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Short note

Investigation of prolate-oblate shape-coexistence in ^{74}Kr

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Abstract. The atomic nucleus ^{74}Kr has been investigated using combined conversion-electron (CE) and γ-ray spectroscopy. In order to confirm the existence of the expected low-lying isomeric 0_2^+ state, the possibility of an electric-monopole (E0) decay to the ground state was examined. The observation of an E0 transition at 508 keV allowed the determination of the mixing between coexisting prolate and oblate shapes.

PACS. 21.10.Tg Lifetimes – 23.20.Lv Gamma transitions and level energies – 23.20.Nx Internal conversion and extranuclear effects – 25.70.Gh Compound nucleus – 27.50.+e 59 A 89

The nuclei in the mass region around A = 75 exhibit a wide variety of shapes including unusually large prolate and oblate deformations, triaxial and spherical shapes. Qualitatively, these features can be understood as a consequence of the different energy gaps in the Nilsson single-particle levels at Z,N = 34 – 40. The coexistence of different shapes in this region is predicted by several different model calculations [1], using either the Hartree-Fock [2] or the Nilsson-Strutinsky [3] approach. Specifically some of the low-lying, excited 0^+ states, frequently observed in these nuclei, are predicted to have an intrinsic shape or deformation different from that of the ground state. ^{74}Kr is a prime candidate for the occurrence of prolate-oblate shape coexistence in this mass region, since the protons around Z = 36 and the neutrons around N = 38 drive the nucleus simultaneously towards a well-deformed oblate and an equally well-deformed prolate shape, respectively.

From high-spin studies [4] it is known that ^{74}Kr shows the properties of a well-deformed prolate rotor for I $\geq$ 4, while the low-spin level scheme is disturbed. It has been proposed [4,5] that this is most likely due to mixing of prolate and oblate states which coexist at low spins. Recently, using the projectile fragmentation of a ^{92}Mo primary beam at the GANIL facility, an isomeric state has been observed in ^{74}Kr [5,6]. Following this investigation, the occurrence of a delayed component in the $2_1^+ \rightarrow 0_1^+$ transition at 456 keV indicates an isomeric state lying less than 100 keV above the 2_1^+ state. However the transition depopulating this new isomer was not observed, and thus, neither the excitation energy nor spin and parity of the isomer could be directly measured. Nevertheless, this result was interpreted as the (hindered) decay from an isomeric 0_2^+ level indicating the predicted oblate-prolate shape coexistence in ^{74}Kr. The investigation presented here aims at the observation of the E0 decay linking the two 0^+ states to confirm the spin-parity assignment and to measure the excitation energy of the isomer.

In the present work the nucleus ^{74}Kr has been investigated at the Vivitron accelerator (IReS Strasbourg) using the GAREL+ setup consisting of 14 large-volume Ge detectors and a magnetic solenoid spectrometer (β-TRONC [7]). A pulsed (interval 480 ns, width 4 ns) 60 MeV ^{19}F beam was used for the reaction ^{58}Ni(^{19}F,p2n)^{74}Kr. In order to detect isomeric decays within the view of the detectors, a carbon catcher (770 μg/cm^2) was mounted behind the thin nickel target (520 μg/cm^2). Energy and timing information (with respect to the beam pulsing) were measured for γ-ray and conversion-electron (CE) singles. In addition, $\gamma\gamma$ and CE-γ coincidences were recorded.

Evidence for the isomeric $0_2^+ \rightarrow 0_1^+$ E0 transition was found at an electron energy of 495(1) keV (see Fig. 1), cor-

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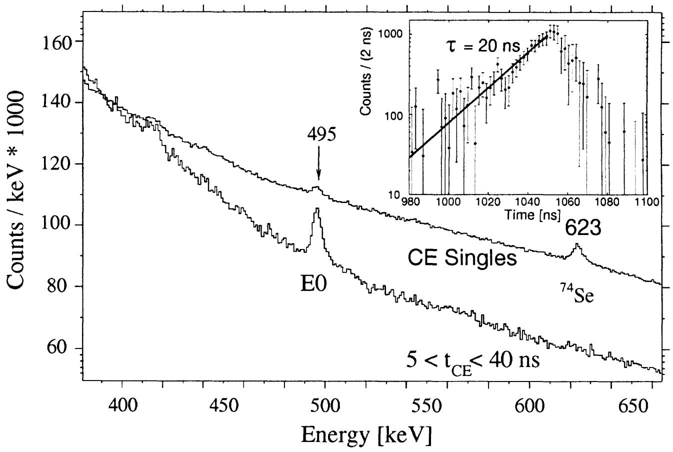

Fig. 1. Conversion-electron singles spectrum obtained in the reaction $^{58}Ni(^{19}F,p2n)^{74}Kr$ compared with the corresponding normalised time-gated spectrum ($5 < t_{CE} < 40$ ns). In the inset the time spectrum for the 495 keV E0 transition is shown

responding to an excitation energy of 508(1) keV for the 0_2^+ state. In agreement with the strictly forbidden $0_2^+ \rightarrow 0_1^+$ γ decay no indication for a γ transition at 508 keV was observed. In Fig. 1 the decay spectrum of this E0 transition is also shown, from which the lifetime was determined to 20±2±7 ns (fit/systematic errors), consistent at the 2σ level with the value of 42(8) ns, obtained by Chandler et al. [5] from the delayed $2_1^+ \rightarrow 0_1^+$ decay.

Since the proposed 0_2^+ state would lie 52 keV above the 2_1^+ state in ^{74}Kr, the observation of a $0_2^+ \rightarrow 2_1^+$ transition would clearly assign it to ^{74}Kr. Unfortunately, this low-energy transition could not be observed in our experiment. Nevertheless, the assignment to ^{74}Kr does not only rely on the lifetime measurement, but also on the observation of two excited states decaying into the 0_2^+ state. In Fig. 2 the CE-γ coincidence spectra are shown, when gating with the isomeric E0 decay (upper panel) or with the 694 and 1233 keV lines feeding the isomer (lower panel). The new partial level scheme of ^{74}Kr was derived in this way. The 694.0(5) keV transition depopulates a state at 1202 keV, which has previously been assigned as 2_2^+ state of ^{74}Kr [4]. The 1233.0(5) keV transition was previously identified to belong to ^{74}Kr, but could not be placed into the level scheme on the basis of $\gamma\gamma$ coincidences only [8]. We assume that the state at 1202 keV is likely to be the 2^+ state of predominantly oblate nature, while the new state at 1741 keV can be interpreted from its energetic position as the band head of the K=2 γ-band in ^{74}Kr [4].

In a simple two-level mixing model [9] the mixed states of spin-parity J^π can be written as linear combination of the pure states of definite deformation:

$$|\Psi_1(J^\pi)\rangle = \alpha_J|\Phi_p(J^\pi)\rangle + \beta_J|\Phi_o(J^\pi)\rangle$$
$$|\Psi_2(J^\pi)\rangle = \beta_J|\Phi_p(J^\pi)\rangle - \alpha_J|\Phi_o(J^\pi)\rangle$$

We denote the energies of the pure states of prolate and oblate shape as $E_p(J^\pi)$ and $E_o(J^\pi)$, respectively, and use the experimental energies $E_i(J^\pi)$ (i=1,2) for the mixed states. The energy difference of the pure states (Δ_J) and

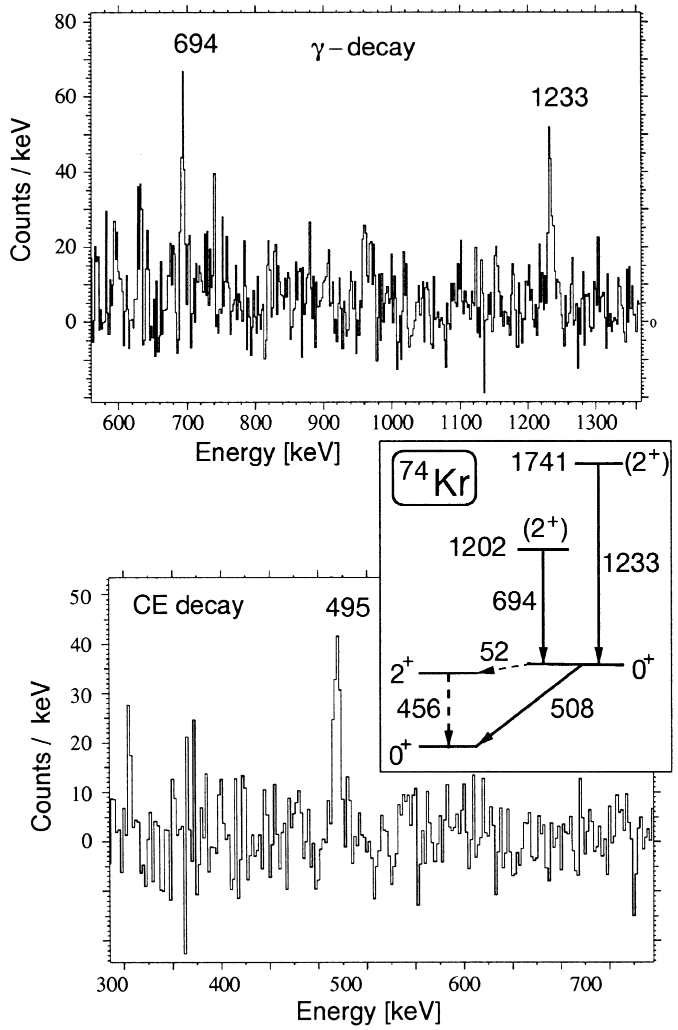

Fig. 2. γ-CE coincidence spectra: γ-ray spectrum gated by the 495 keV CE line (top) and CE spectrum gated by the γ-ray lines at 694 and 1233 keV (bottom), together with the proposed partial level scheme of ^{74}Kr (the dotted transitions were not seen in coincidence with the feeders of the 0_2^+ state)

of the mixed states (Δ'_J) can then be defined as $\Delta_J = E_o(J^\pi) - E_p(J^\pi)$ and $\Delta'_J = E_2(J^\pi) - E_1(J^\pi)$, respectively. The energy difference between the pure and the mixed state is then given as $\delta_J = \frac{1}{2}(\Delta'_J - \Delta_J)$.

From these energy differences the (squared) mixing amplitudes (α_J^2, β_J^2) and the mixing matrix element (V_J) can be calculated :

$$\beta_J^2 = (1 - \alpha_J^2) = \frac{\delta_J}{\Delta'_J} = \left[1 + \left(\frac{V_J}{\delta_J}\right)^2\right]^{-1}$$

$$|V_J| = \frac{1}{2}\left(\Delta_J'^2 - \Delta_J^2\right)^{\frac{1}{2}} = \delta_J\left(\frac{\Delta'_J}{\delta_J} - 1\right)^{\frac{1}{2}}$$

In order to solve the expression we followed the method given by Piercey et al. [10]. For each spin-parity J$^\pi$ three values for either the level energies or the mixing matrix elements are needed. In addition to the experimental energies of the mixed states (E_1&E_2), the unperturbed energy

Table 1. Mixing calculations for coexisting 0^+ states in Krypton isotopes. The data for ^{76,78}Kr are taken from [11,12]

Nuclide	J$^\pi$	Δ'_J [MeV]	δ_J [MeV]	Δ_J [MeV]	V_J [MeV]	β^2_J
^{78}Kr	0^+	1.01718(3)	0.11(2)	0.80(2)	0.31(1)	0.11(2)
^{76}Kr	0^+	0.7700(2)	0.205(6)	0.36(1)	0.340(3)	0.27(1)
^{74}Kr	0^+	0.508(1)	0.263(5)	-0.019(6)	0.254(1)	0.52(1)

of the prolate state (E_p) can be extracted from the high-spin states using a Harris extrapolation. In Table 1 the results of this calculation are summarised for the isotopes ^{74,76,78}Kr.

With decreasing neutron number the excitation energy of the 0^+_2 state (Δ'_J) becomes smaller, while at the same time the perturbation (δ_J), e.g. the energy difference between pure and mixed state, increases. The negative sign of the energy difference of the pure states (Δ_J) in ^{74}Kr signals that the oblate and prolate configuration have exchanged position, e.g. the oblate state has become the dominant configuration in the ground state. In view of a (squared) mixing amplitude of $\beta^2 = 0.52$ for ^{74}Kr such a distinction is, however, rather arbitrary. Extrapolating this trend to even smaller neutron numbers leads us to expect a predominantly oblate ground state of ^{72}Kr, in accordance with recent experimental evidence [13].

The monopole strength $|\rho(E0)|$ can be calculated from the lifetime and the decay branching ratio for K conversion from the 0^+_2 state. Although the $0^+_2 \rightarrow 2^+_1$ transition was not observed in this experiment, an estimate for the upper limit of this decay yields a branching ratio of $0 \leq \frac{I_K(E2)}{I_K(E0)} \leq 100$. With the measured lifetime this leads to limits of the E0 strength of $0.67 > |\rho(E0)| > 0.027$, in agreement with Excited Vampir calculations [5,14] predicting $|\rho(E0)| = 0.17$.

In conclusion, we have observed a new E0 transition from an isomeric 0^+_2 state in ^{74}Kr at 508 keV with a lifetime of 20 ns. A two-level mixing calculation yields maximum mixing between the 0^+ states which can explain the rather large E0 strength of the $0^+_2 \rightarrow 2^+_1$ transition. A measurement of the decay branching ratio of the 0^+_2 state is still desirable to confirm the assignment and to determine the monopole strength more precisely. Although the proposed scenario of prolate-oblate shape coexistence is consistent with the experimental findings, we believe that the final proof will come from Coulomb excitation experiments using a radioactive ^{74}Kr beam.

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