COULOMB EXCITATION OF NEUTRON-RICH ^{44}Ar AT SPIRAL*

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(Received January 3, 2008)

The weakening of the $N = 28$ shell closure and the development of deformation and shape coexistence were addressed in a low-energy Coulomb excitation experiment using a radioactive ^{44}Ar beam from SPIRAL. The 2_1^+ and one higher-lying state in ^{44}Ar were excited on ^{208}Pb and ^{109}Ag targets at two different beam energies. From the collected data it will be possible to extract the B(E2) values between all observed states and to determine the quadrupole moment of the first 2^+ state, providing information on the prolate or oblate character of the deformation.

PACS numbers: 21.10.Ky, 23.20.Js

1. Introduction

The evolution of the nuclear shell structure far from stability is one of the fundamental and still open questions in nuclear structure physics. The erosion of the shell closure in exotic nuclei was first discovered in the so-called "island of inversion" at $N = 20$ where the ground states of neutron-rich Na, Mg and Ne isotopes are dominated by deformed intruder configurations.

The question whether $N = 28$ remains a magic number in the neutron-rich region is still controversial. The systematics of the excitation energy of the first 2^+ state for argon and sulphur isotopes shows only a slight rise

* Presented by M. Zielińska at the XXX Mazurian Lakes Conference on Physics, Piaski, Poland, September 2–9, 2007.

for ^{46}Ar and ^{44}S (as compared *e.g.* with the rapid change observed for ^{36}S at $N = 20$), suggesting that the $N = 28$ shell gap is already reduced. Recent in-beam γ spectroscopy after fragmentation has shown a shape mixing between a strongly prolate ground state and a less deformed oblate excited configuration in ^{44}S [1]. The B(E2; $2^+ \to 0^+$) values measured for neutron-rich sulphur and argon isotopes [2] correspond to relatively large deformation ($|\beta_2| \approx 0.3$ for ^{40,42}S, $|\beta_2| \approx 0.24$ for ^{44}Ar). On the other hand, in a two-proton knockout measurement performed at MSU, the cross-sections for the ^{46}Ar $\to$ ^{44}S and ^{44}S $\to$ ^{42}Si reactions have been found to be significantly smaller than those for other two-proton knockout reactions [3], which was interpreted as a strong indication for the persistence of the $Z = 14$ shell closure at $N = 28$. This conclusion is in a sharp contrast to the recent observation of the first excited 2^+ state in ^{42}Si at a very low excitation energy of 770(19) keV [4].

2. Spectroscopic data on ^{44}Ar

The structure of the ^{44}Ar nucleus was studied earlier using deep-inelastic reactions [5], β decay of ^{44}Cl [6], nucleon removal reactions at relativistic energies [7] and intermediate-energy Coulomb excitation [2]. Several low-lying states have been observed but the resulting level schemes above the 2_1^+ state at 1158 keV are inconsistent. In the deep-inelastic reaction [5] the sequence of three excited states at 1158 keV, 2746 keV, and 3439 keV was observed and spins 2^+, 4^+, and 6^+, respectively, have been ascribed to these levels. On the other hand, a direct transition from the 2746 keV state to the ground state was observed in the β-decay studies, casting doubt on the tentative assignment of spin and parity 4^+ for this state.

The B(E2; $2^+ \to 0^+$) value for ^{44}Ar has been measured using intermediate energy Coulomb excitation [2]. It has been shown recently [8] that in intermediate-energy Coulomb excitation relativistic retardation effects and recoil effects on the trajectories, which are usually not considered at such beam energies, have to be taken into account. Neglecting both effects can result in B(E2) values wrong by as much as 20% [8]. This difficulty is illustrated by the results of the intermediate-energy Coulomb excitation performed in the vicinity of the "island of inversion": the B(E2) values measured for ^{30,32}Mg at RIKEN [9], MSU [10], and GANIL [11] were differing by as much as a factor of two, while in a recent experiment performed at low energy at REX-ISOLDE [12], a B(E2) value has been obtained which is lower than all the disagreeing results from the intermediate-energy measurements.

The availability of an intense radioactive ^{44}Ar beam re-accelerated to barrier energies from the SPIRAL facility at GANIL [13] made it possible to perform a multi-step Coulomb excitation experiment. Contrary to intermediate-energy Coulomb excitation, higher-lying states can be populated in such experiments, which are furthermore sensitive to diagonal matrix elements and allow extracting quadrupole moments and hence the intrinsic shape of a nucleus. Since the electromagnetic excitation probability can be calculated with high precision, a higher accuracy is reached for the B(E2) values as compared to experiments at intermediate energies.

3. Experiment

The radioactive ^{44}Ar beam was produced at the SPIRAL facility at GANIL [13] by fragmentation of an intense ^{48}Ca primary beam of 60 MeV/A energy and a beam current of 3.5 $e\mu A$ which was impinging on the carbon production target of SPIRAL. Radioactive ^{44}Ar ions were re-accelerated with the CIME cyclotron and Coulomb excited on ^{208}Pb and ^{109}Ag targets of 1 mg/cm^2 thickness at beam energies of 3.7 MeV/A and 2.7 MeV/A, respectively. The average beam intensity was 2×10^5 pps at the secondary target position. The γ rays from the Coulomb excited states were detected in the EXOGAM array, comprising 10 large segmented Compton-suppressed germanium clover detectors.

The scattered projectiles and the recoiling target nuclei were detected in an annular highly segmented silicon detector, divided into 16 concentric rings and 96 azimuthal sectors. The active surface of the detector had inner and outer radii of 9 and 41 mm, respectively, and it was placed 25 mm behind the target. It covered scattering angles between 25° and 56° in the laboratory frame, which corresponds to a range between 30° and 130° for the ^{208}Pb target, and between 35° and 130° for the ^{109}Ag target in the center-of-mass frame. The energy resolution of the particle detector was sufficient to distinguish between the scattered projectiles and the target recoils, thus allowing the kinematic reconstruction of the Coulomb excitation event. The segmentation of both the silicon detector and the crystals of the EXOGAM clovers allowed a precise measurement of the emission angle of the γ rays with respect to the velocity vector of the scattered projectile. After Doppler correction a resolution of 10 keV was obtained for a γ ray of 1158 keV. The requirement of coincidence between γ rays and scattered particles helped to suppress the overwhelming background from β decay of the beam. To ensure a purely electromagnetic interaction, the "safe" energy criterion was imposed, *i.e.* for heavy ions the distance of closest approach should be greater than $1.25(A_p^{1/3} + A_t^{1/3}) + 5$ fm. For both targets the beam energies were chosen such that the above criterion was fulfilled for all scattering angles covered by the particle detector.

4. Data analysis

The Doppler-corrected, background-subtracted γ ray spectrum in coincidence with ^{208}Pb recoils is shown in Fig. 1.

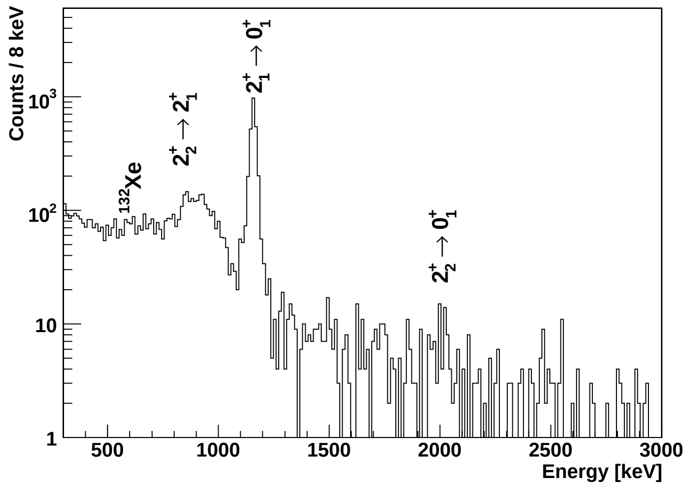

Fig. 1. Total Doppler-corrected γ ray spectrum after Coulomb excitation of ^{44}Ar on a ^{208}Pb target in coincidence with ^{208}Pb recoils.

Data were collected for $\sim$ 100 hours with the ^{208}Pb target and a beam intensity of 2.4×10^5 pps. In addition to the first excited 2^+_1 state, one higher-lying state at 2010 keV, tentatively assigned as 2^+_2, was populated and two γ lines from its deexcitation are observed. A small contaminant of stable ^{132}Xe, which has the same A/q ratio as ^{44}Ar, was present in the beam. However, it was possible to distinguish between ^{44}Ar and ^{132}Xe in the particle detector, and the 668 keV $2^+ \rightarrow 0^+$ transition in ^{132}Xe is barely visible in the spectrum.

With the ^{109}Ag target both projectile and target nuclei were excited, which can be used to normalize the excitation probability in ^{44}Ar with the well known transition strengths in ^{109}Ag. The Doppler-corrected γ ray spectra after Coulomb excitation of ^{44}Ar on the ^{109}Ag target in coincidence with scattered ^{44}Ar ions (a) and ^{109}Ag recoils (b) are shown in Fig. 2. The dependence of the excitation process on scattering angle is clearly visible, for example the $9/2^- \rightarrow 5/2^-$ transition at 676 keV in ^{109}Ag, which requires a multi-step excitation, is enhanced for large scattering angles.

The statistics collected during $\sim$ 50 hours of data taking with the ^{109}Ag target allowed subdividing the data into eight sub-sets corresponding to different ranges of scattering angles (four for recoil detection and another four for scattered projectile detection), as shown in Fig. 3.

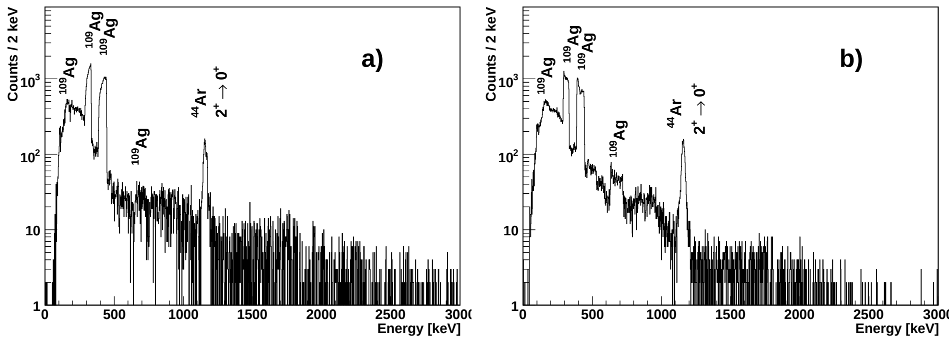

Fig. 2. Total Doppler-corrected γ ray spectrum after Coulomb excitation of ^{44}Ar on a ^{109}Ag target in coincidence with: (a) ^{44}Ar ejectiles, (b) ^{109}Ag recoils.

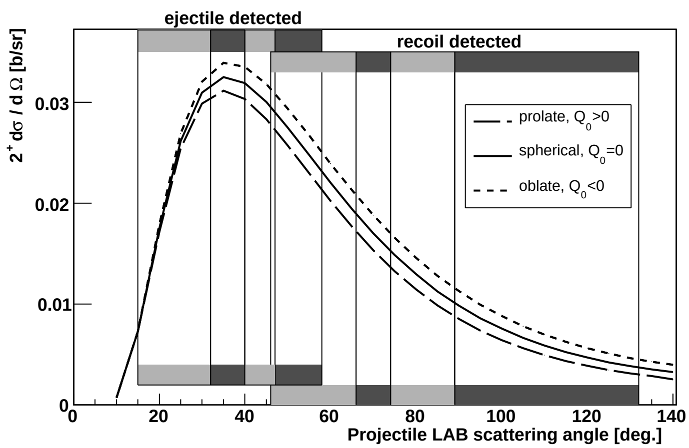

Fig. 3. Differential Coulomb excitation cross-section to populate the 2_1^+ state in ^{44}Ar on a ^{109}Ag target. The three curves correspond to oblate, spherical and prolate deformation. The angular ranges used in the analysis are marked.

The influence of the quadrupole moment of the 2^+ state on its excitation probability varies significantly with scattering angle, thus it is possible to obtain from one experiment information on both the transitional and diagonal matrix elements involved in the excitation process. The three curves corresponding to oblate, spherical and prolate deformation were calculated using the B(E2; $2^+ \rightarrow 0^+$) value from the intermediate-energy measurement and diagonal matrix element estimated using the rotational model.

The Coulomb Excitation Least Squares Fitting code GOSIA [14], which has recently been upgraded in order to handle the simultaneous excitation of projectile and target, is used to determine the B(E2; $2^+ \rightarrow 0^+$) as well as the quadrupole moment. For the smallest scattering angles the influence of the quadrupole moment on the excitation probability of the 2^+ state is below the statistical error of 7% of the corresponding γ ray yield, and it is a reasonable approximation to assume that in this case the observed transition strength depends only on the transitional matrix element. Therefore it is possible to determine the B(E2; $2^+ \to 0^+$) value from the excitation cross-section of the 2^+ state for the smallest angular range using the normalization to known excitation probabilities in ^{109}Ag. The resulting value of the transitional matrix element can then be used to determine the quadrupole moment of the 2^+ state from the remaining data sets. Further constraints come from the Z dependence of the Coulomb excitation cross-section when comparing the data for the ^{109}Ag and ^{208}Pb targets. The data collected with the ^{208}Pb target will also yield the B(E2) values between the 2^+_2 and both the ground state and the 2^+_1 state.

This work was partly supported by the European Community FP6 — Structuring the ERA — Integrated Infrastructure Initiative — Contract EURONS No. RII3-CT-2004-506065.

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