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Onset of collectivity in neutron-rich Sr and Kr isotopes: Prompt spectroscopy after Coulomb excitation at REX-ISOLDE, CERN

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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.

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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 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 $^{98-102}$Sr and $^{96-102}$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}Sr via the measurement of reduced transition probabilities connecting different states and their spectroscopic quadrupole moments, being a direct measurement of the shape.

2. Shape Transition at N = 60

The nuclear structure of neutron rich Sr and Zr isotopes has been extensively studied experimentally in the past [5, 12–14]. In ^{96}Sr, the ground-state band has a vibrational-like character. Two low-lying 0^+ states were established by Jung *et al.* [15] at 1229 and 1465 keV and were interpreted as candidates for a deformed band head. An extremely strong electric monopole transition was observed between the 0_3^+ and 0_2^+ states [13, 16], indicating the presence of a sizable deformation and strong mixing of the configurations. The sequence of the 0_3^+ (1465 keV), 2_3^+ (1629 keV) and 4_2^+ (1975 keV) states was interpreted as a well-deformed rotational band equivalent to the ground-state band in ^{98}Sr, even though the $2_3^+ \rightarrow 0_3^+$ transition remained unobserved. Lifetimes could be established for the 10^+ and 12^+ states in this band [5], from which a moderate deformation of only $\beta_2 = 0.25$ was derived. It was argued that the 0_2^+ (1229 keV) and 2_2^+ (1506 keV) states are the low-spin members of this moderately deformed band, and it was concluded that the onset of deformation around N = 58 is not as abrupt as previously thought, but rather gradual [5]. The 0_3^+ and 2_3^+ states could still be interpreted as being based on a very deformed configuration, especially in the light of the strong $E0$ transition. In ^{98}Sr, one can expect a different scenario. Beyond N = 60, the observed rotational ground-state band of ^{98}Sr points to a large ground-state deformation and the 0_2^+ state at 215 keV, which decays to the ground state via an enhanced $E0$ transition of $\rho^2(E0) = 0.053$ [18], supports the scenario of shape coexistence with a high mixing. However, the rotational ground-state band follows almost a perfect rigid rotor in opposition with a large mixing of the wave functions which should disturb the sequence. A 2_2^+ state has been established 656 keV above the low lying 0_2^+ state. The sequence of the 0_2^+ and 2_2^+ states, very similar to the ground-state band in ^{96}Sr, supports the scenario of shape coexistence.

From the microscopical point of view, the sudden shape change is associated with a sharp modification of the shell structure at N = 60. In the deformed shell model approach, the onset of collectivity can be understood as a results of a competition between the spherical gaps at Z = 38, 40 and N = 56, and the deformed subshell closures at Z = 38, 40 and N = 60, 62 and 64. In the Sr and Zr isotopic chains, a spherical-to-deformed transition takes place when going from 58 to 60 neutrons, thus when the $\nu g_{7/2}$ orbital is being filled. Recently, Shell Model calculations were performed in the Zr isotopic chain in an extended model space [6]. In this work the $\pi - \nu$ interaction between the spin-orbit partner $1\pi\, g_{9/2}$ and $1\nu\, g_{7/2}$ was pointed out as the main mechanism for the shape modification: as the $\nu\, g_{7/2}$ orbital is being filled, the Z = 40 subshell closure between the $1\pi f_{5/2}$ and $1\pi g_{9/2}$ effective single-particle energies (ESPE) is reduced. The $1\pi g_{9/2}$ ESPE has an increasing slope while the $1\pi f_{5/2}$ ESPE decreases more slowly when neutrons are added (see Fig. 1 in [6]). It is now established that this mechanism is responsible for the rapid onset of deformation in n-rich isotopes around N = 20 and N = 28 with different spin-orbit partners [7]. In addition, the shell model calculations propose an interpretation for the 0_2^+ states for N < 60 as being a 2p-2h proton excitation from the $\pi 1f_{5/2}$ orbital. The description beyond N = 60 where extruder orbits from a ^{78}Ni core and the $h_{11/2}$ intruder orbital make the shell model description very challenging.

While theoretical calculations, for example using the Nilsson-Strutinsky method with a Woods-Saxon potential [8], the relativistic mean field theory [9], or the Hartree-Fock-Bogoliubov approach with Gogny interaction [10] reproduce this onset of deformation qualitatively, they differ in the magnitude of the deformation parameters and excitation energies. Most calculations predict slightly oblate ground-state deformations for the lighter isotopes and strongly deformed prolate shapes for the heavier ones. In the transitional region around N = 60 the different shapes are expected to coexist in a narrow energy range. In the potential energy surfaces, the absolute minimum in ^{96}Sr is found to be oblate, while a strongly deformed prolate minimum is found about 1 MeV higher. Oblate and prolate minima are almost degenerate in ^{98}Sr. This scenario is supported by the observation of the excited 0^+ states at 1229 and 1465 keV in ^{96}Sr and at only 215 keV in ^{98}Sr. However, the sign of the deformation is difficult to access experimentally, and so far there is no clear experimental evidence for oblate shapes in the neutron-rich Sr or Zr isotopes. Finally by comparing the different mean field approaches one can notice that calculations carried out with axial symmetry predicted coexisting prolate and oblate minima with almost the same deformation. Calculations using more degrees of freedom predict a slightly oblate configuration coexisting with a large deformed prolate minimum [8–10]. Up to now there is no experimental proof for a large prolate or oblate deformation beyond N = 60.

The goal of the present experimental program is to measure spectroscopic quadrupole moments in both ground state and excited bands around N = 60. In addition, B(E2)'s between coexisting structures and between the states belonging to the excited configuration will provide fundamental information required for a proper description of these nuclei.

3. Coulomb excitation of ^{96,98}Sr

Post-accelerated radioactive beams of ^{96,98}Sr were delivered by the REX-ISOLDE facility at CERN with an average intensity of 1-0.5 10^4 pps (pure ^{96}Sr) and 6.10^4 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 [11]. 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 [19].

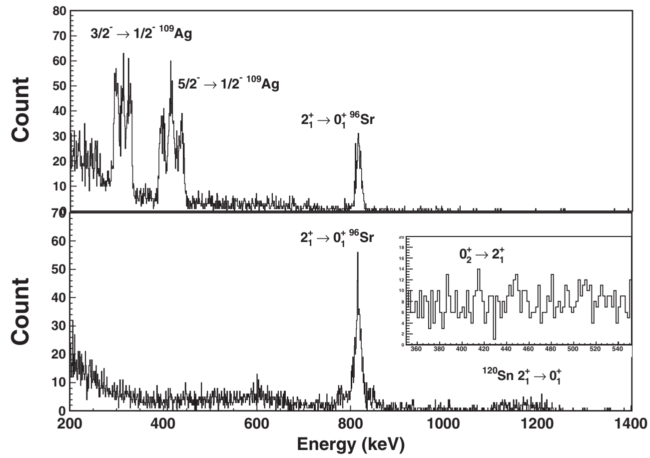

Figure 1. Top: γ-ray spectrum detected in MINIBALL, Doppler corrected for the projectile and following the excitation of a ^{96}Sr beam impinging on a ^{109}Ag target. Bottom: same spectrum for the excitation of ^{96}Sr on a ^{120}Sn target. The insert shows a zoom on the weak $0_2^+\gamma$ decay.

Doppler correction is applied for the projectile assuming detection of ^{96,98}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 $2_1^+ \to 0_1^+$ 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 [20, 21]. 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 $B(E2, 2_1^+ \to 0_1^+) = 462(11)\,e^2fm^4$ and extracted for the first time a preliminary value for the spectroscopic quadrupole moment of the first 2_1^+ state equal to $Q_s = -6(9)\,efm^2$.

From the measurement of the spectroscopic quadrupole moment a weak static deformation can be assigned to the first excited state. For indication, using the deformed liquid drop model, one can extract $\beta \leq 0.14$. The mean deformation of the first 2^+ state is null as its B(E2) is rather large (20 W.u) supporting a quasi-vibrator character for the ^{96}Sr in its ground-state band structure. This deformation is also compatible with a moderate oblate deformation in the ground state calculated in the triaxial mean-field approach.

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 $B(E2, 6_1^+ \to 4_1^+) = 5600(1800)\,e^2fm^4$ 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^+

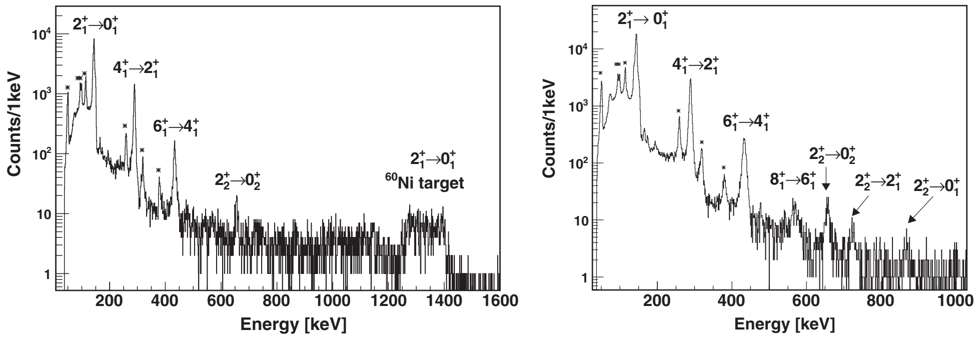

Figure 2. Left: γ-ray spectrum detected in MINIBALL, Doppler corrected for the projectile and following the excitation of a ^{98}Sr beam impinging on a ^{60}Ni target. Right: same spectrum for the excitation of ^{98}Sr on a ^{208}Pb target.

to the ground-state band have been established with values equal to B(E2,$2_2^+ \rightarrow 0_1^+$) = 37(6) e^{2}fm^4 and B(E2,$2_2^+ \rightarrow 2_1^+$) = 75(46) e^{2}fm^4. The B(E2,$2_2^+ \rightarrow 0_2^+$) was also extracted with a preliminary value of 700(186) e^{2}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 $\simeq$–150 efm^2 indicating a large prolate deformation and for the 2_2^+ state equal to $|Q_s| \leq 48$ 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.

4. 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 [22] 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.

5. Conclusion

We have investigated the collectivity and the deformation in ^{96,98}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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References

[1] S. A. E. Johansson, Nucl. Phys. **64** 147 (1965)
[2] D. A Arseniev *et al.*, Nucl. Phys. A **139** 269 (1969)
[3] S. Naimi *et al.*, Phys. Rev. Lett. **105**, 032502 (2010)
[4] M. Albers *et al.*, Phys. Rev. Lett. **108**, 062701 (2012)
[5] W. Urban *et al.*, Nucl. Phys. A **689** (2001)
[6] K. Sieja *et al.*, Phys. Rev. C **79**, 064310 (2009)
[7] O. Sorlin and M.-G. Porquet Prog. in Part. and Nucl. Phys. **61**, 602 (2008)
[8] J. Skalski, S. Mizutori, W. Nazarewicz, Nucl. Phys. A **617**, 282 (1997)
[9] G.A. Lalazissis, M.M. Sharma; Nucl. Phys. A **586**, 201 (1995)
[10] S. Hilaire, M. Girod; http://www-phynu.cea.fr/science-en-ligne/carte_potentiels_microscopiques/carte_potentiel_nucleaire.htm
[11] N. Warr and the Miniball collaboration Eur. Phy. J. A **49** 40 (2013)
[12] H. Mach *et al.*, Nucl. Phys. A **523**, 197 (1991)
[13] G. Lhersonneau *et al.*, Phys. Rev. C **49**, 1379 (1994)
[14] C.Y. Wu *et al.*, Phys. Rev. C **70**, 064312 (2004)
[15] G. Jung *et al.*, Phys. Rev. C **22**, 252 (1980)
[16] K. Kawade *et al.*, Z. Phys. A **304**, 293 (1982)
[17] T. Rzaca-Urban *et al.*, Phys. Rev. C **79**, 024319 (2009)
[18] Nucl. Data. Sheets 98, 335 (2003)
[19] D. Cline, Ann. Rev. Nucl. Part. Sci. 36, 683 (1986)
[20] T. Czosnyka, GOSIA2, 2005, MINIBALL User's Workshop 2005
[21] T. Czosnyka, D. Cline, and C. Y. Wu, Bull. Am. Phys. Soc. **28**, 745 (1983)
[22] E. Clément *et al.*, Phys. Rev. C **75**, 054313 (2007)