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States in ^{40}Ca near 12 MeV Excitation from the ^{39}K(p, γ)^{40}Ca Reaction

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Abstract

Measurements of the ^{39}K(p, γ)^{40}Ca reaction in the region near 12 MeV show that none of the four resonances observed between 12·03 and 12·09 MeV excitation energy in ^{40}Ca has $J^{\pi} = 0^{+}$. If one of these states corresponds to the $\Delta l = 0$ transition seen in the high energy (p, p′) reaction at an excitation energy of 12·06±0·02 MeV, this suggests that the spin and parity of this state are 1^{+}.

1. Introduction

There have been some conflicting results observed in experiments studying the region around 12 MeV excitation energy in ^{40}Ca. For example, in (p, p′) studies at a bombarding energy of 201 MeV and at very forward angles which select only a few states, Crawley *et al.* (1982) and Anantaraman *et al.* (1981 and personal communication) noted a state at 12·063±0·015 MeV which has a $\Delta l = 0$ angular distribution and a strength similar to the known 1^{+} state at 10·32 MeV. However, in measurements of electron inelastic scattering at backward angles, carried out with good resolution, Steffen *et al.* (1980) and Gross *et al.* (1979) claimed no state with any measurable strength at an excitation energy near 12 MeV.

At least three explanations are possible. First, the state could be 0^{+} which would explain the $\Delta l = 0$ angular distribution and its absence in (e, e′) studies. However, the only 0^{+} state seen by Debevec (1972) and Adelburger *et al.* (1972), near this excitation energy in the ^{42}Ca(p, t)^{40}Ca reaction, is the $T = 2, 0^{+}$ state at 11·970±0·012 MeV which should not be excited in the (p, p′) reaction. Second, the state could be 1^{+}, but with cancellation between orbital and spin terms in the M1 operator, which could reduce the strength in (e, e′) yet would not affect the strength observed in (p, p′), since (p, p′) involves only a spin-flip term in the effective interaction. Third, while a 1^{-} state would usually show a $\Delta l = 1$ angular distribution, a 1^{-} state could in principle be excited by the Coulomb interaction. The angular distribution for such Coulomb excited E1 transitions is predicted to resemble $\Delta l = 0$. However, it has been shown recently by Djalali *et al.* (1983) that 1^{-} states are very weakly excited in (p, p′) at 201 MeV in neighbouring $N = 28$ nuclei, so that the B(E1) would have to be very large for the state to have such a large cross section in (p, p′). If the (p, p′) cross section for Coulomb excitation of this state is calculated with the code ECIS (Berg *et al.* 1981), the B(E1) value obtained is $8 \cdot 7 \times 10^{-2}\, e^2\,\mathrm{fm}^2$, corresponding to a

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decay width Γ_0 of 160 eV. By comparison, the strongest 1^- state observed by Raynal (1981 and personal communication) in a (γ, γ') experiment on ^{52}Cr had a B(E1) value about ten times smaller.

In order to cast further light on this situation, we have carried out (p, γ) and $(p, p'\gamma)$ measurements on ^{39}K to study states in ^{40}Ca in the region of excitation energy near 12·06 MeV. Two previous measurements of this reaction have been reported, in both of which NaI crystals were used to detect the γ rays. In the earlier measurement, Bartko and Thwaites (1968), using a natural KI target, reported only one level in this region, at 3·863 MeV (with E_x = 12·099 MeV, calculated by the authors using Q = 8·333 MeV). In the second measurement, with enriched ^{39}KI and ^{39}KBr targets, Heimlich and Mausberg (1970) reported levels at 3·850 MeV (E_x = 12·083 MeV) and 3·880 MeV (E_x = 12·113 MeV). Only the lower of these two values could possibly overlap the energy of the state observed in (p, p'). The proton energy region surveyed in the present experiment was from 3·79 to 3·85 MeV, corresponding to excitation energies in ^{40}Ca from 12·03 to 12·09 MeV. All energies quoted in the present paper were calculated from a Q value of 8·330 MeV as listed in the recent mass tables of Wapstra and Bos (1977, 1982).

2. Experimental Details and Results

A target of KI was used in the experiment, with the K enriched in ^{39}K to 99%. The target preparation procedure involved conversion of KCl to KI and then evaporation on to a clean Ta backing. The backing was cooled by a stream of liquid freon flowing across the back surface of the Ta during bombardment. With this cooling a beam current of about 400 nA could be used without target deterioration. The target thickness was determined from a measurement of the experimental width of the 2·043 MeV resonance peak in ^{39}K$(p, \gamma)^{40}$Ca. The thickness of the target used in the final experiment was 5·0±0·5 keV. The γ rays were detected by a 120 cm^3 Ge(Li) detector placed about 2 cm from the target. For the full energy γ rays, all counts above the double escape peak were summed. For the other γ rays, the sharp full energy peak was used. Data points were taken in one run in 5 keV steps, and then in a second run also in 5 keV steps but displaced by 2·5 keV. Excellent consistency was found between the two runs.

A γ-ray spectrum at a bombarding energy of 3·835 MeV is shown in Fig. 1. The full energy γ ray at 12·06 MeV is seen together with γ rays corresponding to decays of broad underlying resonances through the 3^- and 2^+ states at 3·736 and 3·904 MeV respectively, as well as strong (p, p') γ rays and many low energy γ rays. Since the state of interest was observed strongly in a high-energy proton scattering experiment, which presumably occurs by a one-step direct process, the matrix element connecting the wavefunction of the 12·06 MeV state with the ground state of ^{40}Ca through a one body operator should be large. Since this state must also have low spin, it should decay preferentially to the low lying states of ^{40}Ca. Therefore we studied the resonances observed in (p, γ) to the 0^+ ground state, the 2^+ state at 3·904 MeV and the 3^- state at 3·736 MeV in ^{40}Ca, as well as γ rays from (p, p') to the first excited state of ^{39}K.

The energies of the observed resonances were determined from a calibration based on two independent methods. The first used the energy of a well determined resonance at 2042·8±1·5 keV (Cheng *et al.* 1981) and the second used the energies of the ground state γ-ray transitions, corrected for Doppler shift. The two methods gave resonance energies which agreed within the uncertainties. The resonance strengths S were obtained by comparison with the strength ($S = 14\cdot3\pm1\cdot5$ eV) of the $2\cdot043$ MeV resonance which had been accurately determined by Paine and Sargood (1979).

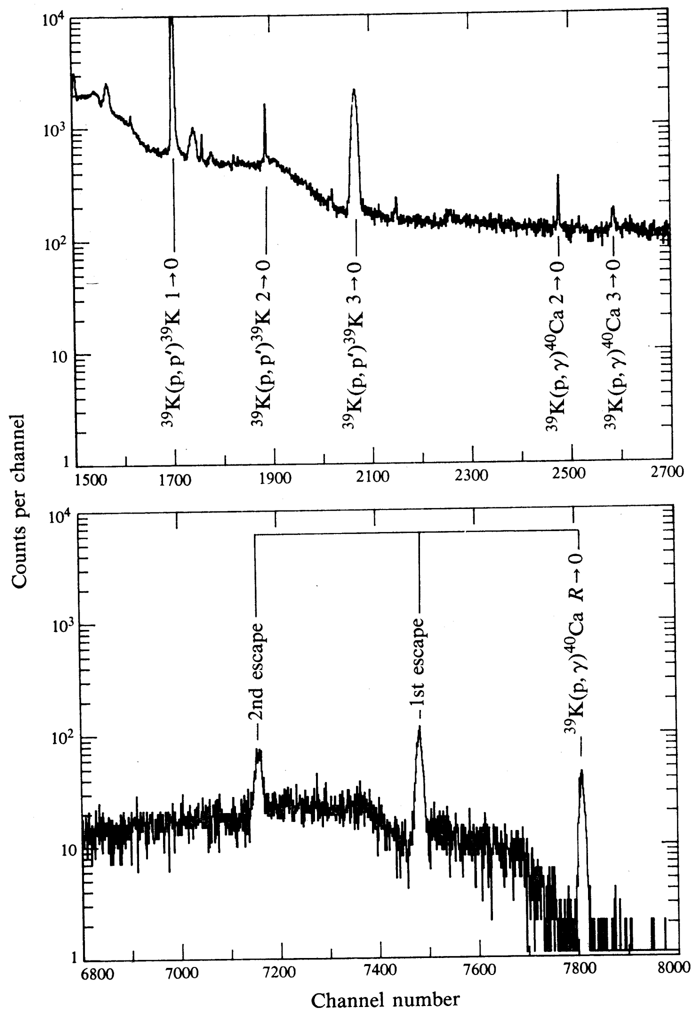

Fig. 1. Two sections of the Ge(Li) detector spectrum. All peaks corresponding to ground state transitions in ^{39}K(p, γ)^{40}Ca and ^{39}K(p, p$'\gamma$)^{39}K lie within the regions shown. The unlabelled peaks in the lower region are either escape peaks corresponding to labelled transitions or background peaks.

Four sharp resonances were observed in the R → 0 channel in the region studied (see Fig. 2). Their energies, and the corresponding excitation energies in ^{40}Ca, are listed in Table 1. The resonance strengths corresponding to the particular channels mentioned above are also given in Table 1. Also shown in Fig. 2 are the excitation functions of the other channels observed.

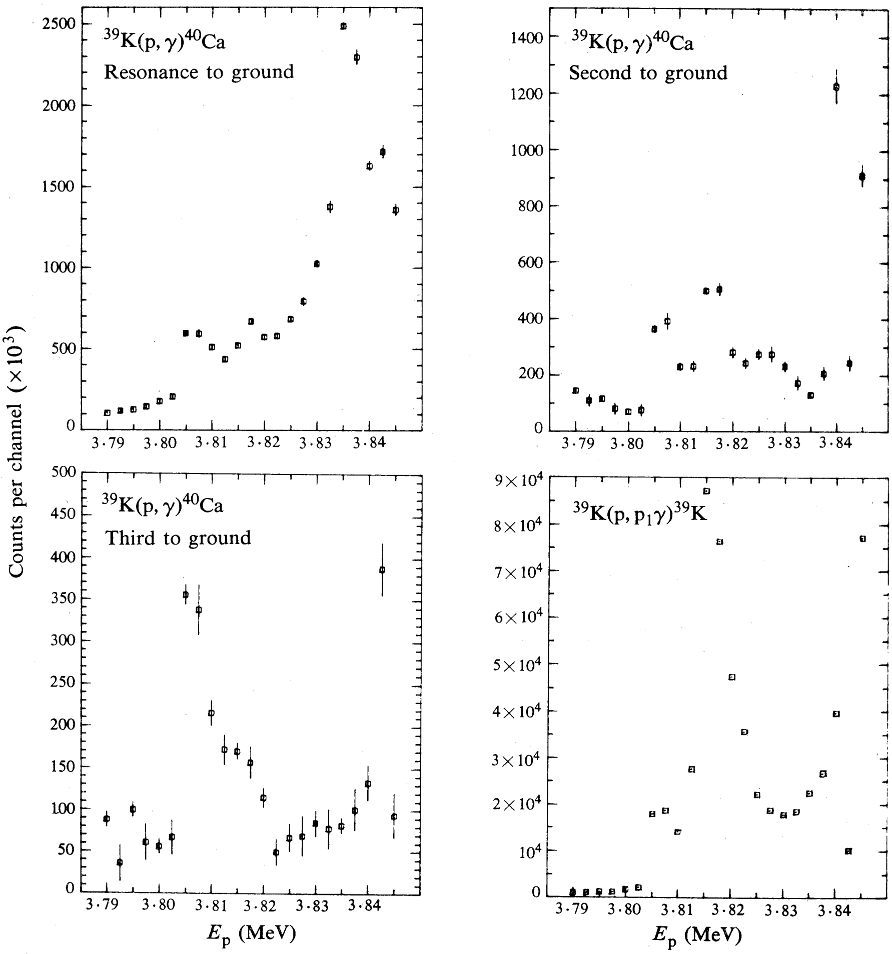

Fig. 2. Excitation function of the R → 0, 2 → 0 and 3 → 0 γ-ray transitions in ^{40}Ca, and the ^{39}K(p, p$_1$ γ)^{39}K reaction. Four resonances are observed in the R → 0 channel.

Table 1. Resonances in ^{40}Ca near 12·06 MeV

E_p^A (MeV)	$E_x(^{40}Ca)$^A (MeV)	Resonance strength (eV) R → 0^+g.s.	$2^+ \rightarrow 0^+$g.s.	$3^- \rightarrow 0^+$g.s.	(p, p$_1$)
3·804	12·038	0·9±0·4	1·0±0·5	2·3±0·8	70±30
3·815	12·049	0·7±0·3	1·2±0·6	0·5±0·2	660±130
3·834	12·068	9±3	—	—	—
3·841	12·074	0·7±0·3	1·5±0·6	1·1±0·5	30±17

^A All energies are to within ±0·003 MeV.

3. Discussion

While one of the resonances is not observed in some of the reactions, since all four resonances are observed to decay by γ emission to the 0^+ ground state of ^{40}Ca, this demonstrates unambiguously that none of these resonances has $J^\pi = 0^+$. Thus, if the state observed in the 201 MeV (p, p′) reaction at 12·06 MeV is one of the four resonances seen between 12·03 and 12·09 MeV, we can conclude definitely that its J^{π} is not 0^{+}. The resonance which comes closest in energy to the 12·06 MeV state is the one at 3·834 MeV (E_x = 12·068 MeV). This resonance has a decay pattern similar to that of the known 1^{+} state in ^{40}Ca at 10·32 MeV (E_p = 2·043 MeV) which has a dominant γ decay to the ground state and a rather small (19·8 eV) proton width for decay to the ground state of ^{39}K (Moreh *et al.* 1982). The only decay mode observed to be resonant at 12·068 MeV is the direct to ground state γ ray. Since the high-energy (p, p′) results imply that the state at 12·06 MeV has $J^{\pi} = 0^{+}$ or 1^{+}, the γ decay suggests that it is most likely a 1^{+} state.

The observation of a further high lying 1^{+} state in ^{40}Ca may seem rather surprising in view of the fact that the 1^{+} state at 10·32 MeV has quite a large B(M1) value. An average of three recent measurements (Gross *et al.* 1979; Moreh *et al.* 1982; Burt *et al.* 1982) gives a value of $1\cdot15 \pm 0\cdot05\,\mu_0^2$ for this transition. This is close to the value predicted by recent theoretical calculations (Gross *et al.* 1979; Burt *et al.* 1982) which include up to 4-particle–4-hole components in the ^{40}Ca ground state or $2\hbar\omega$ excitations. These predictions range from 1·37 to $1\cdot47\,\mu_0^2$. However, a calculation by Brown *et al.* (1983), which predicts M1 strengths throughout the Ca isotopes, gives five 1^{+} states between 9·88 and 12·05 MeV. The predicted B(M1) values of 0·38 and $1\cdot45\,\mu_0^2$ for the two known 1^{+} states at 9·87 and 10·32 MeV respectively (Pringle *et al.* 1982) are in fairly good agreement with the measured values. Two of the other 1^{+} states are predicted to have a total summed B(M1) value of $1\cdot17\,\mu_0^2$. If the 12·068 MeV state is 1^{+} with a resonance strength of 9 eV, the $B(\mathrm{M1})\uparrow$ would be $0\cdot44\,\mu_0^2$. Thus, this observation is quite consistent with the calculation of Brown *et al.*

Some additional evidence for a 1^{+} state has been recently seen by Taddeucci *et al.* (1983) in high-energy ^{40}Ca(p, n) data. A peak is observed at $4\cdot3 \pm 0\cdot1$ MeV excitation energy in ^{40}Sc corresponding to a state in ^{40}Ca at $12\cdot0 \pm 0\cdot1$ MeV, which is consistent with the energy of the peak observed in (p, p′) at $12\cdot063 \pm 0\cdot015$ MeV. The shape of the angular distribution of this peak in the (p, n) reaction indicates that it may have some $\Delta l = 0$ strength, which again is consistent with a 1^{+} assignment.

On the other hand, if this state were to have $J^{\pi} = 1^{-}$, the B(E1) would be less than $5\times10^{-3}\,e^2\,\mathrm{m}^{-2}$. This is more than ten times smaller than the value implied for a 1^{-} state from the (p, p′) results. Thus, if the 12·068 MeV state (or any of the other three resonances observed) does correspond to the state seen in high-energy (p, p′), then a J^{π} of 1^{-} can be ruled out.

To summarize: in the ^{39}K(p, γ) reaction, we have observed four resonances in ^{40}Ca in the region from 12·03 to 12·09 MeV excitation energy. One of these resonances is very close in energy to the state at 12·06 MeV observed in a high-energy (p, p′) measurement. All four resonances decay by γ-ray emission to the ground state. Thus, if any one of these resonances corresponds to the 12·06 MeV state, a J^{π} of 0^{+} is excluded. The evidence favours a J^{π} of 1^{+} for this state. Further support for such an assignment is provided by the observation of an analogue state in ^{40}Sc at 4·43 MeV excitation energy which also has a $\Delta l = 0$ angular distribution.

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