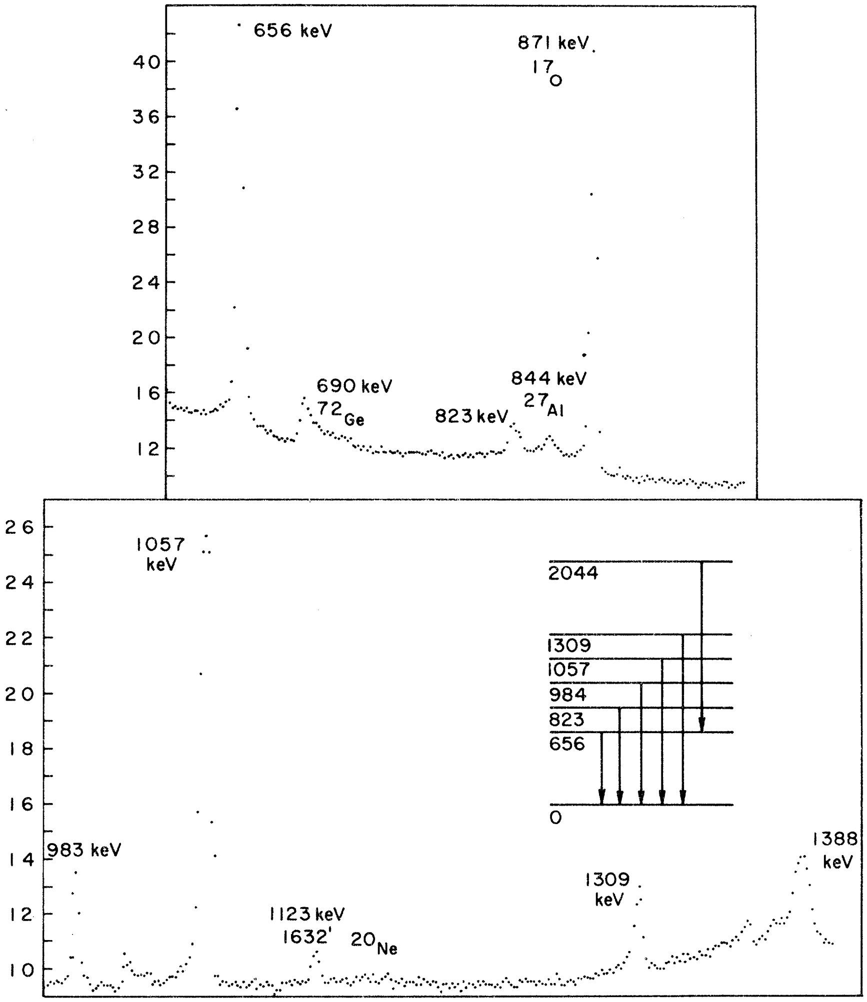

FIG. 1. Pulse-height spectra from the angular-distribution detector. Contaminant peaks are labeled with the isotope of origin. The vertical scale is in thousands of counts. Also shown is a level scheme for ^{20}F with the transitions studied in this experiment indicated.

rections to the angular-distribution data as small as possible. This made solid-angle corrections to the angular-distribution data unnecessary.

III. RESULTS

A typical pulse-height spectra from the angular-distribution detector is shown in Fig. 1. The angular distributions were analyzed by fitting the areas under the peaks to the function

$$W(\theta)=A_0[1.0+A_2P_2(\theta)+A_4P_4(\theta)].$$

The results of these fits are shown in Fig. 2 and Table I. Where no A_4 term is shown, the addition of this term did not significantly improve the fit of the data. The linear polarizations are shown in Table I and were determined from the formula,[7]

$$P=\frac{1-NS}{N-S},$$

where S is the asymmetry ratio of the polarimeter and N is the ratio of counting rate at 0 and 90° to the reaction plane.

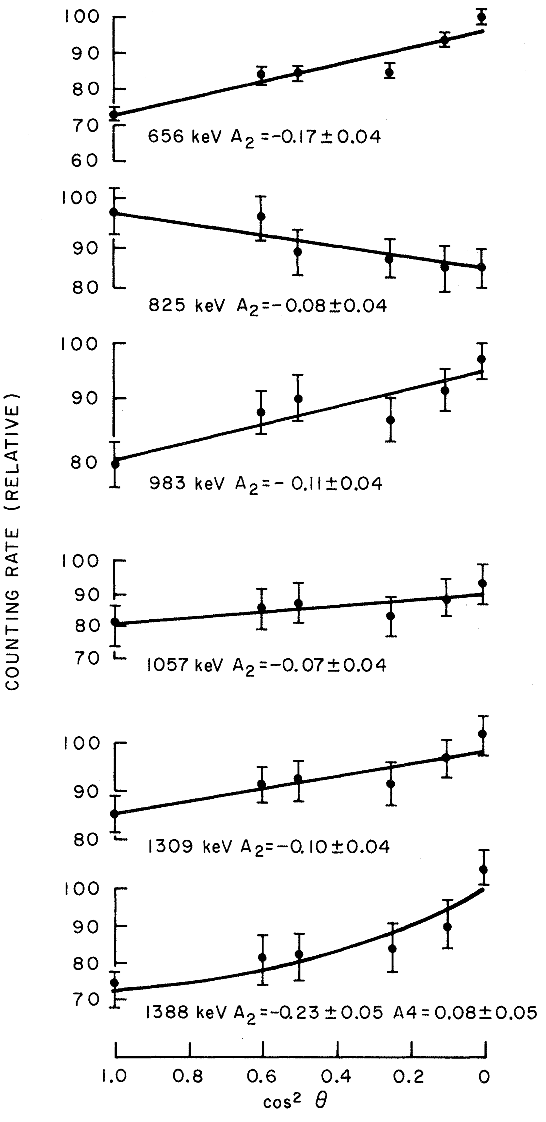

FIG. 2. Angular distributions of γ radiation following the $^{19}F(d,p,\gamma)^{20}F$ reaction at 1.2 MeV.

The polarization of pure $E2$ radiation may be computed from the coefficients of the angular distribution from the formula[8]

$$P=\frac{1+A_2+A_4}{1-2A_2-\frac{1}{4}A_4}.$$

Using the angular distribution coefficients shown in Table I for the 1632-keV transition in ^{20}Ne one finds a polarization $P=1.21\pm0.02$. This agrees with the polarization measured for this transition and thus serves as a check on the calibration of the polarimeter.

The linear-polarization and angular-distribution coefficients for a mixed γ-ray transition allow one to compute the mixing ratio for the transition. In the discussion below, the phase convention for the mixing ratios is that used by Taras,[8] which is the same as that of Rose and Brink.[9] Using the data in Table I, the 656-keV to ground-state transition is found to be mixed $M1/E2$ transition with $\delta(E2/M1)=0.10\pm0.05$. This is in agreement with the mixing ratio found by other workers.[5, 6, 10]

The spin of the 823-keV level is not definitely known, there being a choice of 2 or 4. The parity has not been measured, though it has been assumed to be plus. If the spin-parity of this level is 2+, our data give solutions for the mixing ratio $\delta(E2/M1)=-0.3^{+0.3}_{-2.2}$ or $=0.15^{+1.8}_{-0.1}$. The first root for Δ is barely in agreement with that found

TABLE I. Polarization and angular-distribution data for the γ-ray transitions in ^{20}F. Where no A_4/A_0 term is shown, the addition of this term did not significantly improve the fit to the data.

Transition (keV)	P	A_2	A_4
656	$0.83^{+0.02}_{-0.03}$	-0.17 ± 0.04	
823	$2.3^{+1.1}_{-0.6}$	0.08 ± 0.04	
984	$1.3^{+0.2}_{-0.3}$	-0.11 ± 0.04	
1057	$1.1^{+0.1}_{-0.1}$	-0.07 ± 0.04	
1311	$1.5^{+0.5}_{-0.3}$	-0.10 ± 0.04	
1388	$0.4^{+0.2}_{-0.1}$	-0.23 ± 0.05	$+0.08\pm0.05$
1632	$1.27^{+0.1}_{-0.07}$	0.089 ± 0.003	-0.072 ± 0.003

by other workers, the second root being in disagreement with the results of others workers.[6, 10] If the spin is 4, the ground-state transition must be at least quadrupole. Assuming a spin of 4, and using the formulas from Ref. 8, one can compute the polarization expected for a pure $E2$ transition and find $P = 1.3 \pm 0.2$. This is nearly in agreement with the measured value of $2.3^{+1.1}_{-0.6}$. Based on these data we can make no definite conclusions as to the spin of the level; however the parity is plus.[11]

The 984-keV level has a spin assignment of 1, 2, or 3, and the parity has been assumed to be plus. Again, the measured polarization may be compared to the expected polarization computed from the coefficients of the angular distribution. Using the value of the angular-distribution coefficients found in Table I, the polarization is calculated for a pure $E1$ transition and found to be $P = 1.4^{+0.1}_{-0.2}$. This is in excellent agreement with the measured value of $P = 1.3^{+0.2}_{-0.3}$. These data do not exclude the possibility of positive parity however. Our data are not in agreement with a spin-parity choice of 1^+. For a choice of 2^+ or 3^+ we find a large mixing ratio of $|\delta| = 1.5^{+1}_{-1}$. Using the lifetime from Holtebekk, Stromme, and Tryti,[12] this gives an $E2$ strength of about 100^{+100}_{-80} W.u., a rather large enhancement. If one assumes the negative parity, the $E1$ strength is found to be $|M_{E1}|^2 < 0.001$ W.u.; however this is not unexpected.[4] Other angular-correlation work[10] has placed limits on the mixing ratio of this transition, without regard to parity. For a spin choice of 1, they could not put a restriction on the mixing ratio. On these bases we conclude that the spin-parity of the 984-keV level is probably 1^-, the ground-state transition being pure $E1$.

The spin of the 1057-keV level is known to be 1^+ as deduced from the β decay of ^{20}O. γ-ray angular correlations by other workers put no limit on the mixing ratio for this transition.[10] Our results indicate that the transition is a mixed $M1, E2$ transition, the mixing ratio $\delta(E2/M1)$ ranging anywhere from $+1.0 > \delta > -8.0$. Much smaller limits can be placed on possible values of the mixing ratio from lifetime considerations.[10]

The spin of the 1309-keV level is known to be 1, 2, or 3, and the parity has been assumed to be plus. Bissinger *et al.*[13] is able to put the following limits on the mixing ratio for the ground-state transition from directional correlation measurements with the ^{18}O(^{3}He, p)^{20}F reaction: For $J = 2$, $\delta = 0.04$ or $\delta = 1.88$; for $J = 1$, $\delta = 72$; for $J = 3$, $\delta = 0.42$. The $J = 3$ possibility has been ruled out by Hershberger, Wozniak, and Donahue.[14] Computing the polarization expected for a pure $E1$ transition from the coefficients of the angular distribution shown in Table I, one finds $P = 1.34 \pm 0.15$, which is in excellent agreement with the measured value of $P = 1.54^{+0.45}_{-0.30}$. Again, this does not rule out the possibility of a mixed $M1, E2$ transition; however our results give a satisfactory solution for $J = 2^+$ only. This solution indicates a mixing ratio greater than 0.5, which would represent too large a quadrupole enhancement in terms of the measured lifetime. We conclude, therefore, that the parity of the 1309-keV level is negative. Since our data are in agreement with a pure $E1$ transition, the spin choice of $J = 1$ would be eliminated by the directional-correlation measurements of Bissinger *et al.*,[13] as this requires a large mixing ratio of $\delta = 72.0$. This leaves a spin choice of 2; therefore the spin-parity of the 1309-keV level is 2^-. The 1309-keV to ground-state transition would then be a pure $E1$ transition. The $E1$ strength for the transition would be very small, but the transition is expected to be greatly retarded.[4]

The 2044-keV level has been previously assigned a spin-parity of 2^+.[10] The 1388-keV transition to the first excited state is a mixed $M1, E2$ transition, the mixing ratio previously being determined as $\delta = -0.05$.[10] Our measurements indicate a mixing ratio of $\delta = 0.08^{+0.06}_{-0.1}$, in good agreement with the previous work.

DISCUSSION

Extensive calculations using the full basis of allowed states and seven different Hamiltonians to reproduce the positive-parity states in ^{20}F have been made.[1, 2] A common feature of these Hamiltonians is that they predict a set of states having a spin-parity sequence of 2^+, 3^+, 4^+, 1^+. The best examples of this are the Hamiltonians labeled KB + ^{17}O and K + 12FP in Ref. 2. Both of these reproduce the ordering of the positive-parity states quite well. The low-lying negative-parity states, now identified[15] as the 984- and 1309-keV levels, are consistent with those calculated by coupling a $p_{1/2}$ and a $p_{3/2}$ proton hole to a ^{21}Ne core. Other calculations, based on a ^{12}C core, also reproduce these states.[4]

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Survey of Some Nuclear Properties Given by a Nonlocal Separable Nucleon-Nucleon Interaction

E. Elbaz, C. Fayard, G-H. Lamot, J. Meyer, R. S. Nahabetian, and J. Pigeon
Institut de Physique Nucléaire, Université Claude Bernard de Lyon-1 43, Bd du 11 novembre 1918, 69621 Villeurbanne, France

and

P. Boschan
University R. Eotvos, Budapest VIII, Hungary

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We have determined a set of parameters for a nonlocal separable nucleon-nucleon interaction of the Mongan's case IV form. The M-5 potential thus defined, even if it remains with a poor D-state percentage (1.4%), is shown to give a correct description of the saturation of infinite nuclear matter. It appears also that M-5 gives a correct description of the following nuclear properties: two-nucleon elastic scattering phase shifts below 400 MeV (the phase shifts in the ${}^3S_1+{}^3D_1$ state are those given by the M-IV Mongan's potential, not better) deuteron binding energy and quadrupole moment, scattering length and effective-range low-energy parameters, triton binding energy in a coupled three-body treatment, saturation of infinite nuclear matter, and first-order binding energy of some spherical nuclei. We have compared the results obtained with M-5 and a Tabakin force in a Hartree-Fock description of some even-even nuclei in the $2s$-$1d$-shell nuclei as previously done by Ford, Braley, and Bar-Touv.

I. INTRODUCTION

In recent years a number of local or nonlocal interactions have been obtained which fit all the two-nucleon data at low and intermediate energies. We can mention for example the Hamada-Johnston,[1] Yale,[2] Reid,[3] Gogny, Pires, and De Tourreil[4] local potentials and the Yamaguchi,[5] Tabakin,[6] Hammann,[7] and Mongan[8] nonlocal separable interactions (NLSI). In this paper, we shall look at the results obtained with a particular NLSI.

The virtue of such potentials is the great simplicity they introduce in many physical problems. We recall, for instance, the determination of the binding energy of infinite nuclear matter or the resolution of the three-body problem with the Faddeev-Lovelace-Amado formalism.

The NLSI usually proposed are built in order to give a correct fit of the nucleon-nucleon elastic scattering phase-shifts data below 400 MeV.[9] It is thus well known that the two-body data do not determine the potential uniquely, partly because even the extensive data available are still limited in accuracy and range, and partly because of inherent ambiguities. Some attempts have been made to get, with nonlocal separable potentials, a correct description of the two-body data and binding energy of infinite nuclear matter,[6, 7] but such results are still quite limited.

It is thus tempting to search for NLSI giving simultaneously a correct answer to several nuclear properties, and it is the aim of this paper to show how far we can go in this purpose.

The results presented here have been obtained by a team work and we have tried to define a NLSI yielding a good description of the two-body data (J.P.) and of the triton binding energy in the three-body problem (C.F. and G-H.L.), giving a correct