Alpha-Gamma Angular Correlations in the Reaction $^{40}Ca(d, \alpha\gamma)^{38}K$

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(Received 16 September 1971)

Angular correlations of γ rays deexciting states in ^{38}K have been measured. The reaction $^{40}Ca(d,\alpha\gamma)^{38}K$ (E_d = 4.421 and 5.080 MeV), with θ_α near 180° was used to populate levels of ^{38}K. The decay of levels below an excitation energy of 3.7 MeV is given. Unique spin-parity assignments of 1^+, 1^+, and 2^+ could be made for the second, third, and fourth excited states. In addition, limitations could be imposed on spins and parities of seven other excited states. Multipole mixing ratios of the decay γ rays are given. Yield measurements, averaged over a large incident deuteron energy range, provided information on spin-parity assignments of two excited states.

I. INTRODUCTION

The nucleus ^{38}K, having one neutron and one proton hole coupled to the "inert" ^{40}Ca core, has been the subject of recent interest, both experimental and theoretical. The results of several theoretical calculations have emphasized the inadequacy of the simple shell model to explain the structure of this nucleus. The problem has been treated for two different types of interactions, i.e., the phenomenological modified surface δ interaction (MSDI), and the realistic Tabakin interaction. For three low-lying $T=0$ states in ^{38}K the calculation with both interactions, using configurations of two holes distributed over the $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$ single-particle orbits, agrees poorly with experimental results.[1,2]

Recently a calculation has been done using the MSDI, but with $s_{1/2}$, $d_{3/2}$, and $f_{7/2}$ orbits forming the configuration space.[3] However, the agreement of the level spacings of the $T=0$ states with experimental data was still poor. A modification of this MSDI obtained by adding a tensor force gives the best agreement with experimental transition rates in ^{38}K and also the correct sequence of the 3^+ and 1^+ states. For levels of ^{38}K with odd parity, only a few calculations have been performed.[4,5]

Previous experimental studies of levels in ^{38}K include measurements of angular distributions of outgoing particles in the reaction $^{40}Ca(d, \alpha)^{38}K$,[6-9] the reaction $^{39}K(^3He, \alpha)^{38}K$,[10] and the reaction $^{39}K(d, t)^{38}K$.[11] These measurements have provided l values and spectroscopic factors for low-lying states. From the β^+ decay of ^{38}Ca the spin and parity of the 1696-keV level is known[12] to be $J^\pi = 1^+$. Lifetimes of the 1696- and 2403-keV levels have been measured[13] using the reaction $^{39}K(^3He, \alpha\gamma)^{38}K$, the lifetime of the 458-keV level with the reaction $^{35}Cl(\alpha, n\gamma)^{38}K$.

This paper describes a study of 14 levels of ^{38}K up to 3.7 MeV by means of α-γ angular correlations following the excitation of the levels by the reaction $^{40}Ca(d, \alpha)^{38}K$ with a deuteron energy of 4.421 MeV. These measurements have led to the determination of spins and parities of some excited states, restrictions on several other assignments, and mixing parameters for the deexciting γ rays. A preliminary measurement had been made at E_d = 5.080 MeV. This did not have good enough statistics to lead to useful angular correlations, but did provide branching ratios which could be compared with those found for E_d = 4.421 MeV. For those α groups corresponding to levels previously considered to be single, a significant difference was found in only one case (the level at 3.33 MeV). Further investigation justified the conclusion that a doublet must lie at this excitation energy.

Two yield measurements of the reaction $^{40}Ca(d, \alpha)^{38}K$ were made in the course of this work with an annular detector at θ_α = 180°. As a consequence of a selection rule (Sec. III) there must be a severe suppression of the yield of 0^+, but not of 0^- levels. Application of this rule has substantiated the well-known spin-parity assignment of the first excited state, and restricted the assignment of the 2983-keV level. Preliminary results of the present work have been presented earlier.[14]

II. EXPERIMENTAL PROCEDURE

The experiments were performed with deuterons from the Groningen 5-MV Van de Graaff accelerator.[15] The analyzed beam of approximately 120 nA entered the target chamber, described in a previous publication,[16] after passing through a diaphragm of 1.2 mm diam, 65 cm in front of the target. A second 1.5-mm-diam diaphragm was mounted on the stainless-steel block containing the annular detector, 42 mm in front of the target. The ratio of beam current on this last diaphragm to that passing through the target was better than 1 : 400 during the measurement.

The target was prepared by evaporation of 60 $\mu g/cm^2$ of natural Ca (97% natural abundance of ^{40}Ca) onto a carbon backing of 10 $\mu g/cm^2$. Transfer to the target chamber was accomplished entirely in a very dry nitrogen atmosphere. The α particles were detected by a 40-μm-thick annular surface-barrier Si diode, which was collimated to detect particles between 167 and 172° with respect to the beam direction. The intrinsic resolution of detector and amplifier was 28 keV. The spectrum of α particles in coincidence with γ rays in shown in Fig. 1. The γ rays were detected with a 7.6 × 7.6-cm NaI crystal.

The details of the angular-correlation equipment have been given in an earlier publication of this laboratory.[17] The resolving time, as given by the width of the window on the time-to-amplitude-converter spectrum, was 36 nsec. The true-to-chance ratio for the peaks of interest lay between 10 : 1 and 15 : 1.

The intrinsic isotropy of the goniometer was checked with a radioactive source at the target position. Isotropy within 0.5% was found. During the angular-correlation measurements the pulses from the α-particle group leading to the 458-keV level in ^{38}K were used for monitoring the runs, and the deuteron energy (4.421 MeV) was held constant to within 1 keV.

III. ANALYSIS

The method of analysis follows the procedure developed in this laboratory[16] for use with Method II of Litherland and Ferguson.[18] The technique applied to the analysis of the γ-ray spectra has been described earlier.[17]

In the angular-correlation measurement, the angles of measurement were 28.7, 39.8, 60.8, 75.8, and 84.5°, chosen according to the criterion explained in earlier work of this laboratory.[16, 17] The population of the magnetic substates of the decaying level follows from the analysis of the angular correlations. These are normalized so that $\sum_m p(m) = 1$, where $p(m)$ stands for the sum of the population of $+m$ and $-m$ substates. A selection rule[16] prohibits the population of the $m = 0$ substate for final states with natural parity in the (d, α) reaction on even-even nuclei for $\theta_\alpha = 180°$. This rule is applied below, with allowance for the solid angle subtended by the annular particle detector,

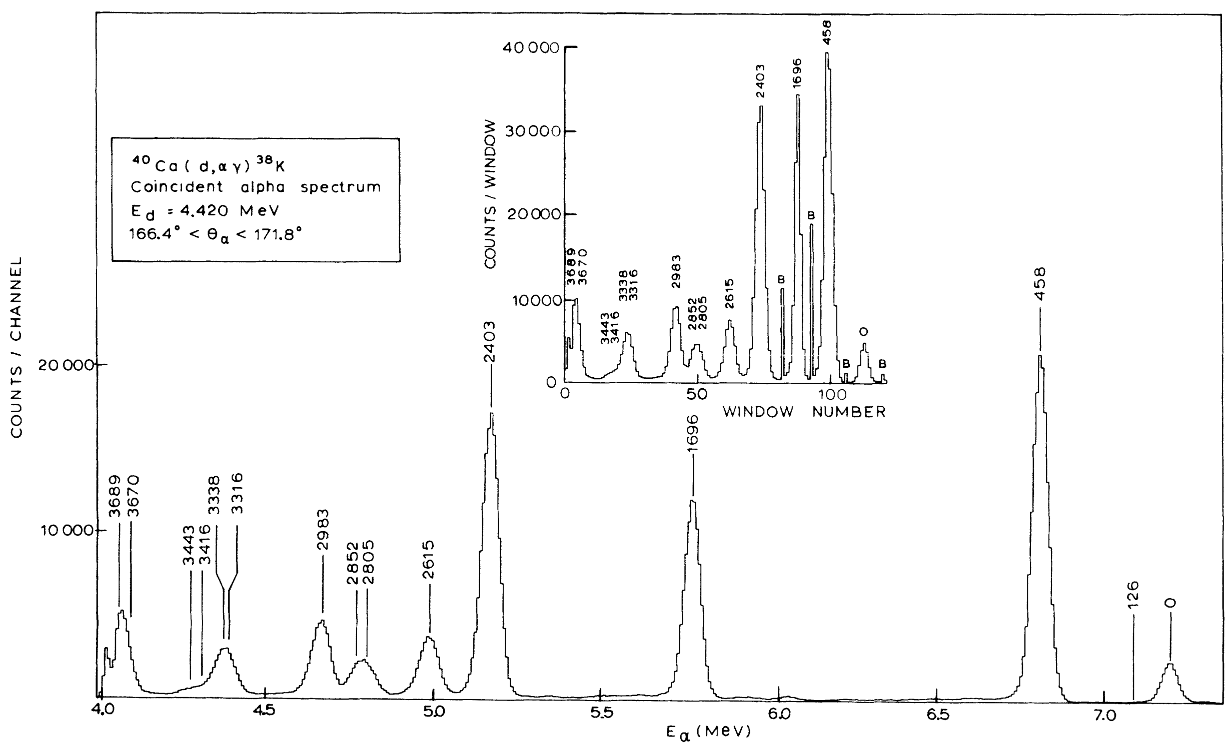

FIG. 1. Charged-particle pulse-height spectrum (energies in keV) coincident with γ rays in the interval 180 keV $\leq E_\gamma \leq$ 3.72 MeV. This spectrum represents the sum of all runs during the angular-correlation measurement. In the insert the "compressed" 128-window α-particle spectrum is shown (see Ref. 17). The isolated points marked B represent broad windows containing only background.

for the determination of the parities of several states.

During the course of this work the lifetimes of the 458-, 1696-, and 2403-keV states have been measured elsewhere.[13] The lifetime of the lowest lying of these was long enough so that a correction for eccentricity had to be applied to our measurements (see below). We have assumed that all of the higher levels have lifetimes which are short enough so that no errors were introduced into the angular correlations. A certain degree of internal evidence that this is correct accrues from the fits to even-order Legendre polynomials. In all cases the fit was good; whereas, for lifetimes longer than 10 nsec an eccentricity of greater than 3 cm would be introduced, making a good fit to even-order polynomials impossible. The possibility cannot be ruled out that a state has a lifetime long enough to produce an error in the results, but too small to lead to unsatisfactory fits.

IV. EXPERIMENTAL RESULTS

The decay scheme of ^{38}K is given in Fig. 2, which also presents the spin-parity assignments from this and previous work. The branching ratios were derived from the intensities of the γ-ray lines in coincidence with α particles exciting the specific level in question summed over the five angles of measurement. As has been shown,[16] these angles give a correct space average of the intensities if the distribution contains no terms higher than $P_4(\cos\theta_\gamma)$. The results are summarized in Table I.

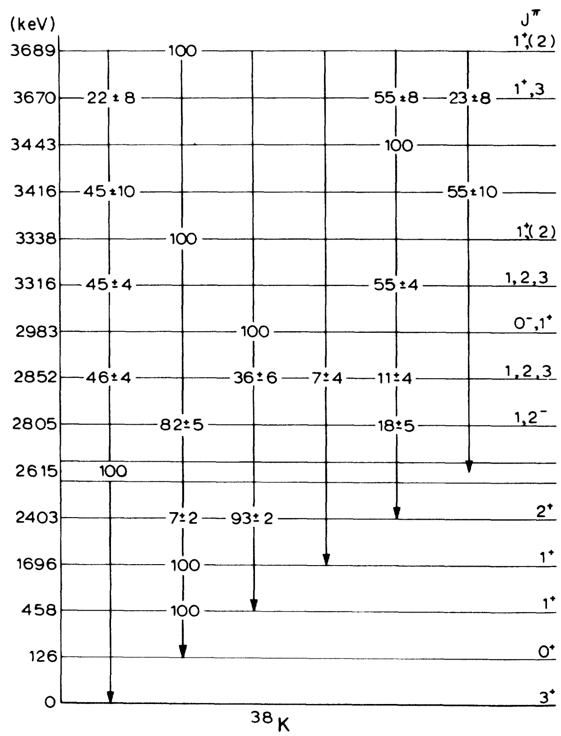

FIG. 2. Level scheme of ^{38}K, with decay modes of the excited states. Except for the lowest levels, most of the information stems from this work.

Ground and 126-keV States

The ground state of ^{38}K is known[19] to have $J^\pi = 3^+$, $T = 0$, and the first excited state, at an excitation energy of 126 keV, is known[19] to have $J^\pi = 0^+$, $T = 1$. The latter assignment is substantiated by a yield measurement of the reaction ^{40}Ca(d, α)^{38}K. In this measurement the incident deuteron energy was varied from 3.45 to 5.8 MeV in steps of 20 keV. The measured intensity ratio of the 126-keV α group to that of the ground-state α group, averaged over this range is approximately 1 : 160. A ratio of 1 : 60 is predicted by a calculation based on the statistical theory of nuclear reactions.[16] The discrepancy of about a factor of 2.7 is due, at least in part, to the T-forbiddenness of the transition to the 126-keV level.[6]

458- and 1696-keV Levels

The 458-keV state decays to the 126-keV state only, and has a meanlife[13] of 740 ± 160 psec. The angular distribution of the 332-keV γ ray has been corrected for the slight eccentricity of the decaying nuclei from the target spot. The corrected distribution gives the unique spin assignment of $J = 1$ with normalized $\chi^2 = 0.94$ (the uncorrected distribution gave a χ^2 of 1.75). From the strong population of the $m = 0$ substate of 0.71 ± 0.02, we can conclude that the parity of this level is positive ($J^\pi = 1^+$). If the parity were negative, the $m = 0$ substate could only be populated because of the finite solid angle subtended by the detector. Assuming a relative population of 5% for $m = 0$, we find a totally unacceptable solution ($\chi^2 \simeq 6000$). The measured and fitted angular correlations are shown in Fig. 3, together with the $J^\pi = 1^-$ solutions with $p(0) = 0$ and $p(0)/p(1) = 0.05$, as an illustration of the selection rule mentioned above. All other spin possibilities give χ^2 values larger than 2000, with the population of the $m = 2$ substates set at 5% of the population of the $m = 1$ substates.

Similarly, in the decay of the 1696-keV level only a transition to the 126-keV state has been seen. In Fig. 3 is also shown the measured angular distribution in this case. This gives also a unique spin and parity assignment $J^\pi = 1^+$ ($\chi^2 = 1.96$), with $p(0) = 0.582 \pm 0.006$. As above, all other spins can be rejected on the basis of large values of χ^2 (>2000).

2403-keV Level

The γ spectra in coincidence with the α-particle group leading to the 2403-keV state summed over the five angles of measurement, with randoms subtracted, is shown in Fig. 4. The branchings through the first excited state at 126 keV and the second excited state at 458 keV were the only ones observed.

Simultaneous analysis of the angular distribution of two transitions (2403 → 458, 458 → 126) did not permit a unique spin assignment: Spins $J=1$ or 2 remained possible. An analysis including the 7% transition (2403 → 126, Fig. 5) rejects the spin $J=1$. This is illustrated in Fig. 6, in which are shown plots of Q^2. The minimum value of Q^2, corresponding to the most probable solution for a given spin assumption, is the usual goodness-of-fit parameter, χ^2. The population of the $m=0$ substate in the minimum of the Q^2 curve is found to be -0.014 ± 0.032, so the $m=0$ substate is not significantly populated. Allowing a population of the $m=2$ substates of 5% of that of the $m=1$ substates (Fig. 6), in order to account for the solid angle subtended by the detector, does not alter this conclusion. In this case the selection rule concerning the population of the $m=0$ substate gives no information. All that can be said is that an assignment

TABLE I. Summary of the results of the analysis of the angular-correlation measurements. In column 2 are indicated the primaries of the cascades analyzed. Except in the case of the decay of the 2852-keV level (see text) all observable γ rays in a cascade were analyzed simultaneously. Braces indicate where two cascades were included in the analysis.

Excitation energy of decaying level (keV)	Transitions analyzed (primaries only given)	Assumed assignment $J^{(\pi)}$	Multipole mixing ratio x	$p\ (m=0)$	χ^2	Number of degrees of freedom F	Confidence level (%)
458	458 → 126	1	0	0.713 ± 0.024	0.94	3	42
		1^-		a	6000	4	<0.1
1696	1696 → 126	1	0	0.582 ± 0.006	1.96	3	13
		1^-		a	2260	4	<0.1
2403	{2403 → 126; 2403 → 458}	2	{0; -0.077 ± 0.012}	-0.014 ± 0.032	1.35	10	24
2805	2805 → 126	1	0	0.11 ± 0.06	0.54	3	65
		2	0	0.30 ± 0.05	0.24	3	85
		2^+	0	a	9.8	4	<0.1
2852	{2852 → 0; 2852 → 458}	1	Undetermined		<1.0	5	>45
		2	Several		<1.8	5	>10
		3	{$0.28<x<0.83$; $x>-0.37$}	0.03 ± 0.09	1.2	5	30
2983	2983 → 458	0	0	(1)	1.1	8	40
		1	Undetermined	0.332 ± 0.015	1.42	6	14
3316	{3316 → 0; 3316 → 2403}	1	{$1.15^{+1.34}_{-0.62}$; 0.47 ± 0.06}	0.91 ± 0.05	0.88	13	58
		2	{0.17 ± 0.15; 0.09 ± 0.04}	0.62 ± 0.16	0.98	13	45
		3	{$-11.3<x<-1.25$; -0.40 ± 0.06}	-0.02 ± 0.025	1.11	13	34
3338	3338 → 126	1	0	0.315 ± 0.062	0.71	3	52
		1^-	0	a	5.0	4	<0.1
		2	0	0.177 ± 0.053	3.4	3	1.5
3670	3670 → 2403	1	-0.158 ± 0.053	0.988 ± 0.055	1.3	10	21
		1^-		a	>23	10	<0.1
		3	-0.017 ± 0.035	0.51 ± 0.31	1.25	10	22
3689	3689 → 126	1	0	0.31 ± 0.08	0.8	3	48
		1^-		a	6.5	4	<0.1
		2	0	0.19 ± 0.07	2.8	3	4

[a] $p(0)/p(1)$ set equal to 0.05.

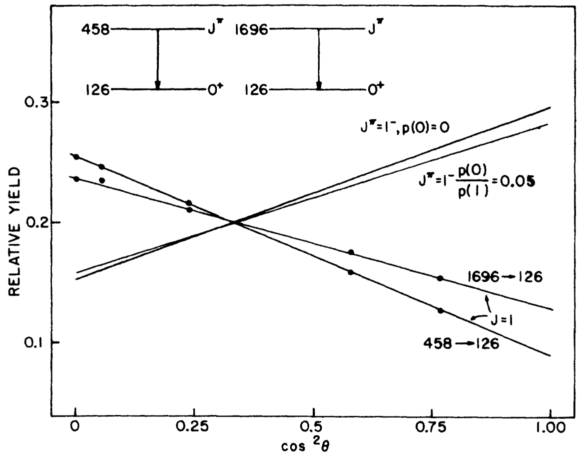

FIG. 3. Angular distributions in the decay of the 458- and the 1696-keV levels. The curves drawn through the data points represent the computer fits. The curves labeled $J^\pi = 1^-$ are explained in the text. The experimental errors are less than the size of the data points.

of $J^\pi = 2^+$ is not ruled out. From Refs. 8, 10, and 11 the parity of this level is known to be positive.

Levels near 2615 keV

Only a transition to the ground state is observed. Jänecke[8] measured two levels at 2.61 ± 0.02 and 2.63 ± 0.02 MeV. The existence of a doublet is not in disagreement with our measurements. We observe a broadening of 11 ± 3 keV of the α peak at the corresponding energy in our spectrum and a broadening of 13 ± 4 keV of the photopeak of the coincident 2615-keV γ ray. Since it is not possible to resolve the decays, no spin assignment was attempted. The angular distribution, corrected for solid-angle attenuation, has normalized coefficients of $P_2(\cos\theta)$ and $P_4(\cos\theta)$, $A_2/A_0 = 0.282 \pm 0.017$, and $A_4/A_0 = 0.011 \pm 0.031$.

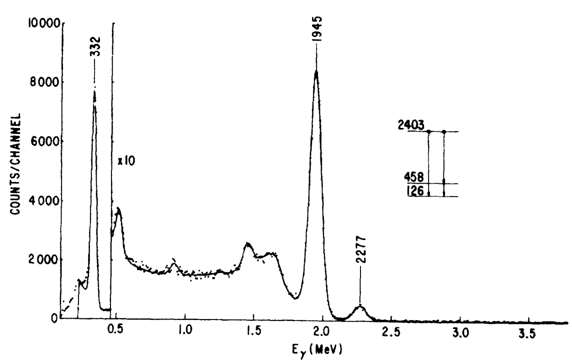

FIG. 4. Spectrum of γ rays in coincidence with α particles feeding the 2403-keV state, summed over five angles. Random coincidences have been subtracted.

2805- and 2852-keV Levels

The γ-ray spectrum, in coincidence with the α group populating the 2805- and 2852-keV states summed over five angles, is shown in Fig. 7, where the decay scheme of both levels is also given. The decomposition of the decay of the two levels was accomplished by analyzing separately the γ spectra in coincidence with each of the windows (Fig. 7, inserts) on the α-particle group leading to these states. The angular distribution of the transition from the 2805-keV state to the 126-keV state allows the spins $J = 1$ or 2 (Table I). The usual criterion of 0.1% or less probability for the rejection of an assignment does not permit the exclusion of zero population of the $m = 0$ substate for the $J = 1$ solution. The $J = 2$ solution gives $m = 0$ a sufficiently large population so that a negative-parity assignment may be made (Table I). No useful analysis could be carried out on the weak 2805 → 2403-keV transition.

In the analysis of the decay of the 2852-keV level, only the first member of the 2852 → 458 → 126-keV cascade could be used, since the second ex-

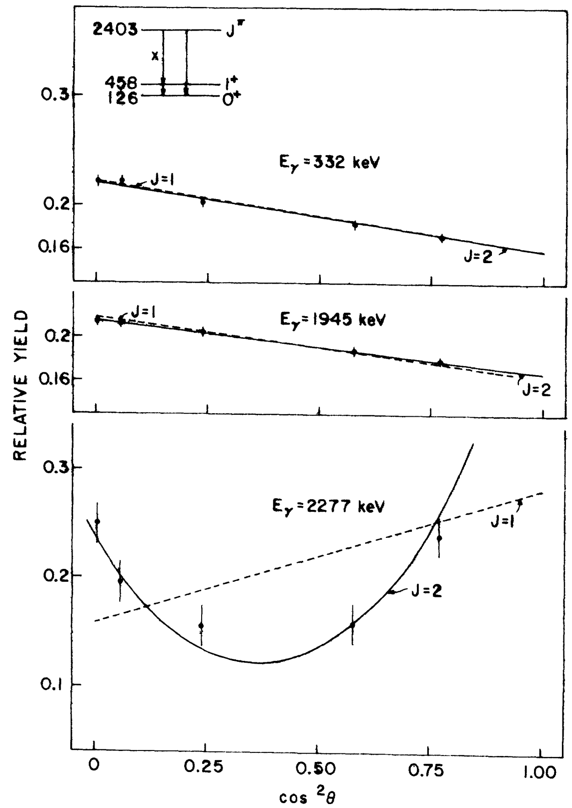

FIG. 5. Measured angular distributions in the decay of the 2403-keV level, together with calculated curves corresponding to the simultaneous analysis of the three γ rays.

cited state is also fed in the decay of the 2805-keV state. Spins 1, 2, and 3 are all permissible solutions. An analysis including the 2852 → 0-keV transition did not improve the selectivity. The weak decays of this level to the 1696- and 2403-keV levels were not useful in the analysis.

2983-keV Level

Only a decay to the 458-keV state is observed (Fig. 8). If there is a transition to the $J^\pi = 0^+$ 126-keV state, the branching ratio must be less then 2%.

The isotropic angular distributions of the 2983 → 458 → 126-keV cascade are equally compatible with $J = 0$ or 1. The plots of Q^2 for different spin possibilities are shown in Fig. 9.

The ratio of average excitation of this level to that of the 1696-keV $J^\pi = 1^+$ level, determined in a yield measurement in which the incident deuteron energy was varied from 4.8 to 5.4 MeV in steps of 25 keV, was found to be approximately 0.5. Hauser-Feshbach calculations were carried out

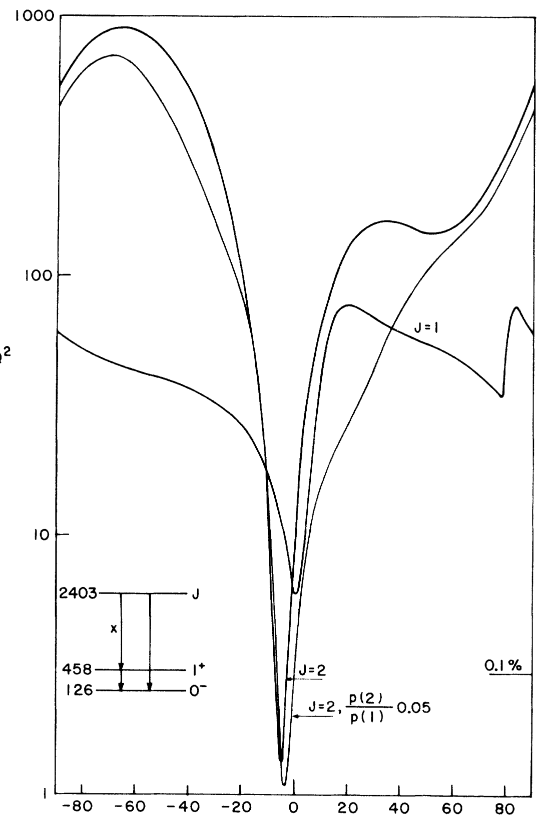

FIG. 6. Curves of Q^2 for spin possibilities 1 and 2 for the 2403-keV level. Accounting for the finite solid angle of the particle detector by allowing a small occupation of $p(2)$ is seen to alter the results only slightly.

with a computer program written by one of the authors (P.B.S.). These provide results compatible with an assignment of 0^- or 1^+ (calculated ratios 0.3 and 0.6, respectively), but rules out a 0^+ assignment (calculated ratio 0.01).

In Fig. 9 a plot is also given of Q^2 for the hypothesis $J^\pi = 1^-$, in which a small (5%) population of the $m = 0$ substate is assumed. This is seen to give an acceptable solution only for a very large value of x. Preliminary results of a lifetime measurement of this state by one of the authors (H.H.) give $\tau_m < 1$ psec. This corresponds to a $M^2(M2)$ of the 2525-keV primary decay of 80 Weisskopf units, ruling out the possibility of this solution. We can conclude that $J^\pi = 0^-$ or 1^+.

3316- and 3338-keV Levels

One level at 3320 ± 20 keV was observed by Jänecke[8] in this region. A weak 3211-keV γ ray in the decay of ^{38}Ca was attributed to a 3337 → 126-keV transition in ^{38}K by Gallmann *et al.*[20] in our measurements we observed three decay modes in the γ spectra coincident with the 3.33-MeV α group, i.e., decays to the ground state, first excited state, and 2403-keV level. The intensity ratio was 1 : 0.95 ± 0.07 : 1.22 ± 0.05 in the $E_d = 4.421$ MeV measurement and 1 : 0.62 ± 0.08 : 1.18 ± 0.04 in the $E_d = 5.080$ MeV measurement. In Fig. 10(a) the high-energy portions of the two spectra are illustrated. We conclude that two levels are present. A scan of the corresponding α peak, as in the case of the doublet near 2.8 MeV, plus adjustment for best fit of the γ-ray energies led to excitation energies of 3316 ± 10 and 3338 ± 15 keV for the members of the doublet. The intensities of the two highest-energy lines are shown as a function of α window number in Fig. 10(b). The distance between the two members of the doublet as derived from this figure is 22 ± 8 keV.

The angular distribution of the 3316 → 2403 → 458 → 126-keV cascade is compatible with $J = 1$, 2, or 3. No further discrimination is obtained by including the 3316 → 0-keV transition.

The analysis of the decay of the 3338-keV state allows $J = 1$ or 2. If $J = 1$, the parity must be positive (Table I). From the large value of χ^2 for the $J = 2$ solution we conclude that the assignment is most probably $J^\pi = 1^+$. This level is quite probably the same as that found by Gallmann *et al.*[20] at an excitation energy of 3337 keV, also with preferred assignment $J^\pi = 1^+$.

Levels near 3440 keV

Three levels with energies 3420 ± 20, 3440 ± 20, and 3470 ± 20 keV were observed by Jänecke.[8] These levels are very weakly excited at the deu-

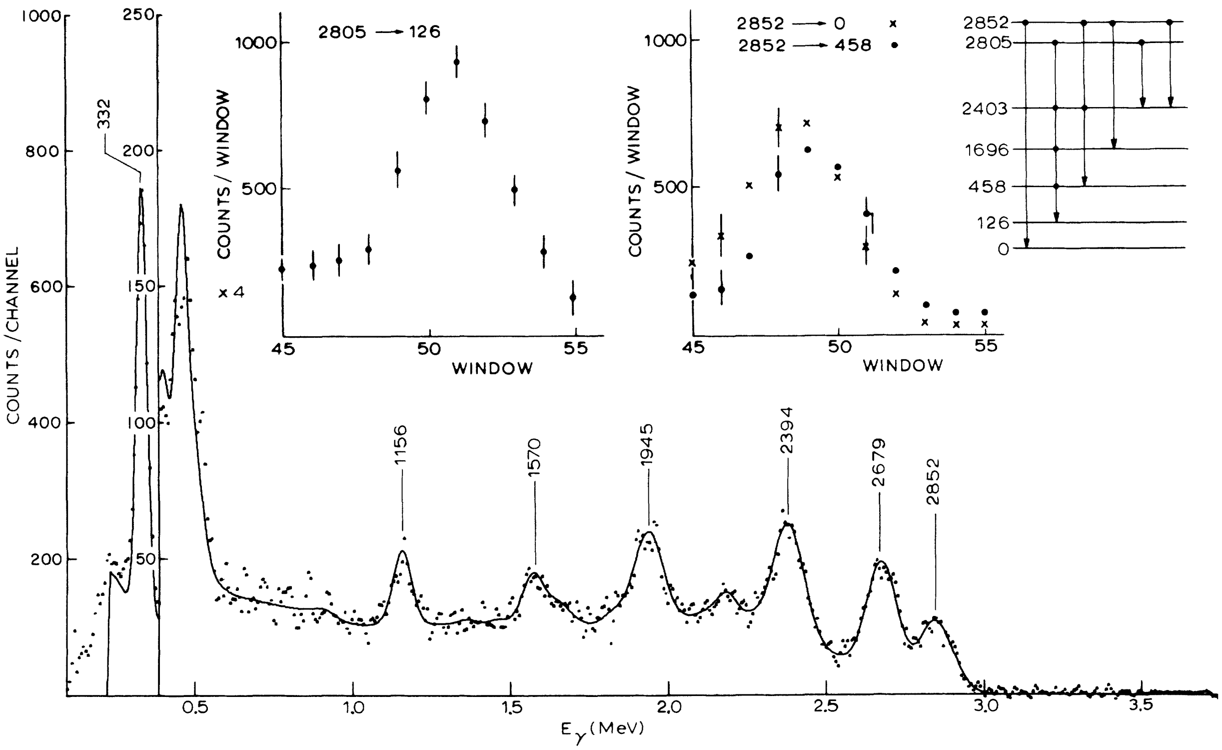

FIG. 7. The total γ-ray spectrum in coincidence with the particle group feeding the 2805- and 2852-keV levels. The inserts show the intensity of three of the most important lines as a function of window position on the α-particle spectrum.

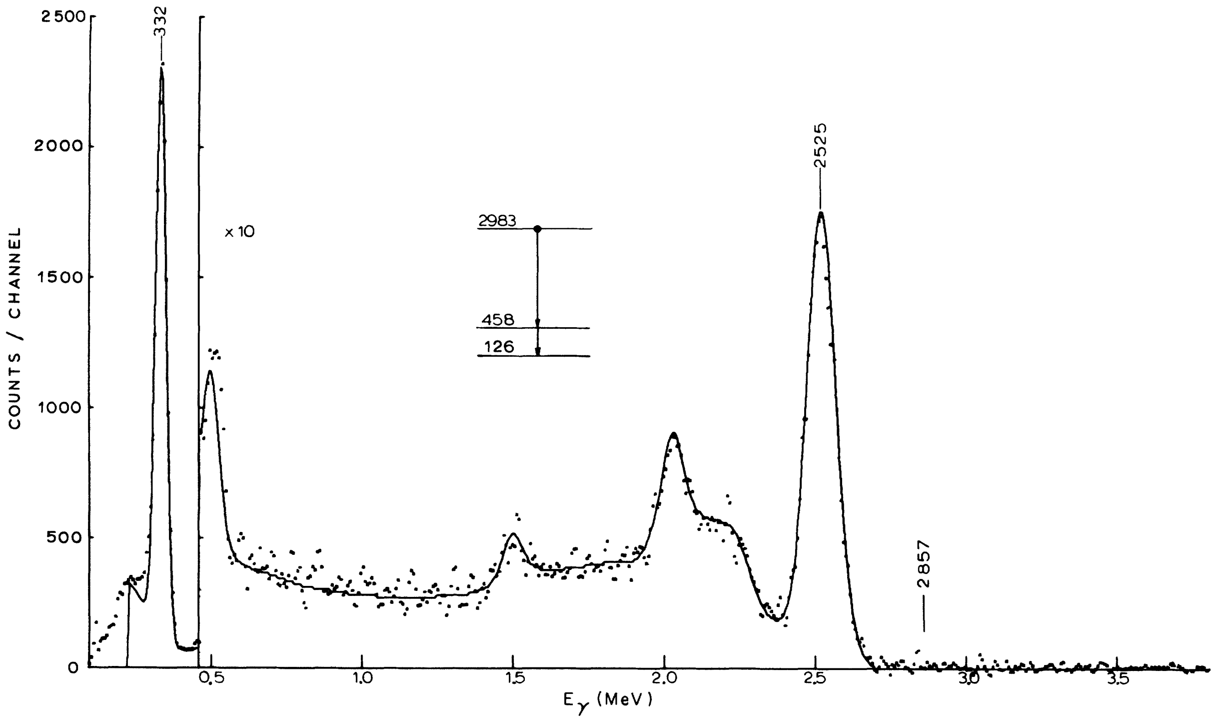

FIG. 8. Spectrum of γ rays coincident with α particles feeding the 2983-keV level. The arrow at 2857 keV indicates the position of the photopeak of the possible transition to the 126-keV (0^+) level.

teron energy employed in our measurements. Only two levels are observed, at 3416±10 and at 3443 ±10 keV (see Fig. 2). The errors in the branchings are very large because of the poor statistics. No useful angular-correlation results were obtained for the same reason.

It is noteworthy that a small peak in the α-particle single spectrum corresponding to an excitation energy of about 3460 keV showed no coincidences with γ rays. We could not explain this peak by an excitation of the ground state or an isomeric state of any known contaminant. If it does correspond to a level in ^{38}K the lifetime must be appreciably longer than 50 nsec.

3670- and 3689-keV Levels

In the range of 3600 to 3700 keV Jänecke[8] observed four levels with energies 3600, 3650, 3670, and 3700±20 keV. An exhaustive analysis of our coincident spectra yielded only two separate levels (or level groups). The level at 3670±25 keV decays to the ground state, the 2403-, and the 2615-keV state. Only one transition from the 3689-keV level (to the first excited state at 126 keV) was observed.

In an effort to determine the spin of the level at 3670 keV, an analysis of the angular distributions (Fig. 11) of the 3670→2403→458→126-keV cascade was carried out. The possible spins are $J=1$ or 3 (Fig. 12), assuming that this level is single. Possible spin (parity) assignments for the 3689-keV level, resulting from the analysis of the 3689→126-keV transition are $J^\pi = 1^+$ or 2 (see Table I). The decay of this level has perhaps been observed by Cline and Chagnon[21] in the β^+ decay of ^{38}Ca. This is in disagreement, however, with the results of Ref. 12.

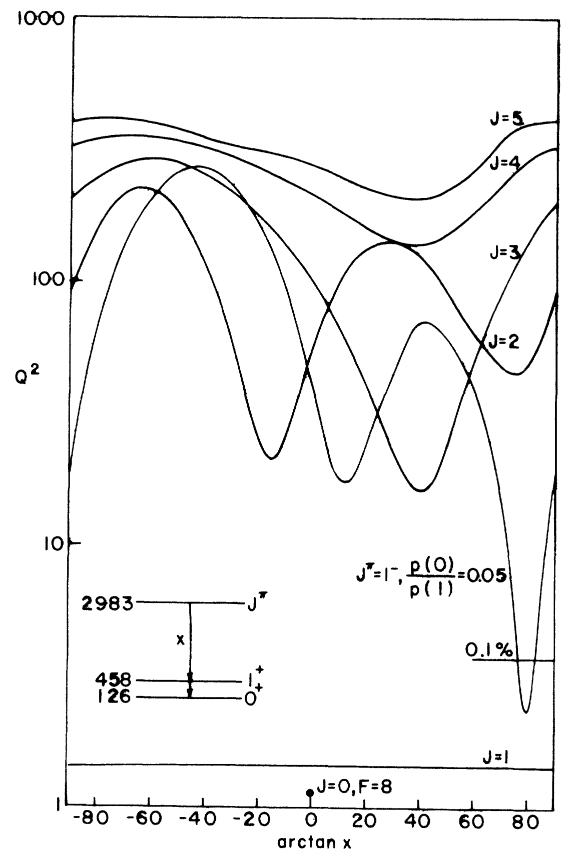

FIG. 9. Plot of Q^2 for different spin possibilities for the 2983-keV level.

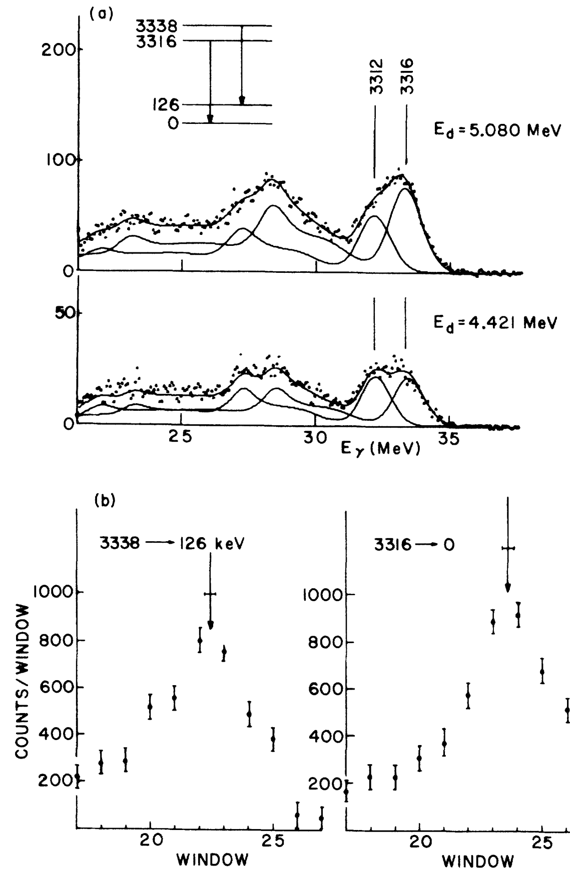

FIG. 10. (a) The high-energy portions of the γ spectra coincident with the α group leading to the doublet at 3.33-MeV excitation energy, taken with two different deuteron energies. The solid lines indicate the decomposition into two components. (b) The coincident intensity of the two highest-energy γ rays as a function of window position on the α-particle peak. The arrows indicate the centroids. All γ rays in the cascade over the second excited state show the same pattern as the 3316→0-keV transition.

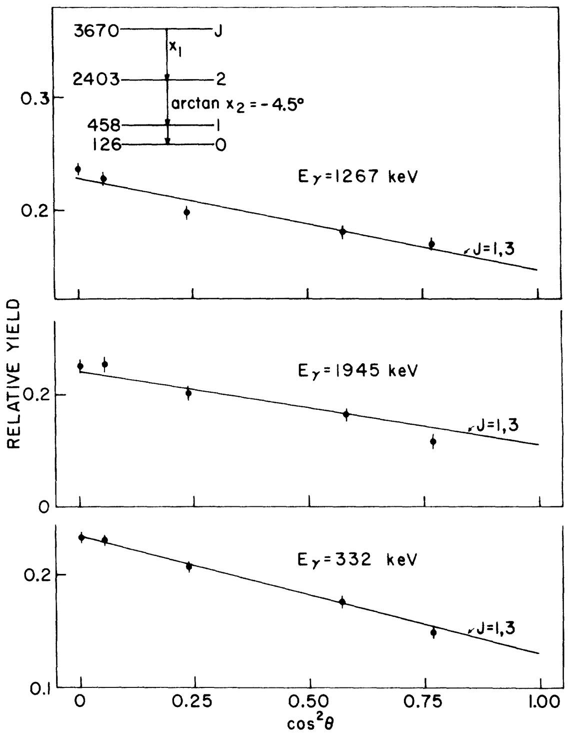

FIG. 11. Fits to the angular distribution of the cascade through the 2403-keV level, deexciting the 3670-keV level.

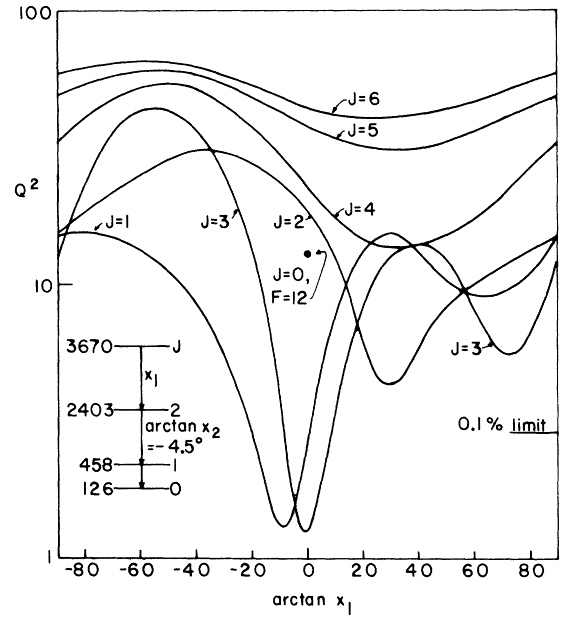

FIG. 12. Curves of Q^2 for different spin possibilities for the 3670-keV level.

V. DISCUSSION

The results of the present work are summarized in Table I and Fig. 2. All of the low-lying levels expected from the two-hole configuration of ^{38}K have been observed and for four of them the spin and parity have been determined. The assigned spin and parity of the 1696-keV state is in agreement with Ref. 12, and that of the 126-keV state with earlier work.[19] The 7% branching to the 0^+ 126-keV state in the decay of the 2403-keV state is not expected from theoretical calculations using the Tabakin interaction.[1]

Levels with negative parity up to about 3.8-MeV excitation energy can be expected to be described by a three-hole configuration with one particle in the $1f_{7/2}$ or $2p_{3/2}$ shell.[4,5] Those with $J^\pi = 4^-$ and 3^- are expected to lie lowest. The doublet at 2615 keV, both members of which appear to decay to the 3^+ ground state only, offers obvious candidates for these levels. The isotropic angular distributions of the decay γ rays make a $J^\pi = 0^-$ assignment to the 2983-keV state attractive although the first 0^- level is predicted to lie above 4 MeV by Erné.[4] Levels in the 2.5- to 3.8-MeV region with positive parity are described by a breakup of the $1d_{5/2}$ shell. A comparison of our data with these calculations does not appear useful in the light of the ambiguity of the spin assignments of the levels in this region.

The authors wish to acknowledge the help received from H. Gruppelaar during the first stage of this work. The cooperation of the other members of the Van de Graaff group in data taking is greatly appreciated. The targets were made by J. A. Reinders and the silicon detector was made by J. L. W. Petersen. The authors are grateful for the permission of D. W. Smits to use the TR 4 computer of the University Computing Center, especially in periods in which it was closed for normal use.

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PHYSICAL REVIEW C VOLUME 5, NUMBER 4 APRIL 1972

Studies on Analog States in ^{33}Cl by Isospin-Forbidden Resonances in the Reaction ^{32}S$(p, \gamma)^{33}$Cl

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The residual activity between bursts of a mechanically chopped beam has been used to measure the yield of the reaction ^{32}S$(p,\gamma)^{33}$Cl systematically in the bombarding energy range $E_p = 3.36$ to 5.41 MeV. Two $T=\frac{3}{2}$ states in ^{33}Cl at $E_p = 3.371 \pm 0.005$ MeV, $E_x = 5.550 \pm .007$ MeV and at $E_p = 5.282 \pm .006$ MeV, $E_x = 7.402 \pm .008$ MeV have been located with the resonance strengths $(2J+1)\Gamma_{p_0}\Gamma_\gamma/\Gamma = 0.76 \pm 0.18$ and 1.50 ± 0.37 eV, respectively. Each of these resonances was narrower than the estimated 2-keV spread in the proton beam. These two states are interpreted as the analogs of the ground and the second excited state of ^{33}P with J^π values $\frac{1}{2}^+$ and $\frac{5}{2}^+$, respectively. γ decay of the lower resonance, investigated with a Ge(Li) detector, shows >88% and <12% branchings to the first excited state and ground state of ^{33}Cl, respectively. The $M1$ strengths of these transitions are compared with those obtained from β analog transitions and with the theoretical predictions based on the many-particle shell-model calculations.

I. INTRODUCTION

Isobaric-analog-state studies have proved to be useful sources of spectroscopic information, since these states tend to have simple shell-model configurations, while the Coulomb-energy difference is such that they can be observed as proton resonances so that the reduced widths for the various decay modes can be extracted directly. Particularly for the low-lying $T=\frac{3}{2}$ states in nuclei with $T_z=-\frac{1}{2}$, proton decay to the $T=0$ states in the neighboring nucleus is isospin forbidden, and hence the analog resonances are narrow.

The lowest $T=\frac{3}{2}$ states in the $T_z=-\frac{1}{2}$ nuclei of the series ($A=4n+1$, $Z=2n+1$) have been identified[1] in the β decay of their $T_z=-\frac{3}{2}$ analogs over the range $2 \leq n \leq 10$. The $T_>$ states in this series are proton unstable and their original identification was in the studies of delayed proton emission.[1] Proton decay is energetically possible only to $T=0$ states in the neighboring ($A=4n$, $Z=2n$) nucleus. Though it is isospin forbidden, proton emission can successfully compete with γ decay, the only energetically available alternative allowed by isospin selection rules, because of the weakness of the electromagnetic interaction. Because low-lying $T_>$ states can be expected to have simple shell-model configurations, there may be strong γ decays to the low-lying $T_<$ states, in which case the $T_>$ states will appear as strong and sharp resonances in the (p,γ) reaction, since the integrated yield over the resonance is essentially proportional to Γ_γ. When $T=\frac{3}{2}$ states in $T_z=-\frac{1}{2}$ nuclei are observed in elastic scattering of protons, the integrated yield is proportional to Γ_{p_0} and is therefore reduced by the operation of isospin selection rules, contrary to the case in radiative capture.

From the study of elastic scattering of protons[2-4] on ^{32}S and delayed-proton studies[5] in the β^+ decay of ^{33}Ar, it has been deduced that the lowest $T=\frac{3}{2}$