Static Quadrupole Moment of the Five-Quasiparticle $K = \frac{35}{2}$ Isomer in ^{179}W Studied with the Level-Mixing Spectroscopy Method

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The spectroscopic quadrupole moment of the high-spin, high-K five-quasiparticle isomer ($K^\pi = \frac{35}{2}^-$, $T_{1/2} = 750(80)$ ns, $E_i = 3349$ keV) in ^{179}W has been determined using the level mixing spectroscopy method. A value $Q_s = 4.00(^{+0.83}_{-1.06})e$ b was derived, which corresponds to an intrinsic quadrupole moment $Q_0 = 4.73(^{+0.98}_{-1.25})e$ b and to a quadrupole deformation $\beta_2 = 0.185(^{+0.038}_{-0.049})$. These values differ significantly from the deduced ground-state quadrupole moments and are in disagreement with the current theoretical predictions in this mass region.

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Several distinct types of isomers are known in atomic nuclei: shape isomers, spin traps, and K isomers [1]. Shape isomers arise when a metastable state decays to a state with a different shape and it is difficult to rearrange the nuclear configuration [2]. Spin traps occur due to the spin selection rules. The decay path to lower energy states requires a large change of the nuclear spin, and therefore the emission of γ rays with a high multipolarity which is strongly hindered [3]. The third type of isomer, known as a "K trap," is caused by the necessity to change the nuclear spin orientation relative to an axis of symmetry. K is a quantum number that represents the projection of the total nuclear spin along the symmetry axis of the nucleus. This type of isomer arises only in axially symmetric, well-deformed prolate nuclei, which means that K is a good quantum number. A number of such states have been established in the Hf-W-Os nuclei in the mass $A \approx 180$ region.

The $Z = 74$ W nuclei are known to exhibit substantial prolate deformations ($\beta_2 \approx 0.25$) in their ground states [4]. These were deduced from Coulomb excitation experiments, in which the reduced transition probabilities (the transition quadrupole moments) of the first excited 2^+ states in even-even $^{180-186}$W isotopes were measured. The present experiments provide for the first time a direct measurement of a static quadrupole moment in the $_{74}$W nuclei.

This paper addresses the following question: Is there a difference between the deformation of the nuclei in their ground states and in their high-seniority multiquasiparticle excitations. The importance of this question is related to the question of the quenching of the pairing correlations in atomic nuclei. The usual approach is by studying the rotational bands, which are built on the K isomer, to deduce the moment of inertia and compare it to that of the ground-state (fully paired) rotational band [5]. Yet, the moment of inertia depends on both the deformation and the pairing, which requires that the deformation be determined experimentally. Prior to our experiments, only the quadrupole moments of the high-K isomers in ^{182}Os ($K^\pi = 25^+$) [6], ^{178}Hf ($K^\pi = 16^+$) [7,8], and ^{177}Lu ($K^\pi = \frac{23}{2}^-$) [9] were known, with deformations which where deduced to be similar to the ground-state values. However, in the case of ^{182}Os, if we use $r_0 = 1.2$ fm to deduce the nuclear radius ($r_0 = 1.1$ fm was used in Ref. [6]), we find a considerable difference between the ground-state and isomeric deformations, which is consistent with recent theoretical calculations [10].

The ^{170}Er(^{13}C$, 4n)^{179}$W reaction at a beam energy of 63 MeV has been used to populate the $K = \frac{35}{2}$ isomer in ^{179}W. A thin self-supporting, 98% enriched, ^{170}Er 500 μg/cm^2 target was used in the experiment. The target thickness was chosen to allow 90% of the ^{179}W nuclei to recoil out of the target. They were in-beam implanted into a thick Tl polycrystalline foil, which served as a level-mixing spectroscopy (LEMS) host and as a beam stopper. The experiments were performed at the CYCLONE cyclotron at Louvain-la-Neuve, using the LEMS technique [11–13]. The experimental setup consists of a split-coil 4.4 T superconducting magnet, a target holder, allowing precise temperature control at the target position in the interval 4–600 K, and 4 Ge detectors, which monitor the target through the holes of the magnet. They are positioned at 0° and 90° with respect to the beam axis [11]. The magnetic field was oriented parallel to the beam axis. Earlier stages of this work were reported in Ref. [14].

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The theory of the LEMS method was described in detail in Refs. [11–13]. It has been shown that the method gives results that are compatible with other techniques and in many cases more appropriate to apply [15,16]. In this Letter we report the first application of this method to study a deformed nucleus. The method can be understood as follows: in a fusion-evaporation reaction, an oriented ensemble of nuclei of interest is produced in their isomeric states. The spins of these nuclei lie in a plain, which is perpendicular to the beam axis. The recoiling nuclei are implanted in a suitable host, where they are submitted to a combined electric quadrupole and magnetic dipole interaction. The anisotropy of the γ radiation is measured as a function of the magnetic field strength. At zero field only the electric quadrupole interaction is present, which is caused by the interaction between the nuclear quadrupole moment and the lattice electric field gradient (EFG). The initial orientation of the nuclear spin ensemble is disturbed because the direction of the EFG is misaligned with respect to the orientation plane. Because of this perturbation, the anisotropy of the emitted γ radiation changes. At high magnetic fields (several tesla), the electric quadrupole interaction becomes negligible compared with the magnetic dipole interaction. The latter causes a Larmor precession of the nuclear spins around the magnetic field vector $\vec{B}$. As the precession axis coincides with the beam axis, this results in preservation of the initial orientation of the nuclear spin ensemble. As a result, the initial anisotropy of the γ radiation is measured. In the intermediate regime, both interactions compete, and a smooth change takes place at a field that depends on the ratio of the quadrupole interaction frequency to the magnetic moment of the isomer. Parallel to our experiments, a TDPAD measurement was performed at the Australian National University (Canberra) in which the magnetic moment of this isomer was derived, yielding a value $\mu = 8.31(8)\mu_N$ [17].

The choice of a suitable host material is crucial for the LEMS experiments, since the measured quadrupole frequency depends on both the nuclear quadrupole moment and the EFG of the material as $\nu_Q = \frac{e}{h} Q_s V_{zz}$. For the LEMS experiments, which are described here, a $_{81}$Tl host was chosen. Tl has a hexagonal structure (hcp) for temperatures below 503 K, and a cubic (bcc) lattice for temperatures above it. The lattice of $_{81}$Tl is close to the ideal crystal and the EFGs of different atoms sitting at substitutional sites are known to be small [18]. It is also well known that, in the hpc phase, the EFG of Tl is strongly temperature dependent and decreases with temperature [19]. Quantitatively, the temperature dependence of noncubic metals follows the $T^{3/2}$ law: $V_{zz}(T) = V_{zz}(0) \cdot (1 - bT^{3/2})$ [20,21]. The LEMS experiment was carried out at $T = 473(1)$ K. The host was heated, which aimed at two goals: to reduce the EFG of W$\underline{Tl}$, and to anneal defects in the Tl host, possibly created during the in-beam implantation. We performed theoretical band-structure calculations based on density-functional theory using the full-potential linearized augmented plane wave (LAPW) method as implemented in the WIEN97 package [22]. In order to test the accuracy of the calculations, the EFG of Tl$\underline{Tl}$ was derived first. An experimental value $V_{zz}(\mathrm{Tl}\underline{Tl}) = 1.7(3) \times 10^{21}$ V/m^2 at 293 K was measured for this system and the EFG was shown to follow the $T^{3/2}$ law [19]. The temperature dependence factor $b = 7.0(11) \times 10^{-5}$ K$^{-3/2}$ was also measured. These yield an extrapolated value $V_{zz}(\mathrm{Tl}\underline{Tl}) = 2.3(4) \times 10^{21}$ V/m^2 at 0 K, which was nicely reproduced by the LAPW calculations. Next, the $_{74}$W impurity in hcp Tl was simulated by a 54 atom ($3 \times 3 \times 3$) supercell approach, allowing full structural relaxation of three shells of neighboring atoms. Spin-orbit interaction was included in the calculation because of the heavy nuclei involved. The EFG was derived from the self-consistent charge density without further approximations [23], and a value of $V_{zz}(\mathrm{W}\underline{Tl}) = 2.54 \times 10^{21}$ V/m^2 at 0 K was obtained. A dedicated experiment was performed to measure the temperature dependence factor b. This study of the EFG of W$\underline{Tl}$ is described in more detail in Ref. [24]. A value of $b = 7.6(^{+0.2}_{-0.4}) \times 10^{-5}$ K$^{-3/2}$ was derived, resulting in a value $V_{zz}(\mathrm{W}\underline{Tl}) = 0.55(^{+0.12}_{-0.08}) \times 10^{21}$ V/m^2 for the EFG at 473 K, accepting the $T^{3/2}$ temperature dependence of the EFG. The large statistical uncertainty on this value is due to the parabolic behavior of the error bar, caused by the $T^{3/2}$ functional dependence. In addition, a theoretical uncertainty of 10% for the LAPW calculation is taken into consideration. This is based on our previous experience [25,26], where the quadrupole moments of ^{57}Fe, ^{77}Se, and ^{100}Rh were determined by using a combination of theoretical EFG calculations and measurements of quadrupole frequencies.

Since a time-integrated curve is measured in a LEMS experiment, single γ-ray spectra were recorded. The ^{179}W $K = \frac{35}{2}$ isomer is a suitable case to study, because about 50% of the γ decay of the high-spin states, which are excited in heavy-ion fusion-evaporation reactions, goes through the isomer which appears to decay predominantly to the $\nu[514]\frac{7}{2}^-$ ground-state band [27]. The prompt background radiation was reduced with the help of the beam-pulsing system which was tuned to provide a beam pulse every 500 ns. A 400 ns time gate was set 100 ns after the beam burst. By accumulating ten spectra per magnetic field, the statistical uncertainties of the intensities of the γ rays of interest could be reduced below 3%. Dead-time corrections were made for the individual detectors. A sample spectrum which displays the delayed γ rays in ^{179}W is shown in Fig. 1.

The LEMS curve, which is presented in Fig. 2, was obtained in this experiment. The anisotropy for the 609, 565, and 358 keV $E2$ transitions, which follow the decay of the $K = \frac{35}{2}$ isomer, was determined at different magnetic fields. The data were analyzed in several ways: by fitting the LEMS curves with and without averaging the data-points obtained in different spectra. All fits converge within the statistical accuracy. A quadrupole frequency $\nu_Q = 53(8)$ MHz was deduced. This value is a

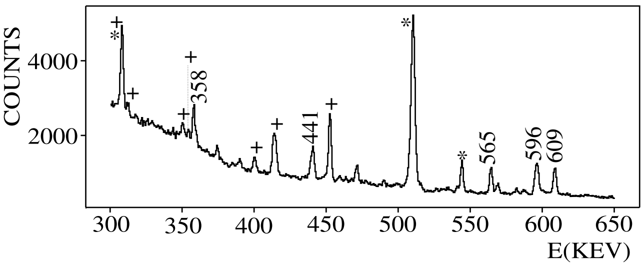

FIG. 1. Spectrum of delayed γ rays as obtained in the ^{170}Er(^{13}C, xn) reaction at 63 MeV. The energies of the $K = \frac{35}{2}$ isomeric decay γ rays are indicated in the figure. Contaminating γ rays, originating either from β decay or from other isomers, are indicated by asterisks or crosses, respectively.

little smaller, but within the error bar of the value published in an earlier status report [14]. It results in a more complete analysis of the experimental data in which the systematic errors which are due to, for example, beam fluctuations were taken into account. The Tl host was heated to a temperature above 503 K during the experiments which allows the full anisotropy of the γ rays to be measured directly. In that case no EFG is present, because the crystal lattice is symmetric and the initial orientation of the nuclear spin ensemble is kept over the full field range. This allows one to conclude that decoupling was reached in the experiment.

Thus, the spectroscopic quadrupole moment of the $K = \frac{35}{2}$ isomer in ^{179}W is found to be $Q_s = 4.00(^{+0.83}_{-1.06})e$ b. Accepting that K is a good quantum number, the measured spectroscopic quadrupole moment is related to the intrinsic quadrupole moment, Q_0, through the relation

$$Q_s = Q_0 \frac{3K^2 - I(I+1)}{(2I+3)(I+1)}. \tag{1}$$

This yields a value $Q_0 = 4.73(^{+0.98}_{-1.25})e$ b, which corresponds to a quadrupole deformation $\beta_2 = 0.185(^{+0.038}_{-0.049})$, taking into account that $Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta_2$, $R = r_0 A^{1/3}$, and $r_0 = 1.2$ fm.

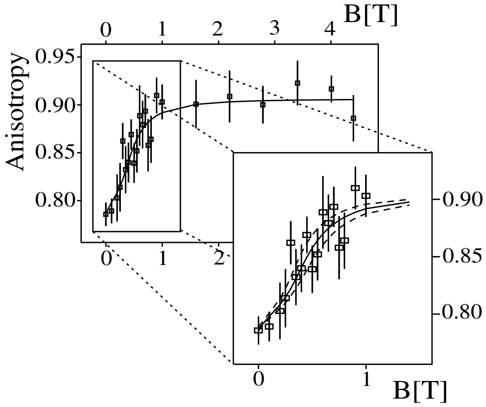

FIG. 2. Sample LEMS curve for the $I = K = \frac{35}{2}$, $E_i = 3349$ keV isomer in ^{179}W, implanted in a Tl polycrystaline foil at a temperature of 473 K. In the intersect the lower magnetic field range is zoomed out. The dashed lines correspond to the upper and lower values for the uncertainties of the quadrupole frequency $\nu_Q = 53(8)$ MHz.

In the upper portion of Fig. 3, the intrinsic quadrupole moment of the $K = \frac{35}{2}$ isomeric state is compared to the ground-state quadrupole moments of the $_{74}$W nuclei, which have been extracted from the reduced transition probabilities [4]. Also the Q_0 values, derived from the measured moments of the $K = 25$ isomer in ^{182}Os and the $K = 16$ isomer in ^{178}Hf, are added to the figure, as well as the ground-state moments for the $_{72}$Hf and $_{76}$Os nuclei. Note that in the case of ^{178}Hf (as well as for ^{177}Lu [9]) the measured ground-state and the isomer quadrupole moments take similar values, while in the case of ^{179}W and ^{182}Os they differ considerably. In addition, an independent value can be obtained for ^{179m}W by using the existing spectroscopic data for the rotational

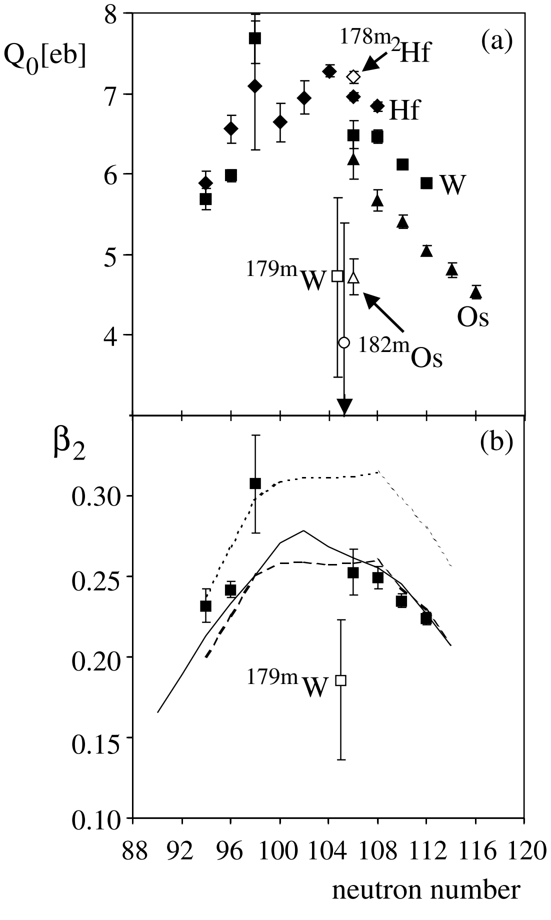

FIG. 3. (a) Systematics of the ground-state quadrupole moments for the $_{72}$Hf (filled diamonds), $_{74}$W (filled squares), and $_{76}$Os (filled triangles) nuclei [4], compared to the intrinsic quadrupole moments of the high-K isomers in ^{179}W (open square for this paper and open circle for Ref. [27]), ^{178}Hf (open diamond) [7], and ^{182}Os (open triangle) [6]. (b) The deduced quadrupole deformations of the $K = \frac{35}{2}$ isomer in ^{179}W (open square) is compared to the systematics of the ground-state deformations for the $_{74}$W nuclei [4], as well as with the hydrodynamic model of Bohr-Mottelson (dotted line) [30], the relation of Grodzins (dashed line) [31], and the calculated ground-state deformations (solid line) [32].

band which is built on top of the $K = \frac{35}{2}$ isomer. From the measured branching ratio of the cascade-to-crossover transitions in this band, $\lambda = 0.26(9)$, a value for $|(g_K - g_R)/Q_0| = 0.045(11)e\mathrm{b}^{-1}$ was derived [27]. Assuming that $g_R = 0.30(5)$, consistent with the systematics of the region [28], and taking into consideration the measured magnetic moment of $\mu = 8.31(8)\mu_N$ for this state [17], a value $Q_0 = 3.9(1.5)e$ b was found. These results demonstrate that the measured values for the quadrupole moments of the high-K isomers in ^{179}W and ^{182}Os do not fit the systematic trends, which were observed for the ground-state moments in the region [4].

In the lower part of Fig. 3 the systematic theoretical predictions for the ground-state deformations of the $_{74}$W nuclei [29] are compared to the values obtained from $B(E2)$ measurements, and to the deduced deformation of the $K = \frac{35}{2}$ isomer in ^{179}W. Hartree-Fock-Bogolyubov calculations within the framework of the tilted axis cranking (TAC) theory [33] permit us to take into account possible consequences of the mixing between bands with different K values. Such effects were found to be small. TAC yields a value for the quadrupole moment of this isomer $Q_s = 5.73e$ b if pairing is treated with the particle number projection (PNP) technique [34] and $Q_s = 5.84e$ b without it (the neutron pairing is zero in this case). These values of the quadrupole moment correspond to an axially symmetric nucleus with deformations $\epsilon_2 = 0.228$ and $\epsilon_4 = 0.038$, which coincide with the calculated ground-state deformations for ^{179}W: $\epsilon_2 = 0.226$ and $\epsilon_4 = 0.039$ and contradict the measured quadrupole moment for the isomer. Independent calculations of the total Routhian surfaces [10] also give very similar deformations for the ground state and high-K bands. The experimental values, which are reported here, are about 2σ off the theoretical estimates. In the case of the six-quasiparticle isomer in ^{182}Os the low value of the spectroscopic quadrupole moment could be understood as being due to triaxiality of the nuclear mean field [10], while in the case of the $\frac{35}{2}$ five-quasiparticle isomer in ^{179}W a consistent explanation is still missing. A possible explanation might be related to the fact that, in order to create a high-seniority state, a few particles need to be excited to high-Ω orbits, which are localized close to the equatorial plane of the nucleus. This changes the nuclear mass distribution and influences the symmetries of the mean field. A configuration dependence in this case cannot be excluded. Similar effects have been discussed for the nuclei in the Mg region [35].

In conclusion, we have measured the quadrupole moment of the $K = \frac{35}{2}$, $E_i = 3349$ keV isomer in ^{179}W. The deduced deformation of this state is smaller compared to the systematic trend of the ground-state deformations of the nuclei in the region, and smaller than the theoretically predicted values. Further improvement of the experimental accuracy is probably needed. At the same time the exploration of other theoretical aspects is necessary, since it seems impossible to explain these differences within the well-established schemes to calculate nuclear deformations in this mass region.

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