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Magnetic Moment and Core Excitation of the $d_{3/2}$ Hole State in Sc^{47}†

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The magnetic moment of the 760-keV level in Sc^{47} has been measured, using the $Ca^{44}(\alpha,p)Sc^{47}$ reaction and the differential time-delay technique, as $\mu=0.35\pm0.05$ nm. The half-life for this level was measured as $t_{1/2}=274\pm10$ nsec. This magnetic-moment result is consistent with an interpretation for this level of no core-excitation admixtures in the $d_{3/2}$ hole wave function.

I. INTRODUCTION

The $d_{3/2}$ proton-hole states in the odd-A Sc isotopes have been located by Yntema and Satchler[1] on the basis of angular distributions for the (d,He^3) pickup reaction. Holland, Lynch, and Nystén[2] have measured the lifetimes of three of these hole states and shown that the $M2$ transition strengths to the $\frac{7}{2}^-$ ground states are hindered by factors of the order of 200. Calculations of Lawson and Macfarlane[3] demonstrate that these $M2$ strengths are sensitive to the admixtures of core-excited states in the single-hole wave functions. Their theoretical estimate of 0.4 for the core-excitation probability qualitatively explains the hindered $M2$ transition probabilities. Nuclear $M2$ transitions and related theories have recently been reviewed by Kurath and Lawson.[4]

The magnetic moments of these Sc hole states are also sensitive to the amount of core excitation. A core-excitation probability of 0.4 would increase the magnetic moment of, for example, the Sc^{47} hole state, by 40% over that expected for no core excitation. The purpose of the present experiment is to make an additional check on the structure of these $d_{3/2}$ hole states in Sc by a magnetic-moment measurement.

The lifetime of the Sc^{47} hole state is convenient for a magnetic-moment measurement by the differential time-delay technique. Using the $Ca^{44}(\alpha,p)Sc^{47}$ reaction, we observed the time dependence of a precession of the angular correlation between the protons populating the Sc^{47} hole state and the de-excitation γ rays. The alignment of the recoil Sc^{47} nuclei was maintained in a Cu target backing, and the precession was accomplished by an external magnetic field. We have previously used this same time-delay technique and the $O^{16}(He^3,p\gamma)F^{18}$ reaction to measure the magnetic moment of the 5^+ state in F^{18}.[5]

II. EXPERIMENTAL METHOD

A diagram of the low-lying levels in Sc^{47} is shown in Fig. 1. The $d_{3/2}$ hole state of interest is the $\frac{3}{2}^+$ level at 760 keV. It has a measured half-life of $t_{1/2}=270$ nsec,[2,6] which implies an $M2$ hindrance of approximately 400 relative to single-particle estimates for the γ-ray transition to the $\frac{7}{2}^-$ ground state. The conversion coefficient for this transition is negligible.

We have described the experimental arrangement previously.[5] A schematic diagram of the apparatus is shown in Fig. 2. The $Ca^{44}(\alpha,p)Sc^{47}$ reaction was used to populate the 760-keV level at a bombarding energy of 7.2 MeV. A target of approximately 100 $\mu g/cm^2$ of Ca^{44} was electroplated on a 10-mg/cm² Cu target backing. An annular solid-state detector was used to detect the protons from the reaction near 180°. This ensured that the corresponding recoil Sc^{47} nuclei ($E=1.3$ MeV) would reach the Cu backing. The calculated range[7] for these recoils in Ca^{44} metal is 320 $\mu g/cm^2$. The 180° geometry also ensured that a known alignment would be initially produced. Copper was chosen as the target backing because its cubic lattice, which exhibits essentially no quadrupole field, is expected to maintain the recoil alignment at a lattice site over the nuclear lifetime. For F^{18} recoil nuclei, the relaxation time in Cu was observed to be $\tau_r>750$ nsec.[5] The high atomic number of Cu also prevents significant background nuclear reactions for α particles at these energies. Elastically scattered α particles from the target and backing were stopped in front of the annular detector with Al foil. The two γ-ray detectors were 3×3-in. NaI(Tl) crystals placed at 0° and 90° with respect to the beam. They were each

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[1] J. L. Yntema and G. R. Satchler, Phys. Rev. **134**, B976 (1964).

[2] R. E. Holland, F. J. Lynch, and K. E. Nystén, Phys. Rev. Letters **13**, 241 (1964).

[3] R. D. Lawson and M. H. Macfarlane, Phys. Rev. Letters **14**, 152 (1965).

[4] D. Kurath and R. D. Lawson, Phys. Rev. **161**, 915 (1967).

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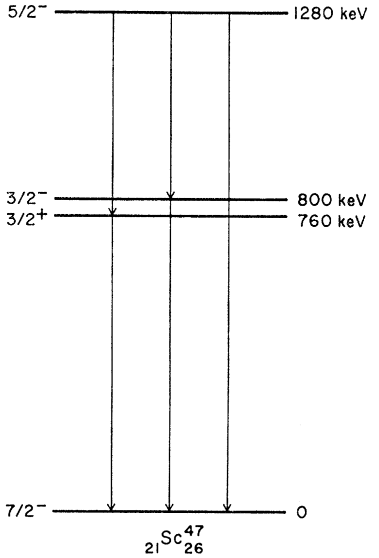

FIG. 1. Diagram of the low-lying levels in Sc^{47}.

placed at 6 cm from the target because of the low yields. The external magnetic field which produced the precession was provided by a permanent magnet whose field was measured as 6100 ± 60 G at the target.

In the experiment, pulses from the particle detector corresponding to protons populating the 76-keV level in Sc^{47} started a time-to-amplitude converter (TAC). The photopeak pulses for the 760-keV γ rays from the NaI(Tl) detectors provided the stop signals for the TAC. The resulting time-delay spectra were routed into different halves of a 400-channel analyzer, depending upon whether the stop signal originated in the 0° or 90° detector. In this way the precession of the angular correlation could be observed simultaneously at both 0° and 90° with respect to the beam. This was important because it effectively doubled the counting rate, and also eliminated the need to reverse the magnetic field. The time resolution of the system was about 20 nsec FWHM, and the time calibration was made using a 10-Mc crystal oscillator.

The time-dependent correlation function for this experiment in the arrangement of Fig. 2 is

$$W(\theta,t)=\{1+A_2P_2[\cos(\theta\pm\omega_Lt)]\}\exp(-t/\tau_m),$$

where $\omega_L=g\mu_NB/\hbar$ is the Larmor precession frequency, $P_2(\cos\theta)$ is a Legendre polynomial of order 2, and τ_m and g are the mean lifetime and the gyromagnetic ratio of the state under consideration. For the $Ca^{44}(\alpha,p)Sc^{47}$ reaction, only the $m=\pm\frac{1}{2}$ magnetic substates of this $\frac{3}{2}^+$ state are populated for point particle detection at 180°. With an annular detector around 180°, the $m=\pm\frac{3}{2}$ substates are expected to be populated only to a small degree. The calculated A_2 alignment coefficient[8] for this measurement is $A_2=+0.143$. When corrected for finite

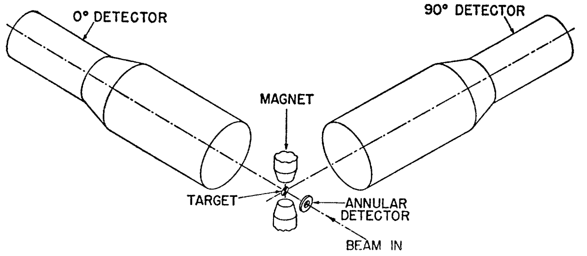

FIG. 2. Sketch of the experimental arrangement for the magnetic-moment measurement.

geometry and time resolution, it is reduced to 0.12. For this alignment and the empirical $d_{3/2}$ proton-hole g factor, the time-dependent correlation functions at 0° and 90° are given by the curves shown in Fig. 3. The actual A_2 coefficient observed in the experiment could be reduced from the calculated initial A_2 due to attenuation in the nuclear alignment during the stopping process, or in the copper backing.

The most convenient way of extracting ω_L from the data for this measurement is to form the ratio

$$R(t)=[Y(90°,t)-Y(0°,t)]/[Y(90°,t)+Y(0°,t)],$$

where $Y(\theta,t)$ represents the yield in the respective time spectra. From the time-dependent angular-correlation function, $R(t)$ can be shown to have the form $R(t)=-3A_2(\cos2\omega_Lt)/(4+A_2)$. Using the calculated initial A_2 corrected for geometry, the amplitude for R is 0.085. A value for ω_L can be obtained by fitting the experimental $R(t)$ to $-\cos2\omega_Lt$. The g factor or magnetic moment can then be directly determined from the rela-

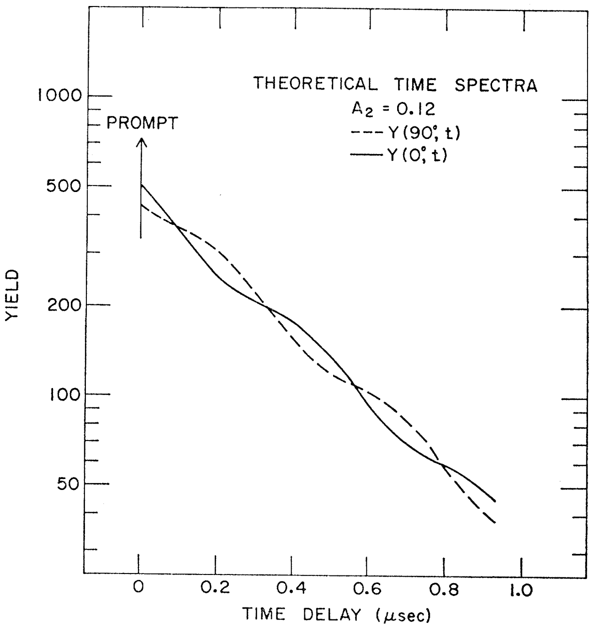

FIG. 3. Time-dependent correlation functions for the experimental arrangement of Fig. 2 calculated for the expected alignment and a value of the Larmor frequency ω_L that is consistent with the empirical $d_{3/2}$ proton-hole g factor.

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[8] A. R. Poletti and E. K. Warburton, Phys. Rev. 137, B595 (1965).

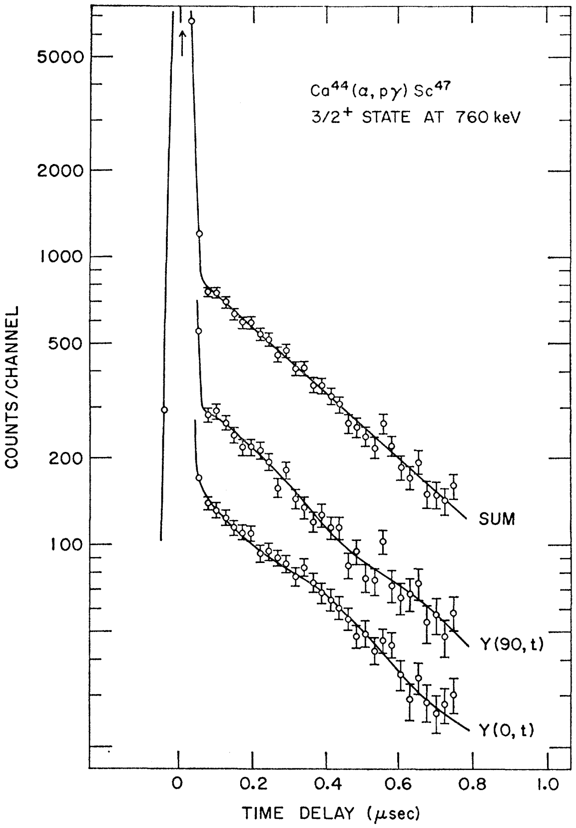

FIG. 4. Time-delay spectra $Y(90°,t)$, $Y(0°,t)$, and their sum. The sum shown in the upper part of the figure is the normal lifetime decay curve for the 760-keV state in Sc^{47}. The ordinates for $Y(90°,t)$ and $Y(0°,t)$ have been adjusted arbitrarily for display purposes. The solid curves drawn through the data for these two spectra were generated theoretically with the amplitude and frequency obtained from the least-squares fit of $R(t)$.

tion $g = \hbar\omega_L/\mu_N B$. With the γ-ray detectors at 0° and 90°, no information is obtained about the sign of the g factor. The sign could be obtained from a measurement at ±45°, for example; however, for the present it is assumed to be positive on the basis of theory.

III. RESULTS

The results for 60 h of running with an α-beam current of approximately 40 nA are shown in Fig. 4. The time spectra $Y(90°,t)$ and $Y(0°,t)$ are shown in the lower portion of the figure. Although the amplitude is small, one can discern out-of-phase modulations in the two logarithmic time slopes. The sum of $Y(90°,t)$ and $Y(0°,t)$ gives the normal lifetime decay curve, shown for these data in the upper part of the figure. The ratio $R(t)$ formed from the experimental data in Fig. 4 is shown in the upper part of Fig. 5. Because of the small amplitude of $R(t)$ and the statistical uncertainties, it is not possible to extract a very precise value for ω_L. One is helped by the fact that at $t=0$, $R(t)$ must be at a minimum since A_2 is positive. A small correction to the position of this minimum is made to account for the fact that 0° is altered slightly by the beam deflection in the magnetic field. A least-squares fit of the observed $R(t)$ to $-\cos 2\omega_L t$ results in a Larmor frequency of $\omega_L = (0.69 \pm 0.10) \times 10^7$ sec^{-1}. The curve shown in the upper part of Fig. 5 represents the best fit to the data. The amplitude obtained from the fit was 0.051, although the value has a large statistical uncertainty.

The ability of a recoil stopping material to maintain a nuclear alignment appears to be affected by radiation damage.[9] A possible cause of this phenomenon is the creation of lattice disorders by the accumulated radiation damage of the recoil ions and the beam. To check on any possible effect of radiation damage on the experimental results, $R(t)$ was formed for $\frac{2}{3}$ of these data; this is shown in the lower part of Fig. 5. Although the best-fit amplitude 0.057 is slightly larger than that for all of the data, the difference is not statistically very significant. Thus no strong evidence for target deterioration was observed. This $R(t)$ yields the same ω_L within uncertainties as that for the data shown in the upper part of Fig. 5.

In an attempt to improve the statistical accuracy of the experiment, an additional 65-h run was made with a Ca^{44} target about twice as thick as the target of the first run. The results yielded an ω_L which within statistics

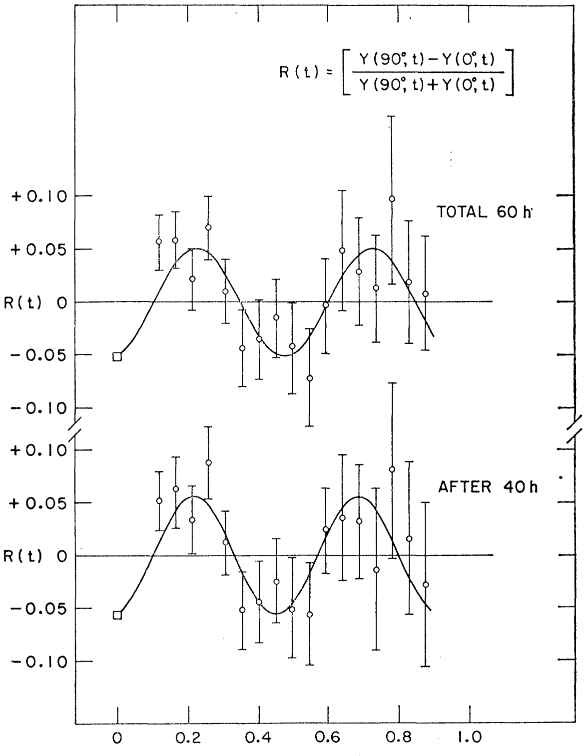

FIG. 5. $R(t)$ for the total 60 h of data and $R(t)$ after 40 h of data. The curves shown are least-squares fits to $\cos 2\omega_L t$ for a fixed $t=0$. Two channels have been summed in this figure.

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[9] K. Sugimoto, A. Mizobuchi, K. Nakai, and K. Matuda, J. Phys. Soc. Japan 21, 213 (1966).

was equal to that of the first run; however, the amplitude of $R(t)$ for this run was reduced to 0.028. This reduction in amplitude is most likely an indication that some of the Sc^{47} recoils were stopped before reaching the Cu backing and thus lost their alignment. Because of the smaller amplitude, the total statistical accuracy of ω_L was not significantly improved.

Using all of the data, the resulting Larmor frequency is $\omega_L = (0.69 \pm 0.09) \times 10^7\ \mathrm{sec}^{-1}$. From this value for ω_L, the g factor for the 760-keV $\frac{3}{2}^+$ level in Sc^{47} is $g = 0.24 \pm 0.04$, and the magnetic moment is $\mu = 0.35 \pm 0.05$ nm. The half-life obtained from fitting the total sum spectrum, displayed in Fig. 6, is $t_{1/2} = 274 \pm 10$ nsec. This lifetime result is in agreement with the two previous measurements,[2,6] which employed a weak β branch from Ca^{47} to populate this state; furthermore, the statistical uncertainty is somewhat reduced.

IV. DISCUSSION

The complete configuration of the Sc^{47} hole state is believed to be predominantly $(\nu f_{7/2})^{-2}(\pi f_{7/2})^2(\pi d_{3/2})^{-1}$, that is, two $f_{7/2}$ neutron holes, two $f_{7/2}$ proton particles, and a $d_{3/2}$ proton hole. For no core excitation, the pairs of $f_{7/2}$ holes and particles are coupled to a $J = 0$, which is just the Ti^{48} ground state. The core excitation suggested by Lawson and Macfarlane[3] can be taken as a configuration[10] where one of these pairs is coupled to $J = 2$, which is the 2^+ first excited state of Ti^{48}. The wave function of the $d_{3/2}$ hole state in Sc^{47} is then simply $\psi = \alpha[\mathrm{Ti}^{48}]^{J=0} d_{3/2}^{-1} + \beta[\mathrm{Ti}^{48}]^{J=2} d_{3/2}^{-1}$, where β is the amplitude of the core-excited portion. The magnetic moment calculated for this wave function[10] is given by the following expression:

$$\mu = (1 - \tfrac{4}{5}\beta^2)\mu(\mathrm{K}^{39}) + (6/35)\beta^2[\mu(\mathrm{Ca}^{41}) + \mu(\mathrm{Sc}^{41})].$$

Of course the empirical magnetic moments are used here, and not the Schmidt limits. The Schmidt value for a $d_{3/2}$ proton hole is $\mu_{\mathrm{Sch}} = 0.12$ nm. For no core excitation, that is, when $\beta^2 = 0$, the magnetic moment is $\mu = \mu(\mathrm{K}^{39})$, which equals 0.39 nm. Using the theoretically estimated value[3] of $\beta^2 = 0.4$, the magnetic moment is $\mu = 0.54$ nm. The experimental value of $\mu = 0.35 \pm 0.05$ nm agrees with the value for $\beta^2 = 0$ and no core excitation, while the predicted value for core excitation of 0.54 nm is definitely outside the experimental uncertainties. The difference between $\mu(\mathrm{K}^{39})$ and the Schmidt value for a $d_{3/2}$ proton hole, however, is not completely understood. Configuration mixing or a changed $M1$ operator, which most likely is the basis for this difference in K^{39}, might be altered somewhat in Sc^{47}. This, of course, would make the theoretical calculation of the magnetic moment for the 760-keV state in Sc^{47} slightly uncertain, and would reduce the strength in the argument against core excitation.

Experimentally, it is possible to obtain an erroneous magnetic moment μ for an alignment that is attenuated with a short relaxation time. This effect, however, would make the observed magnetic moment too large rather than too small. The data show no indication of attenuation, although statistically there is little information. The relaxation time of $\tau_r > 750$ nsec, as observed[5] for F^{18} ions in Cu, would make this effect on the magnetic moment negligible.

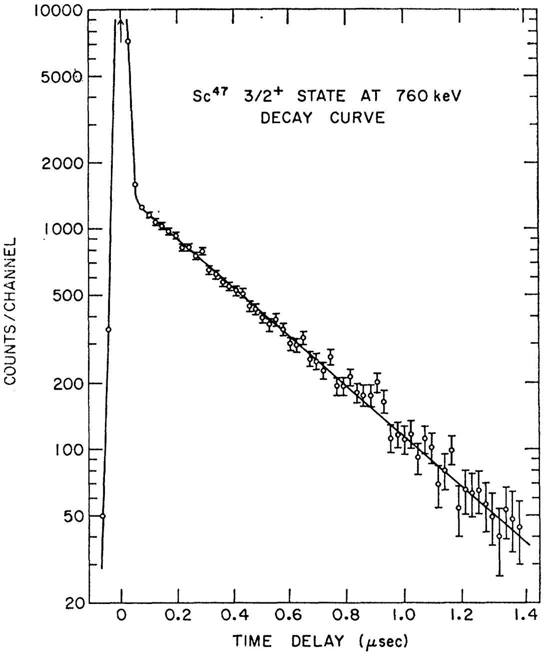

FIG. 6. Lifetime decay curve for the 760-keV level in Sc^{47} obtained from the total sum spectrum. The fitted half-life is $t_{1/2} = 274 \pm 10$ nsec.

Recent information on the $\mathrm{Ti}^{48}(d,\mathrm{He}^3)\mathrm{Sc}^{47}$ reaction by Newman and Hiebert at Oak Ridge National Laboratory[11] indicates that the majority of the $d_{3/2}$ pickup strength goes to the 760-keV state and not to states at higher excitation. Their results give an $\alpha^2 = 0.91$ for the wave function of this state, which leaves β^2 small. These new results are thus consistent with the present magnetic-moment results. If β^2 is small, the problem of the large $M2$ hindrances for the de-excitation of these hole states still remains.

Regarding the observed alignment, it appears that the present results are consistent with those of the previous experiment,[5] where F^{18} ions were stopped in Cu. The observed $R(t)$ amplitudes with the thin target where all the Sc^{47} recoils reached the Cu backing were roughly 30% less than the expected 0.085. A similar attenuation is implied in the A_2 coefficient. No attenuation of the recoil alignment is expected from the atomic hyperfine interaction during the stopping process because of the short stopping time and the decoupling effect of the applied field. For F^{18} ions stopped in Cu, it appeared[5] that about $\frac{1}{3}$ of the recoil ions lost their entire alignment

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[10] L. Zamick (private communication).

[11] R. H. Bassel (private communication).

in a time less than 10 nsec and that the alignment which remained persisted for over 750 nsec. This suggests that perhaps about $\frac{1}{3}$ of the ions come to rest in interstitial sites where a large quadrupole interaction can destroy the alignment in less than 10 nsec, while the remaining ions find lattice sites of the cubic Cu lattice where the alignment is maintained. Since the observed alignment for implanted nuclei of psec lifetimes reach the theoretical estimate in Cu,[12] it is suggested that the relaxation time of the quadrupole interaction at interstitial positions in Cu is 10 psec$<\tau_r<$10 nsec with, of course, some dependence on the magnitude of the quadrupole moment. The fraction of implanted recoils which find lattice sites undoubtedly depends on the kind of recoils and the type of backing material. Sprouse *et al.*,[13] for example, find from Mössbauer experiments that larger fractions of implanted Fe^{57} nuclei reach lattice sites in several different backings in less than 100 nsec.

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[13] G. D. Sprouse, G. M. Kalvius, and S. S. Hanna, Phys. Rev. Letters **18**, 1041 (1967).

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Nuclear Structure of Na^{22}. IV. Gamma-Ray Correlation Measurements*

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γ-γ angular correlations have been measured relative to the α beam in the $\text{F}^{19}(\alpha,n\gamma\gamma)\text{Na}^{22}$ reaction using NaI(Tl) γ-ray detectors. An ancillary determination of γ branching ratios for Na^{22} states of interest was made through γ-γ coincidence measurements utilizing Ge(Li) and NaI(Tl) detector combinations. From these measurements and previous information it was determined that the Na^{22} 1.95-, 2.97-, and 3.06-MeV levels have $J=2$, 3, and 2, respectively. The quadrupole-dipole amplitude ratios of the $1.95\rightarrow0.58$, $2.97\rightarrow1.95$, and $3.06\rightarrow1.95$ transitions were determined to be $+(0.04\pm0.06)$, $+(0.017\pm0.034)$, and $-(0.05\pm0.15)$, respectively; i.e., the results are consistent in each case with pure dipole radiation. From measurements of the angular correlation of the Na^{22} $1.528\rightarrow0.891\rightarrow0$ γ-ray cascade, it was determined that the two members of this $5^+\rightarrow4^+\rightarrow3^+$ cascade have $E2/M1$ amplitude ratios of $-(2.00\pm0.15)$ and $-(3.08\pm0.32)$, respectively. From these mixing ratios and previously determined branching ratios and lifetimes for the Na^{22} 1.528- and 0.891-MeV levels the $E2$ strengths of the $1.528\rightarrow0.891$ and $0.891\rightarrow0$ transitions are 20.7 ± 7.0 and 29.5 ± 4.5 Weisskopf units, respectively. These and other properties of Na^{22} are in accord with a rotational-model interpretation of this nucleus.

I. INTRODUCTION

In this report we present further results in a continuing experimental investigation of the nucelus Na^{22}. Information available on the quantum numbers of the first 18 levels of Na^{22} and the first 3 levels of Ne^{22} is shown in Fig. 1. The figure is taken mainly from previous reports[1–4] from this laboratory on the levels of Na^{22}. Those levels for which spin information was provided by the present work are marked by an asterisk.

Evidence for a collective-model description of the Na^{22} level structure has been discussed previously. It seems likely the Na^{22} ground state, 0.891-, and 1.528-MeV levels are members of a $K=3$ rotational band. Particular interest is therefore attached to the determination of the $E2/M1$ amplitude ratios for the $1.528\rightarrow0.891$ and $0.891\rightarrow0$ transitions. The branching ratios and the lifetimes are known for both the 1.528- and 0.891-MeV states.[1–7] Thus, a determination of these $E2/M1$ ratios would uniquely determine the $E2$ and $M1$ strengths of these two transitions which together with the $E2$ strength of the $1.528\rightarrow0$ transition would provide a further test of the rotational-model interpretation of these 3 states. With respect to this latter interest, it is clear that additional information on spin-parity assignments for the higher-lying Na^{22} levels is also most desirable.

The purpose of the present experimental investigation was therefore twofold: (1) to determine the $E2/M1$ amplitude ratios for the Na^{22} $1.528\rightarrow0.891$ and $0.891\rightarrow0$ transitions; (2) to determine the spins of the 1.95-, 2.97-, and 3.06-MeV levels of Na^{22}. The method we

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* Work performed under the auspices of the U. S. Atomic Energy Commission.

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