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STUDY OF THE NEUTRON-RICH ISOTOPE ^{46}Ar THROUGH INTERMEDIATE ENERGY COULOMB EXCITATION*

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The preliminary value of the reduced transition probability $B(\mathrm{E2}; 0^+ \to 2_1^+)$ in ^{46}Ar has been determined using the Coulomb excitation technique at intermediate energy. The ^{46}Ar was produced in the fragmentation of a ^{48}Ca beam at GANIL. The γ-rays following the Coulomb excitation of the 2_1^+ were emitted in-flight and detected by the 64 $\mathrm{BaF_2}$ detectors of the Château de Cristal array. The relatively low $B(\mathrm{E2})$ value of ^{46}Ar reported in this article supports the semi-magic character of this nucleus due to the persistence of the $N = 28$ shell closure at $Z = 18$.

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1. Introduction

The evolution of the $N = 28$ shell closure has been investigated far from stability using several experimental techniques [1] and it was derived that a progressive onset of deformation occurs below ^{48}Ca. Based on shell model calculations, $^{48}_{20}$Ca is a rigid-spherical nucleus, $^{46}_{18}$Ar has a vibrational character, $^{44}_{16}$S exhibits a shape coexistence, $^{42}_{14}$Si is likely to be oblate and $^{40}_{12}$Mg is expected to be prolate [2]. The progressive decrease in energy of the 2^+_1 states in ^{46}Ar [3], ^{44}S [4] and ^{42}Si [5] isotones indicates a breaking of the $N = 28$ shell closure. This drop in excitation energy usually goes in concert with an enhancement in the B(E2) values. However, this feature depends on the configuration of the state under consideration. Taking into account that the B(E2) reduced transition probability scales with the squared proton to neutron effective charge ratio, a weak B(E2) value is found for a pure neutron state, while a large B(E2) reduced transition probability is found for a state built on pure proton excitations. Therefore, the measurement of the B(E2) reduced transition probability provides useful information on the configuration of the 2^+_1 states.

Two experiments were carried out at the NSCL facility to study the Coulomb excitation of ^{46}Ar at intermediate energy. Rather small and consistent $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ values of 196(39) e^2fm^4 [6] and 218(31) e^2fm^4 [7] were obtained. A larger $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ value of 570^{+335}_{-160} e^2fm^4 [8] has been measured at the Legnaro facility by means of the 2^+_1 lifetime measurement, using the differential recoil distance Doppler shift method. Noteworthy is the fact that the reduced transition probability determined in Refs. [6, 8] for the neighboring ^{44}Ar isotope is in very good agreement. From the theoretical point of view, shell model calculations [2] predict a $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ reduced transition probability in ^{46}Ar consistent with the value obtained in Ref. [8] and a factor of about 2.5 larger than in Refs. [6, 7]. On the other hand, recent relativistic mean field calculations using the DD-PC1 energy density functional [9] foretell a $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ value of about 200 e^2fm^4, in perfect agreement with the results of [6, 7]. Mean field calculations using the Gogny force with the D1S parametrization [10] predict a larger value of 320 e^2fm^4. Being located between the spherical ^{48}Ca nucleus and the deformed ^{42}Si isotope, the ^{46}Ar is a strategic nucleus that needs to be well understood. As experimental investigations and theoretical predictions lead to different results, we re-measured the $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ value of ^{46}Ar.

2. Experiment

A schematic picture of the experimental set-up is shown in Fig. 1.

The ^{46}Ar was produced in the fragmentation of ^{48}Ca^{19+} beam at 60 MeV/A energy with an average intensity of ~ 4 μA in a 145 μm ^{9}Be target. The nuclei of interest were separated from other reaction products in the LISE3 spectrometer [13]. A second setting of the spectrometer was used for the production of a beam of stable ^{44}Ca nucleus. The reduced transition probability $B(\mathrm{E2};\, 0^{+}\mathrm{g.s.}\to 2_1^{+})$ of the ^{44}Ca nucleus is well known [16] (473(20) $e^2\mathrm{fm}^4$), therefore its value can be used for normalization in the determination of the $B(\mathrm{E2};\, 0^{+}\mathrm{g.s.}\to 2_1^{+})$ value in ^{46}Ar.

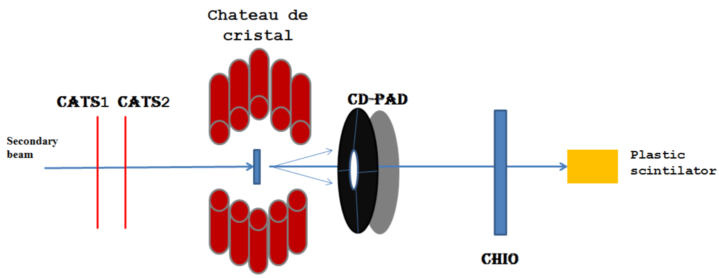

Fig. 1. Schematic picture of the experimental set-up.

Two position sensitive detectors CATS [14] were placed at the final focal plane of the spectrometer. These detectors were used for: (1) reconstruction of the trajectories of the ions, (2) determination of the impact point of the ions on the secondary Coulomb excitation Pb target of 200 mg/cm^2 situated 50 cm downstream the CATS detectors, (3) Time-of-Flight (TOF) measurement with respect to the cyclotron radio-frequency, and (4) coincidence signals between the incoming nuclei and the γ rays.

After passing through the Pb target, the scattered nuclei were detected and identified in a telescope placed at 41.2 cm from the secondary target. The telescope consisted of a Double Sided Silicon Strip Detector [15] (DSSSD) and a residual energy detector (PAD), both having a central hole of 3 cm diameter. This geometry allowed to detect and identify the ions between 1° and 6.5° in the laboratory frame. This angular acceptance ensures that nuclei up to the grazing angle of the reaction are detected. The DSSSD detector consisted of four quadrants with 16 annular strips of 1.9 mm width and 2 mm pitch on the front side and 8 radial strips at 3.4° pitch on the back side. The inter-strip width was 100 μm. The PAD detector consisted of four non-segmented silicon quadrants of 1500 μm thickness, which ensured that all particles that emerged from the DSSSD were stopped in its active area.

The nuclei that underwent Coulomb excitation decayed in-flight by the emission of γ-rays. 64 hexagonal BaF_2 crystals of the Château de Cristal were placed in a close geometry surrounding the Pb target. A coincidence measurement was performed between the prompt γ-radiations and the ions identified in the DSSSD. The γ-ray efficiency was 18% at 1.157 MeV. Nuclei that passed through the central hole of the telescope were identified and counted in an ionization chamber (CHIO) followed by a plastic scintillator.

3. Preliminary results and discussions

The known transition energy (1157 keV) of the $2^+ \to 0^+$ in ^{44}Ca is observed in each individual crystal. According to the Doppler effect, the observed energy depends on the detector angle. This angle-dependent energy value is used to determine the effective angle at which each BaF_2 detector is placed, thereby ensuring an optimized Doppler correction and a proper matching of the sum of the γ-ray energies of all detectors. At intermediate energies, both nuclear and Coulomb excitations can contribute. In order to favor the events originating from a Coulomb excitation, events at forward scattering angle are selected. Assuming semi-classical trajectories, these events correspond to large impact parameters, $b > b_{\rm min}$. Following the prescription of Ref. [17], $b_{\rm min} = 18.84$ fm. This corresponds to "safe" scattering angles between 1° and 4.64° in the laboratory frame for ^{44}Ca. An add-back procedure was applied to the γ-ray energies of the photons detected in adjacent crystals to increase the photo-peak efficiencies.

The background-subtracted Doppler-corrected γ-ray spectrum is shown in Fig. 2. It was obtained by gating on the "safe" scattered ^{44}Ca ions detected in coincidence with the γ-rays within a 3 ns prompt time window. The γ-ray background was obtained from an off-prompt time window, normalized to the prompt condition with the same nuclei selection applied.

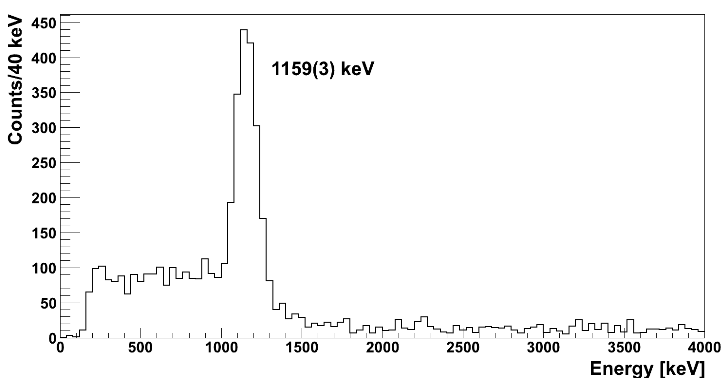

Fig. 2. Background-subtracted Doppler-corrected γ-ray spectrum in coincidence with "safe" scattered ^{44}Ca nuclei.

As for the ^{46}Ar nuclei, the "safe" scattering angles for Coulomb excitation correspond to trajectories between 1° and 3.6°. Taking into account that the B(E2) in ^{46}Ar was measured relative to the known B(E2) in ^{44}Ca, in the data analysis, there were considered only the events that had the same spatial distribution as the ^{44}Ca nuclei. The background-subtracted Doppler-corrected γ-ray spectrum of ^{46}Ar is shown in Fig. 3. It was obtained applying the same procedure as described above for the case of ^{44}Ca nuclei.

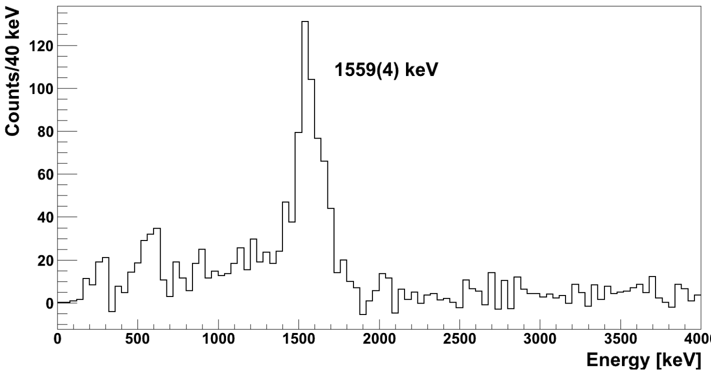

Fig. 3. Background-subtracted Doppler-corrected γ-ray spectrum in coincidence with "safe" scattered ^{46}Ar nuclei.

In the γ-ray spectrum of Fig. 3, along with the 1577 keV peak associated with the de-excitation of the 2^+ state to the ground state in ^{46}Ar, one can see a peak at 542 keV. This transition corresponds to the de-excitation of the first excited state $1/2^-$ to the $5/2^-$ ground state in the ^{45}Ar nucleus, which was populated in the one-neutron removal reaction in ^{46}Ar. The peak at 542 keV becomes clearly visible when removing the "safe" angle condition.

The number of counts in the peaks corresponding to the 2^+_1 energy of the ^{44}Ca and ^{46}Ar was determined by fitting the energy spectra with a Gaussian plus an exponential background function, and the statistical errors were evaluated by applying the error propagation method [18]. A feeding to the 2^+_1 state from the Coulomb excitation of the 2^+_2 level was estimated using Geant4 simulations to 8% in ^{44}Ca and a superior limit of 9% in ^{46}Ar. Using the known reduced transition probability $B(\mathrm{E2};\, 0^+\mathrm{g.s.}\to 2^+_1)$ of ^{44}Ca, a preliminary value of $271^{+22}_{-26}\ e^2\mathrm{fm}^4$ is obtained for the $B(\mathrm{E2};\, 0^+\mathrm{g.s.} \to 2^+_1)$ in ^{46}Ar, a value that is compatible, within one σ, with the results of Ref. [7].

Further work will focus on the extraction of the absolute reduced transition probability $B(\mathrm{E2};\, 0^+\mathrm{g.s.}\to 2^+_1)$ in ^{46}Ar.

4. Summary

A preliminary value of the transition probability $B(\mathrm{E2};\, 0^+\mathrm{g.s.}\to 2^+_1) = 271^{+22}_{-26}\ e^2\mathrm{fm}^4$ has been obtained in ^{46}Ar. This value is smaller than the one obtained by means of lifetime measurement and is in agreement with the previous Coulomb excitations measurements done at intermediate energy. Also, the decrease of the nuclear radii between the shell closures $N = 20$ and $N = 28$ observed in [19] — related to the variation of quadrupole core polarization — suggests a change of deformation, consistent with the reduced transition probability observed in the present analysis. This further supports the semi-magic character of ^{46}Ar and confirms the puzzling deviation to shell model calculations.

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