Table 1
Results of this paper and ref. [4]

$$W = \frac{\text{number of } \pi^- \text{ interacting with hydrogen}}{\text{number of } \pi^- \text{ stopped in the target}}$$

Target	$\pi^0/10^3$ stopped π^-	$W \times 10^3$ (this paper)	$W \times 10^3$ (ref. [4])
H_2	594 ± 48	974 ± 79	-
LiH	24 ± 2	39 ± 3	13.9 ± 1.5
CH_2	8.5 ± 0.7	13.9 ± 1.1	4.4 ± 0.4
CH	3.3 ± 0.3	5.4 ± 0.5	1.7 ± 0.2

determined by measuring the yield of γ rays relative to hydrogen. We have the impression that the discrepancy comes from the determination of the number of pions stopped in the hydrogen target.

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THE SPINS OF THE SECOND, THIRD AND FOURTH EXCITED STATES IN Ca^{40}

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The four lowest excited states in Ca^{40} are known [1] to occurr at E_x = 3.351, 3.730, 3.900 and 4.483 MeV. These levels will be denoted as (1), (2), (3) and (4), respectively.

Level (1), with $J^\pi = 0^+$, decays by interval pair formation [1]. Levels (2) and (3) decay by ground-state γ transitions [1], whereas level (4) decays in a cascade through level (2) ($\gamma_0 < 5\%$, γ_1 and $\gamma_3 < 10\%$)[2].

Information on the spins and parities of levels (2), (3) and (4) has been obtained from electron [1], proton [1,3] and α-particle [1] inelastic scattering angular distribution measurements, and from p'-γ [1,2] and α'-γ [1] angular correlation measurements. The results are $J^\pi = 3^-$, (2^+) and $(1,3,5)^-$ for levels (2), (3) and (4), respectively. All of these assignments depend on the model assumed for the reaction mechanism, which makes it difficult to assess their uniqueness. In general, energy resolution has been insufficient to separate the particle groups leading to levels (2) and (3).

In the present investigation unique spin values of J = 3, 2 and 5 are found for levels (2), (3) and (4), respectively, from γ-γ angular correlation measurements, using the $K^{39}(p,\gamma)Ca^{40}$ reaction.

Protons were accelerated with a 3 MeV Van de Graaff generator. Gamma radiation was detected with two cylindrical NaI scintillation crystals (10 cm long, 10 cm diameter). The target material was K_2SO_4 evaporated onto tantalum backings.

Some twelve resonances were observed in the E_p = 1.0 - 2.8 MeV region. A detailed account of their energies and decay properties will appear elsewhere. The resonances at E_p = 1.105 MeV (weak, and unobserved in previous work[1,4]), 1.309 MeV (one of a triplet with components at E_p = 1.309, 1.310 and 1.315 MeV), 1.348 MeV and 2.045 MeV were used in the work reported below.

From γ-ray single spectra and γ-γ coincidence spectra it was found that both the 1.105 and 1.309 MeV resonances decay through relatively strong fourfold cascades involving Ca^{40} levels at 6.26±0.03, 4.48 and 3.73 MeV (see fig. 1). The angular correlation was measured of the 0.75 - 3.73 MeV γ-ray cascade de-exciting the 4.48 MeV level. The measurements were performed in four different geometries [5]. Coincidence contributions from unwanted cascades were subtracted by using two additional differential discriminators set on pulse-height regions just above the photo-peaks of the 0.75 and 3.73 MeV γ rays [6].

The results were analysed [5,6], for different spin combinations of levels (4) and (2), by considering the multipole mixing of the 0.75 MeV γ ray, and the population probabilities of the magnetic substates of level (4) as unknown parameters, to be determined by least-squares calculus. The spin values tried were $J(4)$ = 0 through 5, $J(2)$ = 1, 2 and 3, with the restriction $|J(4) - J(2)| \leq 2$. A χ^2 criterion was used to select possible solutions. As a first step, the sum of the coincidence counting

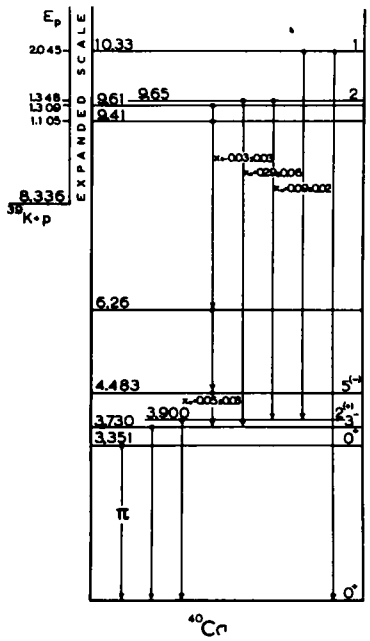

Fig. 1. Energy levels of Ca^{40}. Levels not pertinent to the present work have been omitted. The γ-ray branching of the resonance levels is more complicated than indicated.

rates measured at the two resonances was analysed.

The only spin combination yielding a small χ^2 value (below the 0.1% probability limit [5]) is $J(4) = 5$, $J(2) = 3$. The octupole-dipole amplitude mixing ratios obtained for the (4) → (2) transition at the two resonances, when analysed separately, agree within the experimental error. The average value is $x = +0.05 \pm 0.03$.

The strong 2.045 MeV resonance mainly decays with a ground-state transition, but it also shows a 3% cascade through level (3). Level (2) is not excited ($\gamma_2 < 0.2\%$). From the γ_0 angular distribution and the (r) → (3) → (0) angular correlation (r denoting the resonance state) one obtains, with the procedure outlined above, as the only possible spin combination $J(r) = 1$, $J(3) = 2$. The (r) → (3) transition is mainly dipole ($x = +0.09 \pm 0.02$). The resonance formation parameters (the mixing ratios for channel spin and for proton orbital momentum) are underdetermined. Almost pure s capture in the 1^+ channel (for $J^\pi(r) = 1^+$), or pure p capture mainly in the 2^+ channel (for $J^\pi(r) = 1^-$), would both explain the observed resonance population probabilities $p(0) = 0.38 \pm 0.01$, $p(1) = 0.62 \pm 0.01$.

The results obtained at the 1.348 MeV resonance only confirm the $J = 2$ assignment to level (3). The resonance decays by strong cascades through both levels (2) and (3). The contributions of the 3.73 and 3.90 MeV γ rays were separated by analysing the coincidence pulse spectra measured at different combinations of counter positions. Using $J(2) = 3$, the only possible spin combination yielding a low χ^2 value is $J(r) = 2$, $J(3) = 2$. The mixing ratios found for the (r) → (2) and (r) → (3) transitions are $x = -0.03 \pm 0.03$ and $x = +0.29 \pm 0.06$, respectively. The resonance population probabilities, as obtained from the two cascades, agree within the experimental error. The average values are $p(0) = 0.11 \pm 0.04$, $p(1) = 0.37 \pm 0.08$, $p(2) = 0.52 \pm 0.05$. For $J^\pi(r) = 2^-$, pure p capture (60% in the 1^+ channel, 40% in the 2^+ channel) explains these values. For $J^\pi(r) = 2^+$, the formation fit is more difficult. Pure s capture in the 2^+ channel comes closest, yielding $p(0) = 0.2$, $p(1) = 0.4$, $p(2) = 0.4$.

The measured mean life [1] of level ($\overline{2}$), together with the knowledge of the spin, determines the parity as odd ($J^\pi = 3^-$). The parities of levels (3) and (4) remain undetermined from the present work. Very probably level (3) can be identified with the low 2^+ state found in all even-even nuclides. Level (4) could well be the lowest 5^- state predicted in recent theoretical work [7].

Assignments of 2^+ to level (3) and of 2^- to the 1.348 MeV resonance level would imply E1 - M2 mixing in the (r) → (3) transition. From the measured mixing ratio, combined with estimates of the resonance thick target yield and the cascade branching percentage, one would obtain $|M^2| = 8$ for the ratio of the M2 radiation width to the single particle width. Because of this high value, although perhaps not quite impossible, one would be inclined to favour a 2^+ assignment to the 1.348 MeV resonance.

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