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SPECTROSCOPY AROUND ^{36}Ca*

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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.

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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.

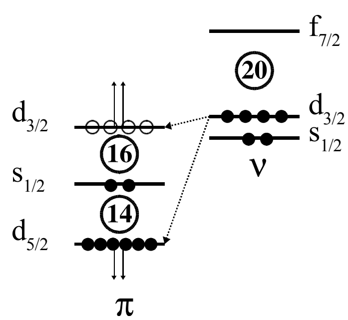

Fig. 1. Illustration of the effect due to the filling of the $\nu d_{3/2}$ orbital in ^{36}S: the tensor interaction shifts the $\pi d_{3/2}$ level up and the $\pi d_{5/2}$ level down in energy.

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

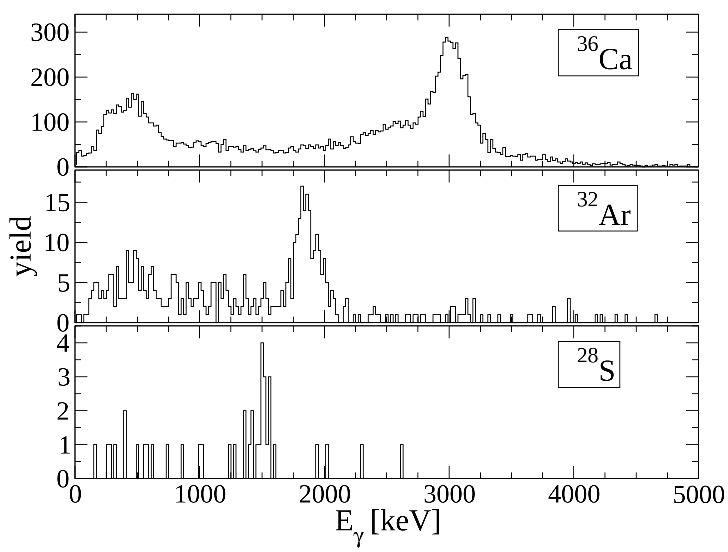

Fig. 2. Gamma-ray spectra for the nuclei ^{36}Ca, ^{32}Ar and ^{28}S. The energies of the 2^+ states have been determined to be 3036(11) keV, 1873(20) keV and 1525(30) keV, respectively.

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].

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 exper-

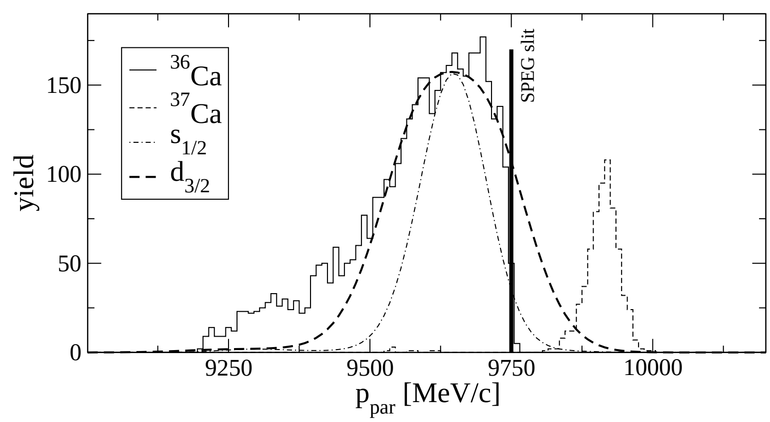

Fig. 3. Inclusive momentum distribution of ^{36}Ca as measured in SPEG. The distribution is cut by a slit suppressing the secondary ^{37}Ca beam. The calculated momentum distributions for one-neutron removal from $d_{3/2}$ or $s_{1/2}$ states were folded with the shape of the distribution of the secondary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

imental 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].

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