EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

A Coulomb-nuclear excitation study of shape co-existence in ^{96}Kr

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CERN-INTC-2017-062 / INTC-P-517
31/05/2017

Abstract: *We propose to study shape-coexistence in the neutron-rich nucleus ^{96}Kr that has also been predicted to have a significant value for the hexadecapole deformation parameter, β_4. The standard Miniball setup will be used and the second excited states will be populated using a ^{96}Kr beam with an energy of 4.8 MeV/u impinging on a ^{196}Pt target. We will take advantage of the higher beam energies provided by the HIE-ISOLDE facility and the inelastic Coulomb-Nuclear Excitation, CNE, technique. In this technique, second excited states have higher populations compared to those in the safe Coulomb excitation. Therefore, the proposed experiment would allow for a detailed study of the low-lying level structure and transition probabilities between the second excited states in ^{96}Kr. The results from this work will be analysed together with available data of the other Kr isotopes and the neighbouring Zr and Sr nuclei. This should help us clarify the onset of collectivity and a possible shape transition in the krypton isotopic chain when moving beyond N=60. In addition, the influence of the hexadecapole deformation on the excitation cross sections, particularly of the 4^+ states, will also be investigated.*

Requested shifts: 21 UT
Beamline: MINIBALL + CD

1. Scientific Motivation

Co-existing shapes in nuclei are now experimentally known to be ubiquitous across the nuclear chart and continue to be a strong focus both for experimental and theoretical works [1]. For nuclear models, it has been challenging to reproduce shape coexistence and shape transition features. This can be attributed to the fact that these phenomena arise due to fine interplays between different shape minima, which are sensitive to the choice of the underlying effective interactions. Experimental studies of shape coexistence in exotic nuclei are essential to provide data for an understanding of the dynamics of correlations between nucleons and the mean-field experienced by them at the limits of stability. Strontium and zirconium nuclei in the A = 100 region show one of the most dramatic shape transitions on the nuclear chart. While the ground states of the isotopes up to N = 58 show an almost spherical configuration, they undergo a rapid change to strongly deformed shapes at N = 60 [1]. It was recently shown, that this can be attributed to a coexisting, deformed configuration becoming the ground state at N = 60, while the spherical configuration becomes non-yrast [2,3]. This phenomenon however, seems to change when moving to the neutron rich krypton isotopes. In contrast to zirconium and strontium nuclei no sudden onset of collectivity was observed at N = 60. This experimental evidence is based on two-neutron separation energies from mass measurements [4] and Coulomb excitation measurements for the even-even ^{92,94,96}Kr nuclei [5]. The phenomenon can also be reproduced in theoretical calculations using an IBM-2 Hamiltonian based on the microscopic Gogny-D1M EDF [5]. These calculations also show a second minimum in the potential energy surface for ^{96}Kr, indicating the co-existence of a prolate deformed shape (see Fig. 1 a)). The influence of this shape coexistence on the low-lying excitation spectrum of ^{96}Kr was modelled by mixing calculations in the IBM-2 which include also proton 2p-2h excitations from the Z = 28 − 40 major shell to the $\pi g_{9/2}$ in reference [6]. Its influence on the yrast 2_1^+, 4_1^+ and 6_1^+ states was found to be small, but it prominently leads to the emergence of low-lying excited 0_2^+ and 2_2^+ states (Fig. 1 b)) which according to the calculations carry mostly 2p-2h prolate character.

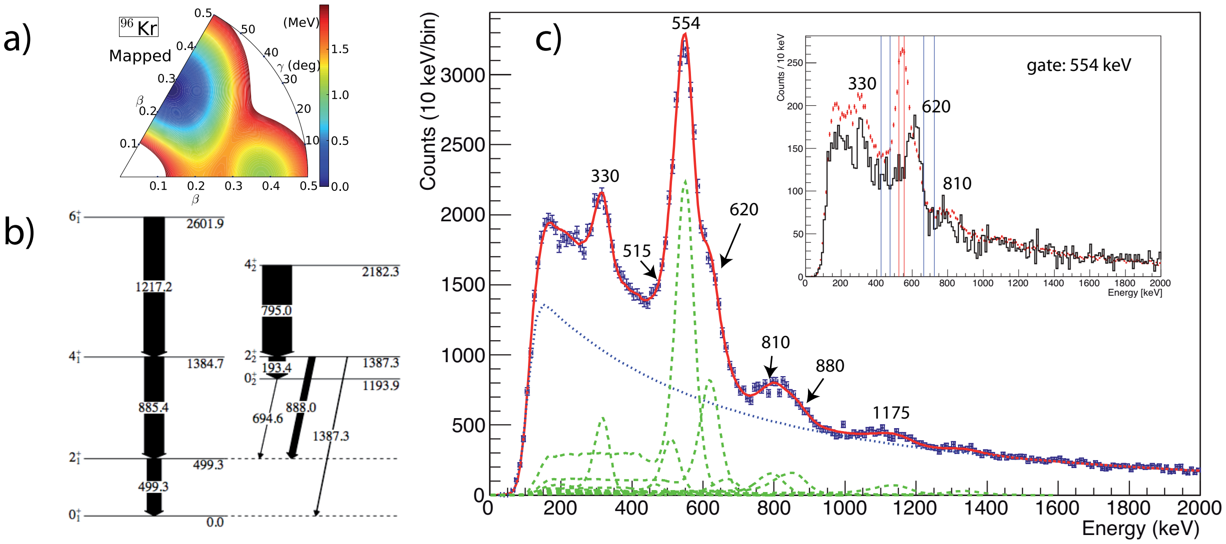

Fig. 1 a) The potential energy surface for ^{96}Kr from the mapped IBM-2 Hamiltonian which takes into account the mixing of regular and the 2p-2h intruder configuration [6]. b) Theoretical level scheme obtained in the configuration-mixing IBM-2 model with ^{90}Zr core. The width of the arrows indicates the calculated B(E2) values. c) Experimental γ-ray spectrum for ^{96}Kr obtained with DALI2 at RIKEN. The red line shows a multicomponent fit of response functions from Geant 4 simulations (indicated in green) together with a double-exponential background (dashed violett line). The inset shows a background corrected γ-γ spectrum in coincidence with the 554 keV line [9].

Recently, spectroscopic data was obtained with AGATA at GANIL, which confirmed the rather smooth evolution of the energy of the first excited 2^+ state in the krypton isotopes up to N = 60 and reported the energy of the 4_1^+ state in ^{96}Kr [7]. However, for the more neutron rich ^{98}Kr and ^{100}Kr nuclei, a measurement using the NaI array DALI2 at RIKEN found a significant reduction of the 2_1^+ energies that suggests an increased level of deformation beyond N = 60 [8]. The same work also for the first time identi-

fies the low-lying (0_2^+, 2_2^+) states in the krypton isotopes, which show first evidence for the lowering of a co-existing, excited band.
Preliminary spectroscopic data for ^{96}Kr after a 1p removal reaction from ^{97}Rb [9] from the same experimental campaign also show several low lying transitions in addition to the established $2_1^+ \rightarrow 0_1^+$ line (Fig. 1 c)). While the RIKEN data are generally consistent with an assignment of a 4_1^+ state at the energy of 1175 keV given in reference [7], they also leave room for a different interpretation of spin and parity 2_2^+ of this state due to the observation of a (presumably ground state) transition with an energy of 1175 keV. A strong 2_2^+ -> 2_1^+ transition at an energy of 620 keV would also agree with the high relative population of the 2_2^+ state (> 50% of 2_1^+) observed for the ^{99}Rb(p,2p)^{98}Kr case. As pointed out in reference [8], the ground states of ^{97,99,101}Rb are understood to be formed by the $\pi g_{9/2}[431]3/2^+$ Nilsson model configuration with large prolate deformation [10, 11]. The high population of (0_2^+, 2_2^+) states in the neutron rich krypton isotopes by proton removal may therefore be understood as a large overlap with the prolate deformed ground state configuration in the rubidium isotopes.

Despite the large ^{96}Kr statistics in the RIKEN experiment the relatively poor resolution of the DALI2 NaI detectors together with the background radiation make a conclusive interpretation of the level population and decay scheme difficult. Therefore, we propose that high resolution γ-ray spectroscopic data to be taken with the MINIBALL array will provide us with a possibility to perform a γ-γ coincidence analysis and should remove the ambiguity regarding the assignments of the low lying states in ^{96}Kr. In particular, the Coulomb-Nuclear Excitation (CNE) at the beam energies provided by HIE-ISOLDE will result in sufficient amount of populations to the second excited 0^+ and 2^+ states as well as other higher lying yrast and non-yrast states, thus providing unique information on their energy locations and decay patterns. In addition, the fact that the sensitivity of the inelastic cross sections to the optical model parameters is not expected to be high around the Coulomb barrier energies, would allow us to extract electromagnetic matrix elements between these states [17]. This will shed further light on the evolution of collectivity when moving beyond N = 60 and yield further data to understand the origins of shape co-existence phenomena in the neutron rich krypton isotopes.

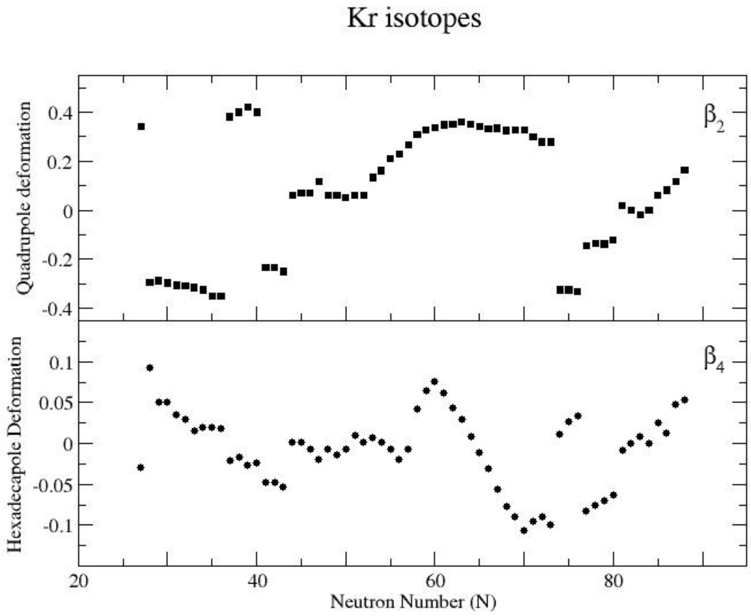

Fig. 2 Calculated deformation parameters for Kr isotopes [15]. The Kr isotopes with extreme proton-neutron ratios exhibit abrupt behaviour, especially near the N=Z line, where shape co-existence sets in.

An additional interest in the case of ^{96}Kr also stems from the predicted hexadecapole deformation (β_4) as discussed in I-152 [11]. It can be seen from Fig. 2, β_4 is expected to have a low value for ^{74}Kr (-0.02) while it is significantly higher for ^{96}Kr (0.08) [5]. Typically, β_4 are expected to exhibit two extrema between two shell-closures, namely, at 1/4th and 3/4th of shell filling [15]. However, this does not seem to be the case for Kr isotopes as can be noted from Fig. 2. Therefore, experimental data would provide an opportunity to address the non-typical trends in quadrupole and hexadecapole deformations and to carry out investigations into their origin. In the presently proposed CNE technique, high sensitivity to β_4 is expected for the populations of the first 4^+ state and in those states coupled to it. We will explore a possibility to extract the hexadecapole moment from the present work and pave the way to future cases of β_4 studies in exotic nuclei.

The experimental technique, rate estimates and beam time.

Assuming the same experimental conditions as in an earlier ISOLDE measurements (IS485) using ^{96}Kr beam [5,6], we calculated excitation cross sections for a realistic beam intensity of 7000 pps on the MINIBALL target. The cross sections have been calculated using the computer code FRESCO [16] for a 460 MeV ^{96}Kr beam on a 2 mg/cm^2 ^{196}Pt target. Electromagnetic transition matrix elements and excitation energies for the 2_1^+, 0_2^+, 2_2^+ and 4_1^+ states have been chosen according to the mixing calculations performed in the IBM-2 [6]. The hexadecapole deformation was chosen to be $\beta_4=0.08$ (cf. Fig. 2), taken from Ref.[15].

Table I shows the total yield for γ-rays originating from the decays of 2_1^+, 0_2^+, 2_2^+ and 4_1^+ states in ^{96}Kr detected with MINIBALL during a measuring time of 168 hours (7 days of beam time or 21 shifts of 8 hours) (Tab. I, column 4). The γ-ray detection efficiency of the MINIBALL detector array was assumed to be 6-16% for the transitions of interest. The γ-rays will be detected in coincidence with scattered ^{96}Kr nuclei detected by an annual (CD) double sided silicon strip detector placed at forward angles and covering an angular range of 16° to 53° degrees in the laboratory frame.

		Safe Coulex	Coulomb Nuclear Excitation
Transition	E_γ [keV]	N_γ [Counts] $E_{Beam} = 380$ MeV Standard CD (lab. ang. 16°-53°)	**N_γ [Counts]** **$E_{Beam} = 460$ MeV** **Standard CD** **(lab. ang. 16°-53°)**
$2_1^+ \rightarrow 0_1^+$	554.1	13353	**16205**
$0_2^+ \rightarrow 2_1^+$	695	37	**89**
$2_2^+ \rightarrow 0_2^+$	193	0	**4**
$2_2^+ \rightarrow 2_1^+$	888	60	**1485**
$2_2^+ \rightarrow 0_1^+$	1387	28	**820**
$4_1^+ \rightarrow 2_1^+$	885	638	**439**

Table I: Expected γ-ray yields in 21 shifts for the low-lying transitions of interest in ^{96}Kr. The yields are given for two different beam energies representing safe Coulomb excitation and the Coulomb-Nuclear excitation method.

We also calculated yields for a beam energy of only 380 MeV for which we expect pure electromagnetic excitation for the given projectile scattering angles (Tab. I, column 3). Comparing the yields for the de-excitation of the non-yrast 0_2^+ and 2_2^+ states, we would like to stress that the proposed measurement has become possible only due to the upgraded HIE-ISOLDE facility. It allows us for the first time to bring the beam and target nuclei close enough and have the influence of nuclear interactions and employ the Coulomb-Nuclear Excitation on the nuclear levels to achieve higher populations. The CNE method was developed by us and originally employed in a novel technique where the beam energies are chosen in such a way that cross sections of 4^+ states in rare-earth nuclei were highly sensitive to the magnitude of β_4, allowing accurate determinations of hexadecapole moments [17].

Considering the MINIBALL efficiency we expect to detect 150, 50 and 10 γ-γ-coincidences with the $2_1^+ \rightarrow 0_1^+$ transition for the $2_2^+ \rightarrow 2_1^+$, $4_1^+ \rightarrow 2_1^+$ and $0_2^+ \rightarrow 2_1^+$ transitions during the total proposed measuring time at a beam energy of 460 MeV, respectively. As the γ-ray spectra are expected to be clean, this should allow unambigous identification of the levels. Nevertheless, usage of a thicker 3 mg/cm^2 ^{196}Pt target is being under consideration, which should further help us identification of the levels and more accurate extraction of the matrix elements.

Summary of requested shifts:

Based on our yield calculations for Coulomb-Nuclear Excitation at a beam energy of 460 MeV we estimate that a total of **21 shifts** will be sufficient to reach the proposed goals. It should be stressed that the near barrier energies will demand consideration of the dependence of inelastic cross sections on the optical model parameters. To carry out such an analysis and minimize error contribution of the optical model to extracted electromagnetic matrix elements, it is important to have data collection during the total amount of the aforementioned beam time and collect sufficient statistics.

Assuming a beam intensity of 7000 pps of ^{96}Kr on a ^{196}Pt target of 2 mg/cm^2 and realistic excitation matrix elements, we expect to have enough statistics in the $2_2^+ \rightarrow 2_1^+$, $4_2^+ \rightarrow 2_1^+$ and $0_2^+ \rightarrow 2_1^+$ transitions to perform the desired γ-γ-coincidence analysis that will give clear evidence for possible shape coexistence and will remove the ambiguity regarding the assignments of the low lying states in ^{96}Kr.
The population of the first excited 4^+ state is sensitive to β_4 and will additionally allow us a possibility to study the non-typical behaviour of hexadecapole moments in the krypton isotopic chain.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	Availability	Design and manufacturing
[if relevant, name fixed ISOLDE installation: MINIBALL + only CD	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards			
	[Part 1 of the experiment/equipment]	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		

- Isotope			
- Activity			
Use of activated material:			
- Description	☐		
- Dose rate on contact and in 10 cm distance	[dose][mSV]		
- Isotope			
- Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*
… kW