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Shape determination in Coulomb excitation of ^{72}Kr

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Abstract: *Nuclei with oblate shapes at low spins are very special in nature because of their rarity. Both theoretical and experimental shape co-existence studies in the mass 70 region for near proton drip-line nuclei suggest ^{72}Kr to be the unique case with oblate low-lying and prolate high-lying levels. However, there is no direct experimental evidence in the literature to date for the oblate nature predicted for the first 2^+ state in ^{72}Kr. We propose to determine the sign of the spectroscopic quadrupole moment of this state via the re-orientation effect in a low-energy Coulomb excitation measurement. In the inelastic excitation of the 2^+ state in ^{72}Kr beam of 3.1 MeV/u with an intensity of 800 pps at REX-ISOLDE impinging on ^{104}Pd target, the re-orientation effect plays a significant role. The cross section measurement for the 2^+ state should thus allow the model-independent determination of the sign of the quadrupole moment unambiguously and will shed light on the co-existing prolate and oblate shapes in this region.*

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Introduction

To first order, the potential energy of a nucleus might be expected to be independent of the sign of its quadrupole deformation parameter (β_2), and as a consequence oblate nuclei (-ve value for β_2) should be as equally probable as prolate nuclei (+ve value for β_2) in nature in regions well away from closed shells. However, experiments tell us that nuclei are largely prolate deformed in their ground states. This feature can be related to various aspects of the nuclear force: there is a stronger binding of prolate nuclei when higher-order multipoles are included in the description of the nuclear deformation in the liquid drop energy [1]. The residual interactions between particles favour a prolate deformation [2] and moving between different shells is more important for K=1/2 states on the prolate side than that between high-K states on the oblate side. As a result of the above, the mechanism that drives a nucleus towards an oblate shape is not very well understood. Thus studies of oblate deformed nuclei are very important in aiding our understanding of nuclear shape polarisation.

Nuclei in the mass 70 region are particularly interesting since they generally have a much larger ratio of valence to core numbers of particles compared with heavier nuclei. Thus the deformation can change significantly from one nucleus to another due to the strong polarising effects of just a few high-j particles. Because of this, the region provides a major challenge to theoretical models. Indeed many calculations, based on the mean-field approach, have been performed (e.g. see [3-5]) and they often differ in the exact location of different shapes. Delineating the exact location of states belonging to the different shapes will therefore provide an important test of these models. Apart from the nuclear structural interest, shape co-existence and any resulting isomerism in nuclei in this region has been suggested to play an important role in determining the reaction and decay rate predictions in X-ray binaries where *rp* processes burn hydrogen and produce heavier elements [6].

The co-existence of prolate and oblate shapes resulting from N=Z=34 and 36 shell gaps in the mass 70 region was predicted nearly two decades ago [7]. Since then, studies on these nuclei have yielded detailed information on their low-lying level structure and led to indirect inferences on shapes from e.g., changes in moment of inertia [8-10] and comparison of measured B(E2) values with calculations [11-13]. However, there have been only a few direct measurements in this region to determine the sign of the quadrupole deformation and distinguish between the prolate and oblate shapes; the recent low energy Coulomb excitation measurements on ^{70}Se and $^{74,\,76}$Kr nuclei [8-19]. A prolate shape for the ground state in ^{70}Se may be inferred from this experiment, which is in conflict with the predicted oblate shape [14-17]. Furthermore, the B(E2:$2_1^+ \rightarrow 0_1^+$) strengths for the ^{74,76}Kr isotopes were found to be strongly reduced in comparison with the other transitions and were interpreted as resulting from *strongly mixed* configurations. The static quadrupole moments were also deduced and were found to be consistent with this interpretation.

Measurements determining shapes in this region, particularly for proton-rich Kr isotopes with A < 74, where configuration mixing in the low-lying nuclear levels is *only moderate*, are thus of vital importance and will serve as critical tests to the nuclear models in predicting co-existence of levels dominated either by oblate or by prolate nature. In this respect, extensive efforts have recently been devoted to both theoretical as well as experimental studies of Kr isotopes [8-13, 17-19]. The studies revealed uniquely interesting level structures indicating a moderate to strong mixing of configurations with prolate and oblate deformations for proton-rich Kr isotopes, in particular for ^{74}Kr . Fig.1 shows the systematics highlighting the trends in the relative positions of the 2_1^+ states of the ground-state band and the excited 0^+_2 states [12]. Here, for each of the cases, the relevant energy levels corresponding to the prolate (left) and oblate (right) configurations are shown. The unperturbed 0^+ states [12], shown as dashed lines in Fig.1, change their relative positions as one moves from ^{78}Kr to ^{72}Kr; they are closest in ^{74}Kr and reverse their locations in ^{72}Kr. This trend together with the proximity of 2_1^+ and 0^+_2 states for ^{72}Kr and ^{74}Kr is taken as an indication of the importance of prolate and oblate configurations at low spins in this region. The low-energy Coulomb excitation measurements on the $^{74,\,76}$Kr isotopes also deduced B(E2) values yielding the magnitude and the sign of the deformations consistent with these trends [19]. From conversion electron and γ-ray spectroscopy studies, Bouchez *et al.* interpreted the 0_2^+ in ^{72}Kr to be the band head of the previously known prolate band [9]. Large E0 matrix elements connecting the ground 0_1^+ and the excited 0_2^+ states were also deduced and interpreted to be evidence for mixed configurations [20], in ^{72}Kr. Two-level mixing calculations (Fig. 2a) suggest a predominantly oblate nature for the low-lying levels. A recent determination of the $B(E2{:}0^+\rightarrow 2^+)$ strength using intermediate Coulomb excitation studies by A. Gade *et al.* deduced the size of the quadrupole deformation that is consistent with an oblate shape, however that was done in a model-dependent fashion [11]. This is also consistent with the energy surface calculations, shown in Fig. 2b, which indicate that the oblate configurations should be lowest in energy, at least upto the spin 2 [6]. Even though the studies suggested ^{72}Kr to be the unique case in this mass region with oblate low-lying and prolate high-lying states, no direct measurements determining the oblate nature have been carried out to date, because of the difficulties in obtaining a ^{72}Kr beam of sufficient intensity. We propose a determination of the sign of the quadrupole moment using a low-energy Coulomb excitation measurement using the REX-ISOLDE facility.

Experiment

The availability of a ^{72}Kr pure beam at ISOLDE provides the possibility of using the conventional method of Coulomb excitation at safe energies below the Coulomb barrier. We aim to determine the sign of the quadrupole deformation parameter in a model-independent manner via the re-orientation effect on the $2_1^+\rightarrow 0_1^+$ γ decay, following the inelastic Coulomb excitation of the 2_1^+ state in ^{72}Kr, using REX-ISOLDE + MINIBALL/CD detector set up. The measurement requires a ^{72}Kr beam intensity of about 800 pps. This is preferable in order to obtain a statistical accuracy of ~ 3% and fix the sign of the spectroscopic quadrupole moment with the proposed setup (see below).

The heavy-ion scattering at safe energies below the Coulomb barrier, as proposed here, can cause multi-step inelastic excitations and thus presents a possibility to distinguish between prolate and oblate nuclear shapes via the re-orientation effect [21]. The systematic uncertainties in the current measurement mainly arise from the experimentally known $B(E2{:}0_1^+\rightarrow 2_1^+)$ values for ^{72}Kr and ^{104}Pd (target) and the estimated couplings to higher levels. The experimental uncertainties in target thickness, beam current fluctuations and γ efficiencies will be minimized by a simultaneous measurement of the well known ^{104}Pd target $B(E2{:}0_1^+\rightarrow 2_1^+)$ value. As indicated below these have *negligible effect* on the determination of the sign.

Fig.3 shows calculations carried out by using the CLX code for the inelastic excitation cross-sections integrated over 4π to the 2_1^+ state in ^{72}Kr Coulomb excited by ^{12}C, ^{24}Mg, ^{28}Si, ^{58}Ni, ^{104}Pd, ^{197}Au and ^{208}Pb targets [22]. For all the calculations shown in the proposal, the beam energy at the center of the target is assumed to be of $E_{lab}(^{72}\mathrm{Kr})$=200 MeV close to the energies available with REX-ISOLDE. Targets of various Z and beam energies were tried in order to optimize the re-orientation effect and the cross section for the 2_1^+ state. For the chosen energy ^{104}Pd gives the maximum population to the 2_1^+ state, if the scattered projectiles are detected with 4π solid angle coverage. Even for the limited angular coverage of the CD detector from 16.2° to 53.3°, the inelastic scattering cross sections remain relatively higher. However, it has slightly less re-orientation effect compared to ^{58}Ni. The choice of the ^{104}Pd target is based on the fact that the $2_1^+\rightarrow 0_1^+$ γ transition of 555 keV can be used for the normalization purposes which minimizes the systematic error coming from target thicknesses, γ efficiencies and beam current fluctuations [14]. Due to the normalization procedure, a systematic error of ~ 6% is introduced which comes from the known $B(E2{:}0^+\rightarrow 2^+)=0.535(35)\ e^2b^2$ value for ^{104}Pd (adopted value from NNDC).

Fig.4 shows the calculated cross sections for the 2_1^+ state in ^{72}Kr Coulomb excited by ^{104}Pd. In predicting yields, a recent determination of A. Gade *et al.* of $B(E2:0_1^+ \rightarrow 2_1^+) = 0.50\ (7)\ e^2b^2$ which corresponds to $B(E2:2_1^+ \rightarrow 0_1^+) = 1000\ e^2fm^4$ was used for the coupling between the 0_1^+ and 2_1^+ states. Furthermore, this value was used to estimate the couplings to all the other excited states and the re-orientation coupling for the 2_1^+ state. Fig.5 gives the $B(E2:J \rightarrow J-2)$ values calculated by Bender *et al.* and from the available data [10, 11]. If there is a 2_2^+ state close to the 4_1^+ state as shown in Fig. 5 from the predictions by Bender *et al* [13], then a low-energy Coulomb excitation leading to multiple excitations can cause second-order processes to deplete the 2_1^+ state and populate the 4_1^+ and 2_2^+ states. Similarly the 2_1^+state can get depleted by the 0_2^+ state. However, the calculated cross sections with the estimated couplings (see the caption of Fig. 4) for the 0_2^+, 2_2^+ and 4_1^+states are only about 4, 0.5 and 3 % of that of the 2_1^+ state, respectively. These depletions cause less than 2% variation in the population of the 2_1^+ state. A 28% re-orientation effect on the 2_1^+ state is expected when $|M_{22}|$ is varied from -0.84 to 0.84 eb as shown in Fig.4 with a *negligibly small uncertainty* essentially coming from the unknown coupling to the $0_2^+$and 2_2^+ states and the value for M_{24} estimated from the experimentally deduced M_{12} matrix elements. The uncertainties in the proposed cross-section measurement mainly come from the statistics in $2_1^+ \rightarrow 0_1^+\ \gamma$ decay (3%) and the experimental $B(E2:0_1^+ \rightarrow 2_1^+)$ value for ^{104}Pd (6%). The M_{12} and M_{22} matrix elements will then be varied to fit the experimental 2_1^+cross section in ^{72}Kr measured to ~ 7% accuracy. A constraint coming from the known $B(E2:0_1^+ \rightarrow 2_1^+)$ value ^{72}Kr should cleanly fix the sign of the quadrupole moment [14].

Even though it is unlikely, as there is no clear evidence or physics basis in the literature, we also consider a worst case scenario, whereby, the re-orientation matrix element is much smaller than the assumed value and the 0_2^+ and 2_1^+ states have much stronger coupling. Clearly, for such a situation, the re-orientation effect and the variations in the cross sections for the 2_1^+ state due to the depletions discussed above will have similar levels. In this case a determination of the sign of the quadrupole moment will not be feasible. On the other hand, with the accurately measured cross-section, a B(E2) value will be deduced with a uncertainty of ~ 7% , much better than that from Ref. [11]. We also note that the observation of the second 2_2^+ state would also be a major achievement that is feasible from such a scenario. However, from the available experimental evidence (e.g., Fig. 2a) on the predominance of the oblate configuration for the ground state in ^{72}Kr, we believe that this worse case situation is not very probable, since a strong coupling between 0_2^+ and 2_1^+ states implies a strongly mixed ground state.

Yields and Beam Time Request

A ^{72}Kr beam of 800 pps at E_{beam}= 223 MeV on a 2 mg/cm^2 ^{104}Pd target for 8 days will yield around 1200 counts corresponding to the $2_1^+ \rightarrow 0_1^+\ \gamma$ transition and hence is expected to result in a cross section measurement with an accuracy better than 7%. As the re-orientation effect is expected to be around 28% as M_{22} is varied from -0.84 to 0.84 eb, it should be possible to cleanly fix the sign of the quadrupole moment. We assume that MINIBALL has detectors spanning over lab angles of 44° to 147° with a γ detection efficiency of 7% at 1332 keV, (with add-back) and the scattered particles are detected in the CD detector with 16.2° to 53.3° angle coverage.

We also request beam time for carrying out the Coulomb excitation measurement on the recently studied ^{76}Kr nucleus [19], which serves as a case for setting up the experiment. Reproduction of the well known matrix elements will help to minimize the systematic uncertainties in the ^{72}Kr measurement.

Considering the difficulties in maintaining the beam intensity over 1+8 days of running time, we request two separate 1+4 day periods of beam time.

Based on the expected yields of ~ 5000 pps/μC, we estimate that for 2 μA proton current and a 8% transmission efficiency to the target we will have at least 800 pps at the target position. If the intensity can be increased further then the experiment can be comfortably carried out with a shorter beam time. On the other hand, a measurement with reduced intensities of 200 pps at the target position will yield ~8% accuracy for the cross section, with which a meaningful analysis can be carried out.

Beam	***Min. Intensity***	***Target Material***	***Ion Source***	***Beam Time***
^{72}Kr	800 pps	Nb metal Powder 50g/cm^2	Plasma Cooled Transfer line	4 + 4 days
^{76}Kr	8. 10^6	Nb metal Powder 50g/cm^2	Plasma Cooled Transfer line	1 + 1 days

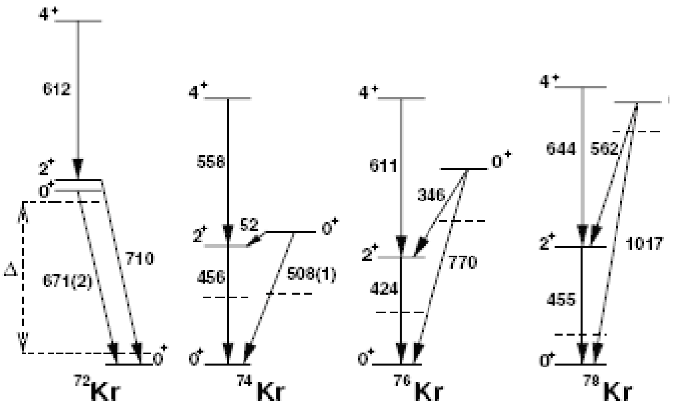
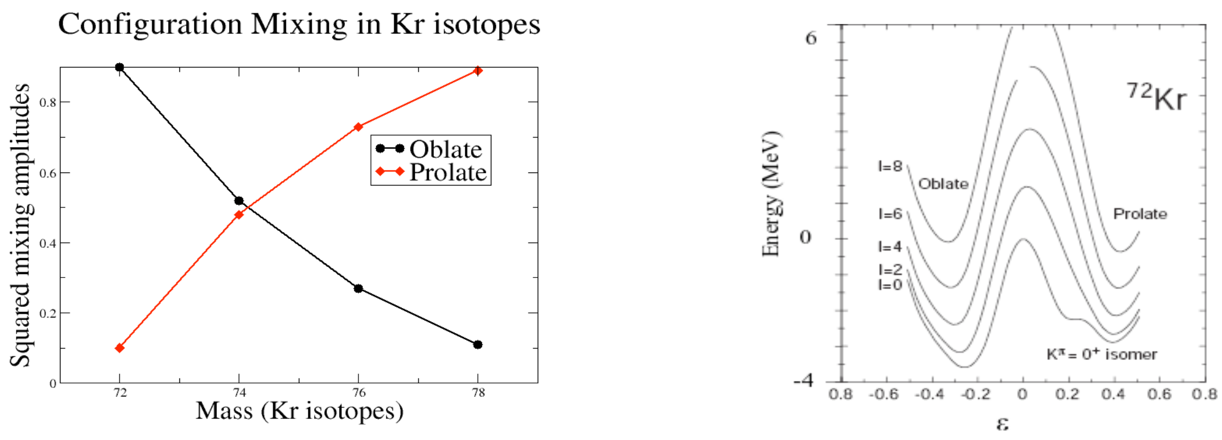


Fig.1: Shape co-existence in Kr isotopes. For each of the cases, the relevant energy levels corresponding to the prolate (left) and oblate (right) configurations are shown. From A=78 to 72 the energy of the excited 0^+ *(*0_2^+*) with respect to* 2^+ *follows a parabolic trend with a minimum at* ^{74}*Kr (taken from Ref.[12]). Dashed lines represent the unperturbed* 0^+*states obtained from the extension of rotational band with a well-deformed shape at high spin. An inversion in their position in* ^{72}*Kr indicates the exchange of roles in prolate and oblate shapes.*



a)

b)

Fig.2: Predominance of oblate configurations in ^{72}*Kr; a) The squared mixing amplitudes in two-level mixing calculations using the energy differences; between perturbed* 0_1^+ *and* 0_2^+*, and unperturbed* 0_1^+ *and* 0_2^+ *[12, 23]. For a given isotope, diamond and circle corresponds to the prolate and oblate components, respectively. In case of* ^{72}*Kr, the oblate component clearly dominates. b) Energy surfaces for various spins as a function of deformation* ε_2 *taken from Ref.[6].* As can be seen oblate configurations persist at least upto spin 2.

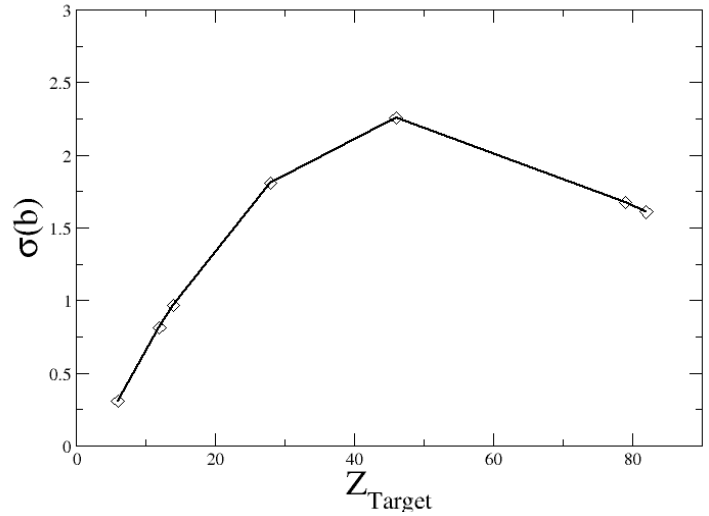


Fig. 3: Inelastic cross sections integrated over 4π calculated using the CLX code for populating 2_1^+ *state in* ^{72}*Kr in Coulomb excitation by targets with various Z values. For a fixed energy of* $E_{lab}(^{72}Kr)$*=200 MeV at the center of the target,* ^{104}*Pd gives the maximum population.*

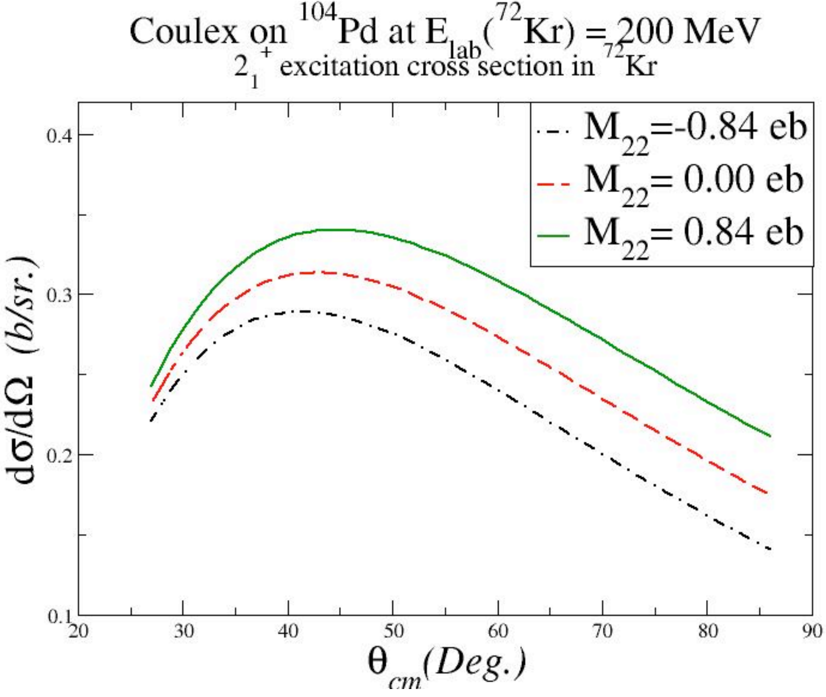


Fig.4: Coulomb excitation cross sections for the 2_1^+ *state in* ^{72}*Kr calculated using the CLX code [22] in the angular range corresponding to the coverage by the CD detector. The calculations are done for* E_{beam}*= 223 MeV which corresponds to* E_{lab}*= 200 MeV at the center of the target. Yields will be reduced by 10% without significantly affecting the re-orientation effect for* E_{lab}*= 190 MeV. The solid, dotted and dashed lines correspond to +ve, zero and -ve reorientation matrix elements for* 2_1^+ *and* 2_2^+ *states, i.e.* M_{12}*. The corresponding total cross sections integrated over the solid angle covered by the CD detector* σ_2 *are 1.17, 1.33 and 1.49 b, respectively. The corresponding cross sections for the* 0_2^+*,* 2^+_2 *and* 4^+_1 *states are about 0.055, 0.006 and 0.037 b, respectively, for* M_{22}*=0 and are similar for +ve and -ve values. The integrated cross sections were cross checked with GOSIA [24]. The coupling between the* 0^+_1 *and* 2^+_1 *states,* M_{02} *=0.7 e b is taken from the recent measurement by A. Gade et al. and for re-orientation matrix element the relation,* M_{22}*=1.1948* M_{02} *from rotational model is used. As the* M_{02} *between the* 0^+_2 *and* 2^+_1 *states is completely unknown we assume an over estimated value*

of 0.7 eb. As the structure of these states is expected to be different, this coupling should be less than that between the 0^+_1 *and* 2^+_1 *states (e.g., see calculations in Fig. 5).*

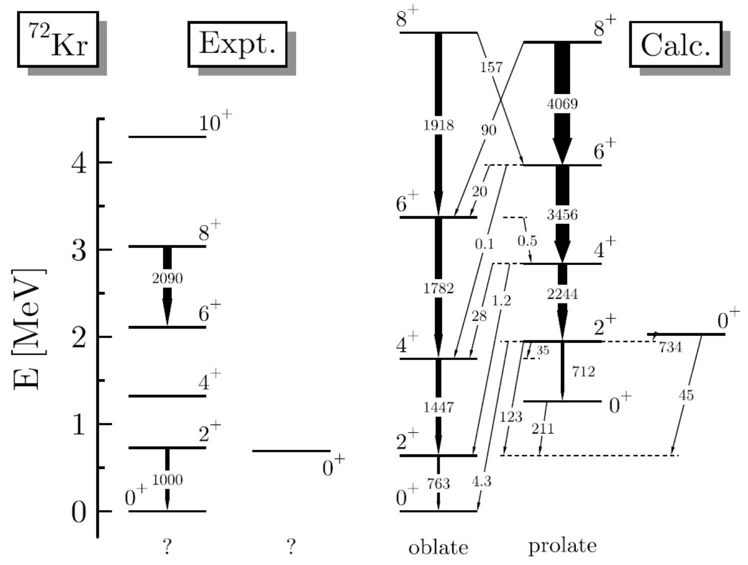


Fig. 5 The B(E2:J→J-2) values in e^2fm^4 *from experiment [10,11] and the calculations from Bender et al.(taken from Ref.[13]).*

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