SHAPE COEXISTENCE AND ISOMERISM IN Kr ISOTOPES*

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New experimental data on very neutron-deficient Kr isotopes extend the systematic of low-lying 0^+ states in this mass region. Clear evidence for shape isomers was found in ^{74}Kr and in the $N=Z$ nucleus ^{72}Kr. Coulomb excitation in inverse reaction kinematics was shown to be powerful method in order to disentangle the different shapes of atomic nuclei.

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1. Introduction

The shape of any atomic nucleus is determined by a delicate interplay between the macroscopic binding energy as given by the liquid-drop mass formula and microscopic effects as determined by the shell structure. When describing the nucleus as a charged liquid drop of particles, interacting via two-body forces, the strong attraction in the volume of the nuclear liquid is counteracted by surface effects, where less nucleons are available for the interaction. Therefore, a nucleus will always prefer to minimise its surface and adopt a spherical shape for essentially the same reason as a normal liquid drop. But the analogy of a nucleus with a liquid is only of limited validity, since the nucleons are subject to quantum-mechanical effects. The correct description by quantum mechanical wave functions results in certain "nucleonic orbits", where the nucleons are preferentially located. These orbits will hence strongly influence the shape of the nucleus.

When describing the nucleus in the shell model an increase in binding energy is always obtained for a low level density at the Fermi surface. Closed-shell nuclei are always spherical in their ground state, since for these specific proton and neutron numbers ("magic numbers") a very strong increase in

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the binding energy is obtained for a spherical shape, very similar to the inert gas configuration of the electron shell. Nuclei between closed shells can exhibit very different shapes depending on the specific combination of proton and neutron number. Here, the higher level density for a spherical shape *decreases* the binding energy and the nucleus will obtain a more stable configuration in a non-spherical (or deformed) equilibrium shape.

The most common shapes correspond (in first order) to ellipsoidal shapes obtained by elongating (prolate shape) or compressing (oblate shape) a sphere along the symmetry axis. In some cases the specific combination of proton and neutron number allows the nucleus to obtain several different shapes. If the total binding energy of the nucleus in its different shapes is similar, a low-lying excited state exists that has a different shape than the ground state. This phenomenon is called shape coexistence. A detailed report on shape coexistence in atomic nuclei can be found in [1].

Under certain circumstances the decay of the nucleus from the excited configuration to the ground state is hindered: The excited state becomes isomeric, *i.e.* it has a relatively long lifetime as compared to the usual decay times for electric quadrupole transitions typical for deformed nuclei. These *shape isomers* present a specific group of isomers, where the electro-magnetic decay is hindered by the different shape of the nucleus in the initial and final state, especially if the mixing between the different shapes is small. Understanding the shape of nuclei and the decay properties of shape isomers presents a stringent test of nuclear models since they depend on the exact position of nucleonic orbitals driving the nucleus to different intrinsic shapes.

2. Shape coexistence in krypton isotopes

Historically the most important examples for shape isomers are the fission isomers in the actinides [2], which are isomers built on the very elongated superdeformed shape of the atomic nucleus [3]. Although located at high excitation energies they are isomeric, because the overlap of the wave functions in the superdeformed (SD) and the normal-deformed (ND) well is extremely small. This was clearly demonstrated by measuring the extremely small E0 matrix element connecting the SD and ND ground state [4]. Due to the relatively low fission barrier in these very heavy nuclei, the main decay path of the isomers often proceeds via fission and not via γ-decay.

While the fission isomers are the text-book example for the existence of very different shapes in one nucleus, shape coexistence is actually a very common feature of atomic nuclei, especially around single closed-shell nuclei and in regions where a high level density occurs for spherical shapes [1]. The mass region around $A = 70$ and here especially the Se and Kr isotopes have a long history as candidates for shape coexistence. Experimental efforts to disentangle their different shapes have been pursued for more than 20 years, but only very recently it became possible to perform measurements which allow a more detailed understanding how shape coexistence develops in these nuclei.

Pronounced shell gaps, which occur for proton number $Z = 36$ at prolate and oblate deformation, play a major role for the structure of the Kr isotopes. The heavier, stable Kr isotopes (with neutron numbers between 44 and 50) are almost spherical, due to the closed neutron shell at $N = 50$. But in the more neutron-deficient isotopes different shell gaps (for neutron numbers between 36 and 42) lead to a pronounced deformation. Here, a well-deformed prolate and an almost equally well-deformed oblate shape are competing in energy. In several Kr isotopes both shapes are expected to occur within a few hundred keV of excitation energy, that is within less than 10^{-3} of the total binding energy. The shape of the ground state hence depends very much on details in the model description, for example the exact form of the mean-field as well as the parameters of the effective interaction used in the calculations. When approaching the $N = Z$ line also the proton-neutron pairing is expected to play a particularly important role [5]. Detailed measurements of the properties of shape co-existing states in the Kr isotopes constitute a precision test for the quality of today's nuclear models.

As one example a theoretical prediction for the structure of ^{74}Kr is shown in Fig. 1. Two minima at prolate ($\beta_2 \simeq +0.4$) and oblate ($\beta_2 \simeq -0.2$) deformation are evident, but the potential energy surface is rather shallow in the γ degree of freedom describing the deviation from axial symmetry. As a consequence the physical states are not expected to be pure, but containing a certain mixture of prolate and oblate wave functions.

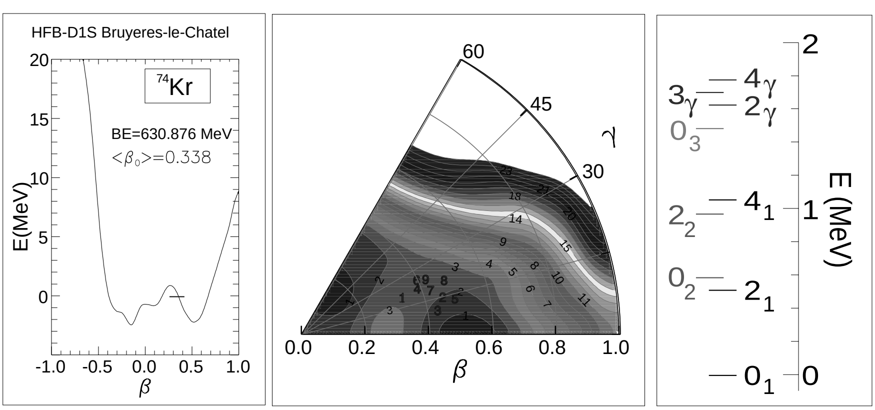

Fig. 1. Potential energy surface for ^{74}Kr obtained by a HFB calculation using the Gogny D1S force [6]. The location of the low energy collective states as obtained from this surface using the Bohr Hamiltonian is also shown.

3. Experimental techniques

Several experiments have been performed by our collaboration[1] during the last few years in order to better understand the development of shape coexistence in Kr nuclei. In-beam γ-ray and conversion-electron (CE) spectroscopy after fusion-evaporation reactions was used to study ^{74}Kr [7], while a Coulomb excitation experiment was performed on ^{78}Kr [8]. In the most recent experiment, we have investigated isomeric states in several neutron-deficient nuclei around $A = 70$, especially in the $N = Z$ nucleus ^{72}Kr, by using for the first time combined γ-ray and conversion-electron spectroscopy after fragmentation reactions [9].

Conversion-electron spectroscopy is an important tool in the investigation of shape isomers. In an even–even nucleus both ground state and shape isomer have the same spin-parity $I^\pi = 0^+$. The electro-magnetic decay between two 0^+ states must be an electric-monopole (E0) transition which can not proceed via the emission of a (single) γ-quantum[2]. The only way to observe (low-energy) E0 transitions is the measurement of conversion electrons. In this process the excitation energy of the nucleus is directly transferred to an electron of the electronic shell. The electron is ejected from the atom with a kinetic energy corresponding to the excitation energy of the nucleus minus the binding energy of the electron. The ejection of K-shell electrons is usually the dominant process, since those electrons have the largest probability to be at the centre of the atom. More generally, conversion electrons allow the measurement of E0 components in nuclear transitions that can also occur between other states with identical but non-zero spin.

A second important technique in order to disentangle the different shapes of a nucleus is Coulomb excitation. Pure Coulomb excitation occurs if the incident beam energy is kept well below the Coulomb barrier ('safe energy'). In this case only the electro-magnetic interaction needs to be taken into account, which can be calculated with high precision. In Coulomb excitation only collective states are populated, *i.e.* states that are linked to the ground state by large electro-magnetic matrix elements. The range of populated states (in spin and excitation energy) is determined by the reaction parameters and by the structure of the excited states. In principal, the electro-magnetic matrix elements connecting these states can be directly determined from the measured cross sections. In favourable cases also static moments including their (relative) signs can be determined using the reorientation effect [10]. Coulomb excitation is thus the only method that can directly distinguish between different shapes of the nucleus, for example

[1] See acknowledgements.

[2] In an E0 transition no angular momentum is transferred, but a γ-ray always carries (at least) 1 $\hbar$ of angular momentum.

whether states of different quadrupole deformation (prolate *vs* oblate) are coexisting, or whether the nucleus is soft with respect to this shape degree of freedom.

4. Summary of experimental results

4.1. Shape coexistence in ^{74}*Kr*

In two experiments at the IReS Strasbourg and at the University of Jyväskylä we investigated ^{74}Kr produced in a fusion-evaporation reaction using combined conversion-electron and γ-ray spectroscopy. The aim of those experiments was to prove the existence of an isomeric 0^+ state for which circumstantial evidence had been found before at GANIL [11]. The observation of an isomeric E0 transitions lead us to the conclusion that an excited 0^+ state with a lifetime of $\tau = 20(9)$ ns exists at an excitation energy of 509 keV (see Fig. 2).

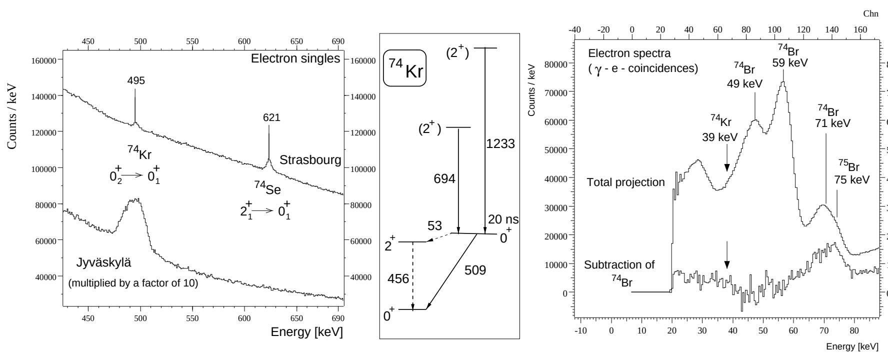

Fig. 2. Results from the investigation of the 0^+ isomer in ^{74}Kr: On the left a comparison of the 495 keV E0 transition as observed in the different experiments; in the experiment at Jyväskylä a thin target was used, avoiding the huge background from β-decay, but increasing the line width due to Doppler broadening effects. In the middle the partial decay scheme is shown with the competing decays of the excited 0^+ state and the new decays feeding the isomer. In the right the low energy part of the electron spectrum from the JYFL data is shown, where a search for the low-energy $0^+ \to 2^+$ transition at 53 keV was performed.

The most important property which can be derived from an electric-monopole decay is the E0 strength which tells us about the difference in mean square radii of the initial and final state and their mixing properties [12]. The E0 strength is inversely proportional to the (partial) half-life for E0 decay [13]. In ^{74}Kr the extraction of the E0 strength is complicated by a competing low-energy E2 decay of the excited 0^+ state to the first excited 2^+ state. This low-energy transition is practically invisible in the large background typical for fusion-evaporation reactions (see Fig. 2). Therefore only limits of $0.13(6) < \mathrm{B(E0)} < 0.18(8)$ can be given for the E0 strength.

4.2. A new shape isomer in ^{72}Kr

In our most recent experiment the fragments from a 73 A MeV ^{78}Kr beam, delivered by the GANIL cyclotrons and hitting a Be target, were separated and identified by the LISE3 spectrometer and finally implanted into a thin Kapton foil. Gamma-rays were measured with a set up of segmented Clover detectors from the EXOGAM collaboration, while conversion electrons were detected with a large area SiLi detector mounted close to the implantation foil. With this method isomeric transitions can be assigned on an event-by-event basis to a given fragment. In this way the isomeric 0^+ state discussed in the previous section could be firmly assigned to ^{74}Kr by correlating the E0 decay to the mass- and charge-identified fragments. While the analysis of this experiment is still in progress, clear evidence for the two competing decay modes of the isomer will be obtained.

In the same experiment a new isomeric E0 decay was observed in the $N = Z$ nucleus ^{72}Kr (see Fig. 3). The corresponding 0^+ state at 671(1) keV with a lifetime of $\tau \simeq 42$ ns is the first excited state in ^{72}Kr [9]. Since in this case the only possible decay of the isomer goes to the ground state, the lifetime directly corresponds to an E0 strength of B(E0) $\simeq 0.065$. This is in fact the first observation of a shape isomer in any $N = Z$ nucleus.

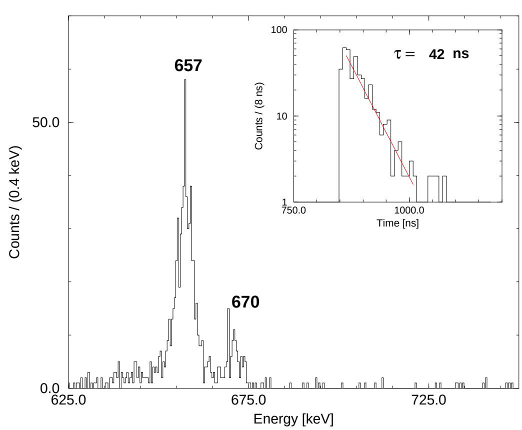

Fig. 3. Results from the fragmentation experiment on ^{72}Kr at GANIL: In the main part of the figure the conversion electron spectrum observed in coincidence with ^{72}Kr fragments is shown; two components of the new E0 decay from K and L conversion are visible at 657 and 670 keV, respectively. The inset shows the decay curve of the E0 transition together with an exponential fit giving a lifetime of $\tau \simeq 42$ ns.

4.3. Coulomb excitation of ^{78}Kr

Coulomb excitation of a ^{78}Kr beam delivered by the JYFL cyclotron was studied using different targets covering a large range in Z (^{208}Pb, ^{48}Ti and ^{26}Mg) and at different beam energies. In addition, also the use of a thick natural Ge target was tested in which the beam was stopped. A set up of position-sensitive parallel-plate avalanche counters (PPAC) was used to measure the scattered particles in coincidence with de-excitation γ-rays. The forward PPAC's covered a scattering angle range from 17° to 69° while the annular backward PPAC was active from 117° to 149°. 12 Compton suppressed Ge detectors were used for γ-detection. Examples for the γ-ray spectra are shown in Fig. 4. First results concerning the transition quadrupole moments are in agreement with the results of earlier lifetime measurements. The static quadrupole moments of the first two 2^+ states indicate a change in sign, as expected for states with different intrinsic shapes, but the data analysis is still in progress.

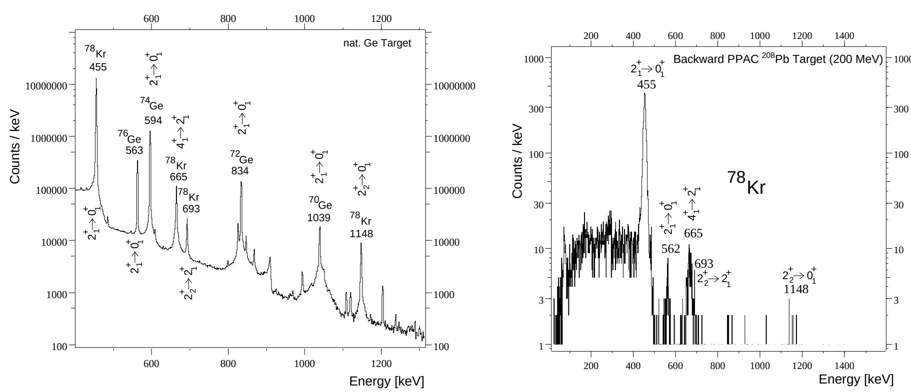

Fig. 4. Results from the Coulomb excitation experiment on ^{78}Kr at JYFL: In the left part a spectrum obtained with a natural Ge target at a beam energy of 180 MeV; the intensity ratio of lines assigned to ^{78}Kr and the lines stemming from the different Ge isotopes, directly allows a determination of the (relative) B(E2) values. In the right part a spectrum from the reaction on a ^{208}Pb target at an energy of 200 MeV, *i.e.* well below the Coulomb barrier where the excitation probability of higher-lying states is very small.

5. Interpretation

The systematic of low-lying 0^+ states in neutron-deficient Kr isotopes is summarised in Fig. 5. First the position of the excited 0^+ states will be discussed. Their energy is continously decreasing with decreasing neutron number reaching a minimum in ^{74}Kr and then increasing again for ^{72}Kr.

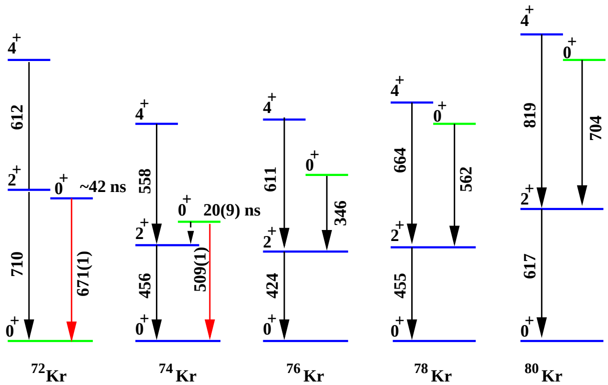

Fig. 5. Systematic of low lying 0^+ states in the Kr isotopes.

When the two 0^+ states are coming closer and closer in energy, an enhanced mixing between these states is expected. The regular rotational band observed at higher spins (not shown in the figure) can be used to determine the position of the unperturbed excited 0^+ state. With this input two-level mixing calculations can be performed (see Table I) showing that the energy difference of the unperturbed 0^+ states in ^{74}Kr is very small, *i.e.* they are practically degenerated. The energy difference observed experimentally, *i.e.* between the perturbed states, is actually a consequence of the strong mixing with a mixing amplitude close to 50 % which pushes them 509 keV apart from each other. In the neighbouring isotopes the mixing amplitude is much weaker.

TABLE I

Mixing calculations for coexisting 0^+ states in Krypton isotopes. From the energy difference of the physical (perturbed) states (Δ') and the perturbation (δ) the energy difference of the intrinsic states (Δ) and the mixing strength (V) can be calculated. The squared mixing amplitude (β^2) is given for the amount of the oblate configuration in the ground state. The data for ^{76,78}Kr are taken from [14, 15].

Nuclide	Δ' [MeV]	δ [MeV]	Δ [MeV]	V [MeV]	β^2
^{78}Kr	1.01718(3)	0.11(1)	0.80(2)	0.31(1)	0.11(2)
^{76}Kr	0.7700(2)	0.21(1)	0.36(1)	0.34(1)	0.27(1)
^{74}Kr	0.509(1)	0.25(1)	-0.02(1)	0.25(1)	0.52(1)
^{72}Kr	0.671(1)	0.06(1)	-0.55(1)	0.19(1)	0.91(1)

A possible scenario explaining the observed behaviour is a shape change of the ground state between ^{74}Kr and ^{72}Kr. In the heavier isotopes the ground state is prolate and the excited oblate state comes closer and closer in energy until they are degenerated in ^{74}Kr. Finally, in the $N = Z$ nucleus ^{72}Kr the oblate state becomes the ground state. This scenario is also supported by the large E0 matrix elements in ^{74}Kr and ^{72}Kr. In both cases a large difference in deformation between the two 0^+ states is needed to explain the observed E0 strength, but in ^{74}Kr we observe in addition almost complete mixing between the states, which leads to one of the largest E0 strengths observed in any nucleus.

6. Conclusion and outlook

Shape isomers occur in the very neutron deficient Kr isotopes, as soon as E2 transitions are forbidden or energetically hindered. The energetic position of the shape coexisting states is well reproduced by HFB calculations (see Fig. 1). Contrary to the situation in the actinides, the mixing between the different shapes is quite large, leading to rather strong E0 matrix elements between the shape coexisting states. It would be very important to see whether the same theoretical calculations can also reproduce the transition matrix elements.

Coulomb excitation in inverse reaction kinematics is a powerful tool to determine electro-magnetic matrix elements as demonstrated by our first results on ^{78}Kr and will also allow the measurement of static electric quadrupole moments. In combination with radioactive ion beams, for example from the SPIRAL facility, a new field for Coulomb excitation measurements will open up, finally allowing us to disentangle the different shapes occurring in this mass region.

The work described in this talk is the result of several experiments performed in different collaborations; the GAREL+ collaboration at the Vivitron accelerator (IReS Strasbourg, France), the SACRED collaboration at the JYFL Cyclotron (Univ. of Jyväskylä, Finland) and the LISE collaboration at GANIL (Caen, France). We are indebted to all accelerator crews for maintaining excellent running conditions and to the local physicists for their invaluable help in setting up and running the experiments.

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