Eur. Phys. J. A **6**, 5–8 (1999)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

High-spin states in the $A = 39$ mirror nuclei ^{39}Ca and ^{39}K

Th. Andersson[1], D. Rudolph[1], C. Baktash[2], J. Eberth[3], C. Fahlander[1], D. Haslip[4], D.R. LaFosse[5a], S.D. Paul[2], D.G. Sarantites[5], C.E. Svensson[4b], H.G. Thomas[3], J.C. Waddington[4], W. Weintraub[6], J.N. Wilson[4,5], B.A. Brown[7]

[1] Department of Physics, Lund University, S-22100 Lund, Sweden
[2] Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[3] Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany
[4] Department of Physics and Astronomy, McMaster Univeriesty, Hamilton, Ontario, L8S 4M1 Canada
[5] Chemistry Department, Washington University, St. Louis, MO 63130, USA
[6] Department of Physics, University of Tennessee, Knoxville, TN 37996, USA
[7] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

Received: 18 August 1999
Communicated by D. Schwalm

Abstract. High-spin states of the mass $A = 39$ mirror pair ^{39}K and ^{39}Ca were investigated via the fusion-evaporation reaction ^{28}Si+^{16}O at 125 MeV beam energy. The GAMMASPHERE array in conjunction with the 4π charged-particle detector array MICROBALL and neutron detectors was used to detect γ rays in coincidence with evaporated light particles. The results of the first high-spin study of the $T_z = -1/2$ nucleus ^{39}Ca are discussed in terms of mirror symmetry and compared to spherical shell-model calculations in the $1d_{3/2}$–$1f_{7/2}$ configuration space.

PACS. 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.40.+z $39 \leq A \leq 58$

Experimental data on doubly magic nuclei and nearby neighbours yield important information on the effective nuclear force. In particular, they provide and test single-particle energies and two-body residual interactions used in spherical shell-model calculations. ^{40}Ca is the last stable doubly-magic N=Z isotope. Similar to the nuclei in the vicinity of ^{56}Ni (cf. [1]) nuclei near ^{40}Ca have barely been studied with heavy-ion fusion-evaporation reactions in the past [2]. Here, we present new experimental information on $^{39}_{19}$K and $^{39}_{20}$Ca which have one proton or one neutron hole relative to the N=Z=20 ^{40}Ca core, respectively. Such mirror systems also test the charge symmetry of the nuclear force, as the difference in their level energies should only arise from slight Coulomb energy differences (CED), which can be related to the spatial correlations of the valence particles, i.e., their wave functions. Broken neutron or proton pairs strongly affect the CED, and it is thus important to study them as a function of excitation energy and spin (cf. [3], and references therein).

Previously, high-spin states in ^{39}K were reported up to some 10 MeV excitation energy and spins $I \sim 10\ \hbar$ [4]. In contrast, excited states in ^{39}Ca were investigated only by means of light-ion induced reactions [2]. A 2797 keV $M2$ transition was found to connect the $7/2^-$ ($1f_{7/2}$) single-particle state with the $3/2^+$ ($1d_{3/2}$) ground state. A level at 3640 keV was suggested to have $I^\pi = 9/2^-$. In addition, eight presumably low-spin levels are reported in the most recent data evaluation [2].

The experiment was performed at the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. High-spin states in nuclei near ^{40}Ca were populated using the reaction ^{28}Si+^{16}O at 125 MeV beam energy. The experimental set-up consisted of the GAMMASPHERE array [5], which at that time comprised 83 Ge-detectors. The array was operated in conjunction with the 4π charged-particle detector array MICROBALL [6], and 15 liquid scintillator neutron detectors. The target was a ~ 0.5 mg/cm^2 thin, self-supporting ^{40}Ca$^{\rm nat}$O foil. The natural abundance of ^{16}O amounts to 99.8%. Thus the only measurable reaction cross section with oxygen arises from this isotope. Reactions originating from ^{40}Ca or ^{16}O can be clearly distinguished. Not only do the recoil velocities differ significantly ($v/c \sim 0.034$ and $v/c \sim 0.057$, respectively), but also their total excitation energy, $E_{\rm tot}$, and the average spin of the compound system. The latter affects the γ-ray multiplicity K. To allow for the determination of

---

[a] *Present address:* Department of Physics, SUNY Stony Brook, Stony Brook, NY 11794, U.S.A.

[b] *Present address:* Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.

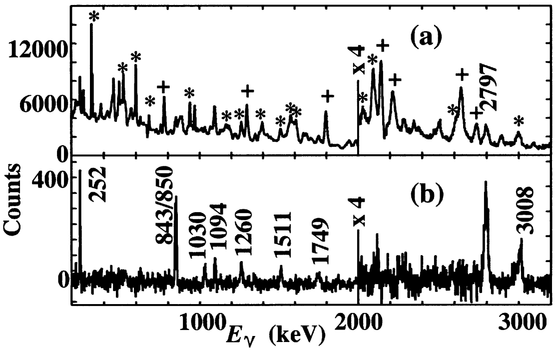

Fig. 1. γ-ray spectra from the reaction ^{28}Si+^{16}O. (**a**) $1\alpha 1n$ gated γ-ray spectrum with contaminations from pure charged-particle evaporation channels substracted. Peaks from ^{37}Ar are marked with a "$*$", those from ^{38}K with a "+". (**b**) The sum of $1\alpha 1n$ gated spectra in coincidence with the 252, 843, 1094, and 2797 keV lines (^{39}Ca). The peaks are labelled with the transition energies in keV

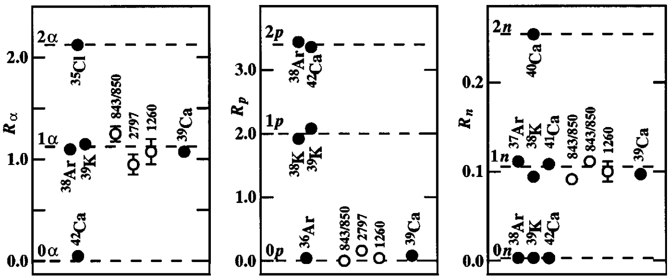

Fig. 2. Ratios of yields R_α, R_p, and R_n of transitions under different particle- and γ-gating conditions. Ratios from known γ-ray cascades in the respective isotopes provide calibration points (filled circles at the left). The ratios of the presumed ^{39}Ca cascade are plotted separately (open circles). They were deduced from spectra γ-gated on the 252 keV line, and are labelled with the transition energy. For R_n, the second point originates from a γ-gate on the 2797 keV transition. Their mean values are plotted as filled circles on the right

K and the released total γ-ray energy, H, the heavimet-absorbers in front of the anti-Compton shields of the Ge-detectors were removed [7]. The sum energy of the evaporated light particles E_{part} were measured (Microball) or estimated (neutron detectors). In a two-dimensional plot of K vs. $E_{\text{tot}} = H + E_{\text{part}}$ the reaction of interest can be selected [8]. The events were then sorted into E_γ projections, E_γ-E_γ matrices, and E_γ-E_γ-E_γ cubes subject to the appropriate evaporated particle conditions. ^{39}K is produced in the $1\alpha 1p$ and ^{39}Ca in the $1\alpha 1n$ channel of the reaction. Protons and α particles were identified and discriminated in the Microball [6]. Neutrons were separated from the γ rays by the combination of pulse-shape analysis of the detector signals and time-of-flight measurements.

Figure 1a shows a γ-ray spectrum gated by one evaporated α and one neutron. Contaminations from pure charged particle channels were eliminated. The channels ^{38}K+ $1\alpha 1p 1n$ and ^{37}Ar+$1\alpha 2p 1n$ dominate the spectrum. They leaked through when the protons escaped detection. Nevertheless, a peak is also visible at the γ-ray energy of 2797 keV. A spectrum in coincidence with this transition, again gated by one α and one neutron, provides additional strong peaks at 252, 843, 850, and 1094 keV. The 843 and 1094 keV transitions were already associated with ^{39}Ca. To rule out any possible doubts of the channel assignment of this sequence, we investigated the intensity ratios $R_p = Y(p\gamma\gamma)/Y(\gamma\gamma)$, $R_n = Y(n\gamma\gamma)/Y(\gamma\gamma)$, and $R_\alpha = Y(\alpha\gamma\gamma)/Y(\gamma\gamma)$. They are shown in Fig. 2. Ratios from known γ-ray cascades provide calibration points (filled circles). The ratios for the cascade of interest are plotted separately (open circles), and with their mean values (filled circles). In summary, the γ rays of interest can be unambiguously assigned to the $1\alpha 1n$ reaction channel ^{39}Ca, consistent with previous results.

In the following, coincidence, intensity, and summed energy relations of γ rays will be discussed. The spectrum in Fig. 1b is the sum of spectra in coincidence with the 252, 843, 1094, and 2797 keV lines. Additional peaks are seen at 1030, 1260, 1511, 1749, and 3008 keV. Together with the sequence mentioned earlier they form the high-spin level scheme of ^{39}Ca, which is shown in Fig. 3b. The small production cross section $\sigma_{\text{exp}} \sim 1$ mb and the necessity to gate on evaporated neutrons prevented us from deducing reliable angular distribution or correlation coefficients. Therefore, the spin-parity suggestions for ^{39}Ca are solely based on the mirror symmetry with states in ^{39}K ($\sigma_{\text{exp}} \sim 200$ mb). The largely extended high-spin excitation scheme of ^{39}K is shown in Fig. 3c. Directional correlations of oriented states $R_{\text{DCO}}(30-83)$ (see [1] for details) were analysed to propose spin and parity assignments for the newly identified states at high excitation energies [9].

In Fig. 3d we compare the results of spherical shell-model calculations (using the code Oxbash [10]) with the experimentally observed levels. We have calculated the excitation energies for ^{39}K (^{39}Ca) within the $d_{3/2}$-$f_{7/2}$ model space, allowing for all possible configurations for seven valence particles. The model space is very truncated with regard to the full sd and full fp configurations. However, here we want to estimate the energies of those states which are formed from the excitation of many particles across the N=Z=20 shell gap. The $d_{3/2}$-$f_{7/2}$ space is the only model space for which such calculations are easily obtainable with existing effective hamiltonians. We investigated the interactions of Sakakura-Arima-Sebe [11] and Hsieh-Mooy-Wildenthal [12] (HMW) and will discuss the results of the latter relative to a zero-particle zero-hole (0p-0h) configuration for the ^{40}Ca ground state. The actual ^{40}Ca ground state with the HMW interaction is 72% 0p-0h. The first excited 0^+ state comes at 4.17 MeV and is 70% 4p-4h.

The calculated wave function for the $3/2^+$ ground state of ^{39}K has a 76% 0p-1h component. The 1p-2h excitation allows for spins up to $13/2^-$. The theoretical $13/2^-$ state at 5.44 MeV (82% 1p-2h) is close to the experimental state at 5.716 MeV. Other states of the 1p-2h multiplet find their immediate correspondence in the

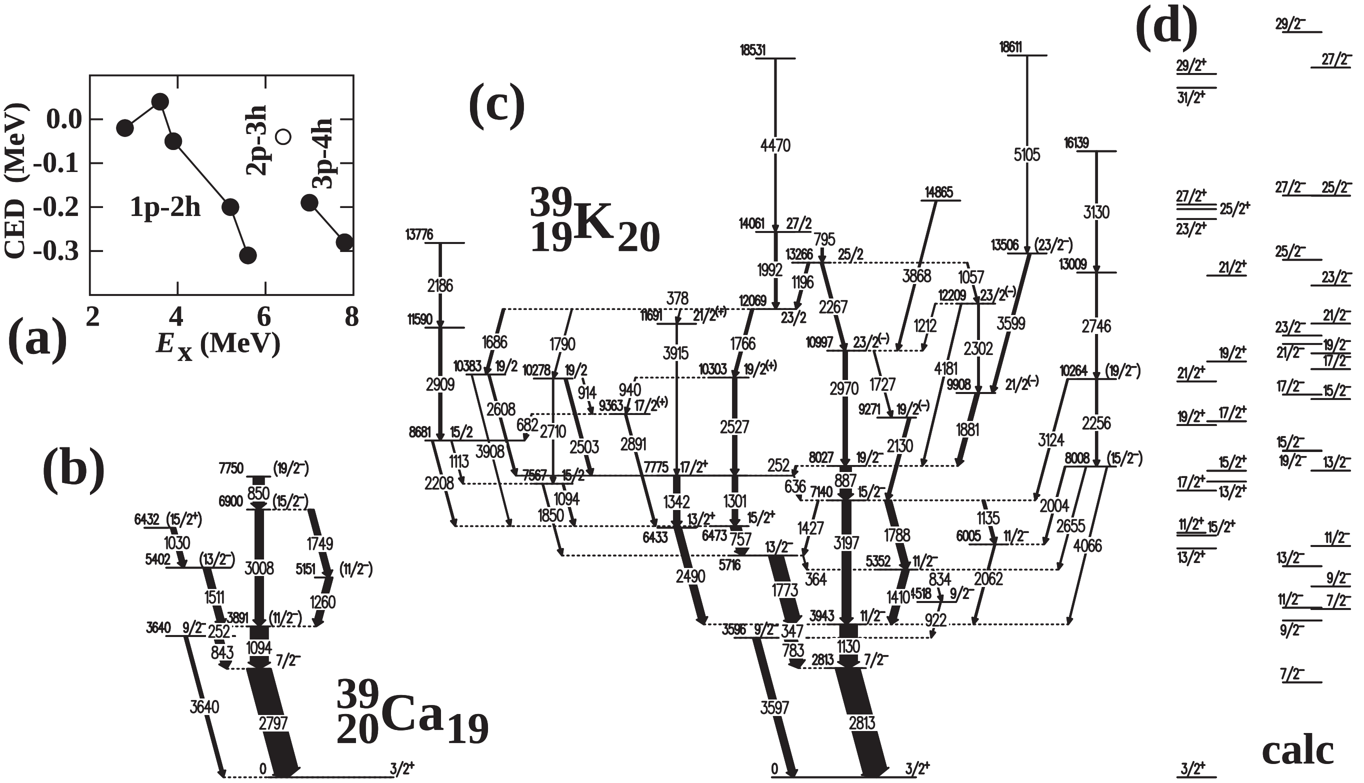

Fig. 3. The Coulomb energy differences (CED) between ^{39}Ca and ^{39}K are plotted as a function of excitation energy E_x (**a**). Note that the $(15/2^+)$ state (open circle) has a small CED. Parts (**b**) and (**c**) illustrate the proposed high-spin level schemes of the two mirror nuclei. The energy labels are given in keV. The widths of the arrows are proportional to the relative intensities of the γ rays. The predictions of shell-model calculations in the $1d_{3/2}$–$1f_{7/2}$ model space are shown on the right (**d**)

level schemes of both A=39 nuclei below 6 MeV excitation energy. The positive parity 2p-3h states reach spin $I^\pi = 21/2^+$. The theoretical $21/2^+$ state at 10.21 MeV (87% 2p-3h) may correspond to the experimental state at 11.691 MeV. Lower members of this configuration include the closely-spaced $13/2^+$-$15/2^+$ states which might be understood as the coupling of the stretched $\pi(f_{7/2})\otimes\nu(f_{7/2})$ 7^+ configuration (which is low-lying in ^{42}Sc) to the K=1/2 component of the ${d_{3/2}}^{-3}$ configuration.

The 3p-4h states again have negative parity with a maximum spin $I = 27/2$. The calculated $27/2^-$ level at 15.00 MeV is 90% 3p-4h. An experimental candidate for this state is at 14.061 MeV. The theoretical lower spin yrast states of this configuration are $15/2^-$ at 8.42 MeV and $19/2^-$ at 8.41 MeV which presumably correspond to the experimental states at 7.140 and 8.027 MeV, respectively. The $19/2^-$ state can be associated with the fully stretched $\pi(f_{7/2})\otimes\nu(f_{7/2})^2$ configuration (known in A=43 nuclei) coupled to the 4h ground state of ^{36}Ar. For higher spins the predicted yrast levels are of 4p-5h (up to $31/2^+$ at 17.78 MeV), 5p-6h (up to $33/2^-$ at 20.74 MeV), or 6p-7h type ($33/2^+$ at 25.40 MeV). Beyond the $d_{3/2}$-$f_{7/2}$ model space states with higher spins can be created most easily by allowing for a hole in the $d_{5/2}$ orbit. They lie some 6 MeV higher in excitation energy.

In Fig. 3a the CED between ^{39}Ca and ^{39}K are plotted as a function of excitation energy. The downsloping trend in the negative-parity states is due to the proton excitations in ^{39}Ca, which lead to lesser and lesser spatial overlap. In contrast, the only known positive parity state is based on a rather symmetric excitation pattern (see above) leading to an almost vanishing difference.

To summarize, we have presented the first high-spin study on ^{39}Ca and extended the known level scheme of ^{39}K beyond the three-particle four-hole excitation scheme. Previous results were confirmed, in particular the assignment of γ-rays to the $T_z = -1/2$ nucleus ^{39}Ca. The level schemes can be understood by shell-model calculations within the $1d_{3/2}$-$1f_{7/2}$ model space. More stringent tests will be provided by lifetime measurements which were recently performed at Euroball.

The authors thank for the support from LBNL and D. Balamuth, S. Freeman, M. Leddy, and C.J. Lister for the neutron detector set-up. This work was supported by the Swedish NFR, the German BMBF [06-OK-862I(0)], the Canadian NSERC, and the U.S. DOE [Grants DE-FG02-96ER40963 (UT), DE-FG05-88ER40406 (WU)]. ORNL is managed by Lockheed Martin Energy Research Corp. for the U.S. DOE under Contract DE-AC05-96OR22464. B.A.B. was supported by the NSF grant PHY-9605207.

References

1. D. Rudolph *et al.*, Eur. Phys. J. **A4**, 118 (1999)
2. P.M. Endt, Nucl. Phys. **A521**, 1 (1990)
3. C.D. O'Leary *et al.*, Phys. Rev. Lett. **79**, 4349 (1997)
4. H.H. Eggenhuisen, L.P. Ekström, G.A.P. Engelbertink, and H.J.M. Aarts, Nucl. Phys. **A305**, 245 (1978)
5. I.-Y. Lee, Nucl. Phys. **A520**, 641c (1990)
6. D.G. Sarantites *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A**381**, 418 (1996)
7. M. Devlin, L.G. Sobotka, D.G. Sarantites, and D.R. LaFosse, Nucl. Instrum. Methods Phys. Res., Sect. A**383**, 506 (1996)
8. C.E. Svensson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A**396**, 228 (1997)
9. Th. Andersson, Diploma thesis, Lund Univ., unpublished
10. B.A. Brown, A. Etchegoyen, W.D.M. Rae, Computer Code OXBASH, MSU Cyc. Lab. Report No. 524 (1986)
11. M. Sakakura, A. Arima, and T. Sebe, Phys. Lett. **61B**, 335 (1976).
12. S.T. Hsieh, X. Ji, R. Mooy, and B.H. Wildenthal, AIP Conference Proceedings 142, 357 (1986)