Gamma-Ray Transitions in $A = 35$ Nuclei

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The mean lifetime of the 1.99-MeV $\frac{7}{2}^-$ level of S^{35} was determined by a measurement of the delayed coincidence between protons and γ rays in the reaction $S^{34}(d,p\gamma)S^{35}$ at $E_d = 4.48$ MeV, with the result $\tau_m = 1.47 \pm 0.07$ nsec. The γ decay of the $\frac{7}{2}^-$, $T = \frac{3}{2}$ analog of this level at $E_x = 7.55$ MeV in Cl^{35} was examined in detail with large-volume Ge(Li) detectors and Ge(Li)-NaI(Tl) coincidence techniques. The γ-ray spectra obtained at the analog state, which appears as a well-known resonance at $E_p = 1211$ keV in the reaction $S^{34}(p,\gamma)Cl^{35}$, revealed the presence of several previously unknown transitions in addition to the known strong analog-to-antianalog $M1$ transition to the $\frac{7}{2}^-$, $T = \frac{1}{2}$ level at 3.16 MeV. Examples are a crossover $M2$ transition from the analog resonance to the $\frac{3}{2}^+$ ground state of Cl^{35} with a strength of 3.0 ± 0.8 Weisskopf units, a mixed $E1$-$M2$ transition ($\delta = 0.44 \pm 0.12$) from the $\frac{7}{2}^-$ antianalog state to the $\frac{5}{2}^+$ level at 1.76 MeV, and a 160-keV transition between the antianalog state and the $\frac{5}{2}^+$ level at 3.00 MeV. Weak transitions which can be interpreted as members of cascades through levels in the region $E_x = 4.3$–5.7 MeV were also identified. It is shown that the $M1$, $E2$, $M2$, and $E3$ strengths of transitions connecting members of the system of parent, analog, antianalog, and ground states can be accurately reproduced by a simple model based upon an inert S^{32} core with active nucleons in the $d_{3/2}$ and $f_{7/2}$ orbits, with bare-nucleon g factors for the magnetic transitions, and with reasonable effective charges for the electric transitions. The wave functions for the $\frac{7}{2}^-$ levels derived from this model are used to predict strengths of mirror transitions in Ar^{35} and K^{35}.

INTRODUCTION

The strong $\frac{7}{2}^-$ resonance at $E_p = 1211$ keV in the reaction $S^{34}(p,\gamma)Cl^{35}$ is known[1] to be the $T = \frac{3}{2}$ analog of the 1.99-MeV level in S^{35}. The main feature of the γ decay of the analog state is a strong analog-to-antianalog $M1$ transition to the $\frac{7}{2}^-$, $T = \frac{1}{2}$ level at 3.16 MeV, which in turn decays (90%) by a mixed $M2$-$E3$ transition ($\delta = -0.16 \pm 0.01$) to the $\frac{3}{2}^+$ ground state. In recent work, the analog resonance has been observed in elastic proton scattering[2] with the result $\theta_p^2(l=3) = 0.16 \pm 0.08$: The mean life and $S^{34}(He^3, d)Cl^{35}$ spectroscopic factor for the antianalog state have been measured with the results $\tau_m = 60 \pm 7$ psec [3] and $S = 0.66$,[4] respectively; and the value $\delta = 0.11 \pm 0.04$ has been reported[5] for the $E3/M2$ mixing ratio of the decay of the parent state to the $\frac{3}{2}^+$ ground state of S^{35}.

In the earlier attempts[1,6] to describe the properties of these $\frac{7}{2}^-$ levels, it was noted that the observed strength of the analog-to-antianalog transition was in agreement with a pure $(f_{7/2}, T = \frac{3}{2}) \to (f_{7/2}, T = \frac{1}{2})$ assumption. Here the implicit assumption was that the two states involved are of the form $|d_{3/2}{}^2(\alpha) f_{7/2}\rangle_{JT}$, where $\alpha \equiv (J_0, T_0) = (0, 1)$ is the spin and isospin coupling of the $d_{3/2}$ nucleons. However, a later shell-model calculation by Maripuu and Hokken[7] based upon the modified surface δ interaction (MSDI) showed that contributions from other antisymmetric (J_0, T_0) couplings ("core polarization") of the $d_{3/2}$ nucleons may be significant in the wave functions. Harris and Perrizo[8] then demonstrated that core polarization was indeed required to explain other known properties of the system ($M2$ strengths and $E3$-$M2$ mixings), although the specific MSDI wave functions gave poor results. Wave functions which did give good agreement with the observed properties then available were derived from the data.

Further consideration of these results suggested, for example, that the analog state should decay by an observable $\Delta T = 1$, $M2$ transition [strength of several Weisskopf units (W.u)] to the Cl^{35} ground state, that additional fragments of the antianalog state (due to the core polarization) should lie in the region above $E_x = 5$ MeV in Cl^{35}, and that the mean lifetime of the 1.99-MeV parent state in S^{35} should be about 1–2 nsec. In the present contribution, we give results of a measurement of the lifetime of the parent level, and of a detailed examination of the γ-decay spectrum of the analog state with large-volume Ge(Li) and NaI(Tl) detectors. Interesting and previously unobserved weak features, such as the above mentioned $\Delta T=1$, $M2$ transition and several other transitions are discussed. The new results are used to derive an improved set of wave functions for the $\frac{7}{2}^-$ levels. These wave functions are then applied to a prediction of transition rates in Ar^{35} and K^{35}.

EXPERIMENTAL PROCEDURE AND RESULTS

Decay of the 7.55-MeV Analog State in Cl^{35}

In principle, this measurement consists simply of obtaining a pulse-height spectrum at the 1211-keV resonance in the reaction $S^{34}(p,\gamma)Cl^{35}$ with sufficient resolution and statistics. If a crossover transition from resonance to the ground state exists, then a comparison of its strength relative to that of the dominant analog-to-antianalog cascade immediately yields its absolute strength. In practice, of course, a number of precautions and auxiliary experiments were necessary to assure that the weak structure observed in the pulse-height spectrum at the correct energy was attributable to a transition from this resonance to the ground state.

Most of the measurements were made at the Aerospace Research Laboratories (ARL). For these, targets of Ag_2S, enriched to 85.61% in S^{34}, were bombarded with protons from the 2-MeV ARL Van de Graaff. The targets were approximately 10 keV thick for protons of 1.2 MeV and were cooled by flowing water, so that beam currents of 15 to 30 μA could be used without appreciable target deterioration. The γ rays were detected with an 80-cm^3 Ge(Li) detector, located with its front face approximately $2\frac{1}{4}$ in. from the target, and the pulses recorded in a 4096-channel analyzer with a gain of 2.38 keV/channel and an equivalent zero-channel intercept of 538 keV. This offset was obtained with a biased amplifier and was found desirable to reduce the analyzer deadtime which would have resulted from the large low-energy counting rate. This detector, with the associated electronics and analyzer, had a full width at half maximum (FWHM) of 3.0 keV for the 1.33-MeV Co^{60} γ ray. The relative-efficiency curve for the detector was obtained in the experimental geometry with the use of Co^{56} and Eu^{154} sources in the low-energy region and the reactions $S^{34}(p,\gamma)Cl^{35}$, $Na^{23}(p,\gamma)Mg^{24}$, and $C^{13}(p,\gamma)N^{14}$ to extend the calibration to 8.9 MeV.

Spectra were obtained with the Ge(Li) detector at 90°, for 2×10^6 monitor counts or about 0.1 C of beam charge, and at 0°, for 1×10^6 monitor counts. The longer run at 90° was dictated partly to obtain better statistics at this angle to determine transition energies more accurately, and partly because the angular distributions of most of the transitions of interest in Cl^{35} are strongly peaked in the forward direction. Spectra were obtained at the two angles to measure the Doppler shifts and the anisotropy of the angular distributions of the observed γ rays. The yield of the reaction was monitored with an 8-in.$\times$8-in. NaI detector, with a single-channel energy window set over the full-energy peak of the 4.38-MeV γ ray.

As will be discussed below, the primary purpose for the Doppler-shift and anisotropy measurements was to aid in the identification of the transition from the compound state to the ground state. Thus, the gain was set to cover the entire spectrum and was not optimum to determine $F(\tau)$ for the lower-energy γ rays. The decay of the compound state was known to be too rapid, and that of the 3.16-MeV state too slow, to be detected by Doppler-shift attenuation methods, and the primary purpose was to distinguish between these alternatives. The results were that all γ rays ascribed to the decay of the compound state showed the full Doppler shift within statistics and all others, except the 3003-keV γ ray, showed no Doppler shift. [For the 3003-keV γ ray, $F(\tau)=0.5\pm0.3$]. Similarly, the anisotropy measurement was made to check the expected strong forward intensity of a $\frac{7}{2}\to\frac{3}{2}$ transition, and to permit intensities to be calculated more accurately. [The latter depends, as does the usual method of measuring relative intensities at 55°, on the assumption that $P_4(\cos\theta)$ terms are negligible.] The information obtained, however, proved to be valuable in the assignment of other transitions as well.

A serious worry in the investigation was the possible presence of summing of the two γ rays in the cascade through the 3.16-MeV state, in view of the large volume and solid angle of the Ge(Li) detector and the anticipated weakness of the crossover transition. The absence of appreciable summing was established in several ways. The first was by inspection of the Doppler shift of the 7.55-MeV γ ray. The γ rays from the compound state will show the full Doppler shift of about 1.45 keV/MeV, or about 10.9 keV for a transition to the ground state and 6.4 keV for a transition to the 3.16-MeV state. The mean life of the 3.16-MeV state is 60 ± 7 psec,[3] so that its decay will cause no Doppler shift in this experiment. Thus, summing would result in only a 6.4-keV shift. The measured shift was 13 ± 3 keV, in agreement with a transition from resonance to ground state. Additional, and much more sensitive, tests of the absence of summing were available because of the relatively large efficiency for full-energy conversion of γ rays in the energy range of interest. The full-energy and double-escape peaks are of equal intensity for γ rays of about 5.5 MeV. If the structure ascribed to a γ ray of 7.5 MeV were to result from summing of 4.38- and 3.16-MeV γ rays, the full-energy peak should be significantly more intense, relative to those of single and double escape, than for a true 7.5-MeV γ ray. As observed, the ratio of intensities of the three peaks agreed within statistics with those expected for a 7.55-MeV transition. Moreover, if there were significant summing, peaks should appear not only at E_γ, $E_\gamma - mc^2$, and $E_\gamma - 2mc^2$, but also at $E_\gamma - 3mc^2$ and $E_\gamma - 4mc^2$. These should appear, in this energy range, with approximate relative intensities of about 3 : 3 : 4 : 2 : 1, respectively. The spectrum obtained at 90° is shown in Fig. 1, where it is apparent that the possible effects from summing are not present at an observable level. Contaminant γ rays from $C^{13}(p,\gamma)N^{14}$ and $F^{19}(p,\alpha\gamma)O^{16}$ are observable and served to assist in the energy calibration of the spectra.

An additional possibility was the presence of a weak resonance in this energy region or of direct capture, either of which might lead to a transition to the ground state. Tests were made to eliminate these as possible sources of competing strength in the observed ground-state transition. First, the off-resonance spectrum, taken at about $E_p = 1207$ keV, was obtained with equivalent beam charge and no evidence for a ground-state transition was found. Next, the anisotropy of the 0 and 90° yield was in agreement for a quadrupole transition from a $J=\frac{7}{2}$ to a $J=\frac{3}{2}$ state. (The statistical accuracy was insufficient to test for the presence of octupole radiation.) Unfortunately, this latter effect could not be used as a check against summing, since both the cascade and crossover transitions lead to similar 0 to 90° ratios.

From the failure of any of the tests to find competing contributions to the strength of the observed 7.55-MeV γ ray, the entire strength, to within its statistical error of ±10%, was attributed to the crossover transition from the analog state to the ground state of Cl^{35}.

As a byproduct of this measurement, new information about other weak decays of the 7.55- and 3.16-MeV states was obtained. This is summarized in Table I and Fig. 2, where the observed intensities and energies have been fitted into a consistent decay scheme. The main decay of the resonance state is, of course, to the antianalog state.

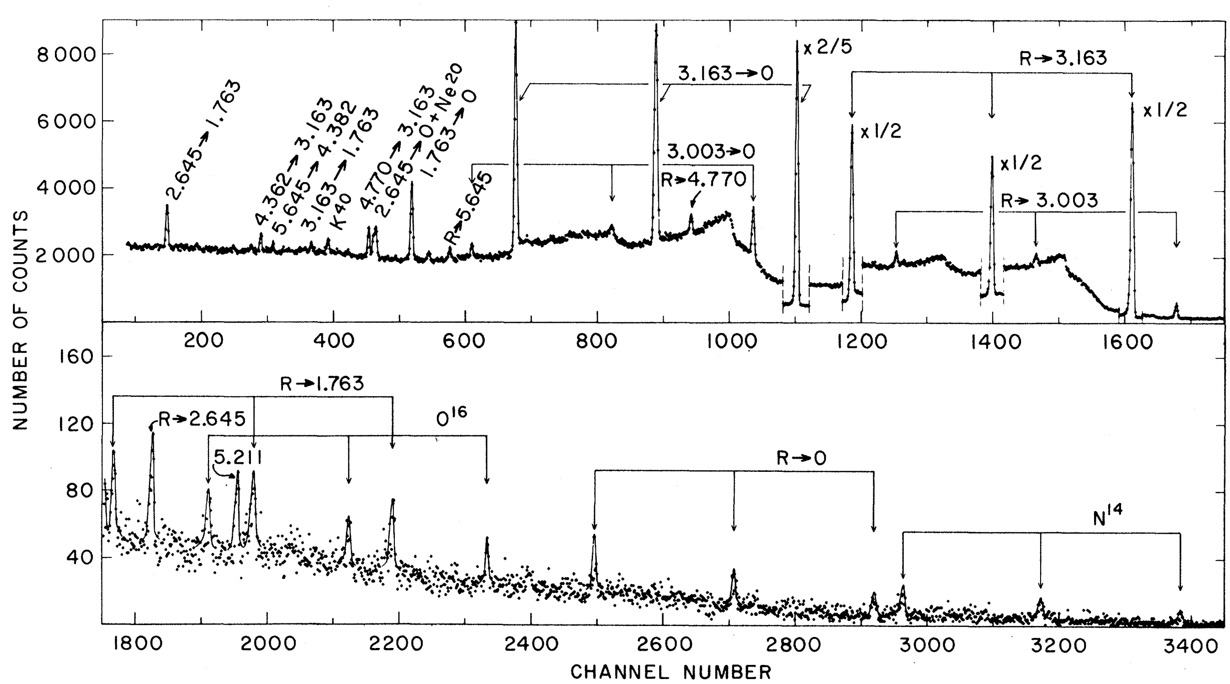

FIG. 1. Pulse-height spectrum from the reaction $S^{34}(p,\gamma)Cl^{35}$ at the 1211-keV resonance obtained with an 80-cm^3 Ge(Li) detector at 90° with respect to the beam. No background has been subtracted. The main peaks are denoted by the corresponding γ-ray energies in keV. Transitions from radioactive background and contaminant reactions are labeled by the radioactive source and residual nucleus, respectively. The 7.546→4.382-MeV transition, shown in Fig. 2, is not resolved from the 3.163→0-MeV transition. Similarly, the full-energy peak of the 5.645→3.163-MeV transition is not resolved from the single-escape peak of the 3.003→0-MeV transition. Their existence was established by the consideration of relative intensities and relative detection efficiencies, in the manner discussed in the text.

The next stronger decay is to the 3.00-MeV state, as previously reported.[1] A number of other weak γ rays were found, some of which could be ascribed to transitions to known energy levels and their known decays,[9] but some of which could only be included by the postulations of new states above 4 MeV. While these postulated states must be regarded as tentative, in all cases shown the required intensities agreed within statistics, and the γ rays which were assigned to transitions from the resonant state showed the full Doppler shift. In addition, the anisotropy of each transition was in agreement with reasonable spin assignments for the assumed decays. For example, a γ ray was found with an energy of 1219 keV. At first, this was assumed to arise from the decay of the 1.22-MeV state to the ground state. However, the 1.22-MeV state is known to have $J=\frac{1}{2}$, so that its decay must have an isotropic angular distribution. The 1219-keV γ ray has a marked anisotropy and, in addition, has a much greater intensity than can be found for any decay which could populate the 1.22-MeV state. Thus, it has been presumed to arise from the decay of a state at 4.38 MeV. γ rays with correct energy and intensity were found to populate such a state. In assigning intensities and multipole strengths in these weak decays, it was assumed that all decays occurred by the lowest-allowed multipole, unless known previously[1] to be otherwise, with the exception of the 1401-keV γ ray, to be discussed below. The multipole strengths were calculated assuming the values $\Gamma_\gamma(7.55)=3.9\pm1.0$ eV[7] and $\tau(3.16)=60\pm7$ psec.[3] The only inconsistency which remained in the proposed decay scheme was in the decay of the state at 1.76 MeV. For this state, which is populated by many cascades, and which is known to decay primarily by $E2$ radiation,[3] a severe departure from a $\cos^2\theta$ distribution can be expected, but cannot be calculated with sufficient accuracy to check the present results.

In spite of the apparently simple spectrum and the wide spacing of the energy levels, a number

TABLE I. Transition strengths for the decays of the 7.55- and 3.16-MeV states in Cl^{35}. Except as noted, the transitions are assumed to occur as the probable lowest multipole. The transition strengths are given in Weisskopf units. The references for the total strengths of the initial states and for the mixing parameters of the mixed transitions are given in the text. The branching ratios used are from the present investigation and are shown in Fig. 2.

E_i (MeV)	E_f (MeV)	Multipole order	Transition strength (W.u.)
7.55	0	$M2$	3.0 ± 0.8
	1.76	$E1$	$(0.9 \pm 0.2)\times10^{-4}$
	2.65	$E1$	$(3.2 \pm 0.8)\times10^{-4}$
	3.00	$E1$	$(1.2 \pm 0.3)\times10^{-3}$
	3.16	$M1$	2.2 ± 0.6
		$E2$	2.0 ± 1.2
	4.38 [a]	($M1$)	(0.021 ± 0.009)
	4.77 [a]	($M1$)	(0.12 ± 0.03)
	5.65 [a]	($M1$)	(0.15 ± 0.04)
3.16	0	$M2$	0.19 ± 0.03
		$E3$	2.9 ± 0.5
	1.76	$E1$	$(1.4 \pm 0.3)\times10^{-8}$
		$M2$	$(6.3 \pm 3.7)\times10^{-3}$
	2.65	$E1$	$(9 \pm 2)\times10^{-6}$
	3.00	$E1$	$(1.5 \pm 0.3)\times10^{-4}$

[a] Parity undetermined but presumed odd in calculation of transition strength.

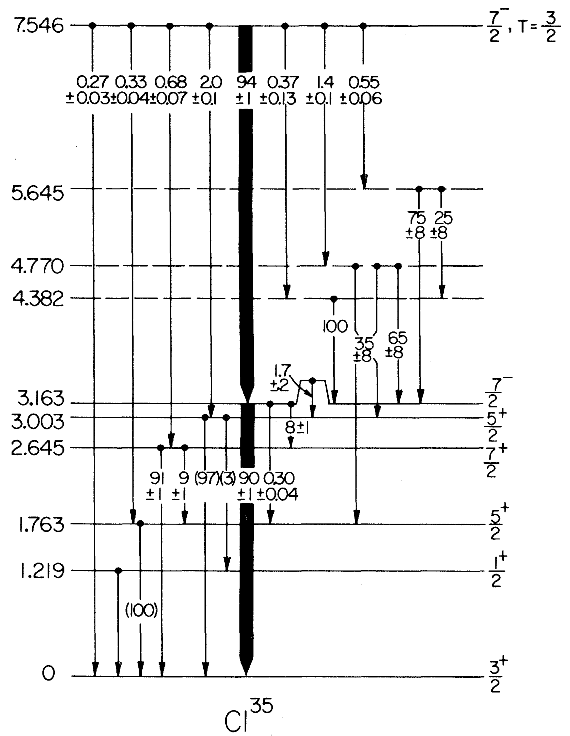

FIG. 2. Decay scheme for energy levels (in MeV) in Cl^{35} deduced from the decay of the 1211-keV resonance in the reaction $S^{34}(p,\gamma)Cl^{35}$. Branching ratios, and their errors, are shown in percentages. The values enclosed in parentheses are taken from Refs. 3 and 9. The excitation energies are assigned errors of ±1 keV, except the postulated states above 4 MeV for which the errors are ±2 keV and the 1.22-MeV state which was not observed in this work. The decay of the 4.38-MeV state has been assumed to be 100% to the 3.16-MeV state (see text). Also, (35 ± 8)% of the decay of the 4.77-MeV state must occur by 3007- and 1763-keV γ rays and/or 1767- and 3003-keV γ rays. While these alternatives could not be resolved in either singles or coincidence spectra from each other and from the stronger 1763- and 3003-keV transitions, they have been assumed to exist and the required intensity has been subtracted from the strength of the latter transitions used in other cascades.

of unfortunate coincidences in energy occur. For the most part, these could be resolved by knowledge of the relative efficiency for full-energy, single-escape, and double-escape conversion. One typical example is that of the 2645-keV γ ray. The double-escape peak is clearly identifiable; however, the full-energy and single-escape peaks are not resolved from the single- and double-escape peaks of the stronger 3163-keV γ ray. The observed strength of the peak at 2652 keV is too strong for the single-escape peak of a 3163-keV γ ray, but agrees well with that required for a combination of this and the full-energy peak of the 2645-keV γ ray. Another example is that of the postulated state at 4.382 MeV. This state must be populated in part by a γ ray of 3164 keV and may decay in part by a γ ray of 4382 keV, both of which are obviously indistinguishable from those of the dominant cascade. As indicated in Fig. 2, the relative intensities are best fit by the assumption that the decay to the ground state of the 4382-keV state is negligible.

The decay found for the 3.16-MeV state contains two previously unobserved features. First, a γ ray with an energy of 1401 keV was found, which could only be included as a transition from the 3.16-MeV state to the state at 1.76 MeV. Next, the population of the state at 3.16 MeV was greater than the sum of the intensities of its decays to the ground state and the states at 2.65 and 1.76 MeV, and the intensity of the decay of the state at 3.00 MeV was greater than that of its population from the resonance state. Therefore, we assumed the existence of a decay from the 3.16-MeV state to the 3.00-MeV state in our analysis of the original data.

Subsequently, this hypothesis was tested by a coincidence experiment at the University of Kansas. In this experiment a 15-cm^3 Ge(Li) detector was used in time coincidence with a 9-in.-diam $\times$4.5-in.-thick NaI(Tl) detector, both at 55° with respect to the beam. Crossover timing was used and those events which occurred within a resolving time of 200 nsec, as determined by a time-to-pulse-height converter, were analyzed and stored as address pairs on magnetic tape by way of an IBM 1800 on-line computer. The stored data were later scanned to find the spectra obtained with the Ge(Li) detector in coincidence with various energy regions of the NaI spectrum. These spectra clearly show that γ rays with energies of 160 and 518 keV are in coincidence with the 4.38-MeV γ ray. Also, the 160-keV γ ray was in coincidence with the lower-energy part of the 3.16-MeV peak in the NaI spectrum, i.e., the 3.00-MeV γ ray, and the 518-keV γ ray in coincidence with an energy window centered about 2.65 MeV in the NaI spectrum.

A similar experiment was also performed at the University of Kansas with a 60-cm^3 Ge(Li) detector and a 5-in. by 5-in. NaI detector. This experiment confirmed the decay scheme postulated through the states at 5.65 and 4.77 MeV, as well as through the known states at 3.00, 2.65, and 1.76 MeV. Unfortunately, this experiment could not confirm the 1401-keV transition between the 3.16- and 1.76-MeV states nor determine the relative intensities of the postulated 3007- and 1767-keV transitions from the 4.77-MeV state. While these coincidence experiments do not establish the sequence of transitions uniquely, in combination with the intensity and Doppler-shift measurements described above, they give strong evidence for the postulated states.

The angular distribution of the 1401-keV γ ray was anomalous, if its position in the decay scheme is correct. However, this can be understood if it occurs by a mixture of $M2$ and $E1$ radiation. In view of the weakness of this transition, such a mixture is not unreasonable. In fact, the observed anisotropy can be explained by a mixing ratio, $\delta(M2/E1) = -0.44 \pm 0.12$, which has been assumed in Table I. The implication of this result will be discussed below. All other anisotropies, other than that of the decay of the 1.76-MeV state, agreed, within statistics, with the known spins and known mixing ratios or with dipole radiation.

Two γ rays of 1824 and 5211 keV (channels 575 and 1955 in Fig. 1) appeared in both the single and coincidence spectra and are believed to occur in the decay of the analog state in Cl^{35}. However, no consistent way could be found to include them in the proposed decay scheme.

Decay of the 1.99-MeV Parent State in S^{35}

The decay of the second excited state of S^{35} has been established to occur only to the ground state via a mixed $E3/M2$ transition.[5] Its spin and parity have been shown to be $\frac{7}{2}^-$.[5] An earlier report predicted a mean life of about 1.7 nsec and cited a preliminary experimental value of 1.5 ± 0.7 nsec.[8] As in the present experiment, this earlier value was based on delayed coincidence between the protons and γ rays emitted in the reaction $S^{34}(d, p\gamma)S^{35}$. However, in this earlier measurement, the γ rays were detected by a NaI detector and ordinary crossover timing was used, with a resultant delay curve with a FWHM of about 8 nsec. Therefore, only the centroid shift relative to the decays from the 1.55- and 2.35-MeV states could be determined. The 2.35-MeV state is known to have a mean life of 0.8 ± 0.2 psec[5]; the 1.55-MeV state is strongly suspected to be $\frac{1}{2}^+$ and to decay therefore with an electronically prompt lifetime.

In view of the excellent preliminary agreement between experiment and theory, it was felt to be worthwhile to see if this agreement persisted with increased precision of measurement. Therefore, the NaI detector was replaced by a plastic scintillator, and constant-fraction pulse-height timing was used. With this apparatus, a prompt-response and constant-fraction pulse-height timing was used. With this apparatus, a prompt-response decay curve with a FWHM of 0.96 nsec for the decay of the 2.35-MeV state was obtained. To within this time resolution, no evidence was seen for a finite lifetime of this state. Deuterons with an energy of 4.48 MeV were obtained from the ARL insulated-core transformer tandem accelerator. The target was prepared by exposing one surface of a self-supporting Ag foil, approximately 100 $\mu g/cm^2$ thick, to sulfur fumes from elemental sulfur enriched to 85.61% in S^{34}. The proton detector was a 500-μ, 50-mm^2 Si detector, located at 40° with respect to the beam direction, and the γ-ray detector was a $1\frac{1}{2}$-in.-diam by 1-in.-thick NE111 scintillator, mounted on a RCA 8575 photomultiplier tube and situated at 90° with respect to the beam.

The decay curve obtained for the γ rays in coincidence with the proton group populating the 1.99-MeV excited state is shown in Fig. 3. The time-

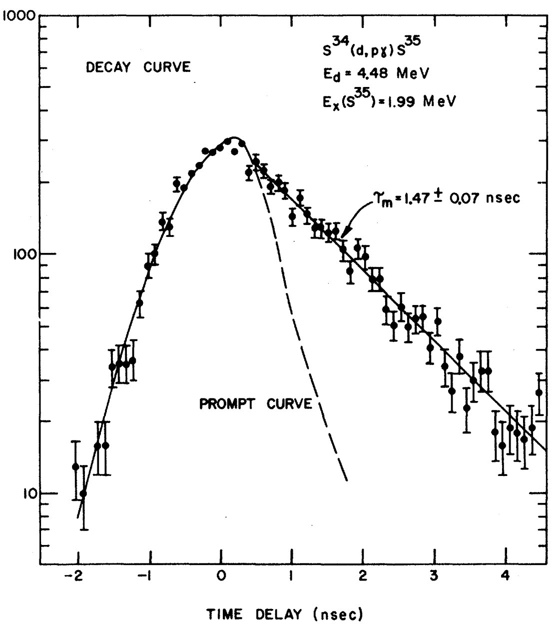

FIG. 3. Time spectrum of the decay of the 1.99-MeV state in S^{35} excited by the reaction $S^{34}(d,p\gamma)S^{35}$. Background has been subtracted. The prompt curve was obtained from the decay of the 2.35-MeV state of S^{35} in the same reaction and was adjusted by matching the spectra in the negative time-delay region. A typical least-squares fit to the data is shown.

to-pulse-height converter and multichannel analyzer were calibrated by introducing known delays between the signals from the γ-ray and particle detectors generated by a common pulser input to both. This calibration was 0.1014 ± 0.0010 nsec/channel over the region of interest. The decay curve was analyzed by fitting a straight line to the logarithm of the counting rate (above background) by least squares. Three trial fits were made for slightly different regions of the decay curve to check for the presence of systematic errors such as a departure from linearity. The results for all three agreed well within the statistical errors of about 4%, and all had acceptable values of χ^2. The average was -14.5 ± 0.6 per channel. The error cited is that of the worst of the three fits. From this result and the calibration, the final value of 1.47 ± 0.07 nsec is obtained for the mean life of this state. The estimated error is believed to be conservative because of the consistency of the calibration measurements and of the results of the different regions of analysis; however, because of the possibility of systematic error in the calibration standards used, we regard it as a reasonable value for the present experiment.

This lifetime measurement, with the value $\delta(E3/M2) = 0.11 \pm 0.04$,[5] allows the calculation of the γ-ray matrix elements in the decay of the 1.99-MeV $\frac{7}{2}^-$ state of S^{35}. The results are $|M|^2(M2) = 0.089 \pm 0.004$ W.u. and $|M|^2(E3) = 1.6 \pm 1.2$ W.u.

TRANSITION RATES AND WAVE FUNCTIONS

Formalism

In a recent paper, Harris and Perrizo[8] showed that properties of the system of $\frac{7}{2}^-$ analog and antianalog levels in the $A = 35$ and 37 nuclei could be described in terms of an inert S^{32} core plus active nucleons in the configuration $d_{3/2}{}^n f_{7/2}$ if spin and isospin recoupling of the $d_{3/2}{}^n$ group ("core polarization") is allowed. In general it was found that good agreement with observed $M1$ and $M2$ transition rates and observed $E2/M1$ and $E3/M2$ multipolarity mixing ratios could be obtained with bare-nucleon g factors by appropriate choice of core polarization in the wave functions for the $\frac{7}{2}^-$ levels. The measurements of the lifetime of the $\frac{7}{2}^-$ level in S^{35} and of the $\Delta T = 1$, $M2$ decay of the analog state in Cl^{35} described in the present paper make possible an improved calculation for the $A = 35$ system. We first present a convenient formulation for transition rates within a $d_{3/2}{}^n f_{7/2}$ system. The results of the specific calculations for S^{35} and Cl^{35} are then given along with predicted properties of $\frac{7}{2}^-$ levels in the $M_T = -\frac{1}{2}$ and $-\frac{3}{2}$ isobars, Ar^{35} and K^{35}.

We consider the parent (P), analog (A), antianalog ($\bar{A}$), and the $\frac{3}{2}^+$ ground states (G) to be of the form

$$|P, A, \bar{A}, \text{ or } G\rangle = \sum_\alpha a_\alpha \, |d_{3/2}{}^n(\alpha) f_{7/2}{}^m \Gamma M\rangle , \qquad (1)$$

where the $\alpha \equiv (J_0, T_0)$ are the possible antisymmetric spin-isospin couplings of the d^n group, $\Gamma \equiv (J, T)$ is the total spin and isospin, and $M \equiv (M_J, M_T)$ represents the projection quantum numbers. An inert S^{32} core with n active nucleons in the $d_{3/2}$ orbit and m (=0 or 1) in the $f_{7/2}$ orbit is assumed. Two types of transitions are considered: (1) the $A \to \bar{A}$, $M1$ and $E2$ transitions; and (2) the (P, A, or $\bar{A}$)$\to G$, $M2$ and $E3$ transitions. The first type involves only single-nucleon transitions between equivalent orbits ($d_{3/2} \to d_{3/2}$ and $f_{7/2} \to f_{7/2}$), whereas the second type involves only inequivalent transitions of the kind $f_{7/2} \to d_{3/2}$.

The total matrix elements $\langle \mathfrak{M}(L) \rangle$ can be written as the sum,

$$\langle \mathfrak{M}(L) \rangle = \sum_{\alpha, \alpha', r} a_\alpha a'_{\alpha'} \times \langle d^n(\alpha) f^m(\beta) \Gamma M_T \| \Omega_0^{L,r} \| d^{n'}(\alpha') f^{m'}(\beta') \Gamma' M_T \rangle , \qquad (2)$$

where the double-barred matrix element in this expression is taken to mean reduced with respect to J but not T. For brevity, the $d_{3/2}$ and $f_{7/2}$ orbitals are denoted by d and f in Eq. (2) and in much of the following. The summation extends over all allowed antisymmetric α, α' couplings of the $d^n(\alpha)$ groups, and the symbol $\Omega_0^{L,r} \equiv \sum_{i=1}^{n+1} \Omega_0^{L,r}(i)$ denotes the appropriate magnetic or electric multipole operator. The rank of the operator in isospin space is given by r, where $r=0$ or 1. For type-(1) transitions, $n=n'$ and $m=m'=1$. Similarly, for type (2), $n'=n'+1$ and $m=1$, $m'=0$. For m (m')$=1$, $\beta(\beta')=(\frac{7}{2}, \frac{1}{2})$ and for $m(m')=0$, β (β') $=(0, 0)$. We adopt the operator phase convention of Rose and Brink[10] in order to preserve a direct comparison of the experimental and theoretical signs of the multipole mixing ratios.

The evaluation of the ($n+1$)-particle matrix elements of Eq. (2) in terms of single-particle reduced matrix elements is performed with standard reduction techniques.[11] With appropriate modification of the Rose and Brink formulation to include isospin, and with convenient algebraic redefinition of some quantities, the result for type-(1) transitions is

$$\langle d^n(\alpha) f \Gamma M_T \| \Omega_0^{\bar{L}} \| d^n(\alpha') f \Gamma' M_T \rangle = \sum_r (-)^{T-M_T+r} \begin{pmatrix} T & r & T' \\ -M_T & 0 & M_T \end{pmatrix} \times (A_{\alpha\alpha'}^{\bar{L}} \langle d \| \Omega^{\bar{L}} \| d \rangle + B_{\alpha\alpha'}^{\bar{L}} \langle f \| \Omega^{\bar{L}} \| f \rangle), \qquad (3)$$

where the definition of the Wigner-Eckart theorem is that of de-Shalit and Talmi.[11] The quantity $\bar{L} \equiv (L, r)$, in direct-product notation. The coefficients A and B are given in direct-product notation by

$$A_{\alpha\alpha'}^{\bar{L}} = n(-)^{\Gamma'} [\Gamma][\Gamma'][\alpha][\alpha'] \begin{Bmatrix} \Gamma' & \Gamma & \bar{L} \\ \alpha & \alpha' & f \end{Bmatrix} \times \sum_\epsilon (-)^\epsilon \langle d^n \alpha | d^{n-1} \epsilon \rangle \langle d^n \alpha' | d^{n-1} \epsilon \rangle \begin{Bmatrix} d & d & \bar{L} \\ \alpha' & \alpha & \epsilon \end{Bmatrix} , \qquad (4)$$

where $\langle d^n | d^{n-1} \rangle$ represents a coefficient of fractional parentage, and

$$B_{\alpha\alpha'}^{\bar{L}} = (-)^{\Gamma+\alpha+\bar{L}} \delta_{\alpha,\alpha'} [\Gamma][\Gamma'] \begin{Bmatrix} \Gamma' & \Gamma & \bar{L} \\ f & f & \alpha \end{Bmatrix} , \qquad (5)$$

where the symbols are defined by

$$\alpha \equiv (J_\alpha, T_\alpha),$$

$$(-)^\alpha \equiv (-)^{J_\alpha + T_\alpha},$$

$$[\alpha] \equiv (2J_\alpha + 1)^{1/2} (2T_\alpha + 1)^{1/2},$$

$$\delta_{\alpha,\alpha'} \equiv \delta_{J_\alpha, J_{\alpha'}} \delta_{T_\alpha, T_{\alpha'}} ,$$

and the 6-j symbol

$$\begin{Bmatrix} \Gamma' & \Gamma & \bar{L} \\ \alpha & \beta & f \end{Bmatrix} \equiv \begin{Bmatrix} J' & J & L \\ J_\alpha & J_\beta & \frac{7}{2} \end{Bmatrix} \begin{Bmatrix} T' & T & r \\ T_\alpha & T_\beta & \frac{1}{2} \end{Bmatrix} .$$

Similarly, the result for the type-(2) transitions is

$$\langle d^n(\alpha) f \Gamma M_T \| \Omega_0^{\bar{L}} \| d^{n+1}(\alpha') \Gamma' M_T \rangle = \sum_r (-)^{T-M_T+r} \begin{pmatrix} T & r & T' \\ -M_T & 0 & M_T \end{pmatrix} C_{\alpha\alpha'}^{\bar{L}} \langle f \| \Omega^{\bar{L}} \| d \rangle , \qquad (6)$$

with

$$C_{\alpha\alpha'}^{\bar{L}} = (-)^{\Gamma+\alpha+\bar{L}} \delta_{\alpha',\Gamma'} (n+1)^{1/2} [\Gamma][\Gamma'] \times \langle d^{n+1} \Gamma' | d^n \alpha \rangle \begin{Bmatrix} \Gamma & \Gamma' & \bar{L} \\ d & f & \alpha \end{Bmatrix} . \qquad (7)$$

The single-particle matrix elements $\langle 1 \| \Omega^L \| 2 \rangle$ are explicitly given by

$$\langle l_1 j_1 \tfrac{1}{2} \| E^{\bar{L}} \| l_2 j_2 \tfrac{1}{2} \rangle = e q^{(r)} I(L) \begin{pmatrix} j_1 & j_2 & L \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix} b_{12} \qquad (8)$$

for electric multipoles (where we have neglected small contributions from the spin part of the electric operator), and

$$\langle l_1 j_1 \tfrac{1}{2} \| M^{\bar{L}} \| l_2 j_2 \tfrac{1}{2}\rangle = i\beta I(L-1) b_{12}\Big[2g_l^{(r)}[l_1][l_2][l_2(l_2+1)]^{1/2}\Big(\frac{L}{L+1}\Big)^{1/2}\begin{pmatrix} l_1 & l_2 & L \\ 0 & 1 & -1\end{pmatrix}\begin{Bmatrix} j_1 & j_2 & L \\ l_2 & l_1 & \frac{1}{2}\end{Bmatrix} - \tfrac{1}{2}g_s^{(r)}[L-(l_1-j_1)(2j_1+1)-(l_2-j_2)(2j_2+1)]\begin{pmatrix} j_1 & j_2 & L \\ \frac{1}{2} & -\frac{1}{2} & 0\end{pmatrix}\Big] \tag{9}$$

for magnetic multipoles. (The symbol β is used here for the nuclear magneton.) Standard notation is used for the 3-j and 6-j symbols. The factor b_{12} is given by

$$b_{12} = -\tfrac{1}{2}[r]\, i^{L+l_1-l_2}(-)^{j_2+1/2}[j_1][j_2]\left(\frac{L+1}{L}\right)^{1/2}\frac{1}{(2L-1)!!}, \tag{10}$$

where

$$[r] \equiv [2r+1]^{1/2}.$$

The isoscalar and isovector effective charge factors are represented by $q^{(r)}$, where $q^{(r)} = [e_p + (-)^r e_n]/e$. Similar expressions hold for the scalar and vector g factors $g_l^{(r)}$ and $g_s^{(r)}$. The symbol $I(L)$ represents the radial integral,

$$I(L) = \int_0^\infty U_1(r) r^L U_2(r) r^2 dr,$$

where

$$I(0) = \delta_{12}.$$

To conserve parity, $L + l_1 + l_2$ must be even for electric, and odd for magnetic multipoles. These conditions also insure that the single-particle matrix elements are real.

The radiative width for given multipolarity L is given by

$$\Gamma(L) = 4k^{2L+1}[(2J+1)(2L+1)]^{-1}|\langle\mathfrak{M}(L)\rangle|^2, \tag{11}$$

where $k = E_\gamma/\hbar c$, and the multipolarity mixing ratios are defined by

$$\delta = k^{L'-L}\frac{\langle\mathfrak{M}(L')\rangle/(2L'+1)^{1/2}}{\langle\mathfrak{M}(L)\rangle/(2L+1)^{1/2}}. \tag{12}$$

Results of Calculations for $A = 35$

In the calculations, bare-nucleon g factors are used for the $M1$ and $M2$ transitions. For $E2$ transitions, effective proton and neutron charges $e_p = 1.5e$ and $e_n = 0.5e$, respectively, are used. Similarly, for the $E3$ transitions, the values $e_p = 1.9e$ and $e_n = 0.9e$ are adopted.[8] The harmonic-oscillator radial integrals are evaluated with a radius $R = r_0 A^{1/3}$, where $r_0 = 1.3$ F. Specific numerical expressions have been presented in Ref. 8 for the $A \to \bar{A}$, $M1$-$E2$ transitions and for the $P \to G$ and $\bar{A} \to G$, $M2$-$E3$ transitions in S^{35} and Cl^{35}. With the appropriate changes of M_T in Eqs. (3) and (6), these expressions can be easily modified to apply to the isobars Ar^{35} and K^{35}. Rather than repeat these expressions and give their modified forms here, we instead derive and compare the results for the $P \to G$ and $A \to G$, $M2$-$E3$ transitions. (The $A \to G$ transitions were not considered in Ref. 8.)

The relevant single-particle matrix elements for the $P \to G$ transitions are

$$\langle f \| M2^{(r)} \| d\rangle = \frac{2\sqrt{105}}{35}[r]\beta I(1) G^{(r)}, \tag{13}$$

and

$$\langle f \| E3^{(r)} \| d\rangle = \frac{2\sqrt{14}}{315}[r] e I(3) q^{(r)}, \tag{14}$$

where $G^{(r)} \equiv \frac{2}{3}g_l^{(r)} - g_s^{(r)}$. The total matrix elements $\langle\mathfrak{M}(L)\rangle$ are obtained from Eqs. (6), (7), (13), and (14) with $\Gamma = (\frac{7}{2}, \frac{3}{2})$, $\alpha = (0, 1)$ and $(2, 1)$, and $\Gamma' = (\frac{3}{2}, |M_T|)$ as follows: For $P \to G$ ($M_T = \pm\frac{3}{2}$),

$$\langle\mathfrak{M}(M2)\rangle = -\frac{\sqrt{105}}{35}\beta I(1) A(M_T)(G^{(0)} - \tfrac{2}{3}M_T G^{(1)}) \times\left(a_{01} - \frac{\sqrt{105}}{7}a_{21}\right), \tag{15}$$

and

$$\langle\mathfrak{M}(E3)\rangle = \frac{\sqrt{14}}{315} e I(3) A(M_T)(q^{(0)} - \tfrac{2}{3}M_T q^{(1)}) \times\left(a_{01} + \frac{\sqrt{105}}{21}a_{21}\right). \tag{16}$$

For $A \to G$ ($M_T = \pm\frac{1}{2}$),

$$\langle\mathfrak{M}(M2)\rangle = \frac{2\sqrt{21}}{21}\beta I(1) A(M_T) G^{(1)}\left(a_{01} + \frac{\sqrt{105}}{35}a_{21}\right), \tag{17}$$

and

$$\langle\mathfrak{M}(E3)\rangle = \frac{2\sqrt{70}}{945} e I(3) A(M_T) q^{(1)}\left(a_{01} - \frac{\sqrt{105}}{105}a_{21}\right). \tag{18}$$

The coefficients of fractional parentage are obtained from Glaudemans, Wiechers, and Brussaard.[12] The coefficients $A(M_T)$ represent the amplitudes of the component $|s_{1/2}{}^4 d_{3/2}{}^3\rangle$ in the ground states of the $A = 35$ nuclei and are taken from recent shell-model calculations by Wildenthal,[13] who obtained $A(\pm\frac{3}{2}) = 0.791$ and $A(\pm\frac{1}{2}) = 0.579$.

The numerical results for the $M2$ strengths (expressed in Weisskopf units) and the $E3/M2$ mixing ratios are as follows: For $P\to G$ ($M_T=\pm\frac{3}{2}$),

$$|M|^2(M2)=0.0310(1-5.338M_T)^2(a_{01}-1.464a_{21})^2, \quad (19)$$

$$\delta\left(\frac{E3}{M2}\right)=-0.1717\frac{1-0.2381M_T}{1-5.338M_T}\frac{a_{01}+0.4880a_{21}}{a_{01}-1.464a_{21}}. \quad (20)$$

For $A\to G$ ($M_T=\pm\frac{1}{2}$),

$$|M|^2(M2)=2.369(a_{01}+0.2928a_{21})^2, \quad (21)$$

and

$$\delta\left(\frac{E3}{M2}\right)=-0.0290\frac{a_{01}-0.0976a_{21}}{a_{01}+0.2928a_{21}}. \quad (22)$$

It can be seen that the $\Delta T=1$, $A\to G$ transition does not depend upon M_T and thus should be the same for Cl^{35} and Ar^{35}. The $\Delta T=0$, $P\to G$ transition does depend upon M_T in such a way that the sign of δ will change between the mirror nuclei S^{35} and K^{35} in accordance with the generally known rule for $\Delta T=0$ mirror transitions. If, as shown below, the signs of the amplitudes a_{01} and a_{21} are the same, then the $A\to G$, $M2$ transition can be quite strong (2–3 W.u.), while the $P\to G$, $M2$ transition will be much weaker (~0.1 W.u.), in agreement with the experimental results discussed in the preceding section.

The values of the amplitudes a_α in the P, A, and $\bar{A}$ states have been determined by use of iterative least-squares techniques. The data used in this calculation, including the data obtained in the present work, are shown in Fig. 4. This figure also shows the corresponding calculated values of the various quantities using Eqs. (19)–(22) above and the expressions in Ref. 8. The nine experimental quantities taken with the two normalization conditions of the type $\sum_\alpha a_\alpha^2=1$ provide 11 equations from which the total of six amplitudes a_α are determined. Also shown in the figure are the predicted values for transition strengths and multipolarity mixings in Ar^{35} and K^{35}. It is of interest to note the very weak $M2$ transition, and the correspondingly large $E3/M2$ mixing ratio $\delta=-0.95$, predicted for the $3.20\to 0$ transition in Ar^{35}.

The wave-function amplitudes a_α resulting from the fit are shown in Table II, where they are compared with the results obtained in Ref. 8 and with the MSDI shell-model calculations of Maripuu and Hokken.[7] The rather significant difference between the present results for the $\bar{A}$ state and those of Ref. 8 can be ascribed to the more accurate ground-state wave functions for S^{35} and Cl^{35} used in the present calculation.

3.163→1.763, $E1$-$M2$ Transition in Cl^{35}

From the known mean life (60 ± 7 psec) of the 3.163-MeV level,[3] the 3.163 ($\frac{7}{2}^-$)→1.763 ($\frac{5}{2}^+$) branching ratio ($0.30\pm 0.04\%$), and the $M2/E1$ mixing ratio ($\delta=-0.44\pm 0.12$), the strengths of the $E1$ and $M2$ components of this transition can be determined (see Table I). The strong inhibition of the 3.16→1.76, $E1$ transition has been noted elsewhere. (See, e.g., Taras and Matas[14] who men-

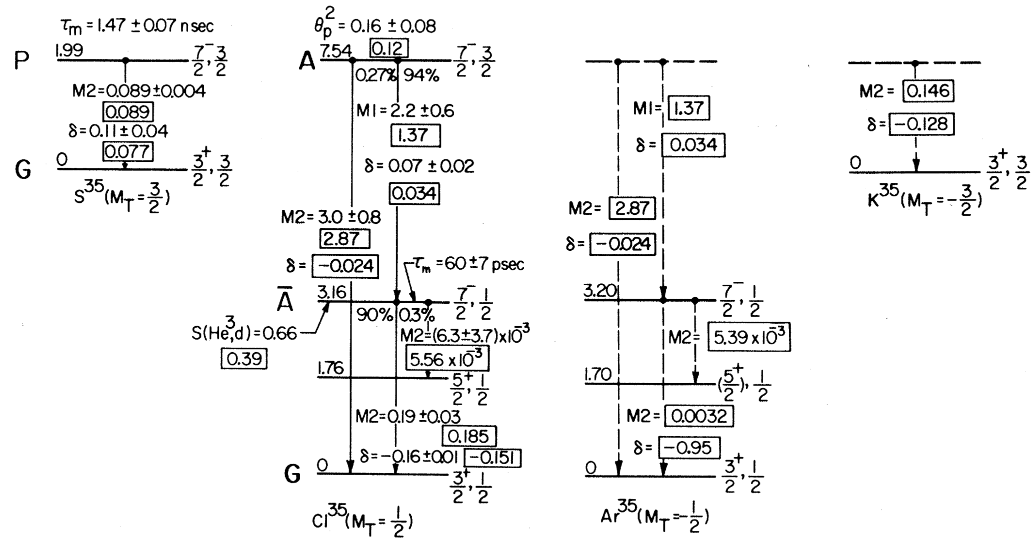

FIG. 4. The system of $\frac{7}{2}^-$ parent (P), analog (A), antianalog ($\bar{A}$), and $\frac{3}{2}^+$ ground states (G), and their mirror levels, in the $A=35$ nuclei. The quantities enclosed in rectangular boxes are values calculated as discussed in the text. Dashed lines indicate as yet unobserved levels or transitions. Sources for most of the experimental data are given in Ref. 8. The lifetime of the P state and the first observation of $A\to G$ and $\bar{A}\to 1.76$ transitions in Cl^{35} are from the present work. The $M1$ and $M2$ strengths are represented in Weisskopf units. Coulomb energy shifts are omitted.

TABLE II. Amplitudes a_α in the wave functions $\sum_\alpha a_\alpha |d^2(\alpha)f\rangle$ for the $\frac{7}{2}^-$ P and A states, and of the $\bar{A}$ state, in the $A=35$ nuclei.

State	$\alpha=01$	$\alpha=10$	$\alpha=21$	$\alpha=30$
P and A [a]	0.89		0.46	
P and A [b]	0.88		0.48	
P and A [c]	0.95		0.17	
$\bar{A}$ [a]	0.94	−0.32	−0.09	−0.09
$\bar{A}$ [b]	0.84	−0.19	0.09	−0.50
$\bar{A}$ [c]	0.86	0.32	0.29	0.15

[a] Present results.
[b] See Ref. 8.
[c] See Ref. 7. Small components from the $d_{3/2}p_{3/2}$ configuration have been omitted.

tion that no explanation for this inhibition is available.) In the model considered above, it can be seen from Eq. (8) and the fact that the multipole operators are one-body operators, that this particular $E1$ transition does not exist for this model. The $M2$ component can be calculated by use of Eqs. (6), (7), and (13). For this purpose we use the $\bar{A}$ wave function obtained above (Table II) and the amplitude 0.298 for the component $|d_{5/2}{}^{12}s_{1/2}{}^4d_{3/2}{}^3\rangle$ in the $\frac{5}{2}^+$ level obtained by Wildenthal. The result is $|M|^2(M2)=5.56\times10^{-3}$ in excellent agreement with the experimental value given in Table I. This result, and the corresponding result for the mirror transition in Ar^{35}, is shown in Fig. 4.

CONCLUSION

New evidence has been given to support a relatively simple description of the negative-parity analog and antianalog state structure in s-d shell nuclei and to emphasize the importance of core recoupling in these states. In the present model, the inhibition of $\Delta T=0$, $M2$ transitions that has been noted earlier, e.g., by Kurath and Lawson,[15] is seen to result in part from the essential role played by core recoupling. Also, an enhanced $\Delta T=1$, $M2$ transition predicted by the model has been found, with the predicted strength of about 3 W.u. The existence of such enhanced $M2$ transitions in other s-d shell nuclei is clearly possible,[8] so caution must be used in making parity assignments with physical arguments which use $M2$ transition strengths. It has been shown possible with this model to describe $M1$ and $M2$ transition strengths reliably with bare-nucleon g values.

Although it is clear that the model considered does remarkably well in reproducing the properties of the system now available, it would be, of course, incorrect to conclude from this that the structure is actually as simple as assumed. It must be true that excitations from the S^{32} core, other odd-parity orbitals ($2p_{3/2}$, $1f_{5/2}$, etc.), and configurations such as $f_{7/2}{}^3$ contribute to some extent to the structure of the system. It would, therefore, be of considerable interest to discover how far the present simplified model can be applied and at what point it fails to account for observable properties. Measurements of the decay properties of the $\frac{7}{2}^-$ levels in Ar^{35} and K^{35} shown in Fig. 4 would be particularly valuable for this purpose. Also a measurement of the magnetic moment of the 1.99-MeV parent state in S^{35} may prove to be a useful test. The mean life $\tau_m=1.47$ nsec is in a range where available techniques may be applicable.

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Nucleon Pickup Reactions on ^{46}Ca†

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The $^{46}Ca(d,t)^{45}Ca$ and $^{46}Ca(d,{}^{3}He)^{45}K$ reactions have been investigated at an incident deuteron energy of 22.4 MeV. The angular distributions have been compared with distorted-wave calculations, and the spectroscopic strength has been extracted. The transitions to the $\frac{3}{2}^-$ levels of ^{45}Ca at 1.435 and 2.82 MeV were observed with a total strength $C^2S = 0.3$. The spectroscopic factor of the ground-state transition for the $^{46}Ca(d,{}^{3}He)^{45}K$ reaction was found to be $C^2S = 1.5 \pm 0.3$. This suggests the probability of measurable core-excitation admixtures in the ground-state configuration of ^{45}K.

I. INTRODUCTION

The neutron and proton pickup in the (d, t) and $(d, {}^{3}He)$ reactions induced by 22.3-MeV deuterons incident on all the stable Ca isotopes except ^{40}Ca and ^{46}Ca have been reported recently.[1] Some admixture of $2p_{3/2}$ neutrons was observed in each of the even-A isotopes, but the admixture in ^{48}Ca was significantly smaller than the ones for ^{44}Ca and ^{42}Ca. In the preliminary results reported for the $^{46}Ca(d, t)^{45}Ca$ reaction, the resolution was too poor to permit observation of the transitions to the $\frac{5}{2}^-$ level at 0.176 MeV or to the $\frac{3}{2}^-$ levels at 1.433 and 2.847 MeV, all of which had been observed in the $^{44}Ca(d,p)^{45}Ca$ reaction.[2] The 25-keV width of the incident deuteron beam would make it impossible to separate the $l=2$ transition to the 1.886-MeV level from the $l=1$ transition to the 1.90-MeV $\frac{3}{2}^-$ level. However, the same situation existed in the $^{42}Ca(d, t)^{41}Ca$ reaction, for which the angular distributions to the 1.94- and 2.01-MeV levels were not separated. That experiment showed clearly that a fairly large admixture of $l=1$ is readily detectable. The $^{46}Ca(d, t)^{45}Ca$ reaction was also studied by Bjerregaard, Hansen, and Satchler[3] at an incident energy of 10 MeV.

The production of ^{45}K by proton transfer in the $^{46}Ca(t, \alpha)^{45}K$ reaction has been reported by Santo *et al.*,[4] who normalized the spectroscopic factors by assuming that $C^2S = 4.0$ for the strongest $l=2$ transition obtained in the $^{48}Ca(t, \alpha)^{47}K$ reaction. The strong ^{40}Ca component in the target material used in the present experiment obviously makes it very difficult to uniquely identify the $^{46}Ca(d, {}^{3}He)^{45}K$ transitions in the present data alone; but it is quite feasible with the aid of the $^{40}Ca(d, {}^{3}He)^{39}K$ results obtained at somewhat higher energy by Hiebert, Newman, and Bassel[5] since both the ground state and the first excited state of ^{45}K occur at deuteron energies at which no ^{39}K levels are strongly excited. As a result, the spectroscopic factors obtained are directly comparable to those obtained for ^{43}K, ^{42}K, and ^{41}K from $(d, {}^{3}He)$ reactions on the other Ca isotopes.[1]

II. EXPERIMENTAL PROCEDURES

The experiment was performed in the 60-in. scattering chamber[6] at the Argonne cyclotron. After magnetic analysis, the energy spread in the 22.4-MeV deuteron beam was about 25 keV. The scattered particles were detected with a (dE/dx)-E telescope of surface-barrier detectors. The target was prepared by evaporating isotopically enriched $CaCO_3$ onto a Formvar backing. The material was enriched to 43.4% in ^{46}Ca; it contained about 5% ^{44}Ca, and the remainder was almost entirely ^{40}Ca. The target thickness was measured by comparing the experimentally measured angular distribution of elastically scattered deuterons with the theoretical angular distribution predicted from the optical-model potential parameters used in the distorted-wave Born-approximation (DWBA) calculations. These parameters fit the elastic deuteron scattering on ^{40}Ca at 21.6 MeV.[7] For the l values encountered in this range of atomic number and deuteron energy, the necessary spectroscopic information can be obtained by measuring the angular distribution between 12 and 30°. The optical-model potential parameters used are listed in Ta-