Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 4

SPECTROSCOPY AROUND ^{36}Ca*

A. Bürger[a], F. Azaiez[b], M. Stanoiu[c], Zs. Dombrádi[d], A. Algora[d]
A. Al-Khatib[a], B. Bastin[e], G. Benzoni[f], R. Borcea[g]
Ch. Bourgeois[b], P. Bringel[a], E. Clément[h], J.-C. Dalouzy[i]
Z. Dlouhý[j], A. Drouart[h], C. Engelhardt[a], S. Franchoo[b]
Zs. Fülöp[d], A. Görgen[h], S. Grévy[i], H. Hübel[a], F. Ibrahim[b]
W. Korten[h], J. Mrázek [j], A. Navin[i], F. Rotaru[g]
P. Roussel-Chomaz[i], M.-G. Saint-Laurent[i], G. Sletten[k]
D. Sohler[d], O. Sorlin[i], Ch. Theisen[h], C. Timis[l], D. Verney[b]
S. Williams[l]

[a]Helmholtz-Institut für Strahlen- und Kernphysik, Univ. Bonn, Germany
[b]Institut de Physique Nucléaire, IN2P3-CNRS, Orsay, France
[c]GSI, Darmstadt, Germany
[d]Institute of Nuclear Research, Debrecen, Hungary
[e]Laboratoire de Physique Corpusculaire, Caen, France
[f]Università degli studi e INFN sezione di Milano, Italy
[g]IFIN-HH, Bucharest-Magurele, Romania
[h]DAPNIA/SPhN, CEA Saclay, France
[i]GANIL, Caen, France
[j]Nuclear Physics Institute of ASCR, Řež, Czech Republic
[k]Niels Bohr Institute, University of Copenhagen, Denmark
[l]Department of Physics, University of Surrey, UK

(Received October 30, 2006)

An experiment was performed to study excited states in neutron-deficient nuclei around Ca. After a first fragmentation of the primary beam, the one-neutron knockout reaction was used to produce ^{36}Ca ions from the ^{37}Ca secondary beam and in-beam γ rays were measured. The energy of the first excited 2^+ state in ^{36}Ca and the cross section for the 1-neutron knock-out reaction from ^{37}Ca at $\approx 45\,A$ MeV were obtained. The 2^+ energy in ^{36}Ca is compared to the mirror nucleus ^{36}S to deduce information on the isospin dependence of the nuclear force near the proton drip line. Furthermore, for two other $T_z = -2$ nuclei, ^{28}S and ^{32}Ar, the deexcitation of the first 2^+ states has been observed.

PACS numbers: 21.10.–k, 23.20.Lv, 27.30.+t

---

* Presented at the Zakopane Conference on Nuclear Physics, September 4–10, 2006, Zakopane, Poland.

In recent years, the structure of extremely neutron- or proton-rich nuclei has been studied intensively, both theoretically and experimentally. In this context, the aim of the present experiment was to measure the excitation energy of the first 2^+ state in ^{36}Ca and compare it to its mirror nucleus ^{36}S. In the ground state of ^{36}S, the $\pi d_{5/2}$ and $s_{1/2}$ as well as the $\nu d_{3/2}$ orbitals are completely filled. In ^{36}Ca, the same orbitals are occupied with neutron and proton shells exchanged. Due to the tensor interaction between the neutrons in the $d_{3/2}$ orbital and the protons in the spin–orbit partner orbitals $d_{5/2}$ and $d_{3/2}$, the $\pi d_{5/2}$ orbital becomes more bound whereas the $\pi d_{3/2}$ orbital becomes less bound while the $\nu d_{3/2}$ shell being filled [1]. Therefore, filling the $\nu d_{3/2}$ shell enlarges the gaps between the $\pi s_{1/2}$ and $\pi d_{3/2}$ levels or between the $\pi s_{1/2}$ and $\pi d_{5/2}$ levels, as illustrated in Fig. 1. These shifts lead to high excitation energies for the first 2^+ states in both ^{36}S and ^{34}Si. These excitation energies are comparable to the 2^+ energy in ^{40}Ca which has been interpreted as a sign of a spherical rigidity. For ^{36}Ca, the mirror nucleus of ^{36}S, the same picture should apply with protons and neutrons exchanged, so that also in this case a high excitation energy can be expected for the 2^+ state.

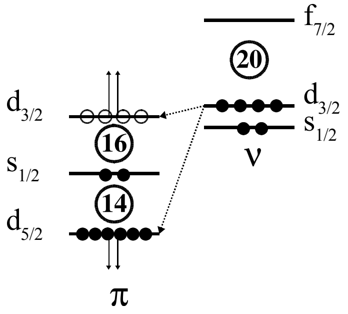

Fig. 1. Illustration of the effect due to the filling of the $\nu d_{3/2}$ orbital in ^{36}S: the tensor interaction shifts the $\pi d_{3/2}$ level up and the $\pi d_{5/2}$ level down in energy.

The experiment was performed at GANIL in Caen, France. The two-step fragmentation technique was used [2] to populate excited states in ^{36}Ca. A primary beam of ^{40}Ca with an energy of 95 A MeV was fragmented on a carbon foil in the SISSI target device [3]. The Alpha spectrometer, optimised for ^{37}Ca or, in a different setting, for ^{36}Ca, was used to purify the resulting beam cocktail with the help of a degrader. Event-by-event identification of the beam particles was achieved using a time measurement between the high frequency of the accelerator and the time signal from a CATS detector [4], that was placed just in front of the secondary target. In the secondary target, a ^{9}Be foil of 200 mg/cm^2 thickness, further nucleons were removed at energies between 60 A MeV before and 35 A MeV after the target. Behind the secondary target, the produced fragments were identified through time-of-flight, $B\rho$ and energy-loss measurements in the SPEG spectrometer [5]. For some settings, suppression of the secondary beam in the focal plane necessitated the placement of an additional slit in SPEG.

Gamma-ray energies were measured with the *Château de Cristal*, an array of 74 BaF_2 detectors [6], that was placed around the Be target. The γ-ray detectors were calibrated using a ^{22}Na source as well as separated and sufficiently intense known transitions in the nuclei ^{28}Si, ^{32}S, ^{34}Ar, ^{29}Si and ^{33}Cl, which were also produced in the secondary target from different beam components. For the Doppler correction of γ-ray energies from in-flight decays, the momentum measured in SPEG was used, assuming that the decays took place in the middle of the target. An add-back procedure was applied to reconstruct energies of Compton-scattered γ-rays. Gamma-ray spectra for the three nuclei ^{36}Ca, ^{32}Ar and ^{28}S are shown in Fig. 2. The energy of the 2^+ state in ^{36}Ca was determined to be $E(2^+) = 3036(11)$ keV, in agreement with the value measured at GSI in a similar experiment [7]. The estimated $E(2^+)$ for ^{28}S and ^{32}Ar are 1525(30) keV and 1873(20) keV, respectively, in agreement with [8].

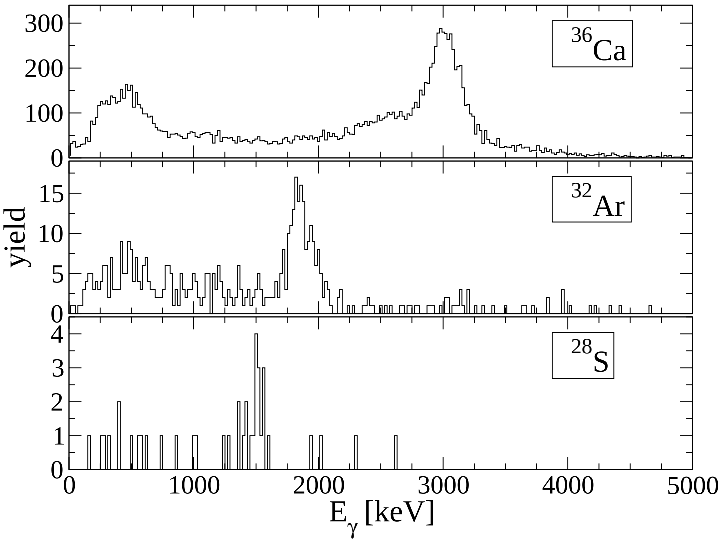

Fig. 2. Gamma-ray spectra for the nuclei ^{36}Ca, ^{32}Ar and ^{28}S. The energies of the 2^+ states have been determined to be 3036(11) keV, 1873(20) keV and 1525(30) keV, respectively.

The measured value for the energy of the first 2^+ state in ^{36}Ca is 255 keV lower than that in the mirror nucleus, ^{36}S. This is, besides ^{14}C–^{14}O where the difference is 422(11) keV, one of the largest mirror energy differences observed so far for first excited 2^+ state. Qualitatively, this might be explained as the combined effect of: *(i)* an almost pure neutron nature of the 2^+ state in ^{36}Ca due to the $Z = 20$ gap, *(ii)* an almost pure proton nature of the 2^+ state in ^{36}S due to the $N = 20$ gap, *(iii)* the almost pure 1-particle 1-hole configurations of the 2^+ states in ^{36}Ca and ^{36}S due to the large $N, Z = 16$ gaps, and *(iv)* the Coulomb energy difference between proton and neutron s and d states.

Figure 3 shows the momentum distribution for ^{36}Ca in comparison with calculated momentum distributions [9–11] as expected for neutron knock-out from the valence orbitals $d_{3/2}$ and $s_{1/2}$. The width of the inclusive experimental momentum distribution fits well to the neutron knock-out from a $d_{3/2}$ state. From the integral of the extrapolated distribution, the number of ^{36}Ca ions was determined. Using the number of incident ^{37}Ca ions and the target thickness, a preliminary experimental cross section for the one-neutron removal $^{37}\text{Ca}\rightarrow{}^{36}\text{Ca}$ of 5.3 (20) mb was obtained, while the calculated cross section is 18.6 mb assuming a knock-out from $\nu d_{3/2}$. The quenching to $\approx 30\,\%$ of the calculated value is similar to what has been found in the case of one-neutron knockout from ^{32}Ar, a nucleus which has a similarly large neutron separation energy [12].

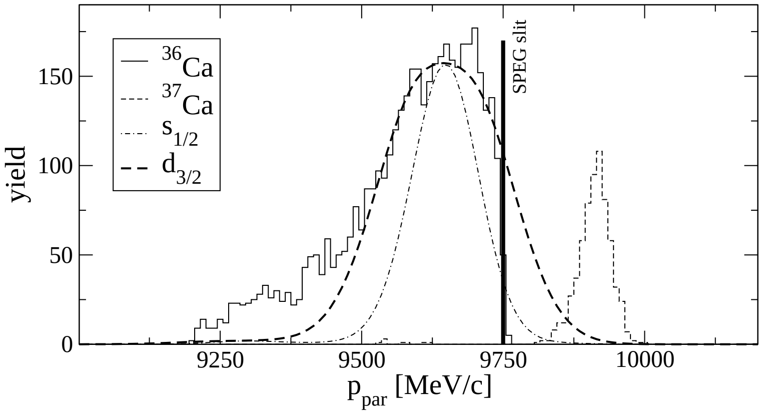

Fig. 3. Inclusive momentum distribution of ^{36}Ca as measured in SPEG. The distribution is cut by a slit suppressing the secondary ^{37}Ca beam. The calculated momentum distributions for one-neutron removal from $d_{3/2}$ or $s_{1/2}$ states were folded with the shape of the distribution of the secondary ^{37}Ca beam, which was obtained from a dedicated run without the slit.

We wish to thank the accelerator crew of GANIL for their smooth running of the secondary beam production and the SPEG technical staff for their support during the experiment. We acknowledge the support from the European Community through the Eurons project Contract No RII3-CT-2004-506065, and from BMBF Germany, Contract No 06 BN 109.

REFERENCES

[1] T. Otsuka *et al.*, *Phys. Rev. Lett.* **95**, 232502 (2005).
[2] M. Stanoiu *et al.*, *Eur. Phys. J.* **A20**, 95 (2003).
[3] E. Baron, J. Gillet, M. Ozille, *Nucl. Instrum. Methods* **A362**, 90 (1995).
[4] S. Ottini-Hustache *et al.*, *Nucl. Instrum. Methods* **A431**, 476 (1999).
[5] L. Bianchi *et al.*, *Nucl. Instrum. Methods* **A276**, 509 (1989).
[6] F.A. Beck, *Nucl. Sci. Research Conference Series* **7**, 129 (1984).
[7] P. Doornenbal *et al.*, *Phys. Lett.* **B**, in press, doi:10.1016/j.physletb.2007.02.001.
[8] K. Yoneda *et al.*, *Phys. Rev.* **C74**, 021303 (2006).
[9] C.A. Bertulani, P.G. Hansen, *Phys. Rev.* **C70**, 034609 (2004).
[10] C.A. Bertulani, A. Gade, *Comput. Phys. Commun.* **175**, 372 (2006).
[11] P.G. Hansen, J.A. Tostevin, *Ann. Rev. Nucl. Part. Sci.* **53**, 219 (2003).
[12] A. Gade *et al.*, *Phys. Rev. Lett* **93**, 042501 (2004).