Properties of the Two States in Ca^{40} near 9.87 MeV*

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The close-lying pair of resonances in the $K^{39}(p,\gamma)Ca^{40}$ reaction, which correspond to excitation in Ca^{40} of about 9.87 MeV, have been measured to be at $E_p=1575.5\pm0.8$ and 1580.0 ± 0.8 keV by comparison with the $Al^{27}(p,\gamma)Si^{28}$ resonance at 992 keV. Gamma-ray spectra obtained for both resonances show both have strong transitions to the ground state and to the first excited state. Weaker cascades through higher levels are also shown. The angular distribution of the ground-state radiation from the $E_p=1580$ keV level leads to an assignment of 2^+ for the level. The radiation from this level to the 3.35 MeV (0^+) first excited state appears enhanced, thus lending support to the suggestion by Pope *et al.* that the 3.35-MeV level may have a stable deformation and that upon this level is built a band of vibrational states at higher excitation. Resonant absorption measurements on the ground-state radiation from the $E_p=1575.5$-keV level gave $\Gamma_t=110\pm30$ eV and $\Gamma_{\gamma0}=1.36\pm0.25$ eV. For the $E_p=1580$ keV level, the yield curve gave $\Gamma_t=1060\pm200$ eV and a yield measurement gave $\Gamma_{\gamma0}=0.80\pm0.26$ eV. At both levels, the (p,α) cross section was measured to be $\leqslant 68$ μb and thus $\Gamma_\alpha \leqslant 0.012$ and 0.068 eV for the lower and upper levels, respectively. The proton widths are thus 110 ± 30 and 1060 ± 200 eV. Arguments are given for $J=1$ assignment for the lower level. An even parity assignment is favored slightly by the experimental data. The possibility of "cross excitation" between the levels in the resonant absorption measurements is considered.

I. INTRODUCTION

THE resonance in the $K^{39}(p,\gamma)Ca^{40}$ reaction first reported near 1.566 MeV[1] was found elsewhere to be two closely spaced resonances.[2,3] The existence of the two closely spaced resonances and the fact that neither was due to K^{41} were verified here. A suspicion on our part that the second resonance might be due to Cl^{35} contamination was proven wrong. In this paper there is given first a discussion of the procedure and results of experiments determining: (a) the yield curves near the two resonances, (b) spectra of the gamma rays emitted in the decay of the two states, (c) angular distributions of the ground-state radiation from the two states, (d) the total width and the radiation width of the lower state (by resonance absorption), and (e) an upper limit to the $K^{39}(p,\alpha)Ar^{36}$ cross section involving these two states. Interpretations of the results of these experiments are then discussed.

II. PROCEDURE AND RESULTS

Yield Curves

Yield curves of gamma rays as a function of proton energy were run for targets of many different thicknesses. Commercial potassium, very pure potassium,[4] normal isotopic composition KCl, enriched $K^{39}Cl$, and enriched $K^{41}Cl$ were used. Protons were furnished by a Van de Graaff generator and the energy of the protons was measured with a 127°, 1-m radius, precision, electrostatic analyzer. A 3-×3-in. NaI crystal was used to detect the gamma rays. One thick-target yield curve of radiation to the ground state is shown in Fig. 1. The energy-scale calibration was by means of the resonance in the $Al^{27}(p,\gamma)Si^{28}$ reaction at 992.0 ± 0.5 keV.[5] Agreement between the values measured here and elsewhere[6] for the energies of other resonances in the $Al^{27}(p,\gamma)Si^{28}$ reaction gives credence to the linearity and correctness of our voltage scale. The resonances in Fig. 1 appear at 1575.5 ± 0.8 and 1580 ± 0.8 keV. The widths of the resonances are the quadrature summations of the instrumental width, the Doppler broadening from the thermal motion of the target nucleus, and the true width. The Doppler broadening for K^{39} targets and 1.5-MeV protons is small enough to be neglected for the levels considered here. The true width of the narrower resonance was measured, as discussed later, by nuclear resonant absorption to be 110 ± 30 eV. This value allows determination of the instrumental width. Assuming the instrumental width is the same for the second resonance as for the first, the true width of the second resonance may be calculated. A weighted average of such calculations made on several yield curves gives a true width of 1060 ± 200 eV for the second resonance.

Gamma-Ray Spectra

Measurements of gamma-ray spectra were made using a 5-×5-in. NaI crystal, a $2\frac{1}{2}$-in. thick lead collimator, a nonoverloading amplifier, and a 256-channel analyzer. Targets of very pure, natural isotopic abundance, potassium were evaporated *in situ* onto tantalum backings. The backings had previously been

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[1] J. H. Towle, R. Berenbaum, and J. H. Mathews, Proc. Phys. Soc. (London) **A70**, 84 (1957).
[2] R. L. Zimmerman and M. K. Moe, Bull. Am. Phys. Soc. **6**, 47 (1961).
[3] A. C. Eckert and E. F. Schrader, Phys. Rev. **124**, 1541 (1961).
[4] Obtained from Mine Safety Appliances Company, Callery, Pennsylvania.
[5] J. B. Marion, Revs. Modern Phys. **33**, 141 (1961).
[6] S. L. Anderson, H. Bö, T. Holtebekk, O. Lönsjö, and R. Tangen, Nuclear Phys. **9**, 509 (1958).

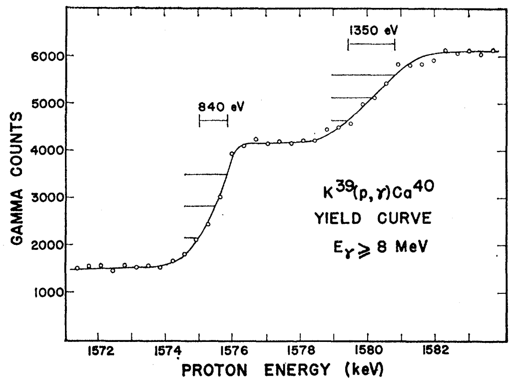

FIG. 1. The resonance doublet in the $K^{39}(p,\gamma)Ca^{40}$ reaction. The interquartile ranges (which correspond to the observed widths of the resonances) are shown. The target thickness is approximately 100 keV.

cleaned by heating to incandescence in vacuum. Three backings were mounted in a rotatable wheel. The axis of the wheel was inclined 45° to the proton beam direction. Distilled water circulated within the wheel and directly cooled the backs of the tantalum disks. Even with water cooling, target evaporation losses limited the maximum useable beam current to about 3 μA.

The axes of the 5-in. crystal and the collimator were inclined 45° to the proton beam. Pulse-height distributions were analyzed and recorded by the 256-channel analyzer. All pulses greater than significant room background were also recorded in a separate scaler. Each pulse-height distribution was run for the length of time necessary to accumulate a certain number of counts in the separate scaler. The energy calibration of the pulse-height distribution was made by use of Na^{22}, Cs^{137}, Co^{60} sources and by the $F^{19}(p,\alpha,\gamma)$, $B^{11}(p,\gamma)$, $C^{13}(p,\gamma)$ reactions.

Standard stripping techniques were applied to the pulse-height distributions obtained. In Fig. 2 are shown the principal gamma rays observed, their relative intensities and the decay schemes believed to exist for the two levels. The potassium targets used to get the data ranged from 30 to 100 keV in thickness. Pulse-height distributions were obtained at $E_p=1572$, 1577, and 1583 keV. The distribution used for the upper level was a difference curve obtained by subtracting the middle-energy data from the upper-energy data nad the distribution used for the lower level was similarly obtained from the lower- and middle-energy data.

Table I gives a summary of the observed gamma rays from the two levels. Some weak gamma rays observed are listed which are not included in the decay schemes shown in Fig. 2.

The absolute yield of the ground-state radiation from each of the two levels was measured both directly and by comparison with the known ground-state radiation yield in the $Al^{27}(p,\gamma)Si^{28}$ reaction at $E_p=771$ keV.[7,7a] Using the absolute ground-state yield and the proposed decay scheme of each level, the absolute yield, $\omega\gamma$, of each level was calculated. For the lower level, $\omega\gamma=1.00$ eV $\pm 30\%$, and for the upper level $\omega\gamma=1.11$ eV $\pm 30\%$.

Angular Distributions

Angular distributions of the ground-state radiation were measured for both levels using a 3-×3-in. NaI

TABLE I. Summary of observed gamma-ray energies and relative intensities for the $E_p=1575.5$- and 1580-keV resonances in the $K^{39}(p,\gamma)Ca^{40}$ reaction. The relative intensities for the two resonances have been normalized according to the results of the yield measurements for the two resonances. Particular care was used in the determination of the energy of the 3.90-MeV gamma ray in the 1575.5-keV resonance in order that it may be properly fitted into the decay scheme. Such an accurate determination could not be made for the corresponding 3.8-MeV gamma ray in the 1580-keV resonance.

1575.5-keV resonance		1580-keV resonance	
E_γ (MeV)	Relative intensity	E_γ (MeV)	Relative intensity
9.9 ±0.1	70	9.9±0.1	47
6.9 ±0.2[a]	2	6.9±0.2[a]	4
6.5 ±0.1	17	6.5±0.1	28
6.0 ±0.1	5	6.0±0.1	10
5.2 ±0.1	3.5	5.6±0.1	8
4.6 ±0.1	3.5	5.3±0.1	9
3.90±0.05	7	4.8±0.1	8
3.5 ±0.2[a]	1	4.4±0.1	10
2.2 ±0.1[a]	2.5	3.8±0.1	19
1.6 ±0.1[a]	2.5	3.5±0.2[a]	1.5
0.5 ±0.1[b]	···	2.2±0.1[a]	2.5
		1.6±0.1[a]	2.5

[a] Not accounted for in the decay schemes.
[b] Assumed to be the annihilation gamma ray arising from the electron-positron pair transition from the 0^+ first-excited state to the 0^+ ground state of Ca^{40}. It definitely appears in the first resonance but was not looked for in the second resonance.

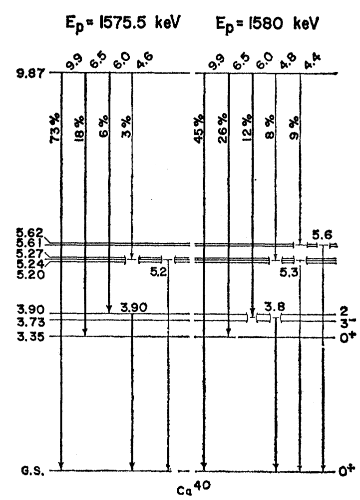

FIG. 2. Proposed decay schemes for the $E_p=1575.5$- and 1580-keV resonances in the $K^{39}(p,\gamma)Ca^{40}$ reaction. The prominent cascades are denoted by the heavier lines.

[7] P. B. Smith and P. M. Endt, Phys. Rev. **110**, 397 (1958).
[7a] *Note added in proof.* The quoted yields and results based upon them have been corrected for the recent revision in the $Al^{27}(p,\gamma)Si^{28}$ yield measurement by Nordhagen and Smith [see P. M. Endt and C. van der Leun, Nuclear Phys. **34**, 118, 119 (1962)].

detector. The front face of the crystal was located 6-in. from the target. KI targets of approximately 100-keV thickness were used. Yield curves of ground-state radiation similar to Fig. 1 were taken at a number of angles. Water cooling was not used on the angular-distribution targets because of the asymmetric absorption of gamma rays in that target chamber. With the simplified target chamber used, target deterioration by evaporation was noticeable even with 1 μA beam currents. The deterioration occurring during a single yield-curve run was observed to be small but the deterioration during the measurements over a series of angles was considerable. To provide normalization data, another 3-$\times$3-in. NaI detector was arranged to detect ground-state radiation emitted at 90° to the proton beam.

A pulse-height distribution was obtained for all gamma rays emitted at each angle for $E_p=1577$ keV and for $E_p=1572$ keV. A difference curve of the two distributions taken at each angle gave the pulse-height distribution for the gamma rays emitted for the 1575.5-keV resonance at each angle. The intensity of ground-state radiation was determined from each difference curve. The angular distribution of the ground-state radiation for the 1575.5-keV resonance thus obtained is plotted in the top half of Fig. 3. This angular distribution was then used to normalize the first step of the yield curves taken earlier. Normalized differences between the first and second steps of the yield curves taken at the various angles gave the angular distribution of the ground-state radiation for the 1580-keV resonance. The data are plotted in the bottom half of Fig. 3.

The angular distributions obtained by a least-squares fit (using an IBM 650) to the experimental data were

$$\begin{aligned}&\text{1575.5-keV resonance,}\quad W(\theta)=1-(0.08\pm0.04)P_2;\\&\text{1580-keV resonance,}\quad W(\theta)=1+(0.12\pm0.07)P_2\\&\qquad\qquad\qquad\qquad\qquad-(0.18\pm0.06)P_4.\end{aligned}$$

No correction has been made for finite-geometry effects.

Resonant Absorption Measurement

A high percentage of radiation emitted by the two states in Ca^{40} is radiation to the ground state. Ca^{40} is available in reasonable amounts both as metal and in compounds. These facts combined with the apparent narrowness of the lower resonance indicated the desirability of a resonance absorption experiment on the lower resonance. As shown earlier, knowledge of the width of the lower resonance allows determination of the width of the upper resonance also.

The technique employed was that used by Smith and Endt.[7,8] Resonant absorption occurs when the absorber is placed at the proper angle where the sum of the energy losses occurring upon emission and absorption is equal to the Doppler energy increment due to the motion of the excited compound nucleus. Using the notation of Smith and Endt, the proper angle is given very closely by

$$\cos\alpha_r=E_0/(2E_pm_pc^2)^{\frac{1}{2}}, \tag{1}$$

where E_0 is the excitation energy of the compound nucleus, E_p is the kinetic energy of the proton, and m_p is the mass of the proton.

The resonant absorption experiment was first done using a 1-deg wide wedge of CaO powder packed between two lead bricks. The CaO density was such that the number of molecules per cm^2 perpendicular to the gamma flux was 2.01×10^{23}. A definite absorption dip was observed centered at 79.3° which was in good agreement with the theoretical value of 79.5°. The statistical error in the area of the absorption dip was $\pm87\%$. The experiment was then repeated using as the absorber 18 sheets (3.75$\times$8$\times$0.01 in.) of calcium metal[9] clamped between two lead bricks. The number of calcium nuclei per cm^2 perpendicular to the gamma flux was 4.62×10^{23}. The absorber-shield sandwich was located on a swinging arm that was pivoted precisely below the beam spot on the target. A 3-$\times$3-in. NaI crystal was mounted so as to intercept gamma rays that passed through the calcium. The swinging arm could be moved about 4° either side of the resonant angle in steps of 3/8°.

The target used was an approximately 100-keV thick layer of pure potassium evaporated *in situ* onto cleaned tantalum. The tantalum backing was mounted on a post so designed that distilled water circulated in the post and directly cooled the back of the tantalum. The post also rotated in phase with the rotation of the absorber-detector supporting arm. The plane of the target was always maintained so that the gamma rays

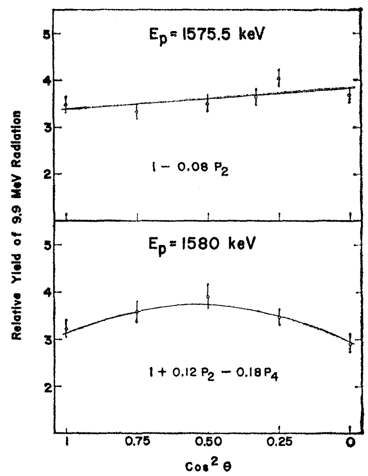

FIG. 3. Angular distributions of ground-state radiation from the resonance levels. θ is the angle between the movable detector and the proton beam direction. The solid lines represent least-square fits to the data (obtained by an IBM 650 computer).

[8] P. B. Smith and P. M. Endt, Phys. Rev. **110**, 1442 (1958).

[9] Obtained from Charles Hardy, Inc., 420 Lexington Avenue, New York 17, New York.

striking the absorber were those emitted at a constant angle of about 5° from the plane of the target. The geometric width of the beam spot on the target, as seen by the absorber, was thus minimized and also variation of the position of the beam spot, as seen by the absorber, was minimized. Beam currents of 8 to 10 μA were used.

The absorber was mounted so the horizontal angle subtended at the center of the beam spot by the far edge of the absorber was 1°. A precise measurement of the angular position and the alignment of the absorber was made by a triangulation method with the aid of a transit. Pulses from the detector were counted if they were accepted by a single-window pulse-height analyzer. The analyzer window was set to accept pulses of amplitude which include the full-energy peak to the "pair-minus-two" peak in the pulse-height distribution for 9.9-MeV gamma rays. Another 3-×3-in. NaI detector was used as a monitor in the 0° position with respect to the proton beam. By means of a single-level discriminator, all monitor pulses were accepted and subsequently counted if their amplitudes were above the maximum amplitude pulse due to the significant portion of room background. With the movable arm in an extreme position, the number of counts accepted by the movable counter system was recorded for a standardized monitor count. The arm was then moved 3/8° and the process repeated, etc. All angles were covered in about 1.3 h. To obtain adequate statistics, the cycle was repeated 50 times.

The gamma rays recorded were background plus ground-state radiation from the lower resonance and from "below-resonance." Background was measured by counting for definite times with no beam on the target. To determine the fraction of counts that were from below resonance, the movable counter, with its window setting unchanged, was placed in the 0° position and a yield curve was run over the first step. Both the background runs and the yield curves were repeated often to obtain sufficient statistical accuracy. The gamma counts obtained using the Ca metal absorber, with the

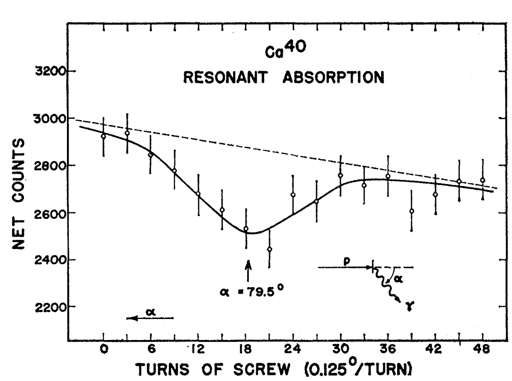

FIG. 4. Resonant absorption of 9.87-MeV gamma rays from the $E_p=1575.5$-keV resonance level in Ca^{40} as a function of angle. The arrow indicates the theoretically expected position of the centroid of the absorption dip. The sloping base line and the solid curve are discussed in the text. Standard counting errors are shown.

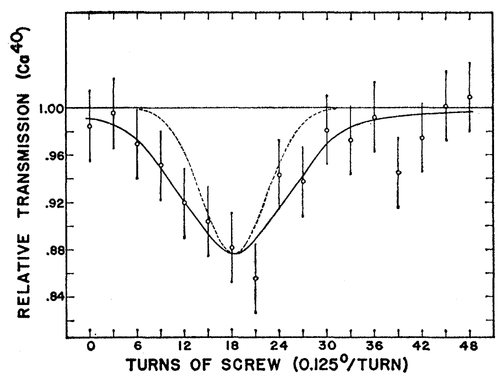

FIG. 5. The absorption curve of Fig. 4 converted to relative transmission. The dotted curve represents the assumed instrumental resolution of 1.2°. The minimum transmission is seen to be about 88% and the area of the absorption dip is $A_\alpha=0.270 \pm 0.049$ deg. The base line has been leveled by a linear "leveling factor."

background and the below-resonance contribution subtracted out, are plotted in Fig. 4. The position of the dip is in good agreement with the expected value of 79.5°. The sloping base line above the resonance dip is believed to be due in part to the angular distribution of the ground-state radiation, in part due to F^{19} buildup on the target and in very small part to a "cross-excitation" effect discussed later. Fig. 5 shows the data after modification with a linear leveling factor. Also shown in the figure is a Gaussian curve denoting our considered estimate of the instrumental width of the experiment. The width of the Gaussian at half-maximum is 1.2°.

To get the true width of the resonance, an approximation method using an IBM 650 was used to fold Breit-Wigner curves of various Γ's into the 1.2° Gaussian curve. The resulting curves were plotted and compared with the dip in Fig. 5. The Γ giving the best least-squares fit was 220 eV. Since the Breit-Wigner curve used itself represented the fold of two Breit-Wigner curves of equal width, one representing the emission of the gamma rays and one representing the absorption of the gamma rays, the true width of the lower level is thus 110 eV. Detailed consideration of the curves of Γ's just above and just below 220 eV lead to a probable error estimate of ±30 eV in the true width.

As shown by Smith and Endt, the area of the absorption dip, the so-called absorption integral, is related to the total width, Γ_t, and the ground-state radiation width, $\Gamma_{\gamma 0}$, by

$$A_\alpha=\int_0^\pi A(\alpha)d\alpha=\frac{\Gamma_t\pi}{2}\left(\frac{d\alpha}{dE_\gamma}\right)_r F(n\sigma_0), \qquad (2)$$

where $A(\alpha)$ is the measured resonant absorption as a function of angle, $(d\alpha/dE_\gamma)_r$ is the reciprocal of the rate of change of gamma-ray energy with angle at the

resonant angle,

$$F(n\sigma_0)=n\sigma_0 \exp(-\tfrac{1}{2}n\sigma_0)[I_0(\tfrac{1}{2}n\sigma_0)+I_1(\tfrac{1}{2}n\sigma_0)], \quad (3)$$

and $I_\nu(z)=\exp(-\frac{1}{2}i\pi\nu)J_\nu(iz)$, where $J_\nu(z)$ is the Bessel function of the first kind. σ_0 is given by the equation

$$\sigma_0=[(2J_r+1)/(2J_g+1)](\lambda^2/2\pi)(\Gamma_{\gamma_0}/\Gamma_t), \quad (4)$$

where J_r and J_g are the spins of the excited and ground states, respectively, λ is the wavelength of the gamma rays and Γ_{γ_0} is the width of the excited state for decay by emission of ground-state radiation. With the aid of a planimeter, the area of the absorption dip in Fig. 5 was measured to be 0.247°. A correction of 0.023° was added to that area to account for the wing area beyond the region of measurement that must exist due to the Breit-Wigner nature of the curve. $(d\alpha/dE_\gamma)_r$ was calculated to be 4.06×10^{-3}°/eV. Therefore $F(n\sigma_0)$ was 0.385 and the value of $(n\sigma_0)$, as read from the figure in Smith and Endt,[8] was 0.43. Since n was 4.6×10^{23}, σ_0 was 9.3 b. Assuming that $J_r=1$ for the lower excited state (arguments for this assumption are given later), using $J_g=0$, and $\Gamma_t=110$ eV, one calculates from Eq. (4) that Γ_{γ_0} is 1.36 ± 0.25 eV.

The (p,α) Cross-Section Measurement

To aid spin- and parity-assignment considerations and also partial-width considerations, an absolute measurement of the (p,α) cross section was made. Approximately 20-keV-thick KI targets mounted on very thin carbon foils were bombarded with protons at energies of 1572, 1577, and 1583 keV. Charged particles leaving the target at approximately 90° angle with respect to the proton beam entered a 90°, double-focusing, magnetic spectrometer. A proton nuclear magnetic moment device measured the magnetic field. A silicon solid-state detector counted particles at the output of the spectrometer. The number of target KI atoms "seen" by the input of the spectrometer was measured by observing the number of Rutherford-scattered protons from the iodine for a given number of bombarding protons. With the magnetic field set to focus alpha particles of 2.545 MeV (the energy expected for α's emitted by the excited Ca^{40} in a transition to the ground state of Ar^{36}), no α's were detected. The upper limit of the (p,α) cross section was calculated to be 68 μb.

III. DISCUSSION

Cross Excitation

In the rare cases in (p,γ) work where two resonances are very close to each other and where each of the levels excited in the compound nucleus has an appreciable decay by ground-state radiation, the interesting possibility exists of "cross excitation" of one level by resonant absorption of radiation from the other level. Cross excitation can occur if the two levels are spaced so closely that the available shifts in gamma-ray energy from the Doppler effect of the recoiling compound nucleus are sufficient to compensate for the level separation as well as for the recoil losses at gamma emission and absorption.

Upon emission at an angle α with respect to the direction of motion of the recoiling compound nucleus, a gamma ray from a transition of energy E_0 will receive an increment of energy

$$\Delta E_1=(E_0m_p/M)(2E_p/m_pc^2)^{1/2}\cos\alpha, \quad (5)$$

where M is the mass of the emitting nucleus. The energy which must be supplied in order that such a photon may excite a different energy level of an identical nucleus is

$$\Delta E_2=E_0^2/Mc^2+\Delta E_d, \quad (6)$$

where ΔE_d is the energy separation of the pair of levels and may be either positive or negative. The resonant angle, obtained by equating Eqs. (5) and (6), is

$$\cos\alpha_r=[E_0/(2E_pm_pc^2)^{1/2}](1+\Delta E_dMc^2/E_0^2). \quad (7)$$

Taking $\Delta E_d=4.5$ keV (the separation in this experiment), one finds $\alpha_r=60.2°$ and 97.6° for the plus and minus cases, respectively. The absorption dip expected at each of these angles would be of the form of a Gaussian curve representing the instrumental width folded into a Breit-Wigner curve. The width of the Breit-Wigner curve would be the sum of the widths of the emitter and absorber levels since it would be the fold of the Breit-Wigner curves for the individual levels.

No experimental observation of either cross-excitation dip was attempted by us since the width of the upper level would make such dips so broad and shallow that the necessary running time would be prohibitively long. In the resonance absorption experiment that was done, however, part of the slope of the base line might be explained by the proximity of a cross-excitation dip corresponding to excitation of the upper level by radiation from the lower level. While a plot of the expected cross-excitation dip had a tail in the region of the experimentally observed dip, the tail could only account for about 1% of the slope of the base line.

Spin and Parity Assignments

Transitions from both resonance levels to the 0^+ ground and first excited states rule out $J=0$ assignments for the levels. These strong transitions make values of $J=3$ or higher very unlikely. These strong transitions, coupled with the lack of strong transitions to intermediate states of angular momenta 2 or 3 make a 2^- assignment for either resonance level highly improbable. Further definite information on level assignments is not available from the observed decay schemes.

The angular distributions of the ground-state radiation do, however, give additional information on the remaining possibilities. The theoretical expressions for the coefficients A_k/A_0 in the expression

$$W(\theta)=\textstyle\sum_k(A_k/A_0)P_k(\cos\theta), \quad k=0,2,4,\cdots$$

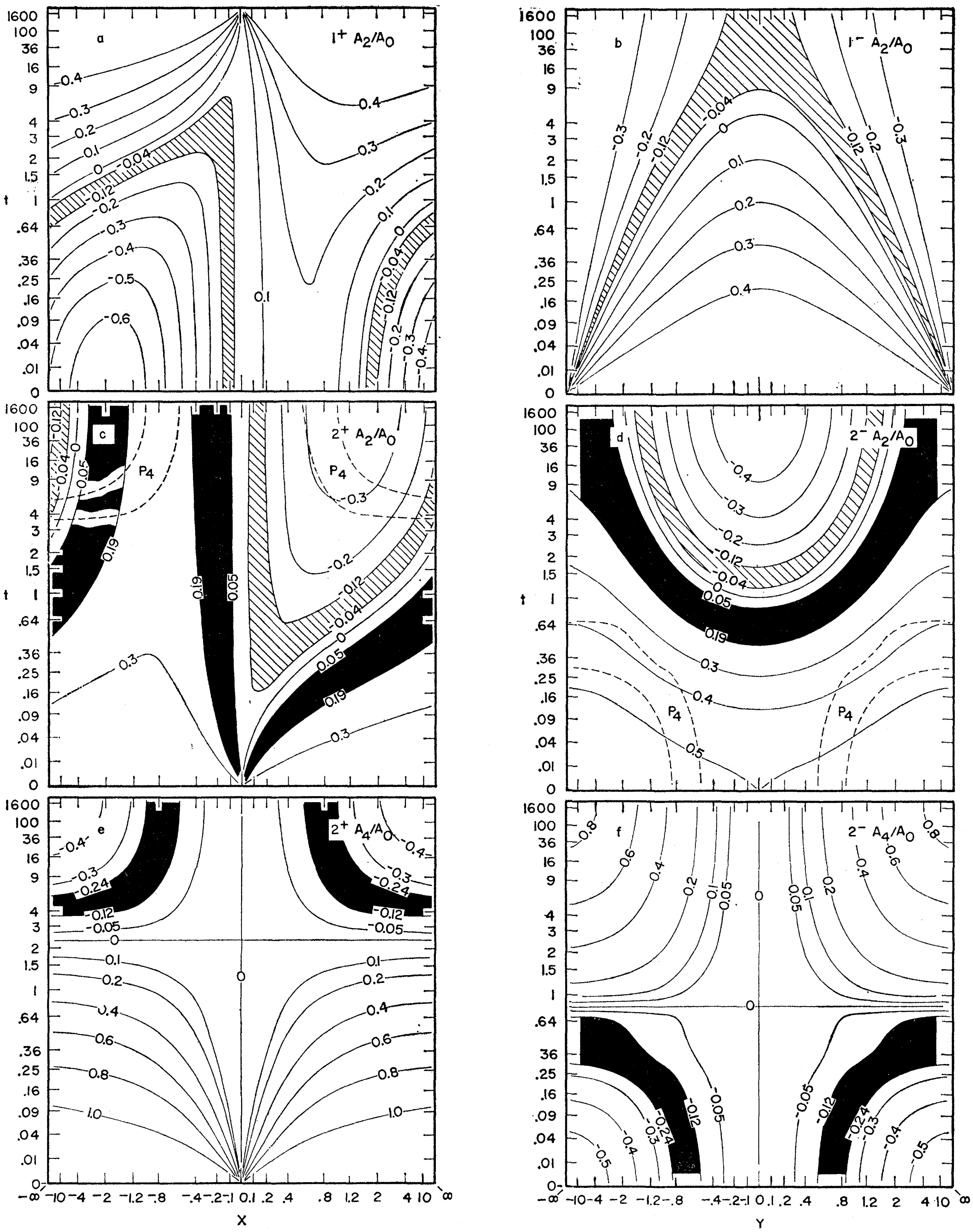

FIG. 6. Contour diagrams for the theoretical values of the angular distribution coefficients for the ground-state radiation in Ca^{40}. The coefficients A_k/A_0 are plotted vs t and X (or Y) for the resonance level assignments $J^\pi = 1^\pm$, $2^\pm$. X and Y refer to orbital angular-momenta mixing where X is the ratio of d- to s-wave amplitudes, and Y is the ratio of f- to p-wave amplitudes. The quantity t represents the intensity ratio of channel spin 2 to channel spin 1 formation. The cross-hatched regions represent the experimentally determined coefficients for the 1575.5-keV resonance, and the solid black regions represent those for the 1580-keV resonance. The regions corresponding to the measured A_4/A_0 coefficient for the 1580-keV resonance are shown superimposed on the $2^\pm$, A_2/A_0 diagrams (Figs. 6c and 6d) as the bands bounded by dashed lines. It is clear that the results are compatible with a 2^+, and not with a 2^- assignment, for the 1580-keV resonance. No definite assignment can be made for the 1575.5-keV resonance from these data.

TABLE II. Coefficients of the expansion $W(\theta)=\Sigma_k(A_k/A_0)\times P_k(\cos\theta)$ for the angular distributions of the ground-state transitions in the $K^{39}(p,\gamma)Ca^{40}$ reaction. X and Y refer to orbital angular-momenta mixing where X is the ratio of d- and s-wave amplitudes and Y is the ratio of f- and p-wave amplitudes. The quantity t represents the intensity ratio of channel spin 2 to channel spin 1 formation.

J^π for the resonance level	A_2/A_0	A_4/A_0
1^+	$-(1/2)\dfrac{X^2(1-t)-\sqrt{2}X}{1+X^2(1+t)}$	0
1^-	$(1/10)\dfrac{5-t(1+4Y^2)}{1+t(1+Y^2)}$	0
2^+	$(1/98)\dfrac{5X^2(7-3t)-7(70)^{\frac{1}{2}}tX}{X^2+t(1+X^2)}$	$(8/49)\dfrac{X^2(7-3t)}{X^2+t(1+X^2)}$
2^-	$(1/14)\dfrac{7(1-t)+2Y^2(4+t)}{(1+t)(1+Y^2)}$	$-(2/7)\dfrac{Y^2(2-3t)}{(1+t)(1+Y^2)}$

for the intensity of the ground-state radiation were computed from the tables of Sharp *et al.*[10] No mixing of gamma-ray multipolarities can occur but entrance channel-spin mixings and proton orbital angular-momenta mixings must be considered. Since the ground state of K^{39} is $3/2^+$, the possible channel spins are 1 and 2 with even parity. If the parity of the compound state is even, s and d waves are assumed to contribute to its formation; if odd, p and f waves contribute. The Coulomb factors $\cos(\xi_{l'}-\xi_l)$, where l' and l refer to the interfering partial waves, were read from the graphs of Sharp *et al.*[11] as $\cos(\xi_2-\xi_0)\approx-\frac{1}{2}$ and $\cos(\xi_3-\xi_1)\approx 0$. These factors, which appear in the orbital angular-momenta interference terms, are quite significant in this reaction. The coefficients A_k/A_0 thus computed are shown in Table II. The coefficients are shown in Fig. 6 where they are plotted as functions of orbital-momenta mixings and channel-spin mixings. The experimentally measured coefficients are also indicated there by curved, cross-hatched bands and by solid bands. The widths of the bands indicate the uncertainties in the measured coefficients.

The P_4 term in the radiation from the 1580-keV resonance level rules out $J=1$ for that level. Inspection of Fig. 6 shows that for a 2^- assignment no combination of mixings is compatible with both the measured A_2/A_0 and A_4/A_0 coefficients. For 2^+, however, with $d-s$ mixing between -23 and -1.4 and with S mixing between 3.7 and 10, compatibility exists with the measured coefficients. For $d-s$ mixing of -0.5 and S mixing greater than 10, near-compatibility exists. Since the bands represent statistical uncertainties, this latter possibility cannot be ruled out. It is concluded that the 1580-keV level is 2^+.

The absence of a significant P_4 term in the ground-state radiation from the 1575.5-keV resonance level does not automatically rule out $J=2$ for that level since A_4/A_0 can vanish for all orbital-momenta mixings and an approximate channel-spin mixing for both 2^+ and 2^-. Inspection of Fig. 6 shows the measured A_2/A_0 compatible with $J^\pi=1^+$, 1^-, 2^+, and 2^-. If the level decayed by alpha emission to the 0^+ ground state of Ar^{36}, the number of possibilities could have been halved but measurements showed no detectable alpha emission. One must therefore resort to less direct arguments for further information.

One may argue, as have Smith and Kuperus,[12] that two levels of the same spin and parity would probably be separated by several tens of keV even if their isotopic spins were different. 2^+ can therefore be considered an unlikely assignment for the 1575.5-keV level because of the proximity of the 1580-keV (2^+) level. A decision between the remaining two possibilities is more difficult and, as is discussed in the following section, 1^+ is favored.

Partial Widths

In the resonance absorption experiment, the 1575.5-keV level was found to have a total width of 110 ± 30 eV and a width for gamma decay to the ground state of 1.36 ± 0.25 eV. The absence of alpha emission means the width for proton emission must be 110 ± 30 eV.

For the 1580-keV level, the total width was measured directly from the yield curve to be 1060 ± 200 eV. Assuming for a level of this width that the width for gamma emission is very small compared to the total width, and knowing that the width for alpha emission is very small, one concludes that the width for proton emission is 1060 ± 200 eV. Thus, using $J=2$, $\omega=(2J+1)/(2I+1)(2s+1)=5/8$, $\omega\gamma=1.11\pm0.33$ eV, and $\gamma=\Gamma_\gamma\Gamma_p/\Gamma_t\approx\Gamma_\gamma$, the width of the state for gamma decay is calculated to be 1.78 ± 0.52 eV. Since 45% of the radiation from this level is from a transition to the ground state, $\Gamma_{\gamma_0}=0.80\pm0.26$ eV.

The strengths of the ground-state transitions of the two resonance levels as predicted by the single-particle model were calculated using the convenient formulas of Wilkinson.[13] The values of $|M|^2$ so obtained for the 1575.5-keV level are in agreement (see Table III) with the distributions of experimental $|M|^2$ for $M1$ or T-forbidden $E1$ transitions found by Wilkinson in the light elements (A less than 20). While Ca^{40} is consider-

[10] W. T. Sharp, J. M. Kennedy, B. J. Sears, and M. G. Hoyle, Atomic Energy of Canada Limited Report No. 97, 1954 (unpublished).
[11] W. T. Sharp, H. E. Gove, and E. B. Paul, Atomic Energy of Canada Limited Report No. 268, 1955 (unpublished).
[12] P. B. Smith and J. Kuperus, Physica **26**, 631 (1960). See also, I. I. Gurevich, and M. I. Pevsner, Nuclear Phys. **2**, 575 (1956–1957) and L. Landau and Y. Smorodinsky, *Lectures on Nuclear Theory* (Plenum Press, Inc., New York, 1959), p. 72.
[13] P. H. Wilkinson, in *Nuclear Spectroscopy*, edited by Fay Ajzenberg-Selove (Academic Press Inc., New York, 1960) Part B, Chap. V. F., p. 858 ff.

TABLE III. Partial widths for the 1575.5- and 1580-keV resonance levels in the $K^{39}(p,\gamma)Ca^{40}$ and the $K^{39}(p,\alpha)A^{36}$ reactions. The strengths of the radiative transitions to the ground state of Ca^{40} are given in Weisskopf units $|M|^2$, and the reduced proton widths θ_p^2 are given in units of $\hbar^2/MR^2$. R_{obs} is the observed ratio of the intensities of the transitions to the first excited state and the ground state. R_W is the ratio of intensities predicted from the single-particle model.

Resonance level E_p(keV)	J^π	Γ_t (eV)	Γ_p (eV)	γ_p^2 (keV)	θ_p^2	Γ_α (eV)	Γ_{γ_0} (eV)	Type of rad.	$\|M\|^2$	R_{obs}	R_W
1575.5	1^+	110 ± 30	110 ± 30	13	0.0068	$\leqslant0.012$	1.36 ± 0.25	$M1$	0.067	0.25	0.29
	1^-	110 ± 30	110 ± 30	35	0.019	$\leqslant0.012$	1.36 ± 0.25	$E1$	0.0018	0.25	0.29
1580	2^+	1060 ± 200	1060 ± 200	120	0.065	$\leqslant0.068$	0.80 ± 0.26	$E2$	1.27	0.58	0.12

ably heavier, there is some evidence[13] that such comparisons may be significant in the medium-light mass range. Unfortunately, however, the comparisons for $E1$ and $M1$ do not distinguish between 1^+ and 1^-. The value of $|M|^2$ for the ground-state transition from the 1580-keV level agrees with the general distribution of $E2$ transition strengths found by Wilkinson.

Since both the ground state and the first excited state of Ca^{40} are 0^+, the angular distributions of radiation arising from transitions to these states from a given resonance level will be identical and one can compare directly the relative intensities of such transitions. In Table III are shown the observed ratio R_{obs} of intensities to the first excited state and to the ground state and the theoretical ratio R_W based on the single-particle model. The R_{obs} for the 1575.5-keV level agree very well with the theoretical value for dipole radiation. The ratio R_{obs} for the 1580-keV level is about five times R_W. Thus, there appears to be a significant enhancement of $E2$ radiation to the 3.35-MeV (0^+) state in Ca^{40}. This observation supports the suggestion of Pope *et al.*[14] that some of the higher states of Ca^{40} may be of collective nature and may be based upon the first excited 0^+ state which perhaps has a stable deformation in contrast with the spherical 0^+ ground state. The presence of several relatively intense cascades through higher-lying levels from the 1580-keV resonance level may also be indicative of vibrational band structure in the level scheme. Other weak cascades not well resolved in this work are suspected to exist.

The proton reduced widths shown in Table III (γ_p^2) were computed from the relation

$$\gamma_p^2=(A_l^2/2kR)\Gamma_p, \tag{8}$$

where A_l^2 are the Coulomb functions and are taken from the tables of Sharp *et al.*[11] using an assumed nuclear radius of 1.4 $A^{\frac{1}{3}}$ Fermis. s-wave formation for even-parity states and p-wave formation for odd-parity states was assumed. (Small admixtures of d or f waves might increase the computed reduced-widths by, at most, factors of 2 or 3.) The reduced widths were also expressed in single-particle units, $\hbar^2/MR^2$, where M is the proton reduced mass and R is the nuclear radius, and are listed under θ_p^2. The θ_p^2 are consistent with the average result $\theta_p^2\gg7\times10^{-5}$ for Ca^{40} found by Clarke *et al.*[15] in a study of levels excited by (p,α) reactions.

An estimate of the reduced widths γ_p^2 can be obtained through the relation[16]

$$\gamma_p^2\approx D/\pi KR, \tag{9}$$

where D is the spacing of levels formed by an incoming proton of given orbital angular momentum, and K is the proton wave number inside the nucleus (taken as 10^{13} cm^{-1}). For a 1^+ assignment (s capture) for the 1575.5-keV level, the γ_p^2 derived from Eq. (8) would require $D\approx150$ keV. A 1^- assignment (p capture) would require $D\approx520$ keV. Clarke *et al.*[15] derive a value $D<240$ keV for $J=0$ levels at 10.3-MeV excitation in Ca^{40}. If one assumes, as they do, that the level spacing varies as $(2J+1)^{-1}$, their result leads to $D<80$ keV for $J=1$ levels. By this argument, therefore, the 1^+ assignment is favored for the 1575.5-keV resonance level.

If one could consider jj coupling a reasonable description of the formation of the 1575.5-keV resonance level, then additional support for a 1^+ assignment would exist in the observed angular distribution of the ground-state radiation. Approximately equal amounts of channel spins 1 and 2 are predicted by jj coupling[16] whether the total angular momentum (spin plus orbital momentum) of the incoming proton is 1/2 or 3/2. Inspection of Fig. 6 shows that for a 1^- assignment and pure p-wave formation, a channel-spin ratio of 9 or greater is required. For a 1^+ assignment, any channel-spin ratio between 0 and 7 and about a 4% admixture of d wave to pure s-wave formation gives a good fit. A 4% admixture is just about what would be expected on the basis of relative penetrabilities of s- and d-wave protons.

The upper limits on the alpha-particle widths Γ_α shown in Table III are computed from the relation

$$\sigma(p,\alpha)=2\pi\lambda_p^2[(2J+1)/(2I+1)](\Gamma_p\Gamma_\alpha/\Gamma_t^2), \tag{10}$$

and the measured upper limit on the cross section, $\sigma(p,\alpha)\leqslant68$ μb. For K^{39} the barrier penetrability strongly favors the proton width over the alpha-particle width

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[16] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952) Chap. VIII, p. 390.

at the excitation energy of this experiment, so the assumption $\Gamma_p \approx \Gamma_t$ is used.

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4.48-MeV Level of Ca^{40}†*

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The reaction $Ca^{40}(\alpha,\alpha'\gamma)$ was studied using particle-gamma coincidence techniques and the 22-MeV alpha-particle beam from the Indiana University cyclotron. The 4.48-MeV level of Ca^{40} is observed to decay strongly to the 3.73-MeV 3^- level. An upper limit of 5% is placed on the intensity of the ground-state transition. The weakness of the ground-state transition is strong evidence against a 1^- assignment for the 4.48-MeV level. This result, together with other data, indicates that the 4.48-MeV level is 5^-.

I. INTRODUCTION

During the past few years several different spin and parity assignments have been made for the 4.48-MeV level of Ca^{40}. A 1^- assignment was suggested by the $Ca^{40}(\alpha,\alpha')$, $E_\alpha = 43$ MeV, angular distribution and $Ca^{40}(\alpha,\alpha'\gamma)$ particle-gamma angular correlation measurements of Shook.[1] The $Ca^{40}(\alpha,\alpha')$, $E_\alpha = 44$ MeV, angular distribution measurements of Saudinos *et al.*[2] indicated a 5^- assignment but did not exclude 1^-. The $Ca^{40}(p,p'\gamma)$, $E_p = 150$ MeV, particle-gamma angular correlation measurements of Rowe *et al.*[3] yielded a 3^- assignment. The present experiment was undertaken to help determine the spin and parity of the 4.48-MeV level.

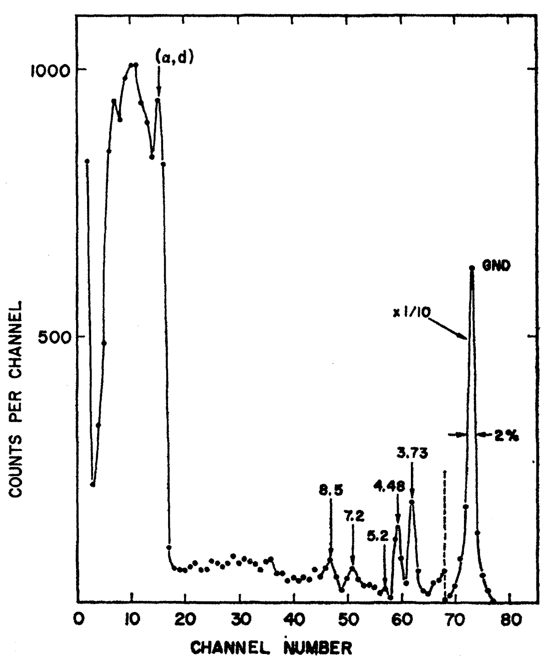

FIG. 1. Charged particle spectrum from the bombardment of a 0.5-mg/cm² natural calcium foil with 22-MeV alpha particles. $\theta_{lab} = 32\frac{1}{2}$ deg.

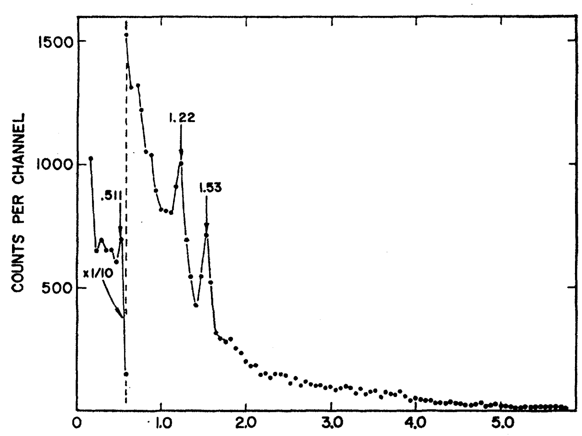

FIG. 2. Single-crystal gamma-ray spectrum from the bombardment of a 0.5-mg/cm² calcium foil with 22-MeV alpha particles. $\theta_\gamma = 90$ deg.

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