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Spectroscopy of neutron-deficient nuclei around ^{36}Ca

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Abstract. An experiment was performed to extend the knowledge of excited states in neutron-deficient Ca isotopes. In particular, the first excited state in ^{36}Ca was searched for to obtain information on the isospin dependence of the nucleon-nucleon interaction near the proton drip line from a comparison with its stable mirror nucleus, ^{36}S. The ^{36}Ca ions were produced using a two-step fragmentation technique with a ^{37}Ca secondary beam, and in-beam γ-rays were measured. First results are the energy of the first 2^+ state in ^{36}Ca, $E(2^+) = 3036(11)\,$keV, and the cross section for the reaction $^{37}\text{Ca} \rightarrow {}^{36}\text{Ca}$ at $61 \cdot A\,$MeV. In addition, the de-excitaion of the first 2^+ state in ^{28}S has been observed.

PACS. 21.10.-k Properties of nuclei, nuclear energy levels – 23.20.Lv Gamma transitions and level energies – 27.30+t mass [20, 38]

In recent years, the isospin dependence of the nucleon-nucleon interaction has attracted much interest from theory [1] and, since exotic beams become more and more available, also in experimental work. 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 proton spin-orbit partners $d_{5/2}$ and $d_{3/2}$ and the neutron $d_{3/2}$ orbital, the proton $d_{5/2}$ orbital becomes more bound whereas the $\pi d_{3/2}$ orbital becomes less bound than for nuclei where the $\nu d_{3/2}$ shell is not completely filled. This enlarges the gaps between the $\pi s_{1/2}$ and $\pi d_{3/2}$ levels and between the $\pi s_{1/2}$ and $\pi d_{5/2}$ levels, as illustrated in figure 1. These shifts lead to high energies for the first 2^+ states in both ^{36}S and ^{34}Si, which from this point of view reflects a spherical rigidity comparable to the doubly magic nucleus ^{40}Ca. For ^{36}Ca, the mirror nucleus of ^{36}S, the same picture should apply with

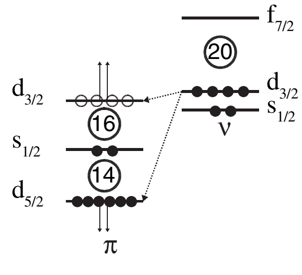

Fig. 1. Illustration of the effect of the filled $\nu d_{3/2}$ orbital in ^{36}S: the $\pi d_{3/2}$ level is shifted up and the $\pi d_{5/2}$ level is shifted down in energy.

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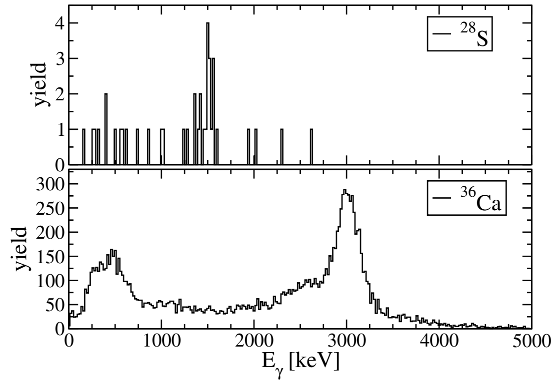

Fig. 2. Gamma-ray spectra for the nuclei ^{36}Ca and ^{28}S. The energies of the 2^+ states have been determined to be 3025(30) keV and 1525(30) keV, respectively.

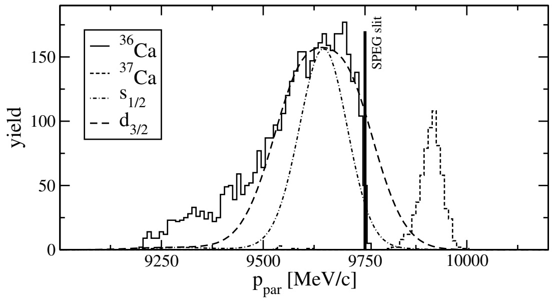

Fig. 3. Inclusive momentum distribution for ^{36}Ca as measured in SPEG, cut to suppress the ^{37}Ca secondary beam. The distribution of ^{37}Ca – measured without secondary target – is shown for comparison. Included are calculated momentum distributions for one-neutron removal from $d_{3/2}$ or $s_{1/2}$ states, folded with the distribution of the secondary beam.

protons and neutrons exchanged, so that also in this case a high excitation energy can be expected for the 2^+ state.

The experiment was performed at the GANIL in Caen, France. To populate excited states in ^{36}Ca, the two-step fragmentation technique was used [2]. A primary ^{40}Ca beam of 95·A MeV was fragmented on a carbon foil in the SISSI target device [3]. The resulting beam cocktail was purified in the Alpha spectrometer, where a degrader was installed which was optimised for ^{37}Ca or, in a different setting, ^{36}Ca. The fragments were identified event by event through a time measurement between high frequency of the accelerator and the time signal from a CATS detector [4], that was placed just in front of the secondary target. The secondary target was a ^{9}Be foil of 1 mm thickness, in which further nucleons were removed at energies between 61·A MeV before and 35·A MeV after the target. Behind the Be target, the produced fragments were identified in the SPEG spectrometer [5] through time-of-flight, $B\rho$ and energy-loss measurements. In some settings, a slit had to be placed in SPEG to suppress the secondary beam.

To measure γ-ray energies, the *Château de Cristal*, an array of 74 BaF_2 detectors [6], was placed around the Be target. The calibration of the BaF_2 detectors was performed using ^{22}Na source data and well 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. Gamma-ray energies from in-flight decays were Doppler-corrected using the momentum measured in SPEG and assuming that the decay took place in the middle of the target. An add-back procedure was applied to reconstruct Compton-scattered γ rays. Gamma-ray spectra for the two nuclei ^{36}Ca and ^{28}S are shown in figure 2. The energy of the 2^+ state in ^{36}Ca has been determined to be $E(2^+) = 3025(30)$ keV. This value is in agreement with the value measured at GSI in a similar experiment [7,8]. For ^{28}S, an energy of $E(2^+) = 1525(30)$ keV was estimated for the first 2^+ state.

From the numbers of particles identified before and after the secondary target, cross sections can be determined. Figure 3 shows the momentum distribution for ^{36}Ca and a comparison with calculated momentum distributions [9–11] as expected for neutron knock-out from $d_{3/2}$ and $s_{1/2}$ states. From the integral of the extrapolated distribution, the number of ^{36}Ca ions was determined. Together with the number of incident ^{37}Ca ions and the target thickness, this leads to a preliminary experimental cross section for the one-neutron removal $^{37}\text{Ca} \rightarrow {}^{36}\text{Ca}$ of 5.3 (20) mb, while the calculated cross section is 18.6 mb. The width of the inclusive experimental momentum distribution fits well to the neutron knock-out from a $d_{3/2}$ state.

As the results are preliminary and the errors are still large, an extensive discussion is only possible after further progress of the analysis. Nevertheless, the present value for the energy of the first 2^+ state in ^{36}Ca is 266 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 a first excited 2^+ state. This could be due to the Coulomb energy difference between a pure s and a pure d configuration involved in the 2^+ state of ^{36}S, as a predominant single particle character is expected due to the large $Z = 16$ gap.

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