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.

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

* Presented at the 41st Zakopane School of Physics

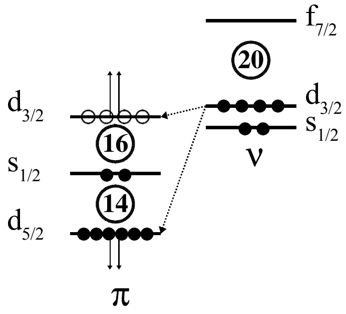

Fig. 1. Illustration of the effect of the $\nu d_{3/2}$ orbital filling in ^{36}S. Due to the tensor interaction, the $\pi d_{3/2}$ level is shifted up and the $\pi d_{5/2}$ level is shifted down in energy.

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

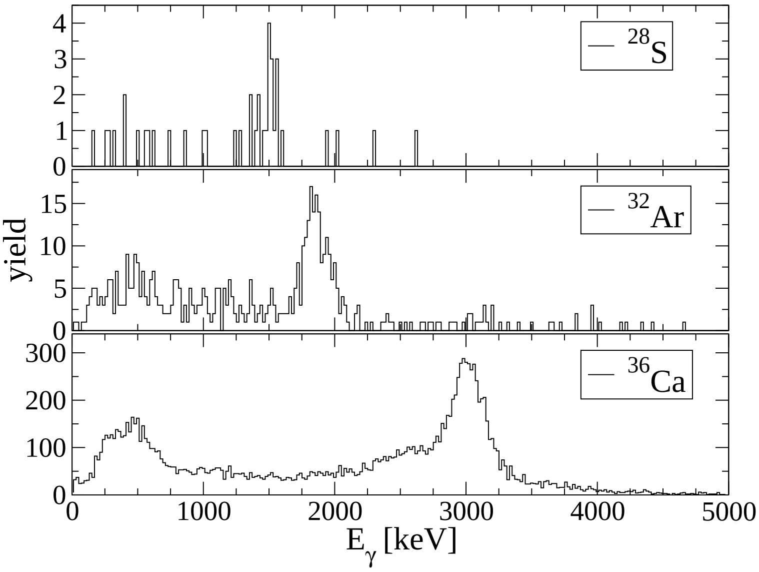

Fig. 2. Gamma-ray spectra for the nuclei ^{36}Ca, ^{32}Ar and ^{28}S. The energies of the 2^+ states have been determined to be 3036(11) keV, 1873(20) keV and 1525(30) keV, respectively.

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).

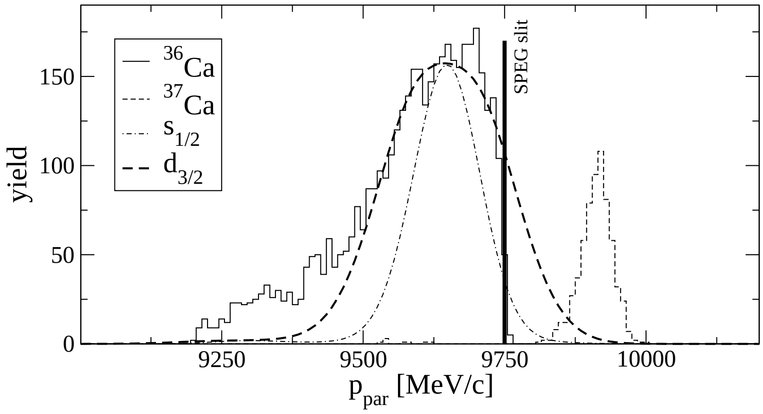

Fig. 3. Inclusive momentum distributions of ^{36}Ca and ^{37}Ca as measured in SPEG. The distribution for ^{36}Ca is cut by a slit that was installed in SPEG to suppress the secondary beam; in the dedicated run for ^{37}Ca this slit was not installed. Included are calculated momentum distributions for 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→^{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 ≈ 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).

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.

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