Investigation of heavy N∼Z nuclei using energetic radioactive ion beams

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1. INTRODUCTION

Heavy self-conjugate nuclei, having the same number of protons and neutrons, are the ideal testing ground to study symmetries of the nuclear hamiltonian and other aspects of modern nuclear structure theory. As one example, intense experimental and theoretical efforts have been undertaken in order to search for a new pairing phase in heavy N=Z nuclei. In the usual T=1 pairing mode protons and/or neutrons couple to spin 0 pairs, but proton-neutron pairs can also be built from a spin-aligned (I=1,T=0) coupling [1]. This T=0 pairing could manifest itself, for example, in the alignment behaviour of rapidly rotating N=Z nuclei [2], since the T=0 pairs would be less affected by the Coriolis force. In order to ascribe such an effect to the presence of a new pairing phase other variables such as a deformation change must be excluded. Another example concerns the super-allowed Fermi decays of N=Z nuclei. High-precision measurements of the comparative lifetimes allow testing the conserved vector current (CVC) hypothesis of the weak interaction and contribute to the determination of the V_{ud} matrix element of the CKM quark-mixing matrix [3]. In this case theoretical corrections have to be applied, which depend very sensitively on the nuclear structure of the parent and daughter nuclei. Finally, several N=Z nuclei may present a waiting point in the astrophysical rapid-proton capture (rp) process. Besides the nuclear masses, also the structure of low-lying states in these nuclei has an important influence on the proton capture and beta-decay rates and can hence influence the rp process path [4].

Understanding these fundamental questions relies strongly on a good theoretical description of the structure of the nuclei at and close to the N=Z line. In this presentation recent experiments using reaccelerated radioactive ion beams will be discussed which will help to improve our understanding of these nuclei. The emphasis of the experimental studies is to improve our knowledge by measuring electro-magnetic matrix elements (transition strengths and static moments) with high precision in order to put modern nuclear structure theory to more stringent tests.

2. SHAPE CHANGES AND COEXISTENCE IN HEAVY N∼Z NUCLEI

Many neutron-deficient nuclei in the mass 70-80 region, especially close to the N=Z line, have a large quadrupole deformation in their ground states. This has been verified experimentally through the observation of rotational bands and by measuring transition rates of the rotational states. Some of these nuclei are expected to exhibit “shape coexistence”, i.e., states of different deformation within a small energy range of less than 1 MeV. Shape coexistence in this mass region is caused by large shell gaps in the single-particle level scheme occuring at both prolate and oblate deformation for certain numbers of protons and/or neutrons. A review of the shape coexistence phenomenon, which occurs also in several other mass regions, can be found in [5].

Many theoretical calculations have been performed for heavy N∼Z nuclei using various mean-field approaches [6–11]. Most calculations give similar equilibrium deformations, but they often differ in the precise values of excitation energies for the shape-coexisting states. Furthermore theoretical information on the expected electro-magnetic transition probabilities and static moments is rarely calculated. These electro-magnetic properties would allow much more stringent tests of the model predictions since they are more sensitive to details of the wave functions, e.g., the mixing properties of the coexisting states.

The neutron-deficient Se (Z=34) and Kr (Z=36) isotopes have played for a long time a major role in the quest for shape coexistence between well-deformed prolate and oblate shapes at low spins. In particular, the N=Z nuclei ^{68}Se and ^{72}Kr are expected to have oblate ground states, but a prolate configuration should also exist at relatively low excitation energy. In the heavier isotopes the situation is expected to be reversed, here an (excited) oblate configuration is competing with a prolate ground state. Experimental support for this shape-coexistence scenario comes from the observation of low-lying excited 0^+ states. The different 0^+ states can be interpreted as the “ground states” of the coexisting shapes. In even-even Kr nuclei, for example, excited 0^+ states have been observed in all isotopes ranging from mass A=80 (stable) to the N=Z nucleus ^{72}Kr. With decreasing neutron number the energy of the excited 0^+ state decreases, reaching a minimum at mass A=74 (see figure 1). In the very neutron-deficient isotopes ^{72}Kr and ^{74}Kr the excited 0^+ state is isomeric (i.e. a “shape isomer”) and it decays (exclusively or predominantly) via an enhanced E0 transition to the ground state [12–14].

The rotational bands observed in all neutron-deficient Kr isotopes show a rather similar behaviour at high spins and the measured moments of inertia correspond to the value expected for the prolate deformation. The energetic position of the low-spin states, however, indicates strong mixing, especially of the 0^+ states. From a two-level mixing calculation

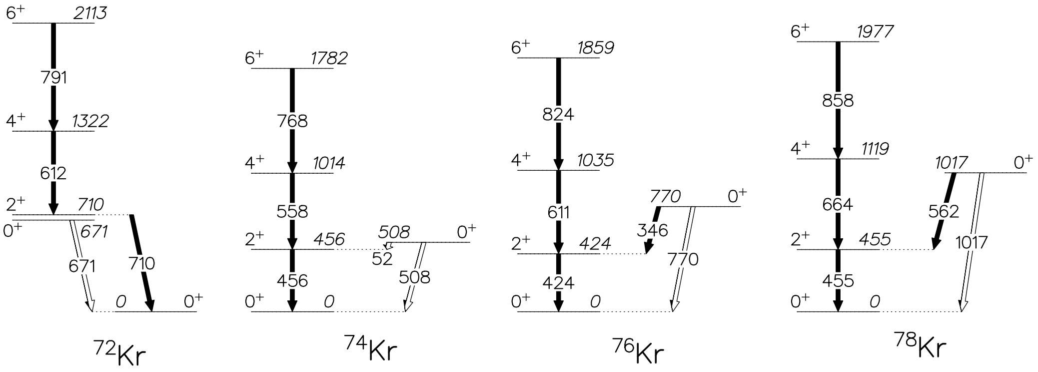

Figure 1. Partial level schemes of the even-even Kr isotopes from ^{72}Kr to ^{78}Kr illustrating the systematics of excited 0^+ states. In ^{76,78}Kr these states were found in beta-decay studies, while in ^{72,74}Kr conversion-electron spectroscopy of fragmentation products was applied. States with proposed prolate configuration are shown on the left, those with proposed oblate configuration on the right of each level scheme. Transitions proceeding via conversion electrons are shown as open arrows.

it can be concluded that the mixing angle increases with decreasing neutron number and that full mixing is reached in ^{74}Kr [14]. In fact, the unperturbed ("intrinsic") 0^+ states in ^{74}Kr are almost degenerate and the observed energy difference of the perturbed ("physical") states is entirely due to the repulsion of the intrinsic states. In the case of ^{72}Kr the level scheme suggests that the rotational band is built on the excited 0^+ state rather than the ground state. Consequently, the ground state in ^{72}Kr must be based on the oblate configuration. Further support for this shape coexistence scenario comes from the measured E0 strength (see table 1). Extremely large values are observed in several isotopes indicating mixed states of rather different deformation.

Table 1
Experimental E0 transition strength ρ^2 of the $0_2^+ \rightarrow 0_1^+$ decays in light Kr isotopes [14].

Nuclide	^{72}Kr	^{74}Kr	^{76}Kr	^{78}Kr
$\rho^2(E0)$	0.072(6)	0.085(19)	0.079(11)	0.047(13)

The proposed shape-coexistence scenario is conclusive, but it is generally based on indirect measures such as the moment of inertia of the rotational bands and the changes in the position of the (low-spin) states due to mixing between the different configurations. Reduced E2 transition probabilities are only available for less exotic nuclei closer to stability and are often limited to the yrast states. From the enhancement of the E2 transition probabilities the deformation can be inferred, but no conclusion on the intrinsic shape (oblate vs. prolate) can be drawn. Finally, static quadrupole moments, which depend on the sign of the intrinsic deformation, are completely unknown in β-unstable even-even nuclei. Precise measurements of these properties are now experimentally possible by performing Coulomb excitation of low-energy beams of radioactive isotopes.

3. COULOMB EXCITATION OF BETA-UNSTABLE KR ISOTOPES

Coulomb excitation is a well established technique to study collective excitations in nuclei. “Collective” states which are linked by large matrix elements to the ground state are strongly populated. In contrast to the electro-magnetic excitation at “relativistic” energies, which is often used today to study radioactive beams at fragmentation facilties, the interaction time in low-energy Coulomb excitation is sufficiently long to allow for the (multi-step) excitation of higher spin states. In stable strongly deformed nuclei, e.g. ^{238}U, spin values in excess of $20\hbar$ have been reached. The excitation energy on the other hand is limited to about 1-2 MeV (per step) due to the adiabatic cut-off.

From the measured Coulomb excitation cross sections the electro-magnetic matrix elements can be inferred. If the incident beam energy is kept well below the Coulomb barrier (“safe energy”) only the electro-magnetic interaction needs to be taken into account, which allows to calculate the Coulomb excitation probability and hence the cross section with very high precision. In favourable cases also static moments including the (relative) signs can be determined. Besides the reorientation effect [15], causing the redistribution of magnetic substates, the interference of transitional and diagonal matrix elements in the solution of the coupled-channels problem gives rise to an increased sensitivity to the static moments. Coulomb excitation is thus the only method that can directly determine the shape of the nucleus in a short-lived excited state. The technique also allows to distinguish between a coexistence of states with different deformation (i.e. prolate vs. oblate shape) and a nucleus which is “soft” with respect to the quadrupole shape degree of freedom.

Until very recently Coulomb excitation experiments were limited to stable nuclei due to a lack of mono-isotopic radioactive ion beams (RIB) at well-defined energies below the Coulomb barrier (i.e. < 5 MeV/u). Earlier attempts to produce such beams from recoiling fusion-evaporation products were not very successful (see [16] for an example on ^{76}Kr). For a precise determination of the matrix elements it is necessary to measure the cross section as a function of the particle scattering angle and therefore, the emittance of the beam is also a major concern. The SPIRAL facility at GANIL (Caen, France) is among those few installations world-wide which can deliver a pure, high-quality RIB. In particular noble gases are produced with very good intensities.

At GANIL a high-energy ($\sim$70 MeV/u) ^{78}Kr primary beam - with an intensity of up to $\sim 2\times10^{12}$ ions/second - is fragmented in a thick Carbon target to produce beams of neutron-deficient β-unstable Krypton isotopes. After an extraction using the ISOL method the isotope of interest is re-accelerated in the CIME cyclotron. High quality beams - practically free from isobaric contaminants - are obtained with intensities of 5×10^5 and $\sim10^4$ ions per second for ^{76}Kr and ^{74}Kr, respectively, measured in the experimental area. Coulomb excitation was performed on thin ($\sim$1 mg/cm^2) ^{208}Pb and ^{48}Ti targets using “safe” beam energies of $\sim$4.5 and 2.6 MeV/u, respectively; the large Z difference of the targets giving an additional constraint on the quadrupole moments.

The de-excitation γ rays were detected in the EXOGAM spectrometer [17], an array of (up to) 16 large segmented Clover Ge detectors; 7 Clover detectors were available for the first experiment on ^{76}Kr, while 11 detectors could be used for the ^{74}Kr run. In both cases the Ge detectors were placed at 90° and 135° with respect to the beam direction. Scattered

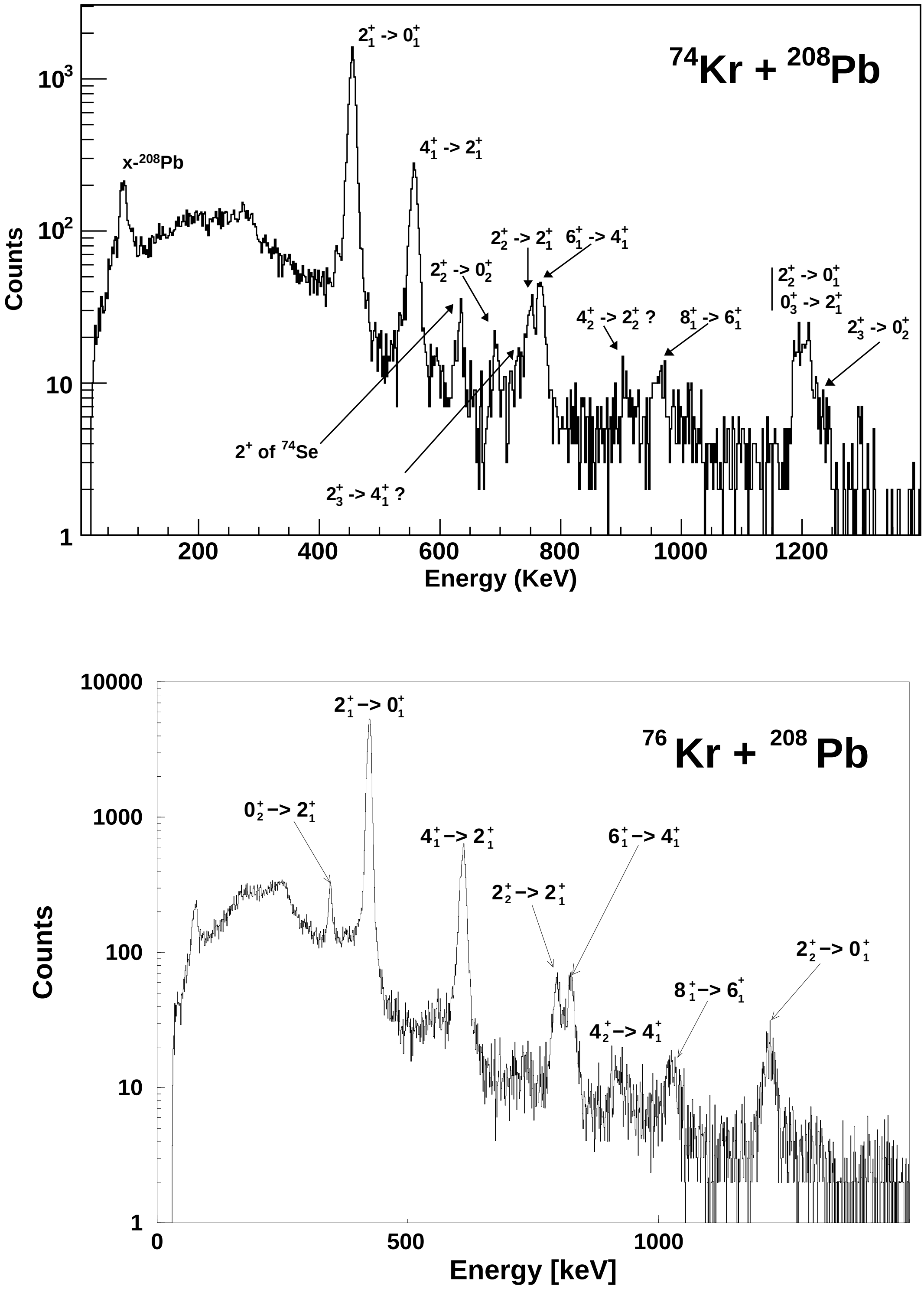

Figure 2. Gamma-ray spectra obtained in coincidence with scattered particles in the Coulomb excitation reactions ^{74}Kr+^{208}Pb at 350 MeV (top) and ^{76}Kr+^{208}Pb at 344 MeV (bottom). The spectra are presented on a logarithmic scale in order to make the weaker transitions visible.

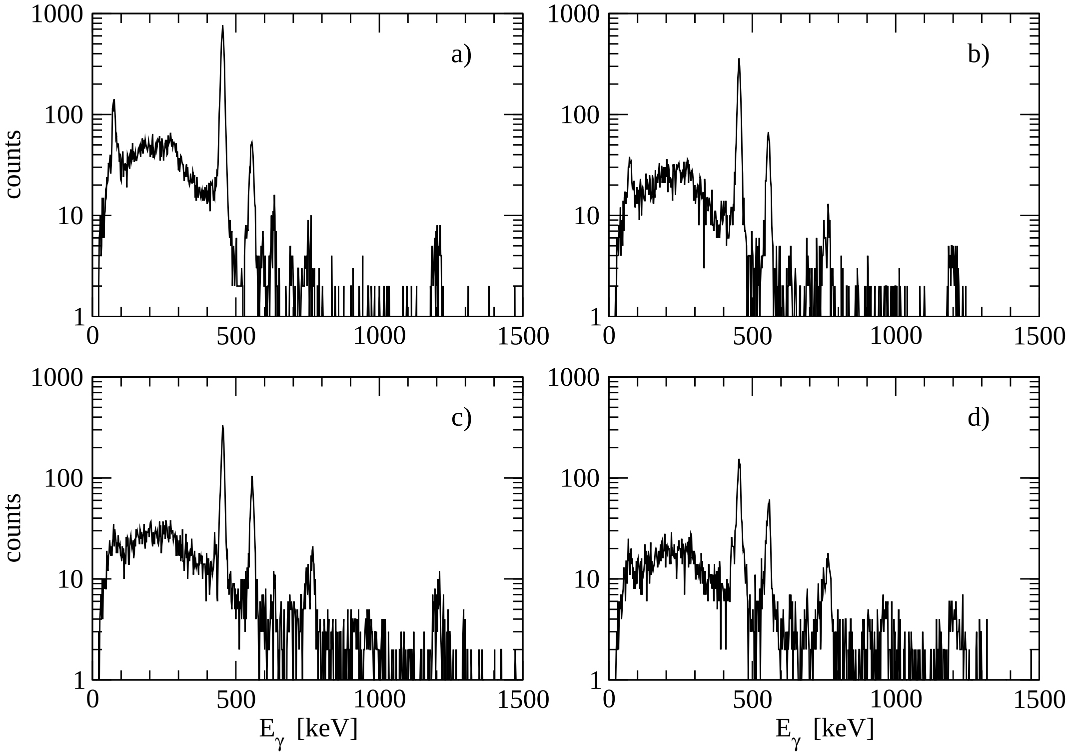

Figure 3. Gamma-ray spectra obtained in the reaction ^{74}Kr+^{208}Pb at 350 MeV, gated on different ranges of scattering angles in the center-of-mass: (a) $24° \leq \theta_{cm} \leq 54°$, (b) $54° \leq \theta_{cm} \leq 74°$, (c) $67° \leq \theta_{cm} \leq 97°$ and (d) $97° \leq \theta_{cm} \leq 145°$ (see text for further details).

beam particles and recoiling target nuclei were measured in an annular Silicon detector placed ∼25 mm downstream from the target and thus covering the angular range from 18° to 56°. This double-sided Silicon detector is sub-divided into 16 angular segments and 48 concentric rings; the rings were electronically combined into 16 signals. The segmentation is used in two ways. The concentric rings determine the different particle-scattering angles in order to measure differential Coulomb excitation cross sections. The two-dimensional bins in combination with the segments of the EXOGAM array allows to determine the relative emission angle of the γ rays rather precisely in order to correct for the strong Doppler-shift effect of the fast moving source (v/c∼10%).

Doppler-corrected γ-ray spectra obtained from the experiments on ^{76}Kr and ^{74}Kr are shown in figures 2 and 3. The requirement to detect gamma-rays and scattered particles in coincidence allows suppressing the predominant background from the radioactive decay of the beam particles in the γ-ray spectra completely. The spectrum quality is excellent, even though for the ^{74}Kr case a small contamination with the isobar ^{74}Se (∼2% of the beam) is apparent. A very good statistical accuracy could be obtained for both nuclei under study; the $2^+ \rightarrow 0^+$ transition in ^{76,74}Kr contains a total of $4{\times}10^4$ and $\sim 10^4$ counts, respectively. From these spectra it can already be concluded that low-energy Coulomb excitation of nuclei with large collectivity is still possible with intensities as low as a few hundred ions per second.

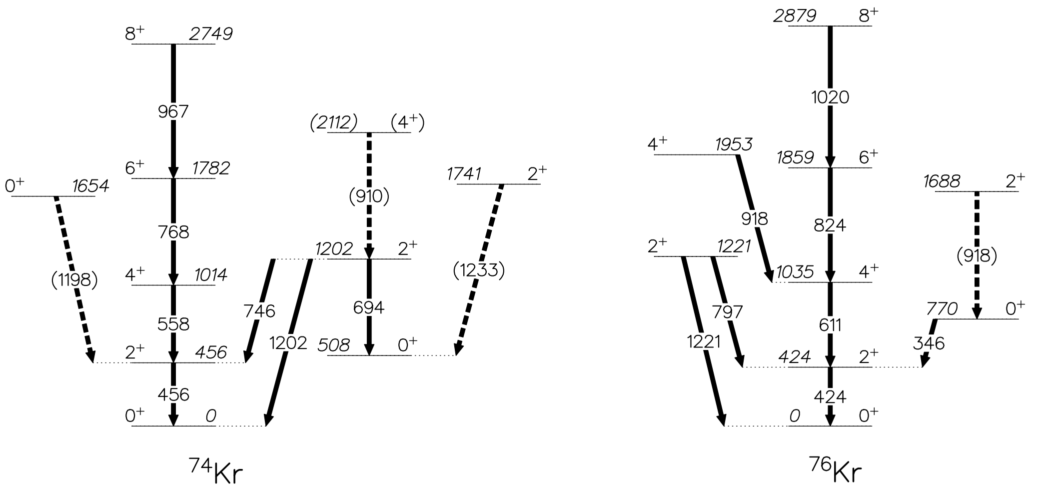

Figure 4. Partial level schemes of ^{74}Kr (left) and ^{76}Kr (right) as obtained from the spectra shown in figure 2. Transitions that could not be identified unambigously are shown as dashed arrows.

In figure 3 the ^{74}Kr data are shown for different ranges of scattering angles. They were obtained by gating on scattered Kr ions at small (a) and large (b) laboratory angles and on Pb recoils at large (c) and small (d) laboratory angles. The figures 3 (a) to (d) thus correspond to increasing center-of-mass (CM) angles, showing characteristic changes in the (relative) population of the different states. Excited states up to spin $8\hbar$ are populated in the ground-state band and evidence for higher lying low-spin states in the side bands is also obtained. The states and γ-ray transitions which were observed in our experimental data on ^{76,74}Kr are summarised in figure 4.

4. RESULTS AND DISCUSSION

The Coulomb excitation analysis was performed using the code GOSIA developed at the University of Rochester [19]. In comparision to a "standard" Coulomb excitation calculation this code also allows to perform a least-square analysis of the input data in order to determine the optimum set of matrix elements. Besides the data on Coulomb excitation probabilities the code also takes into account other known spectroscopic information such as the lifetimes of the states and the branching and mixing ratios of the decays.

Usually, the Coulomb excitation probabilities are determined from the efficiency corrected γ-ray intensities by normalising to the total number of scattered particles in a particular angular range, i.e the integrated Rutherford cross section. Such an analysis requires a precise knowledge of the particle-gamma efficiency corrections. These corrections turned out to be rather complex in the close geometry of our experiment due to difficulties with the centering of the Si detector and the rather large beam spot and beam dispersion (emittance $\sim 16\pi$ mm mrad). Therefore, we have chosen to leave the normalisation factor between the experimental and calculated data as a free parameter of the least-square analysis.

Preliminary results of the ^{76}Kr experiment have already been reported [18] and consequently we will concentrate on the new results obtained for ^{74}Kr. In this case a total of 32 E2 and M1 matrix elements between 10 states enter into the calculation (see the left part of figure 4). These matrix elements are constrained by the measured intensities for the 4 different CM ranges (defined in figure 3) as well as the known lifetimes [20,21] and branching ratios [14,22]. It should be noted that the information on higher-lying low-spin states is particularly important in order to obtain reliable results for the static quadrupole moments of the 2^+ states.

We are not yet in a position to present the final results of the analysis, but the preliminary results can be summarised as follows. The reduced E2 strength of the ground-state band of ^{74}Kr is in agreement with the values obtained from lifetime measurements with the exception of the $4_1^+ \rightarrow 2_1^+$ transition. For this transition we find a larger collectivity indicating that the quadrupole moment is more constant than deduced from the lifetime measurements [21]. The data are in agreement with a large and constant intrinsic quadrupole moment ($Q_0 \sim 3$ eb).

The principal new result concerns the static quadrupole moment of the first and second excited 2^+ states. For the first 2^+ state we find a large positive intrinsic quadrupole moment corresponding to a prolate shape ($\beta_2 \sim +0.4$). This preliminary value agrees rather well with the deformation deduced from the transition matrix elements; a negative quadrupole moment is clearly excluded from our data. For the second excited 2^+ state we find (i) a large E2 strength for the 694 keV transition to the excited 0^+ state and (ii) a negative intrinsic quadrupole moment ($Q_0 \sim -2$ eb). Both findings support the earlier suggestion [13] of a K=0 rotational band with an oblate deformation ($\beta_2 \sim -0.3$). These results present the first unambigous experimental evidence for coexisting states of prolate and oblate deformation in this mass region [23].

5. CONCLUSIONS AND OUTLOOK

Coulomb excitation of radioactive ^{76}Kr and ^{74}Kr beams has been performed at GANIL. Using the reorientation effect we were able to determine for the first time static quadrupole moments of short-lived excited states in beta-unstable, even-even nuclei. This experimental technique should allow for more detailed studies of shapes and collectivity in radioactive nuclei further from stability. The experiments have shown that beam intensities of (a few) hundred ions per second are sufficient to measure the B(E2) value of the first excited 2^+ state in collective even-even nuclei via low-energy Coulomb excitation. Although ^{74}Kr is only two neutrons away from the N=Z nucleus ^{72}Kr, the latter can not be produced currently by the SPIRAL facility with sufficient intensity. We are therefore planning an experiment using the technique of intermediate-energy Coulomb excitation in order to get first estimates of the collectivity of the N=Z nuclei ^{68}Se and ^{72}Kr.

Radioactive beams with higher intensities ($\geq 10^4$ pps) allow more detailed studies. Since at the same time the number of matrix elements increases rapidly additional spectroscopic information is often needed. As an example the precise determination of static quadrupole moments relies on the knowledge of all low lying states which (strongly) couple to the state of interest. Therefore, other experiments using more conventional techniques, such as lifetime measurements, are also needed in order to make best use of the data taken in radioactive beam experiments. In the case of ^{74}Kr we are planning to remeasure lifetimes and other spectroscopic data in a dedicated experiment. This will allow us to eliminate the remaining uncertainties in the Coulomb excitation analysis.

Finally, it should be noted that the planned SPIRAL-2 facility will deliver high-intensity beams from fission fragments accelerated to energies at (and above) the Coulomb barrier. This new facility should allow us performing an extensive Coulomb excitation programme of neutron-rich nuclei located far from the valley of stability.

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