Lifetime measurement in $^{74}$Kr and $^{76}$Kr


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Abstract. Lifetimes of excited states in the ground-state bands of $^{74}$Kr and $^{76}$Kr were measured using the recoil-distance Doppler-shift and the differential decay curve methods. The states were populated in the $^{48}$Ca($^{40}$Ca,α2p) and $^{48}$Ca($^{40}$Ca,4p) reactions. Gamma rays were detected with the GASP array which was coupled to the Cologne Plunger device. The results resolve discrepancies between earlier lifetime measurements and a recent Coulomb excitation experiment. Experimental transition rates are compared to theoretical calculations. The results support a strong mixing between prolate and oblate configurations for the low-spin states, and represent an important basis for the interpretation and understanding of the shape coexistence phenomenon in this mass region.

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The proton-rich krypton nuclei near the $N = Z$ line exhibit some of the best examples for shape coexistence in nuclei. The competition of prolate and oblate shapes in this mass region is caused by large shell gaps that occur both for oblate and prolate quadrupole deformations at proton and neutron numbers 34, 36, and 38. Several theoretical models predict coexisting prolate and oblate states in the nuclei with these proton and neutron numbers [1–7]. While the different approaches generally agree on the equilibrium shapes involved, they find different results for the precise excitation energies of the states and the transition rates between them.

An experimental indication for shape coexistence (in even-even nuclei) is the observation of low-lying excited $0^+$ states. Such a state can be understood as a “second ground state” corresponding to a coexisting shape different from that of the ground state. Such states are indeed observed throughout the chain of light even-even Kr isotopes between $^{72}$Kr and $^{80}$Kr. Their excitation decreases with decreasing neutron number to a minimum in $^{74}$Kr, and increases again in the self-conjugate nucleus $^{72}$Kr. The $0^+_2$ states in $^{72}$Kr and $^{74}$Kr are isomeric (i.e. shape isomers) and decay via $E0$ transitions to the ground state [8–10]. The rotational cascades of the ground-state bands are strongly distorted at low spin, pointing to a mixing of the prolate and oblate configurations. The mixing amplitudes can be inferred from an extrapolation of the rotational bands at high spin. This analysis shows for the ground state of $^{74}$Kr a maximum mixing of the oblate and prolate configurations which are almost degenerate [10]. Together with the energy dependence of the excited $0^+$ states and the electric monopole strengths $\rho^2(E0)$ of the transitions to the $0^+$ ground states, this suggests an inversion of the ground-state shape from prolate in the heavier isotopes to oblate in $^{72}$Kr.

This scenario has recently been confirmed by a direct measurement of the spectroscopic quadrupole moments of states in $^{74}$Kr and $^{76}$Kr through low-energy Coulomb excitation with radioactive beams [11,12]. A large number of both transitional and diagonal matrix elements for the two isotopes was determined in this measurement. The results for the transitional matrix elements are partly in conflict with previously measured lifetimes, in particular for the $4^+$ state in $^{74}$Kr [13]. On the other hand, the precise
knowledge of the transitional matrix elements is needed in this case of Coulomb excitation with weak radioactive beams in order to be sensitive to the reorientation effect, and therefore to determine the spectroscopic quadrupole moments (including the sign of the deformation).

In order to resolve the discrepancies between the recent Coulomb excitation results and the previously published lifetimes, a new measurement of lifetimes has been performed in $^{74}$Kr and $^{76}$Kr using the recoil-distance Doppler-shift method (RDDS). A higher precision was expected from the new measurement, as the lifetime data in the literature for low-spin states in both $^{74}$Kr [13] and $^{76}$Kr [14–16] are based on singles measurements which suffered from contaminations from other reaction products and unknown side feeding. Several lifetime measurements employing the Doppler-shift attenuation method (DSAM) have been performed for $^{74}$Kr [17–19] and $^{76}$Kr [20–22]. They are, however, not sensitive to the relatively long lifetimes below the $6^+$ state in the respective ground-state bands.

The present RDDS measurement was performed using the Cologne Plunger device [23] coupled to the $\gamma$ spectrometer GASP [24] at the Laboratori Nazionali di Legnaro. Excited states in $^{74}$Kr and $^{76}$Kr were populated in the reactions $^{40}$Ca($^{40}$Ca, $\alpha 2p$)$^{74}$Kr and $^{40}$Ca($^{40}$Ca, 4p)$^{76}$Kr at a nominal beam energy of 147 MeV. The target consisted of a $800 \text{ m/cm}^2$ thick layer of $^{40}$Ca evaporated onto a Au foil of 2 mg/cm$^2$ thickness that was facing the beam. The downstream side of the target was also covered by a thin Au layer of approximately 100 $\mu$g/cm$^2$ in order to prevent oxidation. Slowed down in the support layer and the target itself, the average beam energy at the center of the target was 124 MeV. The recoils had an average velocity $v/c = 3.50(5)\%$ and were finally stopped in a Au foil of 12 mg/cm$^2$ thickness. Data were collected for 13 different distances between the target and the stopper foil ranging from 7.5 $\mu$m to 1500 $\mu$m, with an average of 12 hours beam on target for each distance. Gamma rays were detected with the GASP array, which, for this experiment, comprised 32 Compton-suppressed Ge detectors in the so-called configuration II, i.e. in a close geometry without the BGO scintillators of the inner ball. Most of the detectors were placed at forward and backward angles where the sensitivity to the Doppler shift is highest. For the data analysis the detectors were grouped into seven rings with respect to the beam axis. Events were recorded when at least two Compton-suppressed Ge detectors gave coincident signals. For the off-line analysis the data were sorted into $\gamma \gamma$ coincidence matrices. Separate matrices were sorted for all combinations of rings and for all distances.

The spectra in fig. 1 show the first three transitions of the ground-state band in $^{74}$Kr for several distances as indicated. The spectra were observed by the first ring of detectors placed at 36$^\circ$ with respect to the beam axis, so that the components of the transitions emitted in flight are shifted to higher energies. All spectra are gated from above on the shifted components of the transitions directly feeding the state of interest. Different gates were used depending on the angle of the detector in which the gating transition was observed, and the spectra were then added to result in seven individual spectra, one for each angle under which the depopulating transition was detected. Care was taken to set symmetric gates on the shifted components of the peaks in order to avoid a bias toward faster or slower recoil velocities. This procedure was repeated for all 13 distances. The spectra of the 768 keV transition depopulating the $6^+$ state show triple coincidences with a gate on the shifted component of the transition above and an additional gate on either component of the transition below. The triple-coincidence condition eliminated contaminations from cascades with similar transition energies in a negative-parity band of $^{74}$Kr and in $^{75}$Rb, strongly populated in the 3p reaction channel. The intensities of the shifted and stopped components were extracted from these and the corresponding spectra for the other detector angles.

The lifetimes of the states were determined from the intensities of the shifted and stopped components of the transitions using the differential decay curve method [25]. Since the spectra were gated from above, all uncertainties from unknown side feeding are eliminated. The peak intensities of the shifted ($sh$) and stopped ($st$) components have to be corrected for differences in the running time and beam intensity for the different distances. The common normalization factors $N(x)$ for each distance were determined from the total number of coincidences for several strong cascades in different nuclei. For coincidences between transitions directly populating and depopulating the state of interest, the lifetime is extracted from the coincidence intensities for each distance as

$$\tau(x) = \frac{1}{N(x)} \int dE \frac{I_{sh}^{\gamma_1}, \gamma_2^{st}, x}{I_{st}^{\gamma_1}, \gamma_2^{st}, x} \frac{I_{sh}^{\gamma_1}, \gamma_2^{st}, x}{N(x)},$$ (1)