chromatic line at the upper limit of the continuum. From graphical manipulation we estimate our data cannot rule out an excitation contribution of ~5% of the total KL bump. Calculations using hydrogenic wave functions {G. A. Skorobogatov, Teor. Eksperim. Khim. 2, 26 (1966) [transl.: Theoret. Exptl. Chem. 2, 20 (1966)]} predict ~20% of the total KL area might be due to excitation to unoccupied bound states. Our spectrum shape is inconsistent with such a large fraction.

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Low-Lying Levels of ^{40}Ar †

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Seven excited levels of ^{40}Ar have been populated by the ^{40}Ar(p,p') reaction and studied with γ-γ and p'-γ angular-correlation techniques. Spin-parity assignments are: 1461 keV, 2^+; 2121 keV, 0^+; 2524 keV, 2^+; 2892 keV, $(4)^+$; 3207 keV, 2^+ or $1^\pm$; 3507 keV, 2^+ or 1^+; 3681 keV, 3^-. Multipole amplitude mixing ratios are: 2524→1461-keV transition, $\delta(E2/M1)=+0.24$; 3207→1461-keV transition, if $2^+\rightarrow 2^+$, $\delta(E2/M1)=-0.20$, and if $1^\pm\rightarrow 2^+$, $\delta=0$. γ-ray branching ratios for the second to seventh excited levels have been measured. These results, together with lifetimes previously determined by others, are used to calculate $B(E2)$ and $B(M1)$ values which are compared with those of similar levels in ^{42}Ca.

I. INTRODUCTION

In this study, ^{40}Ar spins and parities, γ-ray multipole amplitude mixing ratios, and γ-ray deexcitation branching ratios have been determined within the limits of available techniques. Levels of ^{40}Ar up to 3681 keV have been excited by the inelastic scattering of protons, and their decay modes have been observed with p'-γ and γ-γ coincidence techniques.

Previous measurements include a determination of the energies of many ^{40}Ar levels through use of the ^{40}Ar(p,p') reaction by Benveniste, Booth, and Mitchell,[1] and a ^{40}Cl β-decay study[2] which complements the present work and which provides precise level energies as illustrated in Fig. 1. Earlier work has been summarized by Endt and van der Leun[3] and in Ref. 2. Recently, measurements have been made of branching ratios[4,5] and of the lifetimes of the first three excited levels.[5,6] Differential cross sections for the ^{40}Ar(α,α') reaction have been measured and interpreted.[7] Proton-hole states have been investigated through the ^{41}K$(d,{}^3$He$)^{40}$Ar reaction.[8] Spin assignments have been based on the analysis[9] of (p,p') angular distributions which were obtained using 24.85-MeV protons. Not all of the previous reports on the properties of ^{40}Ar levels are in agreement; some of them will be discussed in Secs. IV and V in connection with the present results. Theoretical calculations of the structure of ^{40}Ar have been few in number.[6,10-14] Since ^{40}Ar has two $d_{3/2}$ proton holes and two $f_{7/2}$ neutron particles, the large-scope shell-model calculations have omitted this "transition" nucleus.

II. EXPERIMENTAL PROCEDURES

Protons from the University of Kentucky 6-MV Van de Graaff accelerator, having energies in the range from 4.7 to 5.8 MeV, were used to bombard a target of gaseous argon at typical pressures of 12 to 20 cm of Hg. After being energy-analyzed by a 90° bending magnet the proton beam was converged by a magnetic quadrupole doublet to a target position which was 14 m from the bending magnet. The gaseous argon was contained within a small cell which was inside of a 12.70-cm-diam aluminum scattering chamber. The cell itself was an aluminum cylinder with height of 1.98 cm and outside diameter of 1.4 cm, closed at the top end and attached to the gas supply system at the lower end. There was a 0.48-cm-wide opening cut in the cell wall, circumferentially through 200°; this opening was sealed by cementing either a 0.000 127-cm nickel foil or a 0.000 345-cm molybdenum foil with epoxy resin. The beam entered and departed, and scattered protons escaped from the gas cell through the foil. An opening 0.64 cm in diameter, also sealed with a thin metal coil, was in the top end of the cylindrical cell to permit scattered protons to exit from the cell along the vertical axis. The beam-energy loss in the gas to the center of the cell ranged from 12 to 10 keV, and in the entrance foil from 56 to 49 keV.

In making the γ-γ correlation measurements, it was desired to record coincident events between a detector fixed at 90° to the incident beam, as is detector A of Fig. 2, and another detector C which is movable over the three arcs of the octant of a sphere centered on the target. Due to the cylindrical symmetry of the reaction, coincidences between detectors B and C as C is moved over arc 1 are equivalent to coincidences between A and C as C is moved over arc 2; hence in the measurements, coincidences were recorded simultaneously between A and C, and between B and C, as C was moved over arc 1. In a separate operation, coincidences were recorded between A and C as C was moved over arc 3. The spectra of γ rays from C in coincidence with selected pulse-height intervals from A and B were retained as data. A, B, and C were 7.62×7.62-cm-diam

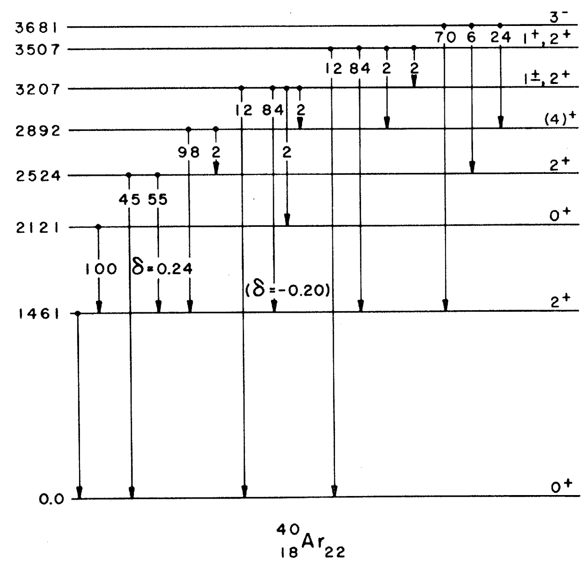

FIG. 1. Low-lying levels of ^{40}Ar. The spin assignments of the 2524- and 3207-keV levels are based on correlation results from this study. The branching ratios (in parts per hundred) and the tentative spin assignment for the 3507-keV level which depends on observed branching ratios are from this study. The parentheses indicate tentative assignments. The level energies are from Ref. 2.

NaI(Tl) crystal detectors located at 10 cm from the center of the gas cell. Typically, in the direct γ-ray spectra taken without coincidence selection, only the very intense γ rays from ^{40}Ar could be identified, due to the yield of γ rays from the proton bombardment of the foil windows and the Faraday cup, and from the interactions of neutrons which are produced in the accompanying ^{40}Ar(p,n)-^{40}K reaction.

In making the p'-γ correlation measurements, the same procedure was used. A and B were 390-μ-depth silicon surface-barrier detectors with collimating slits located at 1.98 cm from the center of the gas cell; C was again a NaI(Tl) crystal detector. The γ-ray spectra were retained as data. For the higher levels of excitation for which a complete angular correlation could not be accomplished, p'-γ coincidence spectra were accumulated with the γ-ray detector located at 55° relative to the incident beam axis in order to obtain the best possible sample of the yield over the sphere.

The proton beam was monitored with a current integrator after collection of the ions in a biased Faraday cup. Typical beam currents were from 0.05 to 0.08 μA. In addition, the inelastically scattered proton yield was monitored directly by the use of a silicon surface-barrier detector located at a fixed angle relative to the incident beam axis; the proton spectra were retained as data.

A conventional "fast-slow" coincidence system was used at a resolving time of $2\tau = 50$ nsec. Single-channel analyzers were used to define the pulse-height limits used in the coincidence measurements. Real-pulse-random and random coin-

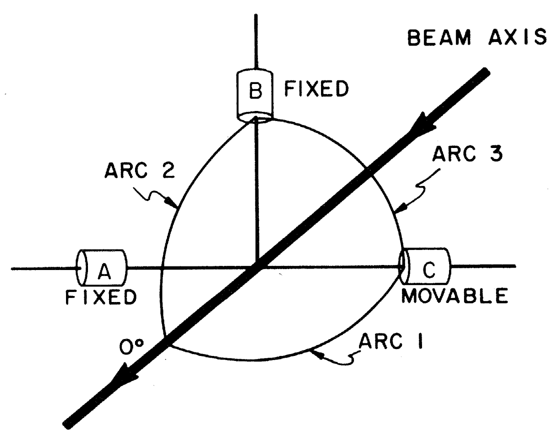

FIG. 2. The octant geometry over which correlation measurements were made. For p-p'-γ correlations the fixed detectors A and B were surface-barrier detectors; for γ-γ correlations they were NaI(Tl) crystal detectors. The moveable detector C was a NaI(Tl) crystal which could be positioned at selected angles on the three arcs of the octant.

cidence spectra were collected simultaneously and stored separately for both the A and C, and B and C coincidence combinations in order that a direct correction for random coincidences could be made. The random coincidences were typically less than 20% of the total coincidences. System "dead-time" corrections were made where appropriate. When appropriate, corrections were made for the effect of energy addition (summing) which occurred when two cascade γ rays chanced to interact in the same NaI(Tl) crystal.

Before taking coincidence data, the p' differential cross section for each final state was obtained with the inelastically scattered protons being observed at 90° relative to the incident beam axis. The p' spectra obtained with a surface-barrier detector, such as the example in Fig. 3, were analyzed to produce the cross-section versus proton-energy curves of Fig. 4. Coincidence data were taken at energies which produced maximum yield, as discussed in Sec. IV. Typically, before each operation a small interval of the cross-section curve would be repeated with smaller energy intervals in order to locate the maximum yield point.

III. METHODS OF ANALYSIS

γ-γ correlations. Method I of Litherland and Ferguson[15] with one detector fixed at 90° was used in the collection of data. The method of analysis has been described elsewhere[15,16]; the present procedure is essentially the same as that of Church, Horoshko, and Mitchell.[17] The angular-correlation function [Eq. (3.42) of Ref. 16] is expanded in Legendre polynomials and as a linear function of the magnetic-substate population parameters $P(\alpha)$ which describe the alignment of the state. For input values of spins and the electromagnetic multipole mixing ratio δ [see Eq. (64) of Ref. 18], the population parameters are determined by means of a linear least-squares fitting procedure, with the restriction that each $P(\alpha) \geq 0$. 157 values of the mixing ratio δ were tried for each set of spins, and a testing quantity Q^2 was computed. Q^2 is a normalized χ^2 quantity, defined by Eq. (4) of Ref. 19, and is discussed in Ref. 20. A Q^2 of approximately unity indicates that the correlation-function value, as computed with a given set of spins, δ, and set of $P(\alpha)$, matches the

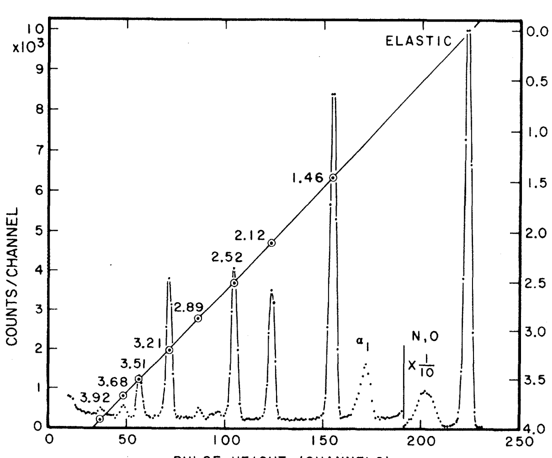

FIG. 3. Spectrum of protons which have been inelastically scattered from ^{40}Ar, at 90° relative to the incident beam and with incident proton energy of 5.67 MeV.

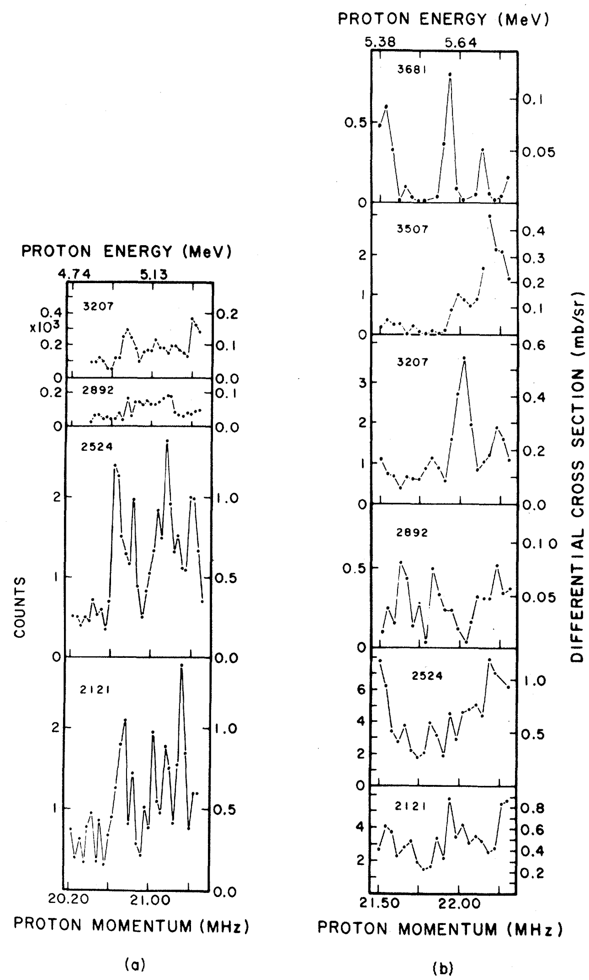

FIG. 4. Differential cross sections for the ^{40}Ar(p,p') reaction, at 90° relative to the incident beam. The basic scale on the abcissa is proportional to the incident proton momentum; the superimposed energy scale has been adjusted to account for beam energy loss in the gas cell window and in the gas target. The data points are at approximately 15-keV intervals. Set (a) covers incident proton energies from 4.74 to 5.37 MeV; set (b) covers from 5.38 to 5.76 MeV. The uncertainties are ±10% for the 2121- and 2524-keV-level groups and ±25% for the others.

corresponding data within a reasonable statistical certainty. The Q^2 vs δ array was plotted for each set of spins (e.g., as in Fig. 9), and from the plotted curves the selection was made of the set of spins and the value of δ which best fitted the data.

p-p′-γ correlations. The data which were taken with the p' detector located at 90° were analyzed according to the formalism of Biedenharn.[18] The assumption was made that the reaction proceeds through an intermediate level in the compound nucleus having sharp spin and parity, such that it could be treated as a Breit-Wigner single level with no interference from nonresonant background. This condition was realized experimentally by the taking of data at a well-defined resonance for the production of the final excited state, a resonance which has been identified[21] as being an isobaric analog of a level in the parent nucleus ^{41}Ar. The correlation equation [Eq. (117) of Ref. 18] was coded for computer use. Once the values of l_1 and l_2, the orbital angular momentum quantum numbers for the incident and departing proton, and the spins of the intermediate level and the final state were specified, the adjustable parameters were the channel-spin mixing ratio δ_{cs} and the γ-ray multipole amplitude mixing ratio δ. The channel-spin amplitude mixing ratio is defined as the ratio of scattering matrix elements, as in Eq. (127) of Ref. 18. Since ^{40}Ar has a 0^+ ground level, γ transitions to the ground level are pure multipole radiation, and δ has a known value; in such cases, for a given set of spin values the channel-spin mixing ratio δ_{cs} is the only parameter to be determined by comparison with data.

TABLE I. Branching ratios of the low-lying levels of ^{40}Ar as determined from p'-γ measurements in the present work.

Level (keV)	Transition	Branching ratio (%)
2121	→ 1461	100
2524	→ 0	45 ± 5
	→ 1461	55 ± 5
2892	→ 1461	$98^{+2}_{-3.4}$
	→ 2524	2 ± 2
3207	→ 0	12 ± 5
	→ 1461	84 ± 2
	→ 2121	2 ± 2
	→ 2892	2 ± 2
3507	→ 0	12 ± 5
	→ 1461	84 ± 2
	→ 2892	2 ± 2
	→ 3207	2 ± 2
3681	→ 1461	70 ± 3
	→ 2524	6 ± 3
	→ 2892	24 ± 6

157 values of the channel-spin mixing ratio were tried for each set of spins, and the testing quantity Q^2 was computed. From a graph of Q^2 vs δ_{cs} the best choice of δ_{cs} and the accompanying set of spins was made [e.g., as in Fig. 7(a)]. The channel-spin mixing ratio thus obtained was used in the analysis of p-p'-γ_1 data, taken at the same resonance, where γ_1 denotes the γ-ray transition to a level of known spin other than the ground level. In this case, the γ-ray multipole amplitude mixing ratio δ is the only unknown parameter, and it can be determined by a comparison with the data. The correlation data for the 2524-keV level were analyzed in this way. For use along arc 3 of the octant, the angular factor of the correlation equation was written in terms of even powers of $\cos\phi$, where ϕ is the dihedral angle, and the coefficients were computed. The numerical results were the same as those given in Ref. 18.

γ-ray yields. The p'-γ coincidence spectra were first corrected for random coincidences, deadtime, and where applicable, for cascade γ-ray summing effects. Then, using standard spectra and a computer fitting program, the yield of each γ ray was extracted. Such yields as a function of angle of detection furnished the correlation data. Also, after suitably weighting each yield with the experimentally determined efficiency for detection, the γ-ray branching ratio for each level was determined.

IV. RESULTS

The differential cross sections of Fig. 4 were taken in order to locate maxima in the yield at which coincidence data could be efficiently taken. Resonances were not necessary except in one case as discussed in connection with the 2524-keV level. An outstanding feature is that the yield of the p' group which populates the 2892-keV level is uniformly low at all bombarding energies. The excitation curve for the first excited 2^+ level at 1461 keV will be discussed in a future paper. Results of the branching-ratio measurements are summarized in Table I. In the discussions which follow, the level energies are taken from the ^{40}Cl β-decay study.[2]

2121-keV Level

Two γ-γ correlations were obtained along arc 1, first with γ_1 gating the spectrum of γ_2, and then with γ_2 gating the spectrum of γ_1. In both cases the theoretically predicted 0-2-0 correlation, $W(\theta) = 1 - 0.82p_2(\cos\theta) + 0.53p_4(\cos\theta)$, was closely reproduced. The γ-ray spectrum was obtained by the p'-γ coincidence method; no evidence was found to indicate a crossover transition to the ground energy level, in complete agreement with the 0^+ assignment.[3]

2524-keV Level

Several spin-parity assignments have been made for this level. An assignment of 2^+ has been made on the basis of p-p'-γ correlation experiments,[3] inelastic proton scattering,[9] and γ-ray distributions from the $n,n'\gamma$ reaction.[22] Spin-parity of 0^+ or 1^- had been suggested by earlier measurements.[3]

In the present work correlation measurements of both the p-p'-γ and γ-γ types were made. Data were taken at incident proton energy of 5.21 MeV where the excitation function has a sharp maximum, as illustrated in Fig. 4. The p'-γ coincidence spectrum for the deexcitation of this level is shown in Fig. 5. This spectrum was obtained by summing, channel-by-channel, the several individual spectra which were taken at various angles over the arcs of the octant. From this composite spectrum, branching ratios were obtained, with the result of $(45\pm5)\%$ to the ground level, $(55\pm5)\%$ to the 1461-keV level, and an upper limit of 1% to the 2121-keV level. These values agree closely with those of Kossler and Winkler,[5] which are 43, 57, and <1%, respectively.

The p'-γ_0 correlation data over the three arcs of the octant are shown in Fig. 6. Triple-correlation analysis with the Krauss-Biedenharn equation as described in Sec. III gave the best fitting to the ground-level transition data with spin-parity 2^+ for the 2524-keV level and with either $\frac{5}{2}^+$ or $\frac{5}{2}^-$ for the intermediate level in ^{41}K. These choices were made from the Q^2 vs δ_{cs} diagram of Fig. 7(a), where δ_{cs} is the channel-spin mixing ratio. This ambiguity in parity is typical of those cases for which one of the two values of channel spin $J'+\frac{1}{2}$ can combine with l to give the compound-nucleus spin J, and the other value of channel spin $J'-\frac{1}{2}$ can combine with $l+1$ to give the same J. A Breit-Wigner analysis of elastic and inelastic scattering of protons at this bombarding energy by Buerger, Place, and Kern[21] has shown that the reaction proceeds through a $\frac{5}{2}^+$ level in ^{41}K. Consequently, with this choice, the correlation results give $l_1=2$, and $l_2=0$. Then, for $J(2524)=2$, the channel spin has only the one possible value of $2+\frac{1}{2}=\frac{5}{2}$, and the fitting to the data is independent of δ_{cs}, as indicated in Fig. 7(a) by the straight line for this set of parameters. The calculated p'-γ correlation using these parameters is shown in Fig. 6 in comparison with the data. Values of spin-parity other than 2^+ all gave unsatisfactory fits to the data over a wide range of combinations of l_1, J, and l_2. Nor, for spin-parity 2^+ did other values of the ^{41}K spin-parity give satisfactory fits; the best of the other ones came with $J=\frac{3}{2}$, as shown in Fig. 7(a).

Once the channel spin had been fixed as $\frac{5}{2}$ and the intermediate level as having spin-parity $\frac{5}{2}^+$ it was possible to continue the analysis, using the p'-γ_1 data, based on the coincident yield of the 1063-keV γ ray for the transition 2524 → 1461 keV. In this case the γ-ray multipole mixing ratio δ was the only variable parameter. The best fit was obtained at $\delta=-10$ and 0.24, as shown in the Q^2 vs δ curve of Fig. 7(b); the latter value has been selected, since it also is a result of the γ-γ

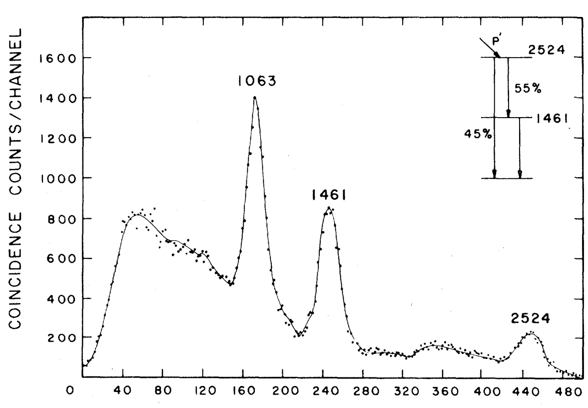

FIG. 5. The spectrum of γ rays in coincidence with inelastically scattered protons which leave the ^{40}Ar nucleus in the 2524-keV level. This is a composite spectrum obtained by summing individual spectra which were collected at several angles over the arcs of the octant. The random coincidence contribution has been subtracted.

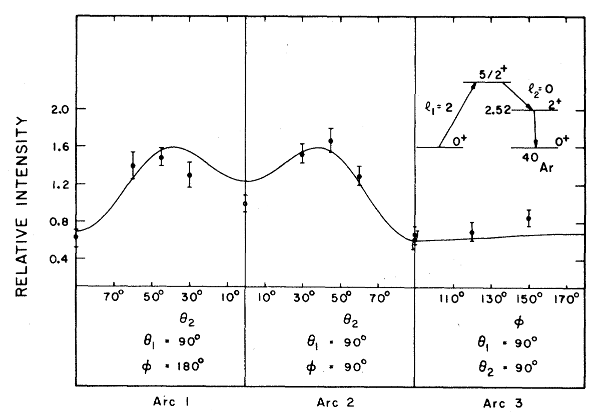

FIG. 6. Data from the p-p'-γ triple correlation for the (2524 → 0) transition, over the three arcs of the octant. The proton detector was located at 90° to the incident beam. The curve is the best theoretical fit, with the parameters shown on the diagram and channel spin equal to $\frac{5}{2}$.

correlations which will be discussed next.

The γ-γ correlation data over the three arcs of the octant are shown in Fig. 8. Analysis by "Method 1" techniques as outlined in Sec. III gave the Q^2 vs δ curves of Fig. 9, where δ is the electromagnetic multipole mixing ratio. The best fit is obtained for $0 \leq \delta \leq 1$, which agrees with only one of the two possible values which result from

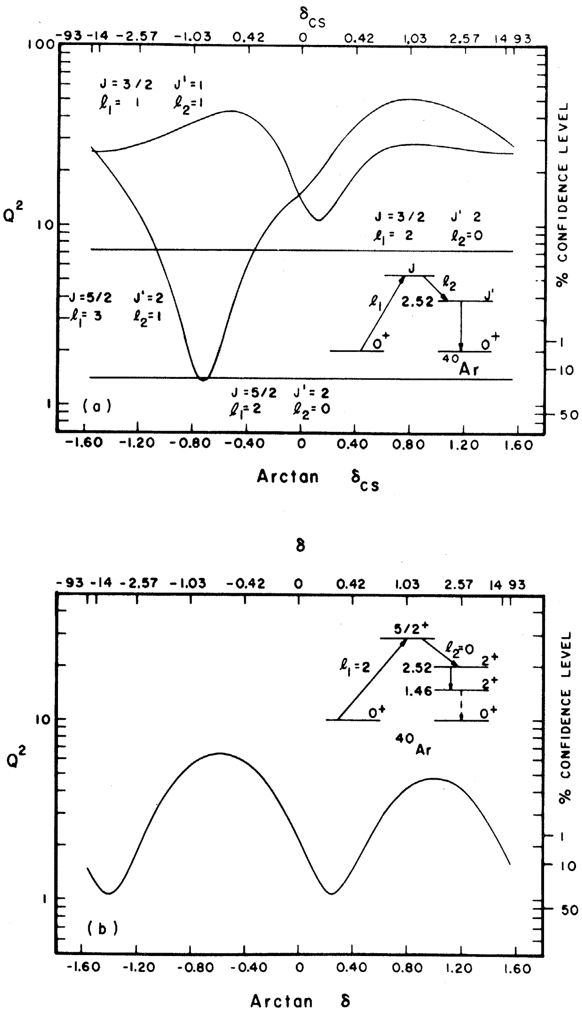

FIG. 7. (a) The normalized χ^2 function Q^2 vs the channel-spin mixing ratio δ_{cs} for the p-p'-γ_0 triple correlation, for the 2524 → 0 transition. Of the three $J' = 2$ choices which are shown, the smaller Q^2 is obtained with the intermediate level in ^{41}K having $J = \frac{5}{2}$. The ambiguity in parity has been resolved by another measurement (see Ref. 21) which determines that the spin-parity of the ^{41}K level is $\frac{5}{2}^+$, hence the parameters of this reaction are $l_1 = 2$, and $l_2 = 0$. The best choice of parameters with $J' = 1$ gives an unacceptable fit, as shown. (b) The normalized χ^2 function Q^2 vs the γ-ray multipole amplitude mixing ratio δ for the p-p'-γ_1 triple correlation, for the 2524 → 1461 transition. Best agreement results for $\delta = 0.24$, and $\delta = -10$. The latter is rejected, since it does not give an acceptable fit for the γ-γ correlation.

the p-p'-γ correlation. The fit is not very discriminating, and so the quoted value of $\delta = 0.24 \pm 0.10$ is taken from the p-p'-γ results. The best fits as obtained with $J' = 1$ and 2 are shown in Fig. 8 in comparison with the data.

As the result of these measurements, it was concluded that a firm assignment of 2^+ can be made for the spin-parity of the 2524-keV level.

2892-keV Level

The yield of inelastically scattered protons from reactions which populated this level was so low that it was not possible to make a correlation measurement. In any case, data taken with a NaI(Tl) crystal detector would have been very difficult to interpret, since the cascade γ rays in the sequence 2892 → 1461 → 0 have very nearly the same energies. The branching was determined by collecting p'-γ coincidence spectra for a total of 25 h with the γ-ray detector placed at 55° relative to the beam axis. No ground-level crossover transition was observed with an upper limit of 1%. The branching proceeds with 98% to the 1461-keV level and 2% to the 2524-keV level. These results differ somewhat from those of Kossler and Winkler[5] who report 94.6 and 5.4%, respectively.

The branching as observed is consistent with spin-parity of 4^+ which has been assigned by others.[3,9] Since it is the final level of a decay from the 3^- level at 3681 keV, it is not likely to be the 0^+ level which is predicted by Ref. 14 to be at approximately this energy. Additional arguments in support of 4^+ are made in Sec. V, through comparison with ^{42}Ca.

3207-keV Level

A γ-γ correlation measurement was made at

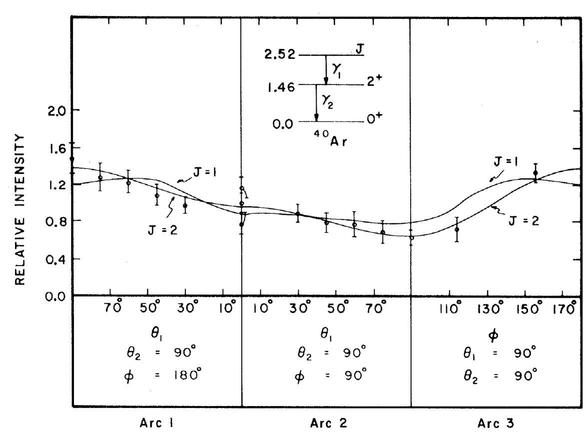

FIG. 8. The γ-γ angular correlation data for the 2524 → 1461 → 0 cascade. The choice of $J = 2$ gives the best fitting.

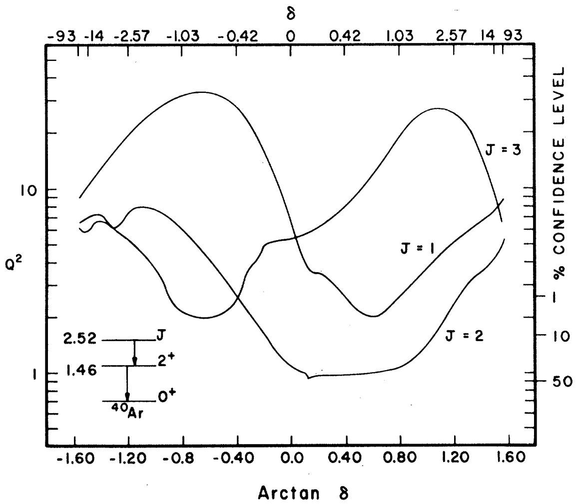

FIG. 9. The normalized χ^2 function Q^2 vs the γ-ray multipole amplitude mixing ratio δ for the γ-γ angular correlation for the 2524→1416→0 cascade. The choice of $J=2$ gives the best fit, with $\delta=0.4\pm0.6$; the tabulated value of $\delta=0.24$ is taken from the more definite p-p'-γ correlation.

incident proton energy of 5.67 MeV, on the 3207 →1461→0 cascade. The correlation data are shown in Fig. 10, and the Q^2 vs δ curves which result from these data are shown in Fig. 11. The best fits to the data for spins 1 and 2 are shown in Fig. 10. Unfortunately, it was not possible to make a choice between spins 1, 2, and 3 from this correlation. If the spin is 2, the multipole amplitude mixing ratio lies in the range $-\infty \leq \delta \leq -0.04$, with best agreement at −0.20. If the spin is 1, the mixing ratio lies in the range $-0.14 \leq \delta \leq +0.31$, with best agreement at 0. However, in this region of the nuclear table, spin-1 levels are at much higher energy. Spin 3 was rejected on the basis of the ^{41}K(d, ^{3}He)^{40}Ar reaction for which analysis[8] results in spin-parity 1^+ or 2^+ for this level; also, in the present work a transition to the ground level has been observed and this is not expected from a spin-3 level. From the ^{40}Cl β-decay data,[2] even parity is indicated but not required. Thus, the spin-parity is probably 2^+. However, an alternative assignment[7] of 1^- cannot be disregarded, since it is supported by the analysis of ^{40}Ar(α, α') results which has given other spin assignments in agreement with the present work.

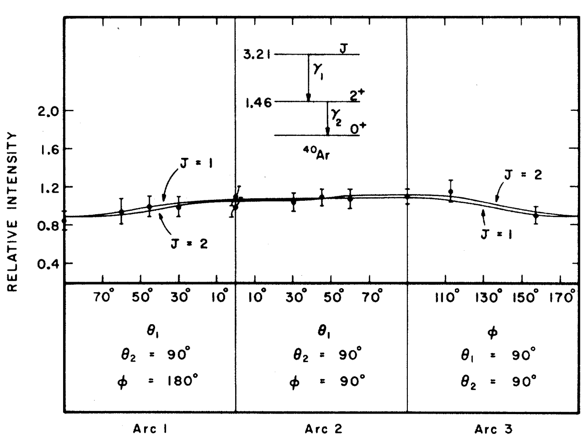

FIG. 10. The γ-γ angular correlation data for the 3207 →1461→0 cascade, over the three arcs of the octant. $J=1$ and $J=2$, are equally acceptable, as shown by the curves. The random coincidence contribution has been subtracted.

A p'-γ coincidence spectrum was collected for 19.33 h with the γ-ray detector placed at 55° relative to the incident beam. The branching from this level proceeds with 12% to the ground level, 84% to the 1461-keV level, and 2% to each of the 2121- and 2892-keV levels. These results do not agree with those of Kossler and Winkler,[5] who report a larger fraction (40%) to the ground level.

3507-keV Level

γ-ray branching-ratio data were taken for this level at incident proton energy of 5.76 MeV; p'-γ coincidence measurements were made at several angles over the arcs of the octant. Counting times were 4 h for each angle. It was necessary to sum the data taken at the various angles in order to

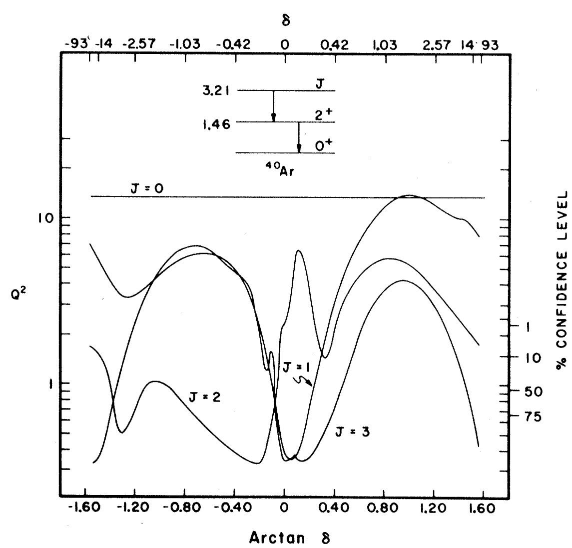

FIG. 11. The normalized χ^2 function Q^2 vs the γ-ray multipole amplitude mixing ratio for the γ-γ angular correlation, for the 3207→1461→0 cascade. No choice between $J=1$, 2, or 3 can be made since the minimum Q^2 is reached for each choice. However, $J=2$ is favored by other experimental evidence and is consistent with the γ-ray branching ratios.

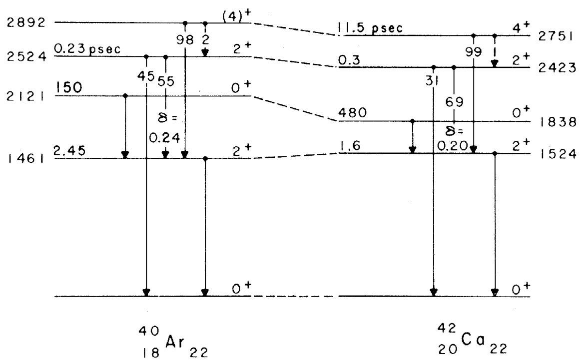

FIG. 12. Comparison between low-lying levels of ^{40}Ar and those of ^{42}Ca. Energies are in keV, lifetimes in psec, and branching ratios in parts per hundred. Mean lifetimes for the 1461-, 2121-, and 2524-keV levels of ^{40}Ar are from Ref. 31, 33, and 6, respectively. Lifetimes for the 1524- and 2423-keV levels of ^{42}Ca are from Ref. 26, and for the 1838- and 2751-keV levels from Ref. 27 and 32, respectively. The mixing ratio in ^{42}Ca is from Ref. 28, and the branching ratios in ^{42}Ca are from Ref. 26.

TABLE II. $B(\sigma\lambda)$ values and transition strengths in ^{40}Ar and ^{42}Ca. Values of lifetimes and mixing ratios used are displayed in Fig. 12.

Transition $E_i \to E_f$	$J_i \to J_f$	$\sigma\lambda$	$B(\sigma\lambda)$ (e^2 F$^{2\lambda}$)	$\lvert M\rvert^2 = \frac{B(\sigma\lambda)}{B_{sp}(\sigma\lambda)}$
^{40}Ar				
1.46→0.0	2→0	$E2$	49	6.4
2.12→1.46	0→2	$E2$	40	5
2.52→0.0	2→0	$E2$	15	2
2.52→1.46	2→2	$E2$	76	9
		$M1$	0.001 22	0.06
2.89→1.46	4→2	$E2$	...	...
^{42}Ca				
1.52→0.0	2→0	$E2$	62	7
1.84→1.52	0→2	$E2$	556	64
2.42→0.0	2→0	$E2$	10	1.2
2.42→1.52	2→2	$E2$	123	14
		$M1$	0.001 92	0.097
2.75→1.52	4→2	$E2$	25	2.9

get a sufficiently good spectrum so that branching ratios could be determined. Branching ratios are 12% to the ground level, 84% to the 1461-keV level, and 2% to each of the 2892- and 3207-keV levels. Previous workers did not report the ground-level transition. The yield to the ground level was too weak to permit a p'-γ_0 correlation analysis, and the p'-γ transition to the 2^+ level at 1461 keV could not be analyzed without ambiguity, because two continuously variable parameters enter in such p-p'-γ cases. The low yield caused γ-γ correlation data points to be so scattered the "Method I" analysis was not meaningful.

The observation of the transition to the ground level removes the possibility of the spin being 0 and renders spin 3 or larger to be unlikely. Hence spin 1 or 2 is most probable. Again, spin 1 is predicted at much higher energy, so spin 2 is most probable. From the ^{40}Cl β decay,[2] even parity is indicated but not required by the data.

This level is not populated by the ^{40}Cl β decay,[2] so its energy was not as well known as that of the other levels. From the p' spectra it was possible to make a determination by comparison with the energies of the other levels. The average of many trials was 3507 keV with a rms deviation of ±4 keV. This value is 11 keV lower than the earlier result, in accord with the corrections which have been made to other levels in this energy range.[2]

3681-keV Level

The low yield of inelastically scattered protons prevented the taking of correlation data. At bombarding energy of 5.62 MeV, a p'-γ spectrum was obtained using two p' detectors and with the γ-ray detector placed at 55° relative to the incident beam. The branching proceeds with 70% to the 1461-keV level, 24% to the 2892-keV level, and 6% to the 2524-keV level. The coincidence counts which fall at the energy of a possible ground-level transition are accidental coincidences within the statistical uncertainty, and the branching to the ground level is evaluated to have an upper limit of 1%.

There is evidence that this level is a 3^- level, probably similar in structure to the 3^- levels which have been identified in many other even-even nuclei in this part of the nuclear table at excitations of 3 to 4 MeV. Its excitation in the ^{40}Ar-(α, α') reaction is very similar to that of the 3^- level at 3.73 MeV in the ^{40}Ca(α, α') reaction[23]; its angular distribution maxima in the (α, α') reaction at 21.5 and 22.0 MeV are out of phase with the maxima for the 2^+ level at 1461 keV, and hence an odd-parity level is indicated[7]; this level is not excited in the proton-pickup reaction ^{41}K$(d, {}^3$He$)$-^{40}Ar as are the even-parity levels[8]; and the ^{40}Cl β decay is best explained with a 3^- assignment but the analysis does not unambiguously require it.[2]

V. DISCUSSION AND CONCLUSIONS

The spins, branching ratios, and multipole mixing ratios which have resulted from this study are given in Fig. 1 and in Table I. More details are given for each level under Results. The spins of the 2121- and 2524-keV levels have been confirmed as 0 and 2, respectively. The spin-parity of the 2892-keV level is tentatively 4^+. The 3207-keV level has spin-parity 2^+, with $1^\pm$ as a possibility; there is no evidence for two levels in this energy region as was once suggested,[8] so this must be the level which was earlier given spin 4.[22] The 3507-keV level, due to its decay to both 0^+ and 2^+ levels, has been assigned spin of 2 or 1. Finally, the γ-ray branching from the level at 3681 keV is consistent with 3^- for its spin-parity. The many p' spectra which were obtained did not give evidence of any new levels.

A comparison between ^{40}Ar and ^{42}Ca has been made by Dzhelepov and Peker.[6] They observed that both nuclei have a pair of $f_{7/2}$ neutrons and at least one pair of $d_{3/2}$ protons, and that a similarity of levels could result if excitations occurred such that two $d_{3/2}$ protons were promoted to $f_{7/2}$ states in each nucleus. Detailed calculations of the properties of excited levels of ^{42}Ca have been made by Gerace and Green,[24] and by Flowers and Skouras,[25] using four-particle-two-hole (4p-2h) deformed states mixed with two-particle spherical states, with satisfactory agreement with experimental results. Selections from the available data[26-33] for the first four excited levels of ^{42}Ca and ^{40}Ar are displayed in Fig. 12. Due to the data added by the present study, it was possible to compute for ^{40}Ar the $B(\sigma\lambda)$ and the strengths $|M|^2$, as given in Table II. The similarities are evident. Thus it appears that in ^{40}Ar the two 2^+ and the 4^+ levels may be part of the 0, 2, 4, 6 sequence of levels due to the $(f_{7/2})^2$ configurations, with the spin-2 level being fragmented due to the 4p-2h states just as in ^{42}Ca the spin-2 level is fragmented due to the 4p-2h states. Also, it appears that the second 0^+ level in ^{40}Ar may have a large component of the 4p-4h states, just as in ^{42}Ca the second 0^+ level has a large component of the 4p-2h states. Confirmation awaits a detailed shell-model calculation.

A recent shell-model calculation[14] for ^{40}Ar treats 0^+ levels and predicts that there will be levels at 1.98, 2.96, and 4.10 MeV. As can be seen from Fig. 1, there is no evidence from existing experimental results that there is a 0^+ level below 3681 keV other than the one at 2121 keV. Another shell-model calculation[12] predicts four 2^+ levels but it gives energies which are higher than the experimental values.

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New Observations in the $A = 49$ Decay Chain; Levels in ^{49}Sc and ^{49}Ti†

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The γ rays from 8.7-min ^{49}Ca and from 57.4-min ^{49}Sc have been measured with a 40-cm^3 Ge(Li) detector. It is proposed that ^{49}Ca decay populates levels in ^{49}Sc at 2228.6, 2371.8, 3084.4, 3516.6, 4071.9, 4493.3, and 4738.2 keV. The ^{49}Sc decay populates levels in ^{49}Ti at 1622.6 and 1761.9 keV. Limits on probable spin and parity values for these levels have been established. Mixing ratios for the 1408.9-keV γ ray were obtained from angular-correlation measurements. Weak transitions observed in this study provide further insights into the structure of ^{49}Sc levels, in particular, the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ hole states.

I. INTRODUCTION

The nucleus $^{49}_{21}$Sc$_{28}$ is interesting from a nuclear-structure viewpoint, since it has one proton outside the doubly magic $Z = 20$, $N = 28$ core. Recently, Mann and Bloom[1] conducted (β) (circularly polarized γ) correlation studies to determine the amount of isospin impurity in the 3.08-MeV state due to mixing between the analog states[2] at 11.56 MeV and the probable antianalog state at 3.08 MeV. In the analysis of their results, Mann and Bloom[1] made the critical assumption that no $\frac{3}{2}^-$ state in ^{49}Sc other than the one at 3.08 MeV was populated in ^{49}Ca β decay. A state at 4.50 MeV ($J^\pi = \frac{1}{2}^-$ or $\frac{3}{2}^-$ from $l_p = 1$) was well known from ^{48}Ca(^{3}He, d) studies by Armstrong and Blair,[3] and by Erskine, Marinov, and Schiffer,[4] and from ^{48}Ca(d,n) studies by Grandy, McDonald, Dawson, and Neilson.[5] In an earlier study[6] of ^{49}Ca by our group at Oak Ridge National Laboratory a 1409-keV γ ray was tentatively associated with ^{49}Ca decay. This transition could deexcite the 4.50-MeV level to the 3.08-MeV level. To settle this question, we restudied the ^{49}Ca decay with better γ-ray resolution and higher source strengths. Several new weak transitions were observed which provide further insights into the structure of ^{49}Sc levels. We have also carried out angular correlation experiments relating to the 4.50-MeV level.

As a natural extension of the study of ^{49}Ca decay, we have investigated the decay of ^{49}Sc to levels in ^{49}Ti. The only previous report of γ-ray emission in ^{49}Sc decay is that by Rezanka *et al.*[7] who observed [with a NaI(Tl) detector] a single γ ray of energy 1.78 ± 0.04 MeV and intensity 0.03 per 100 decays of ^{49}Sc.

II. DECAY OF ^{49}Ca

A. Experimental Results

We measured the ^{49}Ca γ spectra with a 40-cm^3 Ge(Li) detector system with a low counting-rate resolution of 2.1 keV for the ^{60}Co 1333-keV line. To obtain sufficient counting statistics to extract weak transitions from the Compton continuum, we obtained the ^{49}Ca spectra using a "mobile" source technique. The measurements were begun with the source at approximately 10 cm from the detector face; as the counting rate decreased, the source was moved closer to maintain a constant counting rate. In this manner we "extended" the 8.7-min half-life to 1 h. The constant counting rate also reduced peak shifting and resultant broadening. Figure 1 depicts the result of a 1-h measurement with a ^{49}Ca source produced by the ^{48}Ca(n,γ) reaction in the Oak Ridge research reactor.