Evidence for a Smooth Onset of Deformation in the Neutron-Rich Kr Isotopes

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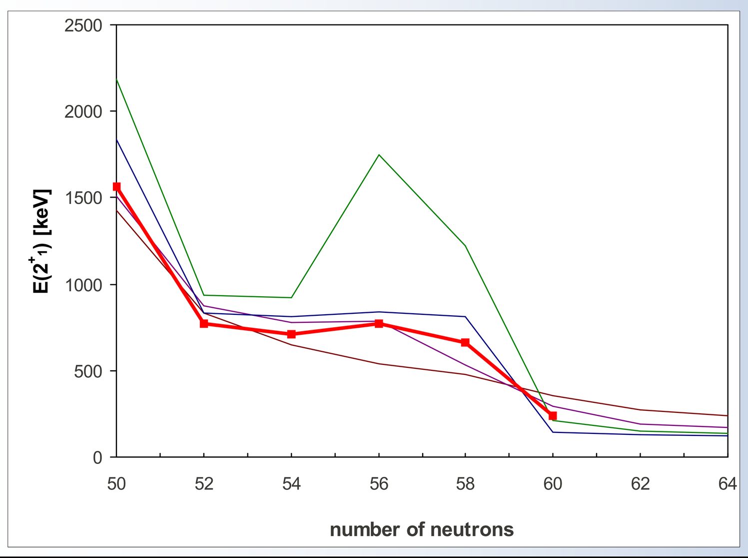
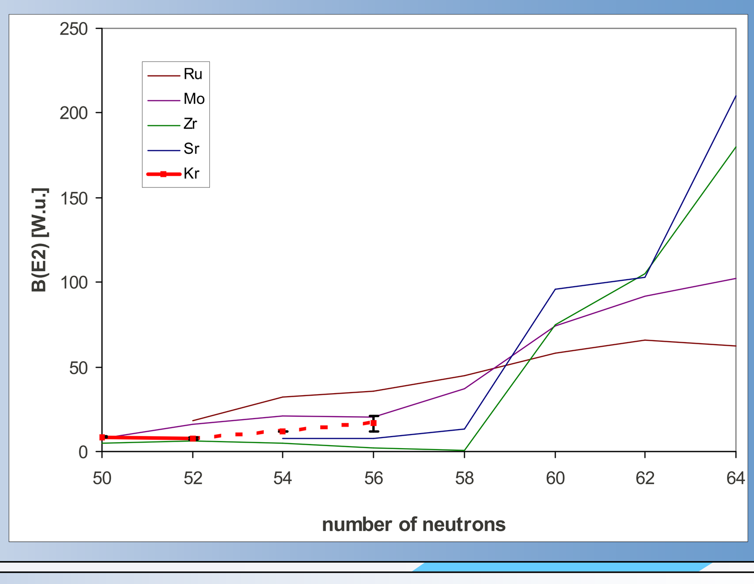
Motivation:

Nuclei in the neutron-rich A≈100 mass region are well suited for the understanding of evolution of nuclear deformation from spherical to strongly deformed ground state shapes. By adding only a few neutrons to the N=50 shell closure, deformation and, thus, collective effects occur quickly. For the Z=40 (Zr) isotopes, the neutron number N=56 becomes an effective shell closure, so that ^{96}Zr exhibits characteristics of a doubly-magic nucleus. Adding only a few neutrons more, the Zr-isotopes get strongly deformed. This behaviour indicates a shape phase transition around N=60. For the Z=38 (Sr) isotopes the systematics show a similar behaviour, whereas for the Z=42 (Mo) and Z=44 (Ru) isotopes, this rapid change of the shape seems to be attenuated.

The aim of this work was to investigate the behaviour of the even-even Z=36 (Kr) isotopes in this phase transition region by determining the energies of the 2_1^+ states and their E2 decay transition strengths to the ground state in ^{94}Kr (N=58) and ^{96}Kr (N=60). Information on the energies of the first excited 2^+ states exist only for the Kr isotopes up to N=58. For N=60, contradictory results on this observable were published recently [1,2]. Whereas Information on the B(E2) values exist only for the neutron-rich Kr isotopes ^{86}Kr, ^{88}Kr and ^{92}Kr [3].





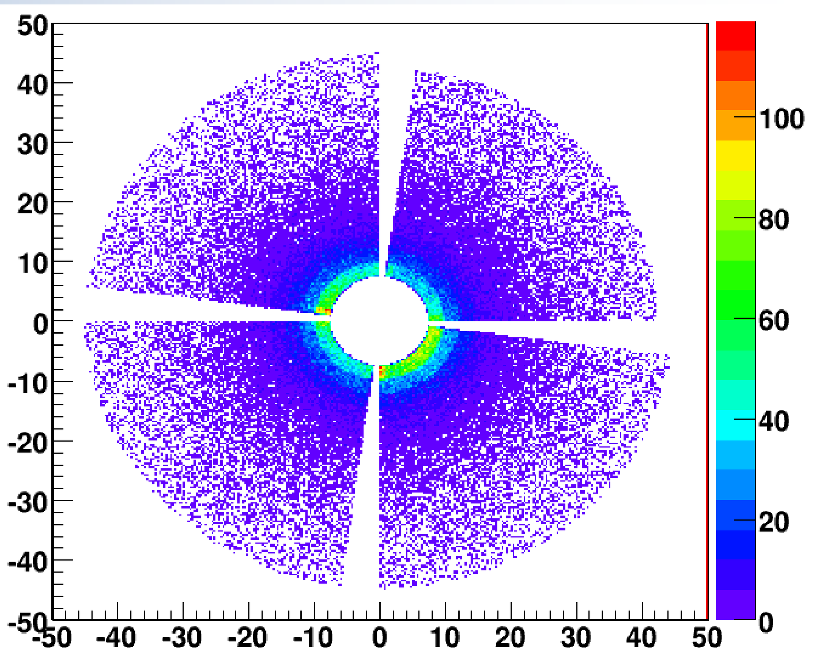
Experiment:

The experiment was performed at the REX-ISOLDE [4] facility at CERN using the high-efficiency Miniball spectrometer. By bombarding an UC_x-target with high energetic protons (~GeV) a spallation reaction was induced, in which a variety of ions were produced. The ^{94}Kr ions were selected from the secondary beam by using the "High Resolution Separator" (HRS), which supports a mass resolution of about M/ΔM=5000. Afterwards the ^{94}Kr ions were induced into the REX-ISOLDE post-accelerator, where they were collected (REX-TRAP), charge-bred (REX-EBIS) and post-accelerated (REX-LINAC) to a final energy of 2.85 MeV/u.

We chose different Pt targets with well known transition energies and transitional and diagonal matrix elements. In a Coulomb-Excitation (Coulex) reaction excited states in ^{94,96}Kr and Pt were populated.

For the detection of the scattered particles, a Double-sided Silicon Strip Detector (DSSD) was used, consisting of 4 quadrants, each of them with 16 rings at the front and 12 strips at the back of the quadrant. In the right figure, the front view of the DSS detector is shown. Obviously, the beam was centred in the middle of the detector.

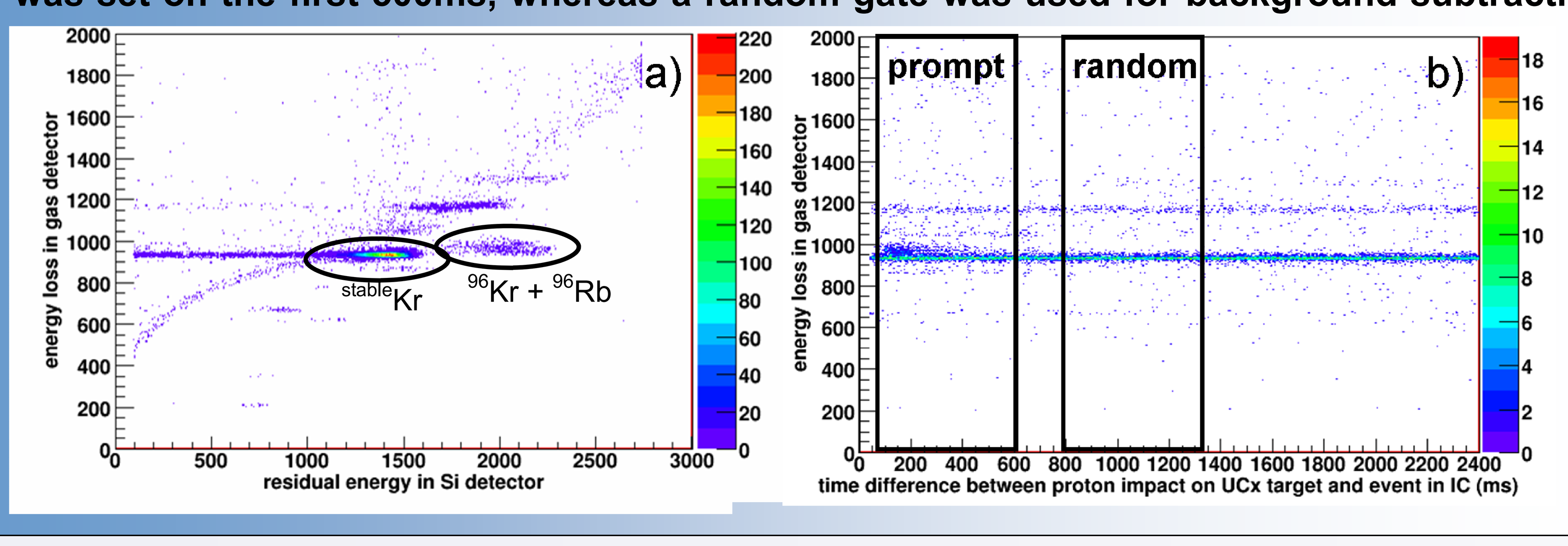
For the detection of the emitted γ quants, the high-efficiency MINIBALL spectrometer [5] was used, which consists of eight Miniball-Cluster detectors with 18 segments per Cluster.



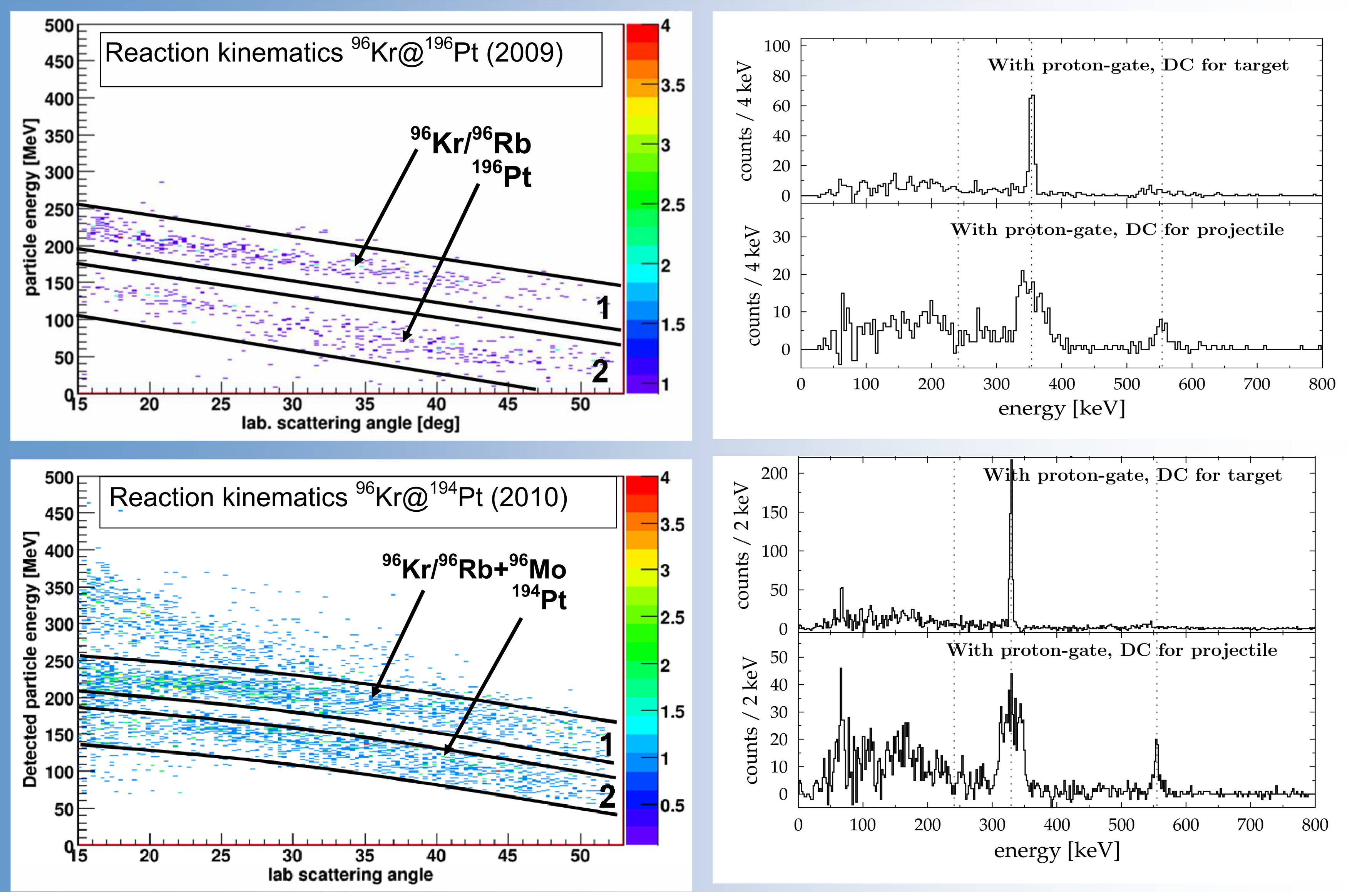
Determination of beam composition:

For the determination of the beam composition a ΔE-E telescope was used, consisting of an ionization chamber (IC) to measure the energy loss of penetrating particles and a silicon detector to measure the residual energy of the particles. Fig. a) shows a typical ΔE-E plot, taken in the ^{96}Kr experiment in 2010. The circled particle bump was identified as an admixture of ^{96}Kr+^{96}Rb.

Fig. b) shows the time structure of the detected particles, i.e. the energy loss vs. the time difference between the proton impact on the UC_x target and the event in the ionization chamber. To eliminate influences on the γ-spectra from stable beam contaminants an additional prompt gate was set on the first 500ms, whereas a random gate was used for background-subtraction.



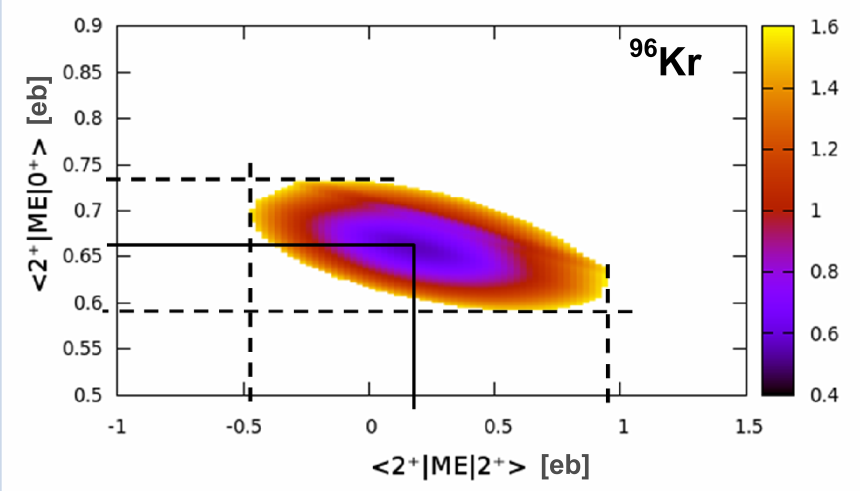
Analysis of the Doppler-corrected γ-spectra:



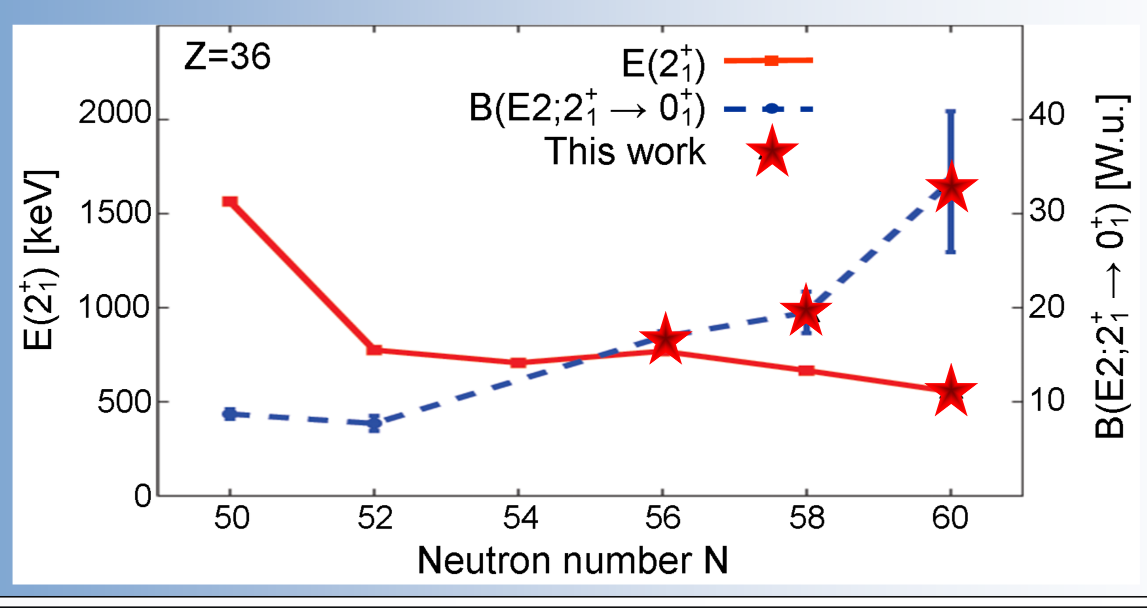
The Coulex measurements were performed using ^{196}Pt (2009), respectively ^{194}Pt (2010) targets. The respective reaction kinematics are shown in the left plots. We set two particle gates, one at each band of scattered particles and analyzed the coincident γ-spectra, which are shown in the right plots. Due to the fact, that deexcitation γ-rays are emitted while the nucleus is still in flight, the emitted γ-rays appear Doppler-shifted in the spectra. This was corrected, once for the target masses, as well as for the projectile masses. The energy of the $2_1^+ \rightarrow 0_1^+$ γ-transition in ^{96}Kr of 241keV, as published in [1], was not confirmed. But, based on our analysis, a new transition energy was assigned to the $2_1^+ \rightarrow 0_1^+$ γ-transition in ^{96}Kr of 554.1keV.

Determination of absolute E2 decay transition strengths:

The $B(E2;2_1^+ \rightarrow 0_1^+)$ values of ^{94,96}Kr were obtained via the normalization method, using the computer code GOSIA2 [6,7]. Since the Coulomb-excitation cross-section depends on the transitional matrix element $<2_1^+|ME|0_1^+>$ and the diagonal matrix element $<2_1^+|ME|2_1^+>$, a χ^2 surface scan was performed for the determination of both matrix elements. The best value, i.e. the value with the lowest χ^2, and its uncertainties were obtained by projecting the 1σ surface to the respective axis, as indicated by the black lines in the plot.

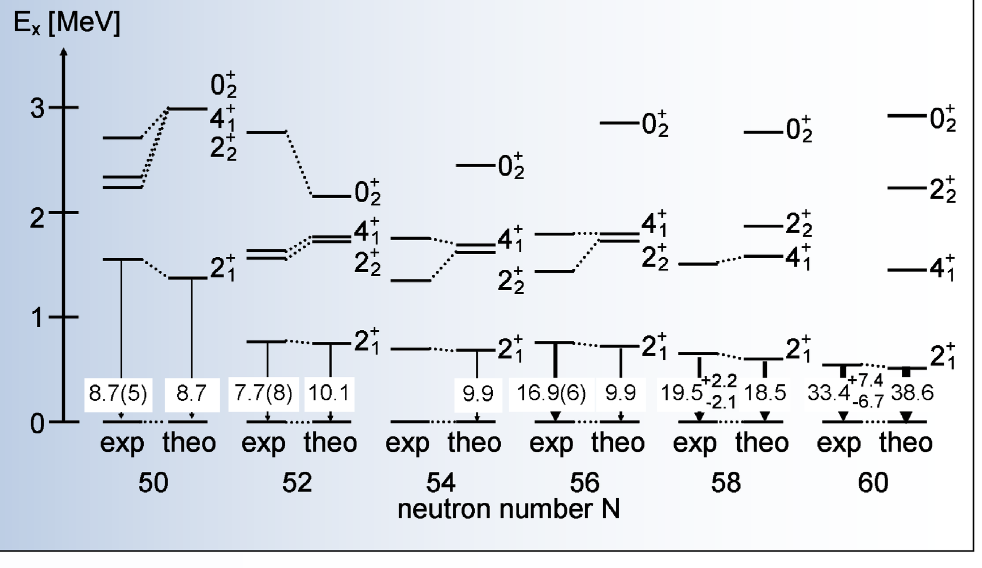


Systematics including the new results:



Comparison to IBM-2 calculations:

Energies of excited states in $^{86-96}$Kr were calculated within the framework of the Interacting Boson Model 2 following the "mapping" method described for instance in [8,9]. The parameters of the IBM-2 Hamiltonian within the framework of the Extended Consistent Q Formalism were obtained by mapping the Hamiltonian to a potential energy surface obtained via Constrained Hartree-Fock-Bogoliubov calculations, based on the Gogny-D1S effective interaction. The IBM-2 calculations based on the mapping method yielded excitation energies of 0^+, 2^+ and 4^+ states in $^{86-96}$Kr [10], which are compared to the experimental energies in the right figure.



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