Addendum to the IS485 experiment:

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

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Abstract   We propose to study the nuclear properties of the neutron-rich krypton isotopes: the unstable even-even nucleus ^{96}Kr. In July 2009 we had the opportunity to perform an experiment at REX-ISOLDE at CERN utilizing the high-efficiency MINIBALL γ-ray spectrometer to study the deformation of the neutron-rich nuclei ^{94}Kr and ^{96}Kr. The experiment on ^{94}Kr yielded reasonable information about the energy of the first excited state and the B(E2) connecting it to the ground state. The previously known energy of the first 2^+ state was confirmed to be 667keV and, for the first time, the B(E2) value to the first 2^+ state from the ground state was determined. The second experiment on ^{96}Kr was interrupted after 9h due to a CERN-wide power failure. The data collected in these 9h yielded surprising results on the energy of the first 2^+ state. The previously published energy of 241keV was not confirmed, but another transition was observed at higher energy. So, in August 2010 again we had a second attempt to perform the ^{96}Kr experiment. It turned out, that the proposed transition at 241keV still could not be confirmed and the new transition at higher energy appeared again. Unfortunately, problems with contaminants in the radioactive ion beam occurred, so that a determination of the B(E2) value was again not possible. Currently, there are two competing values for the energy of the first 2^+ state in ^{96}Kr, which require completely different interpretations in terms of the evolution of deformation in the Kr-isotopes. Thus we propose to repeat the experiment on ^{96}Kr requesting another 4 days of beamtime.
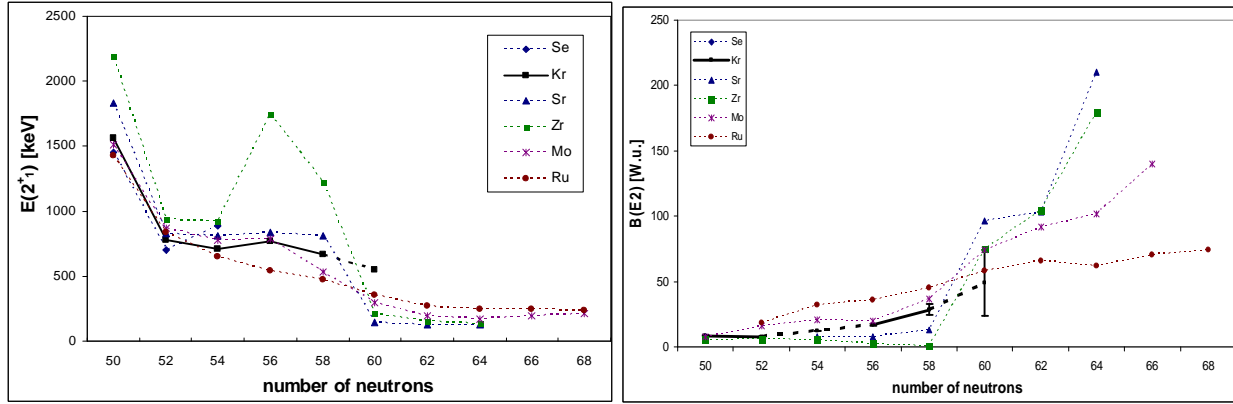
Fig 1: Energy and B(E2) systematics of isotopic chains in the A ~ 100 mass region. The thick black lines indicate the Kr (Z=36) systematics. The preliminary results obtained in 2009 for ^{94}Kr and ^{96}Kr are already included in the plots.

Physical motivation   The study of shape evolution all over the nuclear chart is of general interest. Especially the region around the A=100 mass region provides a testing ground for the onset of deformation by adding only a few neutrons to the N=50 shell closure. It has been shown that the N=40 becomes a well-deformed shell closure for both neutron-deficient Sr and Zr isotopes due to the strong p-n interaction between strongly overlapping $1\pi g_{9/2}$ and $1v g_{9/2}$ orbitals. On the neutron-rich side N=56 becomes locally an effective spherical shell closure and ^{96}Zr (Z=40; N=56) exhibits E(2^+) and B(E2) like a doubly magic nucleus (see Fig.1). Adding only a few neutrons, deformation sets in quickly in ^{100}Zr (Z=40; N=60). A similar behavior is observed in the neutron-rich Sr and Mo isotopes. There is clear evidence for a quick onset of deformation in both isotopic chains. This very sharp passage from spherical shape to stable deformation is of constant theoretical interest. The first theoretical studies attributed the onset of deformation to the strong p−n interaction between spin-orbit partner orbitals $1\pi g_{9/2}$ and $1v g_{7/2}$ [1]. The experimental data obtained later did not support this hypothesis and another theoretical explanation was advanced [2, 3], which emphasizes the role of the intruder $1v h_{11/2}$ 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 $1\pi g_{9/2}$ orbitals, but the $1g_{9/2}$ and $1v h_{11/2}$ 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 [4]) 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 may happen at N=60 for Z=38 and Z=40.

Recently, two studies of the nucleus ^{96}Kr have been published [5,6], imply contradictory descriptions of the shape. Whereas the first published results by N. Mărginean *et al.* [5] imply a rapid change of the shape from ^{94}Kr to ^{96}Kr, as is the case for the Sr, Zr and Mo isotopes, the second publication by Naimi *et al.* [6] implies a smooth change of shape, comparable to the Ru isotopes. Thus, there are two independent works on ^{96}Kr both telling a completely different story about the onset of deformation in the neutron-rich Kr isotopes. Clear results from a Coulomb excitation experiment would answer this question.

Experimental runs 2009 and 2010
94Kr: The beam compositions were determined using a ΔE-E telescope, consisting of an ionization chamber, to measure the energy loss of charged particles, which is proportional to the atomic number Z in first order, and a silicon detector to measure the residual energy of the particles. The resulting plots from 2009 ((a),(b)) and 2010 ((c),(d)) are shown in Fig 2. We were able to calibrate the ionization chamber with reference to the atomic number Z using a beam-mixture of different stable isotopes provided by the REX post-accelerator. A gate on the strong component at channel ~900 and projection to the y-axis (Fig.2 (b)) shows a two-peak structure at Z=36/37. Due to the instability of ^{94}Kr (Z=36), it decays to the daughter nucleus ^{94}Rb (Z=37). The ratio of the two peaks corresponds to the estimate assuming a pure ^{94}Kr beam extracted from the ISOLDE target which decays to ^{94}Rb during the known time of trapping, charge breeding and transport to the Miniball setup. Another beam component at channel ~150 was identified as ^{21}Ne in a 5^+ charge state coming from the REX-EBIS. In 2010 the beam composition did not look that clean. Again the main component was made up by a mixture of ^{94}Kr and ^{94}Rb (Fig.2 (d)) that again reflected the expected ratio. The ^{21}Ne component was also present in the beam, but additionally, there were three more components. One at channel ~ 1900, one at ~2600 and a third component appears in the overflow channel at channel 3840. After analyzing the collected Coulomb excitation data on ^{94}Kr, the beam contamination corresponding to the ΔE overflow was identified as ^{188}Hg in a 44^+ charge state. Beyond that, the ΔE-E plot indicates lots of scattered ^{94}Kr/^{94}Rb

that entered the ionization chamber with less energy than 2.83 MeV/u, which might be due to scattering of these particles at the beam line, the collimators or other beam line components. Obviously, this was not the case in 2009.
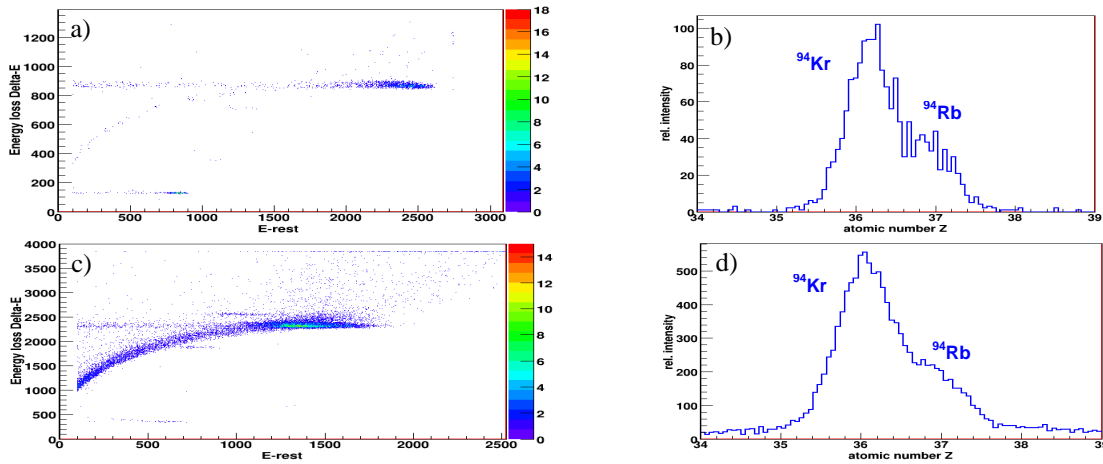

Fig 2: Results of the measurement of the beam composition of the ^{94}Kr-beams from 2009 (a) and 2010 (c). Fig. (b) shows the spectrum obtained with the ionization chamber, calibrated with respect to the atomic number Z and gated on the region from Z=34 to Z=39. A two-peak structure appears at Z=36/37, reflecting the ration of ^{94}Kr to ^{94}Rb expected from the radioactive decay law.

In both experimental runs we used a ^{196}Pt target due to the very well-known matrix elements of the low-energy states in this nucleus, with the investigated reaction being ^{196}Pt(^{94}Kr,^{94}Kr*γ)^{196}Pt*. The scattered particles were detected by a Double Sided Silicon Strip Detector (DSSSD), with which we were able to determine the energy of the scattered particles with respect to the scattering angle. In Fig 3 the particle-gated, background-subtracted and Doppler-corrected γ-ray spectra are plotted. Fig 3a) shows the γ-ray spectrum obtained in 2009. The Doppler-correction has been performed for mass 94, so that the γ-ray peak at 667 keV, which corresponds to the ground-state transition of the first 2$^+$ state in ^{94}Kr, was as well corrected as the peak at 217 keV, which belongs to the ground-state transition of the first excited state in ^{94}Rb. The γ-ray peak belonging to the target-excitation at ~350 keV is smeared out, because it was 'corrected' with the wrong mass. Using the computer code GOSIA a preliminary B(E2) value for the 2$^+_1$ → 0$^+_1$ transition and the quadrupole moment of the first 2$^+$ state in ^{94}Kr were determined.

Fig 3b) shows the resulting γ-ray spectrum obtained in 2010, again with Doppler-correction for mass 94. The peaks at E=217 keV and E=667 keV are visible again (Fig. 3b). But performing the Doppler-correction for mass 188 (Fig 3c)), a peak appears at E=413keV, which corresponds to the ground-state transition of the first 2$^+$ state in ^{188}Hg. To determine the transition strength of the ground-state transition of the first 2$^+$ state in ^{94}Kr, the contribution from the ^{188}Hg and ^{94}Rb has to be taken into account.
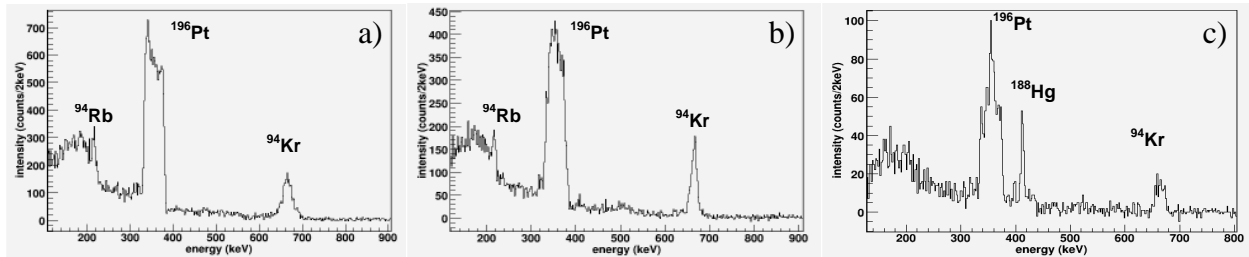

Fig 3: Particle-gated, background-subtracted and Doppler-corrected γ-ray spectra of 2009 (a) and 2010 experimental runs (b,c). In plots a) and b) the Doppler-correction had been performed for mass 94, plot c) is the resulting γ-ray spectrum with particle gate on the scattered ^{188}Hg ions and the Doppler-correction for mass 188.

96Kr: In Fig 4 the beam composition during the experimental runs in 2009 and 2010 is shown. In 2009 we were able to collect data for 9 hours, until a CERN-wide power-failure forced us to stop the experiment. The beam composition in 2009 was measured only at the beginning of the run and it is shown in Fig.4a). The strongest contaminant as seen in fig.4a) were the stable ^{83,84}Kr. The region of ^{96}Kr+^{96}Rb particles is also indicated by a red circle in Fig.4a). By zooming on this region in the ΔE spectrum, again a two-peak structure appears at Z=36/37 (Fig. 4b), as in the mass 94 measurement. The ratio of these two peaks again corresponds well to the estimate assuming the in-flight decay of an initially pure ^{96}Kr beam from the HRS during the transport to the Miniball setup. After the beam composition

measurement, the Coulomb excitation measurement was performed and unfortunately no further measurements with the ionization chamber were made. Therefore, when the analysis of the Coulomb excitation data showed no trace of [83,84]Kr we could only assume that these strong beam components vanished soon after the beginning, so that we had practically a pure [96]Kr/[96]Rb beam during the Coulomb excitation experiment in 2009.

In 2010, we had the opportunity to continue the experiment and we collected data for 16 additional hours. The beam composition in 2010 was measured regularly and is shown in Fig. 4c). Obviously, the beam was made up by different strong components, which were not present in 2009. From the Coulomb excitation data we were able to identify the one of the strong components as [192]Hg. The strongest component had been identified by the ISOLDE target experts as [96]Mo from the ion source, which we also confirmed by analyzing the Coulomb excitation data.

The presence of Hg and Mo in the beam suggests malfunction of the cold transfer line of the ISOLDE target in 2010.
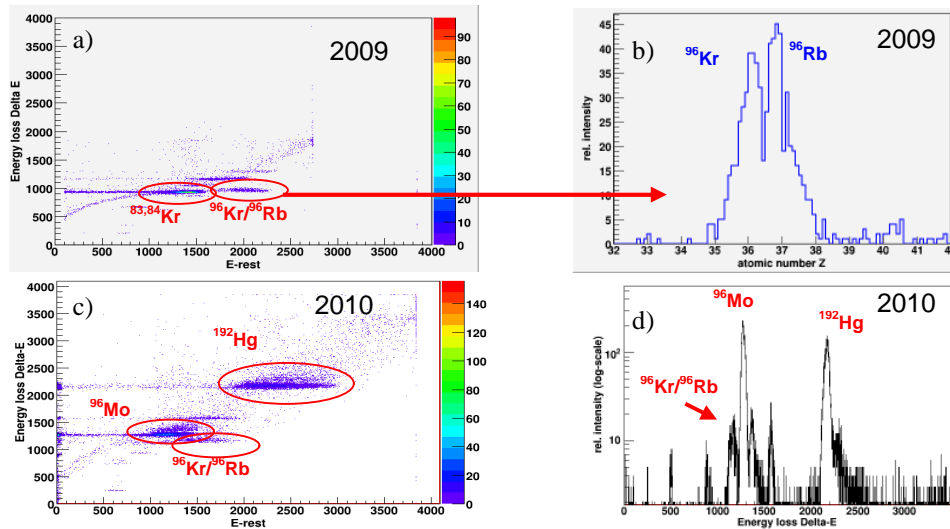

Fig 4: Results of the measurement of the beam composition of the [96]Kr-beams from 2009 (a) and 2010 (c). Fig. (b) shows the spectrum obtained with the ionization chamber, calibrated with respect to the atomic number Z and gated on the region from Z=32 to Z=42. A two-peak structure appears at Z=36/37, reflecting the ratio of [96]Kr to [96]Rb expected from the radioactive decay law.

In 2009 we used the same [196]Pt target as in the [94]Kr measurement, the investigated reaction being [196]Pt([96]Kr,[96]Kr*γ) [196]Pt* . The particle-gated, background-subtracted and Doppler-corrected γ-ray spectrum is shown in Fig. 5a). The proposed γ-ray energy of 241 keV for the $2^+_1 \rightarrow 0^+_1$ transition in [96]Kr was not confirmed, but, another peak appeared in the γ-ray spectrum at an energy of ~554 keV, for which a Doppler-correction assuming an emitting nucleus with mass 96 seems to produce good results. Therefore, the only possibilities of the origin of this γ-ray line, thus, are [96]Kr or [96]Rb. The level scheme and gamma decay strengths in [96]Rb are known from the work of Pinston *et al.* [7] and although a level at the energy of 554 keV exists, its direct decay to the ground state is weak and its predominant decay is via cascades of two/three lower-energy gamma-transitions, the strongest cascade of which is the 93 keV + 461 keV. These lower energy transitions should then appear in the γ-ray spectrum which is not the case. Thus, we propose the 554keV γ-ray peak to originate from [96]Kr and, moreover, due to the missing 241keV transition, this would imply an excitation energy of 554 keV for the first 2^+ state in [96]Kr. A preliminary B(E2) value with a very large uncertainty, due to the low statistics in this γ-ray peak, was obtained.

In 2010 we changed the target to [194]Pt, because the new γ-ray transition at 554 keV might be affected by the 520keV $4^+_1 \rightarrow 2^+_1$ transition in [196]Pt. So the investigated reaction was [194]Pt([96]Kr,[96]Kr*γ) [194]Pt*. The nucleus [194]Pt similar to [196]Pt has well known transitional and diagonal matrix elements of the low-energy level-scheme and in addition there are no disturbing γ-ray transitions in the vicinity of the proposed 554keV γ-ray transition in [96]Kr. Fig. 5b) shows the particle-gated, background-subtracted and for mass 96 Doppler-corrected γ-ray spectrum. Again, a γ-ray transition at 241keV was not observed, but several γ-ray transitions do appear, which are produced by projectile excitation of the different beam components. Especially the γ-ray peak observed in 2009 at 554keV appears in the γ-ray spectrum once again. Due to the different target and the different beam composition compared to 2009, the observation of this γ-ray peak is an additional argument for the energy of the 2^+_1 state in [96]Kr being 554 keV. The Coulomb excitation of [96]Mo projectile is visible at 778 keV and the Coulomb excitation line of [192]Hg projectile can be found at 417keV. Since the higher mass projectiles have higher total energy one can gate on higher energies in the DSSSD particle spectrum and after Doppler-correction for mass 192 (Fig. 5c)) this γ-ray peak clearly shows up while the 554keV and 778 keV γ-ray peaks disappear. From the ratio of the target excitation of [194]Pt and the projectile excitation of [192]Hg a preliminary value for the B(E2) transition strength of the $2^+_1 \rightarrow 0^+_1$ transition in [192]Hg was obtained. To determine the B(E2) transition

strength of the $2^+_1 \rightarrow 0^+_1$ transition in ^{96}Kr, all beam components have to be considered, including ^{96}Mo, ^{192}Hg and all other components. Unfortunately, we are not able to identify all components due to missing projectile excitations. Furthermore, all these unidentified components perform Coulomb excitation at the target, so that the target excitation peak effectively grows. Thus, a normalization of the ^{96}Kr projectile excitation on the ^{194}Pt target excitation peak is not possible with the 2010 data.

Another point is that, although we know that ^{96}Rb is in the beam, we could not identify ^{96}Rb lines [7] in the γ-spectra (Fig. 5) as it was the case for ^{94}Kr + ^{94}Rb (Fig. 3 a), b)). This we currently attribute to the low statistics in both runs.

In order to be able to solve the mystery of this new line at 554keV and to finish the Coulomb excitation study of ^{96}Kr, disturbed once by the power cut and secondly by strongly contaminated radioactive beam, we request an additional beam time.
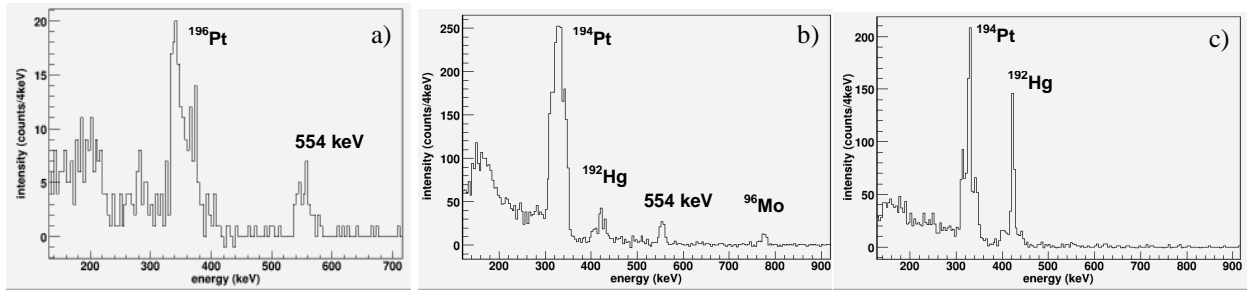

Fig 5: Particle-gated, background-subtracted and Doppler-corrected γ-ray spectra of 2009 (a) and 2010 experimental runs (b,c). In plots a) and b) the Doppler-correction has been performed for mass 96; plot c) is the resulting γ-ray spectrum with particle gate on the scattered ^{192}Hg ions and the Doppler-correction for mass 192.

Rate estimates and beam time request

As in the original proposal the measurement would require a UCx target and a MK7 (Plasma ion source + cooled transfer line) providing the yield quoted in the ISOLDE yields database, i.e. 1.3×10^5 ^{96}Kr ions/µA proton beam. Based on the Coulomb excitation cross-section determined from the 2009 run we estimate a rate of about 60 counts per shift for the 554 keV line (tentative $2^+ \rightarrow 0^+$ in ^{96}Kr). Therefore we request 10 shifts for performing the measurement.

The experimental run from 2010 has shown that a measurement of the beam composition is essential. Especially the ratio of the Kr ions and the Rb ions, produced after beta-decay, can only be obtained by a measurement of the beam composition using the ΔE-E telescope. Thus, beside the pure Coulomb excitation measurement we require an additional shift to monitor the beam composition and another one for setting up the beam.

Thus, the total beamtime request is 12 shifts.

Table 1: Beam requirement and shifts for the ^{96}Kr experiment.

Beam	Min. Intensity	Target material	Ion Source	Required shifts
^{96}Kr	$1.3 \cdot 10^5$	UCx	MK7 (Plasma ion source + cooled transfer line)	10 shifts (data-taking) 1 shift (beam setup) 1 shift (beam monitor)

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