Eur. Phys. J. A **7**, 147–148 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

New states in ^{44,46}Ar isotopes from deep-inelastic heavy ion reaction studies

B. Fornal[1], R. Broda[1], W. Królas[1], T. Pawlat[1], J. Wrzesiński[1], D. Bazzacco[2], S. Lunardi[2], C. Rossi Alvarez[2], G. Viesti[2], G. de Angelis[3], M. Cinausero[3], D. Napoli[3], J. Gerl[4], E. Caurier[5], F. Nowacki[6]

[1] H. Niewodniczański Institute of Nuclear Physics, 31-342 Kraków, Poland
[2] Dipartimento di Fisica dell'Universitá and INFN Sezione di Padova, 35131 Padova, Italy
[3] INFN Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy
[4] GSI, Darmstadt, Germany
[5] Institut de Recherches Subatomiques, 67037 Strasbourg Cedex 2, France
[6] Laboratoire de Physique Théorique, 67084 Strasbourg Cedex, France

Received: 11 November 1999
Communicated by J. Äystö

Abstract. In-beam γ-rays in neutron-rich *sdfp* shell nuclei, produced in deep-inelastic collisions of ^{48}Ca projectiles on ^{48}Ca target nuclei, have been studied using Ge multidetector array EU-ROBALL III. New yrast states in heavy argon isotopes have been identified.

PACS. 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.40.+z $39 \leq A \leq 58$ – 25.70.Lm Strongly damped collisions

Neutron-rich nuclei close to the N=28 shell gap have recently attracted a particular interest triggered by a possible existence of anomalies in the shell closure. Indeed, the measured half-lives of β-decaying ^{44}S and $^{45-47}$Cl nuclei were found much shorter than those predicted by calculations, which might indicate an unexpected shape transition in that region. On the basis of self-consistent mean-field calculations Werner et al. [1] suggested, that the major N=28 shell gap disappears when approaching Z=16 and the energy surfaces become very soft with close lying and shallow minima corresponding to different deformations.

Some of these exotic nuclei have been investigated using a technique of intermediate-energy Coulomb excitation of radioactive beams. Energies of the 2_1^+ states and B(E2; $0_{g.s}^+ \rightarrow 2_1^+$) values in ^{40,42}S and in ^{44,46}Ar [2] have been measured. Similar study has been performed with the relativistic radioactive ion beam taking advantage of larger cross-sections for Coulomb excitations at those energies [3]. In ^{44}Ar candidates for higher lying excitations: a second 2^+ level and a 4^+ state, were suggested.

In a series of recent experiments we have shown that the yrast spectroscopy of hard-to-reach neutron-rich nuclei, populated in heavy-ion multinucleon transfer reactions (at bombarding energies of ~15% above Coulomb barrier), can be studied very successfully in γ-γ thick target coincidence measurements (e.g. [4,5]). In such deep-inelastic collisions the population of yrast states at moderate spins is strongly favoured.

A possibility to access new nuclei in the N=20–28 neutron-rich region is offered by the ^{48}Ca beam. We performed an experiment at the Tandem accelerator in Laboratori Nazionali di Legnaro bombarding a target of 0.74 mg/cm^2 ^{48}Ca (backed by 40 mg/cm^2 of evaporated ^{208}Pb) with a beam of 140 MeV ^{48}Ca ions. The γ-γ coincidences were collected with the Euroball III array. Fusion-evaporation was a main reaction channel whereas multinucleon transfer processes, leading to nuclei from the vicinity of ^{48}Ca, accounted for less than 1% of the total reaction cross section. Despite this very low production yield investigation of excited states in some of nuclei around ^{48}Ca was possible due to the high resolving power of the Euroball array.

Scheit et al. [2] observed states in ^{44,46}Ar using the intermediate-energy Coulomb excitation method and proposed the 2_1^+ states of ^{44}Ar and ^{46}Ar at 1144(17) keV and 1554(26) keV, respectively.

We searched for these transitions in the $\gamma\gamma\gamma$ prompt coincidence cube from ^{48}Ca + ^{48}Ca reaction by examining the cross coincidence relationship between complementary Ar and Ti reaction products. Double gates set on prompt transitions in ^{52}Ti displayed two γ-rays of 1158.0 keV and 1588.4 keV energy, which were not known previously. The reversed gates showed that both lines are in mutual coincidence and the intensity pattern of prompt yrast transitions from ^{52}Ti isotope observed in coincidence with the 1158 keV and 1588 keV lines indicated clearly that these

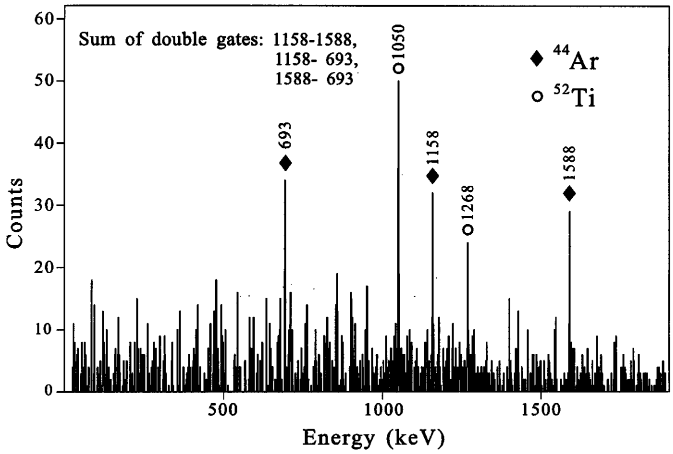

Fig. 1. Coincidence γ-ray spectrum for ^{44}Ar and ^{52}Ti complementary products of the ^{48}Ca (140 MeV) + ^{48}Ca reaction. It was obtained by summing partial spectra associated with different combinations of double gates on ^{44}Ar lines: 1158–1588 keV, 1158–693 keV and 1588–693 keV.

γ-rays occur in the partner nucleus ^{44}Ar. In addition, by setting a double gate on the 1158 keV and 1588 keV lines another 692.9 keV γ-transition in ^{44}Ar was found. A spectrum resulting from the sum of double gates set on the ^{44}Ar lines is shown in Fig. 1. Examination of intensity relations between 1158, 1588 and 693 keV γ-rays settled clearly the ordering of these transitions, which form a cascade connecting states at 1158, 2746 and 3439 keV excitation energy. There is no doubt that a level at 1158 is the 2^+ excitation in ^{44}Ar observed at 1144(17) keV by Scheit et al. The higher state at 2746 is a candidate for the 4^+ excitation. Indeed a level around the same energy was identified at 2.61(16) MeV using the relativistic-energy Coulomb excitation techniques [3] and a 4^+ assignment was suggested for it. Finally, the level at 3439 keV is a perfect candidate for the seniority $2(f^2_{7/2})6^+$ yrast state.

Similar analysis, performed by employing gates set on known prompt γ-rays in ^{50}Ti, displayed a 1577 keV γ-ray from a partner nucleus ^{46}Ar. It is almost certain that this γ-ray is the sought $2^+ \rightarrow 0^+_{g.s.}$ transition observed by Scheit et al. at 1554(26) keV. This finding settles much more accurate energy of 1577(1) keV for the 2^+ excitation in ^{46}Ar.

The systematics of known yrast levels in heavy Ar isotopes, including newly placed excitations is shown in Fig. 2.

Theoretical description of the properties of neutron-rich *sdfp* shell nuclei was undertaken by Retamosa et al. [6] within the shell model framework. Very good agreement between predictions and experimental results on the 2^+ excitation energies and B(E2;$0^+_{g.s.} \rightarrow 2^+_1$) values for ^{40,42}S and ^{44,46}Ar was achieved. A conclusion was drawn that, at N=28 in the very neutron-rich regime the magicity persists, even if somewhat eroded by the large neutron excess.

Our new data on higher excitations in ^{44}Ar offer a more stringent test of these large-scale shell model calculations and interactions used [6]. We have performed such calculations for the ^{44}Ar and ^{46}Ar nuclei and their results are compared with the experimental findings in Fig. 2. The agreement is very good for the 2^+ states and satisfactory for higher lying yrast levels. In addition, in ^{44}Ar, the analysis of calculated spectrum and corresponding E2 transitions shows the appearance of a low lying γ-deformed band (2^+, 3^+, 4^+ triplet), suggesting gamma softness. Further investigations of this behaviour would be welcome. On the other hand, in ^{46}Ar, our data confirm the increase of excitation energy of the first 2^+ level, which is in line with the persistence of magicity at N=28. Such phenomenon is indeed predicted by our calculations.

This work has been supported by the Polish Scientific Committee under grant no. 2P03B-150-10, and by the Italian-Polish collaboration.

References

1. T.R. Werner et al., Phys. Lett. **335B**, 259 (1994).
2. H. Scheit et al., Phys. Rev. Lett. **77**, 3967 (1996).
3. S. Wan et al., Eur. Phys. J. **A6**, 167 (1999).
4. R. Broda et al., Phys. Rev. Lett. **68**, 1671 (1992).
5. B. Fornal et al., Acta Phys. Pol. **B26**, 357 (1995).
6. J. Retamosa et al., Phys. Rev. **C55**, 1266 (1997).

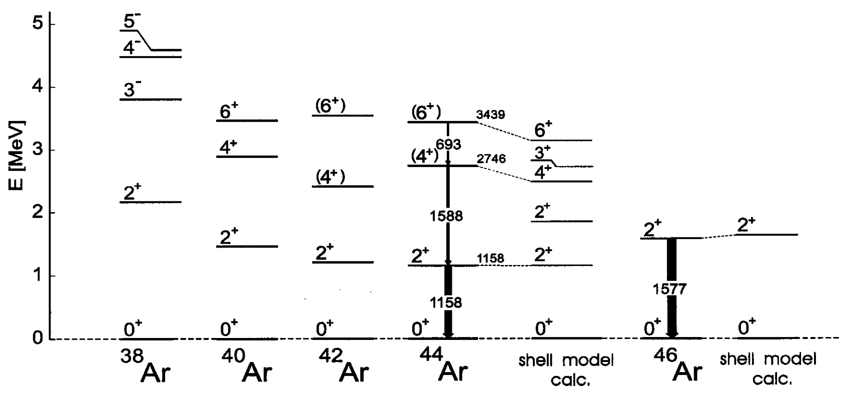

Fig. 2. Systematics of yrast states in neutron-rich Ar isotopes. Arrows indicate the transitions observed in this work. For ^{44}Ar and ^{46}Ar the experimental data are compared with the results of the shell model calculations.