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

Coulomb Excitation of ^{94,96}Kr beam — Deformation in the neutron rich Krypton isotopes

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Abstract

Recently the energy of the 2_1^+ state in the N=60 ^{96}Kr nucleus was determined to be 241 keV [1]. This was the first experimental observation of an excited state in this highly exotic nucleus. The 2_1^+ state in ^{94}Kr is located at 665.5 keV, i.e. $E(2_1^+)$ drops by more than 400 keV at N=60. This lowering of the 2_1^+ energy indicates a sharp shape transition behavior which is somewhat similar to that discovered in the Sr and Zr isotopic chains at N=60. The deformation expected for the 2_1^+ state of ^{96}Kr, as resulting from the $E(2_1^+)$ energy based on the semi-empirical relation of Raman *et al.* [9] is $\beta_2 = 0.31$, which is, however, considerably smaller than that for Sr and Zr (≥ 0.40). The sudden decrease of $E(2_1^+)$ from N=58 to N=60 does not fully agree with the more gradual change of deformation deduced from laser spectroscopy measurements of mean square charge radii [2], although for ^{96}Kr, in particular, these are consistent with a β_2 value of about 0.31. It is thus of considerable interest to characterize the nuclear shape evolution in the most neutron-rich Kr isotopes looking at transition matrix elements.

Thus we propose to measure the $B(E2)$ values for the first excited 2^+ in ^{94}Kr and ^{96}Kr, which will directly determine the deformation of the states. The present proposal is the natural extension of our previously performed Coulomb excitation experiments on the ^{88}Kr and ^{92}Kr nuclei, where the determination of B(E2;$2_1^+ \rightarrow 0_1^+$) was possible for the first time [3].

The use of a UC$_x$ primary target coupled with a plasma source by a cooled transfer line is at present the best choice for production of neutron-rich Kr isotopes [4]. The separated ^{94,96}Kr beams have to be charge-bred and post-accelerated by the REX set-up. The 3 MeV/u beam will be scattered on a ^{108}Pd target and scattered ions will be detected with the DSSSD charged particle detector (CD detector) covering forward scattering angles.

Coulomb Excitation γ-rays will be measured with the MINIBALL detector array.

1 Physical motivation

One of the most interesting shape evolutions on the nuclear landscape is encountered along the Sr and Zr isotopic chains, and it was extensively investigated, both experimentally and theoretically. While N=50 is a good spherical shell closure, the N=40 becomes a well-deformed shell closure for both Sr and Zr proton-rich isotopes due to the strong $p-n$ interaction between strongly overlapping $1\pi g_{\frac{9}{2}}$ and $1\nu g_{\frac{9}{2}}$ orbitals. On the neutron-rich side, neutron number 56 becomes an effective spherical shell closure, and ^{96}Zr (Z=40, N=56) is quoted as a doubly magic nucleus. With only four neutrons more, the N=60 ^{98}Sr and ^{100}Zr are strongly deformed, and this very sharp passage from spherical shape to stable deformation attracted, ever since it was experimentally observed, a constant theoretical interest. The first theoretical studies attributed the onset of deformation to the strong $p-n$ interaction between spin-orbit partner orbitals $1\pi g_{\frac{9}{2}}$ and $1\nu g_{\frac{7}{2}}$ [5]. The experimental data obtained later did not support this hypothesis, and another theoretical explanation was advanced [6, 7], which emphasizes the role of the intruder $1\nu h_{\frac{11}{2}}$ orbital in generating the deformation at N=60. The same mechanism which generates deformation for N=Z=38,40 is reflected on the neutron-rich side. The high-l intruder orbitals are strongly overlapping, and on the neutron-rich side those are not the identical $1g_{\frac{9}{2}}$ orbitals, but $1\pi g_{\frac{9}{2}}$ and $1\nu h_{\frac{11}{2}}$ orbitals. The correlated occupation of Nilsson states derived from these spherical orbitals is at present accepted as the major factor in stabilizing the deformation.

The rapid change in deformation in the A=100 region can also be understood (see also [8]) as a lowering of intruder states. The energy of intruder configurations depends on the size of the energy gap to be overcome and the strength of the p-n interaction. In extreme cases of small gaps and/or strong p-n interaction, the deformed intruder state may drop below the "normal" states and become the new ground state, as it may happen at N=60 for Z=38 and Z=40. Therefore, from a global perspective, the physics we are going to address is somehow similar to that addresssed by studies on the "Island of Inversion" in lighter systems, like the Mg isotopes.

We discuss below the existing experimental data which support the present proposal.

Recently, the energy of the first excited 2_1^+ state of ^{96}Kr was measured [1]. This is presently the only excited state known in this nucleus. The 2_1^+ has a rather low energy of 241 keV, much lower than the analogous state in ^{94}Kr, E(2_1^+)=665.5 keV. The $E_x = 241$ keV energy in ^{96}Kr would correspond, through the empirical relationship of Raman *et al.* [9] to a deformation $\beta_2 = 0.31$.

Fig. 1 shows the experimental data which led to the assignment of the 2^+ state of ^{96}Kr. The nucleus was observed in a recent thin-target experiment we performed at the PRISMA/CLARA setup at Laboratori Nazionali di Legnaro (Italy)[1]. Neutron-rich nuclei were produced from the fission of ^{238}U induced by bombarding a 1 mg/cm^2 ^{238}U target with 1 GeV ^{136}Xe beam. The mass and atomic number of the fission products were identified using the large-acceptance magnetic spectrometer PRISMA[11], and the γ-rays coming in coincidence were detected with the clover array CLARA[12]. Prompt gamma rays from hundreds of isotopes were observed in this way. In particular the N=60 Sr and Zr were relatively well populated, while the more exotic ^{96}Kr is just above the observation limit of the setup, as can be seen from Fig. 1. Only one discrete line was observed for ^{96}Kr and was assigned to be the $2_1^+ \rightarrow 0_{gs}^+$ transition. One particular observation must be made regarding the low intensity of the $2_1^+ \rightarrow 0_{gs}^+$ 145 keV transition observed for ^{98}Sr : since it was a thin-target experiment gamma rays from levels with lifetime around 1 ns are partially emitted when the reaction products are out of the view of CLARA.

The evolution of the energy of the first excited 2^+ state along different isotopic chains (Se, Kr, Sr, Zr, and Ru) is shown in Fig. 2.

One can see that the krypton chain still presents a rather abrupt decrease, although less than in the case of Sr and Zr. For the Se isotopes (Z=34) the latest isotope in which this quantity is known is ^{88}Se, and the decrease after N=52 seems to anticipate a more gradual pattern than in the case of Kr. On the other side of Sr and Zr, the Ru isotopes show a quite gradual transition to moderate deformations at large N values (Mo isotopes, not shown for the clarity of the figure, are intermediate between Zr and Ru).

Besides the extreme cases of Z=38 and Z=40, abrupt changes in deformation were also observed for other elements in the Z≈40 region. As mentioned in [2], the most pronounced

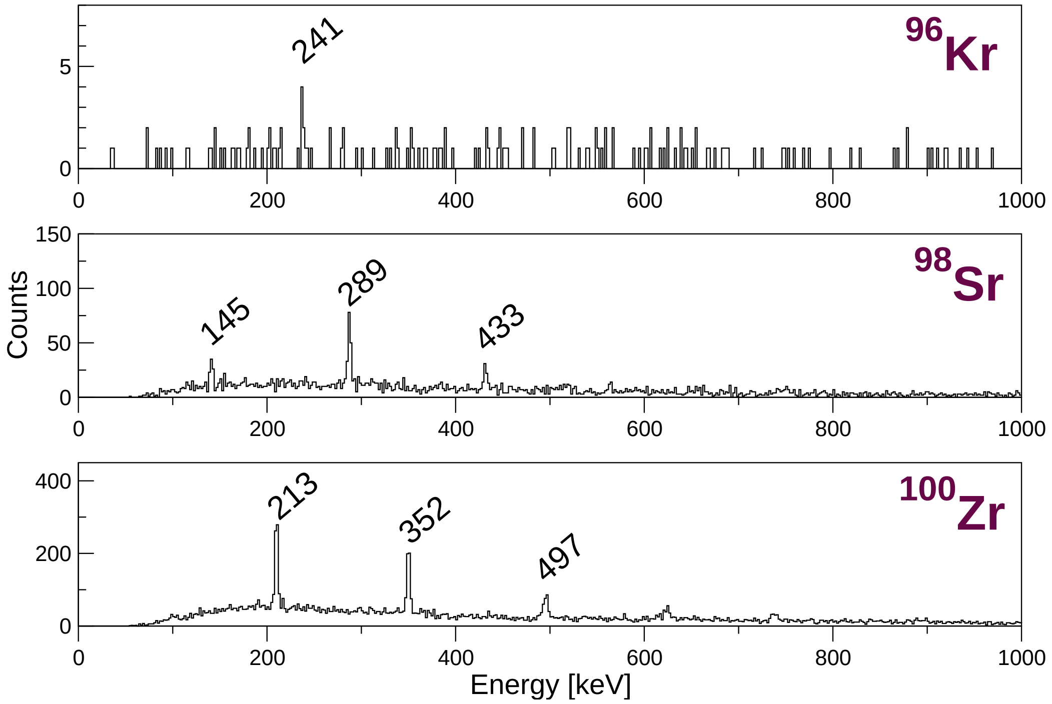

Figure 1: Gamma-ray spectra of N=60 isotones, as obtained in the PRISMA/CLARA experiment. Fission products of ^{238}U were detected with the magnetic spectrometer PRISMA, while the γ rays coming in coincidence were observed using the clover array CLARA. The presented spectra have 2 keV per channel [1].

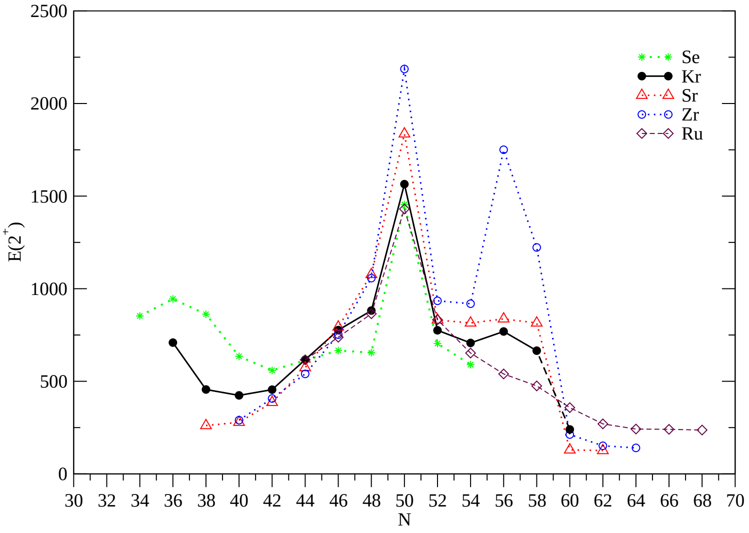

Figure 2: Systematics of E(2_1^+) in the A=100 region. The recent result of E(2_1^+) for ^{96}Kr indicates a rather sharp onset of deformation at N=60 [1].

transition is found for rubidium, strontium, and zirconium, and then diminishes gradually with increasing proton number. A special situation appears to exist in the Kr isotopes, according to the results of the laser spectroscopy experiments [2]. In this article, mean-square charge radii were measured up to the N=60 nucleus ^{96}Kr. No rapid changes in mean-square charge radii were found up to N=60, unlike the cases with Z>36. The explanation for this finding was that the lower number of protons leads to a reduced p-n interaction of the prolate neutron shell gap at N=60 with the proton $g_{9/2}$ orbital, i.e. the deformed intruder state does not become the groundstate.

The experimental situation is shown in Fig. 3.

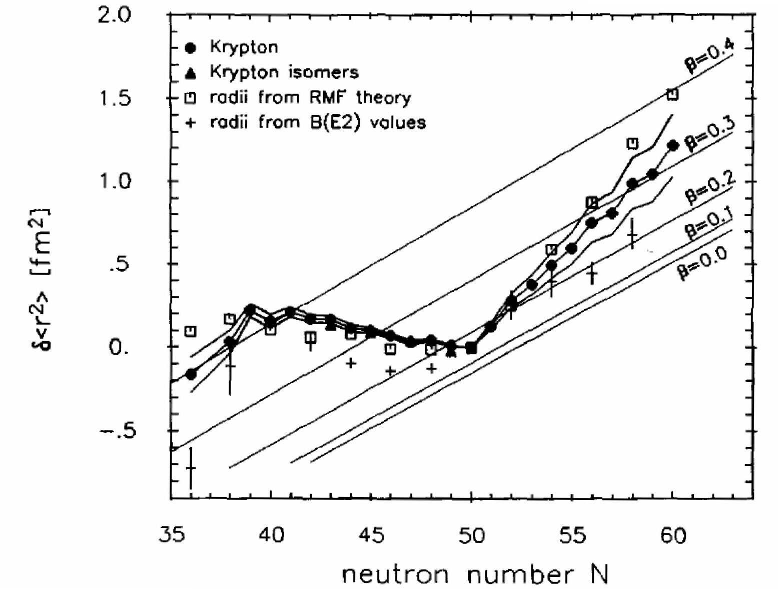

Figure 3: Measured mean-square charge-radii of krypton nuclei as a function of the neutron number. Isodeformation lines are from the finite-range droplet model (Fig. 3 from [2]).

For krypton isotopes N>50, no lifetime information on 2_1^+ states were available prior to our IS423 Experiment, and excitation energies were known up to N=58 only. The excitation energies E(2_1^+) are almost constant for N=52 to N=58, and as a consequence the same was expected for the B(E2) values. This would be in good agreement with the findings of Ref. [2].

In our IS423 experiment, we were able to determine B(E2;$2_1^+ \rightarrow 0_1^+$) values for ^{88}Kr (N=52) and ^{92}Kr (N=56) [3]. In contrast to what was believed before, the B(E2) strength grows from 8.8 W.u. in ^{88}Kr (N=52) to 17 W.u. in ^{92}Kr (N=56). These B(E2) values provide deformation values β_2 of 0.13 and 0.18, respectively. In Fig. 3, different deformation values are drawn, and compared with lines calculated from a finite-range droplet model. For isotopes with N up to 48, there are deformation values (crosses) determined from measured B(E2) values, and they are in generally good agreement with those determined from the laser spectroscopy experiments. In these isotopes, however, the deformations deduced on the basis of the Grodzins formula [10] are systematically much lower. On the neutron rich side, N above 50, Fig. 3 (taken from Ref. [2]) shows only values deduced from the Grodzins relation (crosses). For ^{88}Kr this value is about 0.2, which is in good agreement with the laser determination, but differs from the value 0.13 deduced from the Coulomb excitation measurements [3]. For ^{92}Kr, the Grodzins value is rather close to the value 0.18 deduced from the Coulomb excitation measurements, and differs strongly from the laser spectroscopy value. For ^{96}Kr, the value deduced on the basis of the 2^+ energy is 0.35 (Grodzins formula), or 0.31 (Raman formula), both values being close to that deduced from the laser spectroscopy measurements. Note the differences between the two empirical formulas: for the even Kr isotopes 88 to 96, the values of β_2 as deduced from Grodzins/Raman are as follows: 0.21/0.19; 0.22/0.20; 0.20/0.18; 0.21/0.19; and 0.35/0.31, respectively. The more realistic formula of Raman *et al.* [9] gives deformation values somewhat smaller than those of Grodzins [10], which are therefore even further from the laser spectroscopy values.

Thus, the rather fragmentary experimental knowledge for the neutron-rich Kr isotopes is rather confusing at present. Measurements of the B(E2) values for both ^{94}Kr and ^{96}Kr are highly desired in order to better characterize the shape transition at N=60. An eventual disagreement between the data derived from B(E2) values and those derived from laser spectroscopy mean-square charge radii raises interesting questions concerning the microscopic description of this mass region. The main goal of our experiments is to verify what kind of shape transition the krypton nuclei undergo at N=60, and correct our picture on the deformed orbitals and the p-n interaction in this region.

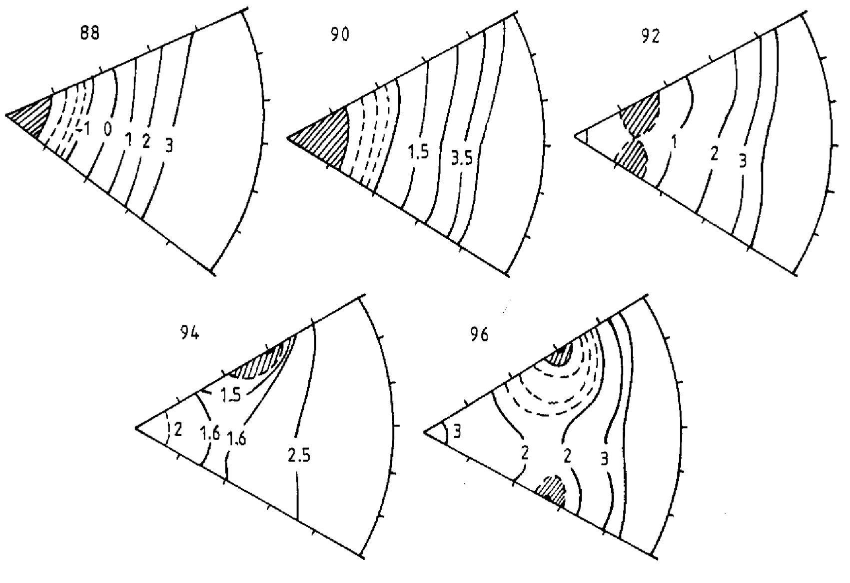

Figure 4: Potential energy surfaces for krypton. The full curves are equipotentials traced in steps of 1 MeV. The regions of minimum energy are hatched. The broken curves are additional equipotentials drawn in steps of 0.25 MeV. The figures on the equipotentials are the potential energy values in MeV (taken from [13]).

The scenario of a transition towards deformation at N=60 gets support from potential energy surface (PES) calculations [13]. The authors were able to reproduce the effects at N=60 for strontium and zirconium and predict correctly magnitude and sign (prolate) of the deformed 2_1^+ state in ^{100}Sr. The calculated potential energy surfaces for the krypton chain shows a rather similar transition to a prolate deformed minimum ($\epsilon \sim 0.30$) at N=60.

2 Experimental method

The ^{94,96}Kr beam, separated in ISOLDE source cooled transfer line and magnetic separator, will be post-accelerated to about 3 MeV/A using the REX set-up.

The beam will undergo Coulomb excitation after collisions with ^{108}Pd target which can be easily Coulomb-excited itself. Measurement of the resulting γ-rays energy will be performed simultaneously with scattered particles energy measurements. The particle-γ coincidence condition will be imposed to reconstruct the collision kinematics and reduce background of the γ energy spectrum.

Since the absolute efficiency normalization of the experimental set-up is very difficult, we prefer to rely on independent Coulomb excitation of both projectile (unknown B(E2)) and target (known). A newly developed version of the Coulomb Excitation Data Analysis Code *GOSIA 2* [14] is capable of performing a simultaneous fit of both projectile and target excitation to find an unknown matrix element describing the first 2^+ state excitation.

3 Counting rate estimate

In case of the ^{94}Kr nucleus we expect a slight increase of collectivity in comparison to ^{92}Kr. We estimated a value of B(E2;$2_1^+ \rightarrow 0_1^+$)=20 W.u., which leads to a matrix element of $\left\langle 0_1^+ || E2 || 2_1^+ \right\rangle$=0.5 eb. An influence of a quadrupole moment of the 2^+ state and 4^+ state coupling was tested using Rotational Model values of related E2 matrix elements. Most probably, the experiment will not be sensitive to the diagonal matrix element of the first 2^+ state but model-based predictions will still be possible. Feeding from the next (4^+) excited state gives less than 1% of contribution to the 2^+ state decay yield and is negligible.

An integrated yield of about 200 $\frac{\mathrm{mb}}{\mathrm{sr}} \cdot \frac{\mathrm{mg}}{\mathrm{cm}^2}$ was calculated as a result of yield integration over target thickness (2 mg/cm^2 assumed) and particle scattering angle range (15.5° – 50° for the CD detector) with the *GOSIA* code [15].

ISOLDE yields for noble gases and a UC$_x$ primary target were measured from [4]. The ^{94}Kr yield is quoted to be $3.3 \times 10^6/\mu$C. Due to recent updates this value is now $1 \times 10^7/\mu$C. Assuming a realistic REX efficiency of 2% and typical PSB SuperCycle set-up and additional contribution from the decay in REXTRAP/REXEBIS, one may expect about 1.8×10^5 ions/sec on a target.

MINIBALL's absolute efficiency at E$_\gamma$ $\approx$700 keV should be around 10%. Combining these numbers one gets 0.24 counts/sec or 864 counts/hour or 20700 counts/day in the first ($2_1^+ \rightarrow 0_1^+$) transition.

We checked these numbers starting from our ^{92}Kr data from IS423. The 2.1 MeV/u ^{92}Kr beam was delivered for 15 hours on a ^{109}Ag target. We collected a total of 6200 counts (Doppler corrected and background subtracted). From this we calculated a yield estimate for the ^{94}Kr experiment, based on a comparison of the calculated absolute cross sections, the beam intensities, and the MINIBALL efficiencies. From this we get a more realistic estimate of 390 counts/hour or 9360 counts/day.

The halflife of ^{94}Kr is known to be 212(5) ms, i.e. of the same order as the breeding time. Therefore roughly 50 % of the ^{94}Kr ions will β-decay to rubidium on its way to the MINIBALL target which reduces our counting rate estimate by a factor of two. Postaccelerated rubidium nuclei will lead to Coulomb excitation of the target nuclei. As our results rely on a relative measurement to target excitations, this effect must be corrected for in the analysis. As rubidium nuclei are not transferred in the watercooled MK7 transfer line, the fraction of rubidium nuclei is determined by the decay losses in REXTRAP and REX-EBIS. Consequently, one day of beamtime (3 shifts) will lead to about 4700 counts which should be sufficient for a determination of B(E2;$2_1^+ \to 0_1^+$). After having identified the ^{94}Kr $2_1^+ \to 0_1^+$ transition, we will immediately switch to the challenging ^{96}Kr case.

In the case of the ^{96}Kr nucleus we expect a large increase of its B(E2) value, similar to the case of strontium and zirconium at N=60. As a conservative estimate we assume a value of B(E2;$2_1^+ \to 0_1^+$)=50 W.u. for our calculation, which is still a factor of two smaller compared to ^{98}Sr.

The ISOLDE yield is expected to be $5 \times 10^5/\mu$C. This is in the same order as in the case of the successful ^{80}Zn experiment [16]. We calculated an integrated cross section of $\sigma(2_1^+) = 3.87$ b. The half life of ^{96}Kr is $T_{1/2} = 80(6)$ ms. Assuming a total flight time after production of 200 ms, only a fraction of 18% of the ^{96}Kr ions will survive. This effect is partly compensated by the larger cross section and higher γ-ray efficiencies compared to the ^{94}Kr case. In total we calculate a count rate (again based on the more realistic estimate starting from ^{92}Kr data) of 13.8 counts/hour or 1662 counts during 5 days of beamtime. Note, that this means 1662 counts in a particle-gated, proper Doppler-shifted and background-subtracted peak.

Consequently, the beamtime request is 21 shifts, divided as:

Beam requirements				
Beam	Min. intens. ions/sec (REX)	Target material	Ion Source	Shifts
^{94}Kr	1×10^7	UC$_x$	MK7	3 (data taking)
^{96}Kr	5×10^5	UC$_x$	MK7	15 (data taking)
				3 (setup, change of beam)

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