

Onset of collectivity in ^{96,98}Sr studied via Coulomb excitation

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Abstract. A rapid onset of quadrupole deformation is known to occur around the neutron number 60 in the neutron-rich Zr and Sr isotopes. This shape change has made the neutron-rich $A = 100$ region an active area of experimental and theoretical studies for many decades now. We report in this contribution new experimental results in the neutron rich ^{96,98}Sr investigated by safe Coulomb excitation of radioactive beams at the REX-ISOLDE facility, CERN. Reduced transition probabilities and spectroscopic quadrupole moments have been extracted from the differential Coulomb excitation cross section supporting the scenario of shape coexistence/change at $N=60$. Future perspectives are presented including the recent experimental campaign performed at ILL-Grenoble.

1 Introduction

Fission fragment spectroscopy has been used for decades to probe shells and shape evolution far from stability. In particular, the evolution of the deformation in n-rich isotopes around $N=60$ has attracted

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many theoretical and experimental works. Already in the 60's, S. A. E. Johansson has shown that the light fission fragments of a ^{252}Cf source with mass around $A=110$ belong to an island of large stable deformation [1]. First theoretical work carried out with phenomenological approaches predicted that Sr and Kr with mass greater than 100 belong to a region for which the equilibrium shape is axially symmetric and oblate. The maximum of deformation should be observed in $^{98-102}\text{Sr}$ and $^{96-102}\text{Kr}$ and a transition from the spherical shape at $N=50$ to highly deformed nuclei is predicted [2].

From the systematics of the 2-neutron separation energies extracted from mass measurements for $Z=32$ to $Z=45$, an increase of the binding energy is observed in Rb, Sr, Y and Zr isotopes at $N=60$ [3]. The onset of stability observed for these elements has been interpreted as a consequence of the deformation. The low Z border of the phenomenon has been recently established in the Kr isotopic chain where no deviation from the standard trend toward the drip line is observed [3]. In addition, the first excited states have been observed in all even-even nuclei up to $N=60$. The systematics of the excitation energy of the first 2^+ states for Sr and Zr isotopes shows a sudden drop at $N = 60$ for both isotopic chains and by applying a simple geometrical model one can relate it to a change of deformation from $\beta=0.17$ to $\beta=0.4$. Consistently with the mass measurement [3], the decrease of the energy of the first 2^+ between ^{94}Kr and ^{96}Kr is smooth [4]. In addition, low lying 0^+ states have been identified in the Zr and Sr chains and similarly to the 2_1^+ state, an abrupt drop of the 0_2^+ energy is observed at $N=60$. Low lying 0_2^+ states are a long standing indication of shape coexistence. In this picture, excited 0^+ states for $N<60$ might correspond to a deformed configuration which becomes the ground state at $N=60$ as the spherical configuration becomes non-yrast. The strong dependence of related spectroscopic properties on the number of protons and/or neutrons makes of these nuclei a very challenging case for various theoretical models. In this framework, we have investigated the shape transition in the Sr isotopic chain using Coulomb excitation reaction. Collectivity and nuclear deformation have been studied in $^{96,98}\text{Sr}$ via the measurement of reduced transition probabilities connecting different states and their spectroscopic quadrupole moments, being a direct measurement of the shape.

2 Coulomb excitation of $^{96,98}\text{Sr}$

Post-accelerated radioactive beams of $^{96,98}\text{Sr}$ were delivered by the REX-ISOLDE facility at CERN with an average intensity of $1-0.5 \cdot 10^4$ pps (pure ^{96}Sr) and $6 \cdot 10^4$ pps (80% pure ^{98}Sr) at 2.87 MeV/A and 2.82 MeV/A respectively to the Coulomb excitation setup of the MINIBALL HPGe array [5]. Each of the beams was scattered on two different targets: ^{109}Ag , ^{120}Sn for ^{96}Sr and ^{60}Ni , ^{208}Pb for ^{98}Sr . De-excitation γ -ray spectra are sorted in prompt coincidence with scattered particles detected in the annular silicon strip detector for scattering angles ensuring a pure electromagnetic process [6]. Doppler correction is applied for the projectile assuming detection of $^{96,98}\text{Sr}$ recoils using both the position information of the particle detector and the electric segmentation of the MINIBALL detectors.

The γ -ray spectra following the Coulomb excitation of the ^{96}Sr beam are presented in figure 1. In both spectra, the $2_1^+ \rightarrow 0_1^+$ transition in ^{96}Sr is observed as well as the excitation of the target. In case of the heavier target a weak transition corresponding to the 0_2^+ decay is visible in the insert. The Coulomb excitation analysis was performed using the least squares fitting code GOSIA [7, 8]. A standard χ^2 function is constructed from the measured γ -ray yields of both the projectile and the target, and those calculated from a complete set of electromagnetic matrix elements, both transitional and diagonal, between all known states involved in the excitation process. Combining the data set from both target and using the differential Coulomb excitation cross section, we have significantly improved the measurement of the $B(E2, 2_1^+ \rightarrow 0_1^+) = 462(11) e^2 fm^4$ and extracted for the first time a

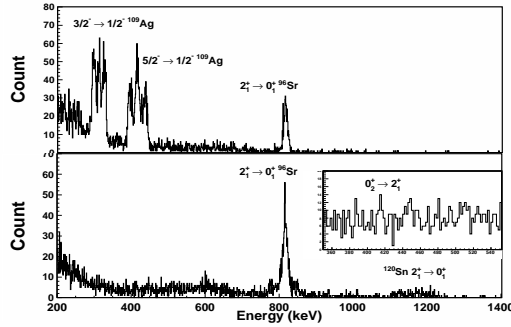


Figure 1. *Top* : γ -ray spectrum detected in MINIBALL, Doppler corrected for the projectile and following the excitation of a ^{96}Sr beam impinging on a ^{109}Ag target. *Bottom* : Same spectrum for the excitation of ^{96}Sr on a ^{120}Sn target. The insert shows a zoom on the weak $0_2^+ \gamma$ decay.

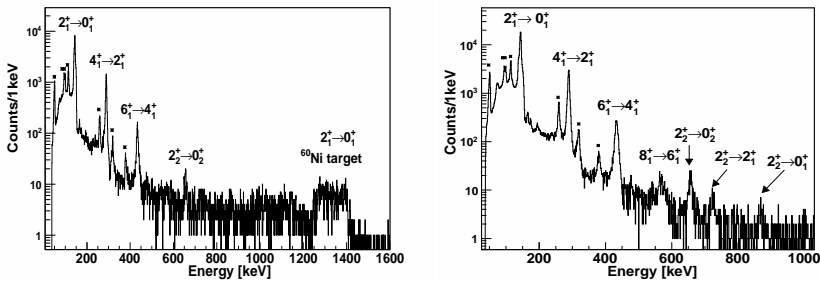


Figure 2. *Left* : γ -ray spectrum detected in MINIBALL, Doppler corrected for the projectile and following the excitation of a ^{98}Sr beam impinging on a ^{60}Ni target. *Right* : Same spectrum for the excitation of ^{98}Sr on a ^{208}Pb target.

preliminary value for the spectroscopic quadrupole moment of the first 2_1^+ state equal to $Q_s = -6(9) \text{ efm}^2$.

The γ -ray spectra following the Coulomb excitation of the ^{98}Sr beam are presented in figure 2. In agreement with the shape transition scenario, the spectra are rather different from those of ^{96}Sr . In both spectra, the decay from the rotational ground-state band populated up to spin 8^+ and the decays from the 2_2^+ are observed. Unknown transitions visible in the spectra are marked with asterisks. They neither belong to the known level scheme of ^{98}Sr , nor exhibit $\gamma - \gamma$ coincidences with known decays. Therefore, we assume that they belong to the main contaminant of the beam, ^{98}Rb , for which no excited state have been reported so far. The known lifetimes of the 2_1^+ , 4_1^+ , 8_1^+ , 10_1^+ and 0_2^+ states were used as additional data points in the GOSIA fit. As a results, a preliminary value for the $B(E2, 6_1^+ \rightarrow 4_1^+) = 5600(1800) \text{ e}^2\text{fm}^4$ has been extracted. The value fits perfectly with the systematics of the rotational ground-state band which is consistent with the behavior of a very good rotor with an almost constant transitional quadrupole moment in the intrinsic reference frame. Preliminary $B(E2)$ connecting the 2_2^+ to the ground-state band have been established with values equal to $B(E2, 2_2^+ \rightarrow 0_1^+) = 37(6) \text{ e}^2\text{fm}^4$ and $B(E2, 2_2^+ \rightarrow 2_1^+) = 75(46) \text{ e}^2\text{fm}^4$. The $B(E2, 2_2^+ \rightarrow 0_2^+)$ was also extracted with a

preliminary value of $700(186) e^2\text{fm}^4$, very similar to the $B(E2, 2_1^+ \rightarrow 0_1^+)$ in ^{96}Sr . Finally, preliminary spectroscopic quadrupole moments have been extracted for the 4_1^+ , 6_1^+ , 8_1^+ states with an average value of $\approx -150 \text{efm}^2$ indicating a large prolate deformation and for the 2_2^+ state equal to $|Q_s| \leq 48 \text{efm}^2$. One can notice the similarity in terms of $B(E2)$ and Q_s between the $2_1^+ \rightarrow 0_1^+$ and $2_2^+ \rightarrow 0_2^+$ in ^{96}Sr and ^{98}Sr , respectively, supporting the shape coexistence scenario. This complete set of electromagnetic matrix elements will be compared with advanced theoretical models and in particular with calculations beyond the mean-field which provide $B(E2)$'s and spectroscopic quadrupole moments for a large number of excited states.

3 Spectroscopy at EXILL and perspective

The Kr isotopes will be the subject of the next experimental investigations. In opposition to the Sr and Zr at $N=60$, the two-neutron separation energy and the excitation energy of the first 2^+ state do not show any abrupt change in the systematics. Does the 2^+ energy in ^{96}Kr reflect a large mixing of the different configurations as established in the light isotopes close to the $N=Z$ line [9] or the gain in binding energy due to the deformation and/or correlation is not strong enough only 2 proton away from the Sr isotopes? Does any shape isomer exist in this isotope? Extending the level scheme in ^{96}Kr is the purpose of experiment being part of the EXOGAM campaign at ILL (EXILL). Future measurements in next generation ISOL facilities using the post-accelerated fission fragment beams and the Coulomb excitation technique will allow to determine the electromagnetic properties.

4 Conclusion

We have investigated the collectivity and the deformation in $^{96,98}\text{Sr}$ at $N=60$ using the Coulomb excitation technique at REX-ISOLDE. Spectroscopic quadrupole moments have been extracted and are compatible with the shape inversion and shape coexistence scenario between a deformed and a spherical configuration. Detailed comparisons with theoretical models will be performed with advanced calculations based on the mean-field approach. A microscopical interpretation based on exact shell model or Monte Carlo shell model should also be investigated. A recent experiment performed at the ILL reactor will soon provide new spectroscopic data in the Kr isotopic chain and in the future, the use of the post-accelerated fission fragment beams from ISOL facilities will allow us to investigate the electromagnetic properties of the transitional key nucleus ^{96}Kr .

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