Spectroscopy around ^{36}Ca

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An experiment was performed to study excited states in neutron-deficient nuclei around Ca. A one-neutron knockout reaction was used to produce ^{36}Ca ions from a ^{37}Ca secondary beam, and in-beam γ-rays were measured. 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. 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 $\approx 45 \cdot A\,$MeV were obtained. Furthermore, for two other $T_z = -2$ nuclei, ^{28}S and ^{32}Ar, the de-excitaion of the first 2^+ state has been observed.

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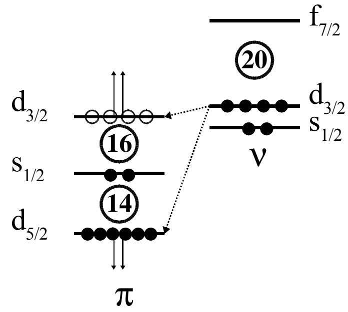

Fig. 1. Illustration of the effect of the $\nu d_{3/2}$ orbital filling in ^{36}S. Due to the tensor interaction, the $\pi d_{3/2}$ level is shifted up and the $\pi d_{5/2}$ level is shifted down in energy.

In recent years, an intensive research activity was devoted to the study of nuclear structure of extremely neutron- or proton-rich nuclei, both theoretically and experimentally. In this context, we aimed in the present experiment 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 (1). Assuming that the effect of the filling of the $\nu d_{3/2}$ on the $\pi s_{1/2}$ is weak, 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 fig. 1. These shifts lead to high excitation 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 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. 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 $95{\cdot}A$ 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, ^{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

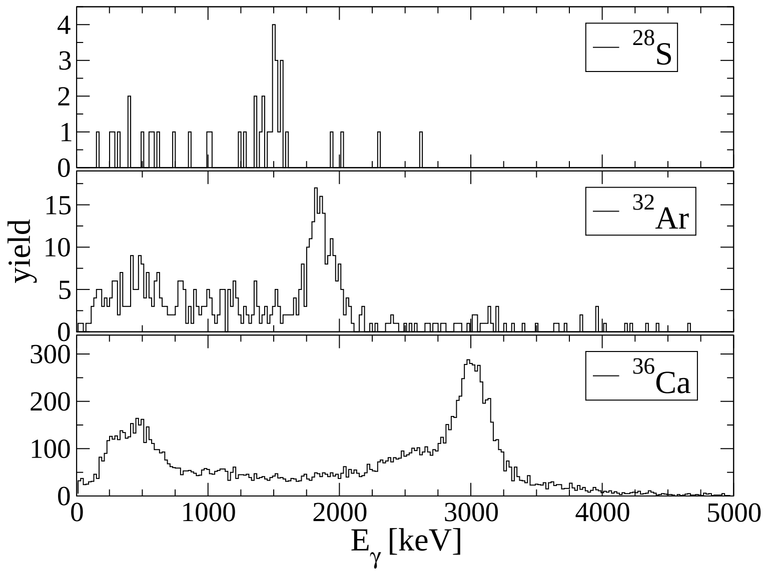

Fig. 2. Gamma-ray spectra for the nuclei ^{36}Ca, ^{32}Ar and ^{28}S. The energies of the 2^+ states have been determined to be 3036(11) keV, 1873(20) keV and 1525(30) keV, respectively.

the secondary target, a ^{9}Be foil of 200 mg/cm^2 thickness, further nucleons were removed at energies between $60{\cdot}A$ MeV before and $35{\cdot}A$ 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 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. The Doppler-correction for γ-ray energies from in-flight decays used the momentum measured in SPEG, assuming that the decays took place in the middle of the target. An add-back procedure was applied to reconstruct Compton-scattered γ-ray energies. 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 has been 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 is $\approx 1525(30)$ keV, and $\approx 1873(20)$ keV for ^{32}Ar, which is 50 keV above the value reported by Cottle *et al.* (8).

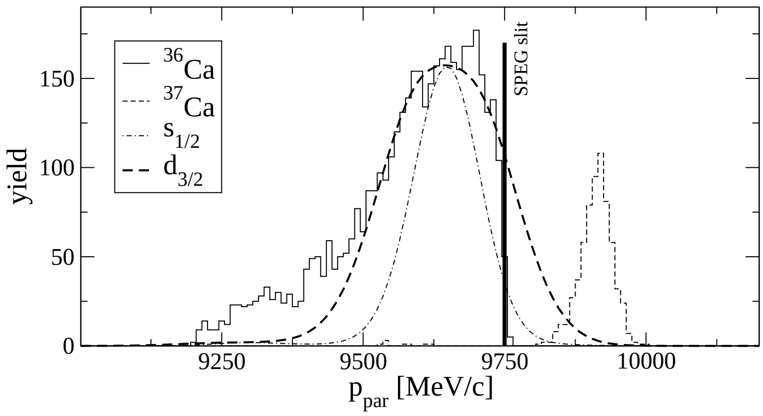

Fig. 3. Inclusive momentum distributions of ^{36}Ca and ^{37}Ca as measured in SPEG. The distribution for ^{36}Ca is cut by a slit that was installed in SPEG to suppress the secondary beam; in the dedicated run for ^{37}Ca this slit was not installed. Included are calculated momentum distributions for one-neutron removal from $d_{3/2}$ or $s_{1/2}$ states, folded with the distribution of the secondary beam.

The measured 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. Qualitatively, this might be explained as the combined effect of: (i) an almost pure ν nature of the 2^+ state in ^{36}Ca due to the $Z = 20$ gap, (ii) an almost pure π 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 $Z, N = 16$ gaps, and (iv) the Coulomb energy difference between typical s and d states.

Figure 3 shows the momentum distribution for ^{36}Ca and a comparison with calculated momentum distributions (9; 10; 11) as expected for neutron knock-out from the valence orbits $d_{3/2}$ 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}Ca$\rightarrow^{36}$Ca of 5.3 (20) mb was obtained, while the calculated cross section is 18.6 mb assuming a knock-out from $\nu d_{3/2}$. This represents a quenching of $\approx 30\,\%$ 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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