EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE-Neutron-Time-of-Flight Committee

Shape coexistence in neutron-rich Sr isotopes: Coulomb excitation of ^{96}Sr

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Abstract

The nuclei in the mass region $A \simeq 100$ around Sr and Zr show a dramatic change of the nuclear ground-state shape from near spherical for $N \leq 58$ to strongly deformed for $N \geq 60$. Theoretical calculations predict the coexistence of slightly oblate and strongly prolate deformed configurations in the transitional region. However, excited rotational structures based on the highly deformed configuration, which becomes the ground state at $N = 60$, are not firmly established in the lighter isotopes, and the earlier interpretation of a very abrupt change of shape has been challenged by recent experimental results in favor of a rather gradual change. We propose to study the electromagnetic properties of the neutron-rich nucleus $^{96}_{38}$Sr$_{58}$ by low-energy Coulomb excitation using the REX-ISOLDE facility and the MINIBALL detector array. Both transitional and diagonal matrix elements will be extracted, resulting in a complete description of the transition strengths and quadrupole moments of the low-lying states. These results will provide important benchmarks for the understanding of the shape evolution in this mass region.

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Motivation

The neutron rich Sr and Zr isotopes are characterized by a sudden onset of quadrupole deformation at neutron number $N = 60$. This becomes evident already from the excitation energies of the first 2^+ states. Fig. 1 shows the dramatic drop in the excitation energy of the 2^+ states at $N = 60$ for both the Sr and Zr isotopes. While theoretical calculations, for example using the Nilsson-Strutinsky method with Woods-Saxon potential [1], the relativistic mean field theory [2], or the Hartree-Fock-Bogoliubov approach with Gogny interaction [3] reproduce this onset of deformation qualitatively, they differ in the details 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. Potential energy curves for ^{96}Sr and ^{98}Sr are presented in Fig. 1. The absolute minimum in ^{96}Sr is found to be oblate, while the strongly deformed prolate minimum is found about 1 MeV above. Oblate and prolate minima are almost degenerate in ^{98}Sr. This scenario is supported by the observation of excited 0^+ states at 1229 and 1465 keV in ^{96}Sr and at only 215 keV in ^{98}Sr. However, oblate shapes are difficult to prove experimentally, and so far there is no clear experimental evidence for oblate shapes in the neutron-rich Sr or Zr isotopes.

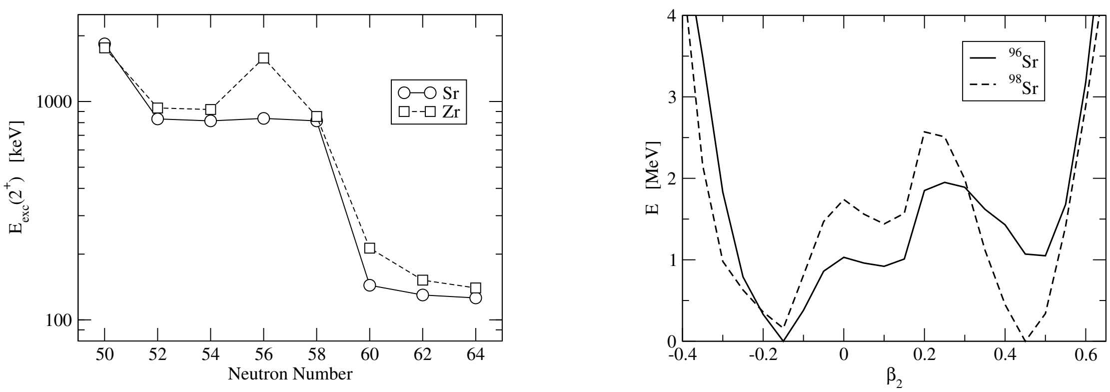

Figure 1: *Left:* Excitation energies of the 2_1^+ states for the chains of Sr and Zr isotopes. *Right:* Potential energy as a function of quadrupole deformation for ^{96}Sr and ^{98}Sr [3].

The nuclear structure of neutron rich Sr and Zr isotopes has been studied extensively in the past both in prompt and decay spectroscopy using the ISOL technique, spontaneous fission sources, or fusion-fission reactions [4–7]. Level schemes of ^{96}Sr and ^{98}Sr are shown in Fig. 2. The highly collective 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 $\rho^2(E0) = 0.053$ [8], supports the scenario of shape coexistence. The situation is less clear in ^{96}Sr. The ground-state band has a vibrational-like character, and the small $B(E2; 2_1^+ \rightarrow 0_1^+)$ value extracted from the lifetime of 7(4) ps [4] is consistent with a near-spherical ground state. Two low-lying 0^+ states were established by Jung *et al.* [9] at 1229 and 1465 keV and were interpreted as candidates for a deformed band head. An extremely strong electric monopole transition of $\rho^2(E0) = 0.18$ was observed between the 0_3^+ and 0_2^+ states [5, 10], indicating the presence of a sizeable deformation and strong mixing of the configurations. Electric monopole transitions from the excited 0^+ states to the ground state were not observed. The sequence of the 0_3^+ (1465 keV), 2_3^+ (1629 keV), and 4_2^+ (1975 keV) states was interpreted as the well-deformed rotational band equivalent to the ground-state band in ^{98}Sr, even though the $2_3^+ \rightarrow 0_3^+$ transition remained unobserved.

Recently prompt spectroscopy experiments yielded a rather regular rotational structure above the 4_2^+ state extending up to spin 18^+ [6, 7]. Lifetimes could be established for the 10^+ and 12^+ states in this band [6], from which a relatively small deformation of only $\beta_2 = 0.25$ was derived, much smaller than the ground-state deformation of ^{98}Sr, which is assumed to be $\beta_2 \approx 0.4$. It was argued that the 0_2^+ (1229 keV) and 2_2^+ (1506 keV) states form 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 [6]. 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. However, the higher-spin members of such a structure, which are not observed, should then rapidly become yrast. The extremely strong $E0$ transition can only occur if the 0_2^+ and 0_3^+ states are strongly mixed, and the branching ratio of the transitions from the 4_2^+ state indicates also a strong mixing of the 2_2^+ and 2_3^+ states [7], so that the low-spin levels are displaced in energy and cannot

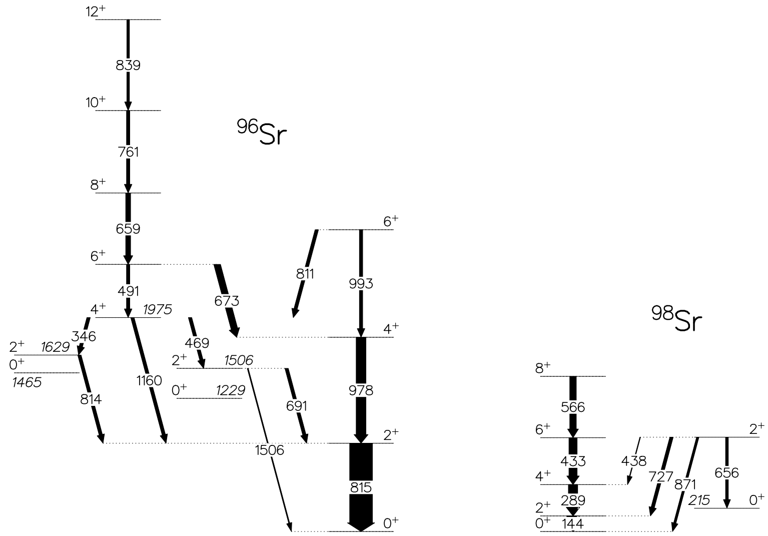

Figure 2: Partial level schemes of ^{96}Sr [6, 7] and ^{98}Sr [8].

easily be grouped into rotational bands. The measurement of transition strengths and intrinsic quadrupole moments is therefore essential to understand the complex shape coexistence and the onset of deformation in this region. Only the quadrupole moments can give direct evidence for the predicted oblate shapes.

We propose to study ^{96}Sr by projectile Coulomb excitation at low energy well below the Coulomb barrier. This well-established technique can provide a complete set of both transitional and diagonal matrix elements. The B(E2, $0^+_1 \rightarrow 2^+_1$) value that is only poorly known from a lifetime measurement (7 ± 4 ps) will be established with high precision. The $B(E2)$ values related to the $0^+_{2,3}$ and $2^+_{2,3}$ states will give important insight into the structure of these states and their collectivity and mixing. The measurement will be sensitive to the spectroscopic quadrupole moment of at least the 2^+_1 and possibly the excited 2^+ states, giving direct information about the shapes involved, in particular about a possible oblate deformation of the ground-state band. Modern theoretical approaches like configuration-mixing calculations using the generator coordinate method (e.g. [11]) are capable of calculating static and transitional matrix elements of shape-coexisting states, and the proposed measurement would represent an important test of such models.

Experimental details

Sr ions have not yet been accelerated at REX-ISOLDE. The production yield for ^{96}Sr ($T_{1/2} = 1.07$ s) has been measured to be $5.7 \cdot 10^6$ per μC of protons using the SC driver and a UC$_x$ target. In order to obtain a beam of ^{96}Sr free from isobaric contaminants such as ^{96}Rb, we propose to extract ^{96}Sr^{19}F molecules from the production target. The mass separator will be tuned to the mass 115 of the molecule. Even thought contaminants like ^{115}In will get into the EBIS, a rather pure beam of ^{96}Sr can be extracted after the break-up of the molecule. Using a neutron converter before the primary target will help to minimize the In production. This extraction scheme and the resulting production yield should be tested and optimized before the experiment. This beam development has strong synergies with the development of Ba beams, which have similar chemical properties, for the ISOLDE experiment IS411. The ^{96}Sr ions will be accelerated to the maximum energy of about $2.9 \cdot A$ MeV by the REX accelerator.

We propose to use a secondary ^{120}Sn target for the Coulomb excitation of the projectiles. This choice is a compromise between the Coulomb excitation cross section and the mass asymmetry for a better distinction in energy between scattered projectiles and target recoils. The prompt γ rays emitted after Coulomb excitation will be detected in the MINIBALL spectrometer of germanium detectors in coincidence with the scattered particles detected in an annular segmented silicon-strip detector. The silicon detector (CD) covers scattering angles between 16.3° and 53.3° in the laboratory frame. The detection of scattered projectiles corresponds to a range of scattering angles between 29.5° and 93° in the center-of-mass frame, whereas the detection of the recoiling target covers the range $73.5° \leq \theta_{cm} \leq 147.5°$. Both projectile and target will be detected in the overlapping range. The particle energies are shown as a function of scattering angle in Fig. 3. The distinction between ^{96}Sr and ^{120}Sn is problematic only for the innermost rings of the silicon detector which contribute only little to the total excitation cross section. In order to minimize the dead time in the CD detector, a slow extraction of the ^{96}Sr ions from the EBIS should be attempted.

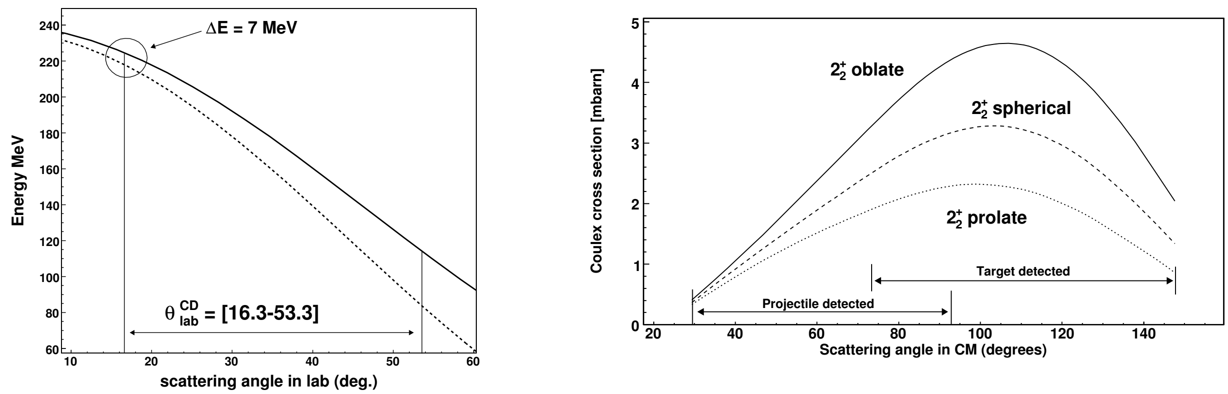

Figure 3: *Left:* Kinetic energy of the projectiles and target recoils as a function of the laboratory scattering angle. The energy loss in the target has been taken into account. *Right:* Differential Coulomb excitation cross section for the 2_2^+ state for different signs of the quadrupole moment. The vertical lines indicate the range of scattering angles covered by the silicon detector for detection of either the projectile or the target recoil.

To minimize systematic errors, the γ-ray yields measured for the ^{96}Sr projectiles will be normalized to the γ rays following the Coulomb excitation of the ^{120}Sn target ($E(2^+)$=1171 keV), for which the matrix elements are well known. The excitation probability of higher-lying states can be normalized to that of the 2_1^+ state. In this case the absolute number of incident ^{96}Sr ions is not needed and systematic errors from beam contaminants can be excluded. The analysis will be performed using the code GOSIA [12, 13] to determine the set of transitional and diagonal matrix elements that best describes the observed γ-ray yields in a χ^2 minimization.

Coulomb excitation calculations and rate estimates

In order to evaluate the feasibility of the experiment we have performed Coulomb excitation calculations based on the known spectroscopic information and different hypotheses for the collectivity of the states. The known spectroscopic parameters for the low-lying states in ^{96}Sr are listed in table 1. Even though the lifetime of the 2_1^+ state has a very large uncertainty, this value can be used to estimate the population of the state. Depending on the properties of the higher-lying states and the static quadrupole moments, the cross section to populate the 2_1^+ state integrated over the range of scattering angles covered by the silicon detector is of the order of 1 to 1.5 barn.

Urban *et al.* [6] deduced a transitional quadrupole moment of $Q_0^t = 2.20(15)$ eb from lifetimes measured for the 12^+ and 10^+ states, from which they derived a quadrupole deformation of β_2=0.25 for the rotational cascade above the 4_2^+ state. If we assume that the 0_2^+ and 2_2^+ states belong to this rotational band, we can use the rotor model to extrapolate the transitional matrix elements between these states, and together with the branching ratios this allows estimating the Coulomb excitation cross sections. The sign of the deformation enters the calculations via the reorientation effect. Table 2 shows the cross sections calculated for various states and for different signs of the quadrupole moments of the 2_1^+ and 2_2^+ states. Rigid rotor values were assumed for the diagonal matrix elements. The cross sections are integrated over the range of scattering angles covered by the silicon detector. The differential cross section for the 2_2^+ state is shown in Fig. 3 for different signs of the deformation. Even though the absolute cross section for the 2_2^+ state is about two orders of magnitude smaller than for the 2_1^+ state, there is a very strong dependence on the sign of the quadrupole moment.

In order to determine the beam time required to perform the proposed measurement, we use the measured production yield for ^{96}Sr of $5.7 \cdot 10^6$ per μC of protons from the SC driver as a conservative estimate. Higher yields are expected using the PS Booster. Assuming a proton intensity of 2 μC/s and a transmission of 1% for the REX accelerator, we expect 10^5 pps on the MINIBALL target. With a total

Table 1: Experimentally known lifetimes [4] and branching ratios [7].

I_i	τ	I_f	E_γ [keV]	rel. I_γ
2_1^+	7 (4) ps	0_1^+	815	100
0_2^+	167 (17) ps	2_1^+	414	100
0_3^+	9.7 (1.4) ns	0_2^+	235	$E0$
		2_1^+	650	100
2_2^+	< 9 ps	0_1^+	1506	56(15)
		2_1^+	691	100
2_3^+		0_1^+	1629	12.2(11)
		2_1^+	813	100
		0_2^+	398	5.3(4)
4_1^+		2_1^+	978	100
4_2^+		2_1^+	1160	50(3)
		2_2^+	469	100
		2_3^+	348	22(4)

Table 2: Estimate of the Coulomb excitation cross sections in mb assuming different combinations of signs for the quadrupole moments of the 2_1^+ and 2_2^+ states. A negative sign corresponds to an oblate and positive to a prolate shape. See text for further details.

I^π	2_1^+ (−) 2_2^+ (−)	2_1^+ (+) 2_2^+ (−)	2_1^+ (−) 2_2^+ (+)	2_1^+ (+) 2_2^+ (+)
2_1^+	1460	1130	1470	1140
4_1^+	40	37	40	37
0_2^+	25	23	24	23
2_2^+	21	22	11	11
4_2^+	2.2	2.6	0.8	0.9

absorption efficiency of 7% at 1.3 MeV for MINIBALL comprising eight triple clusters and a target thickness of 2 mg/cm^2, we find the γ-ray yields given in table 3.

Our recent Coulomb excitation experiments with radioactive ^{74}Kr and ^{76}Kr beams from SPIRAL, which successfully achieved similar goals, can be used to estimate the required beam time. The total level of statistics for the $2_1^+ \rightarrow 0_1^+$, $0_2^+ \rightarrow 2_1^+$, and $2_2^+ \rightarrow 2_1^+$ transitions in ^{76}Kr was 40000, 2000, and 1000, respectively, which was sufficient to determine the static quadrupole moments for both the 2_1^+ and 2_2^+ states. To reach a similar level of statistics, we require 7 days of radioactive ^{96}Sr beam, excluding time for set-up and test measurements to optimize the extraction scheme. The production yield fo ^{98}Sr should also be measured during such beam tests in order to evaluate the feasibility of a possible follow-up experiment on ^{98}Sr.

Table 3: Estimated γ intensities using the assumptions described in the text.

I_i	I_f	E_γ [keV]	counts/day
2_1^+	0_1^+	815	11440
4_1^+	2_1^+	978	274
0_2^+	2_1^+	414	248
2_2^+	2_1^+	691	60
2_2^+	0_1^+	1506	20
4_2^+	2_2^+	469	6
2_3^+	2_1^+	814	30

Summary

We propose to study the shape evolution and shape coexistence in the neutron-rich Sr isotopes through Coulomb excitation of ^{96}Sr. Both transitional and diagonal matrix elements will be determined in a differential Coulomb excitation measurement utilizing the reorientation effect. The set of transitional matrix elements linking the low-lying states will give insight into the collectivity of the different rotational structures and their mixing. The static quadrupole moments of the 2_1^+ and 2_2^+ states will shed light on possible oblate

shapes which are predicted theoretically. The experimental determination of the matrix elements for the shape coexisting states will give important constraints for modern nuclear structure theories describing such phenomena. We ask for seven days of ^{96}Sr beam to perform the proposed experiment.

Beam requirements

Beam	Min. intensity	Target material	Ion Source	Shifts
^{96}Sr	10^5 pps	UC_x	Positive surface	21 (data taking)+3 (set-up)

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