QUADRUPOLE MOMENTS OF HIGH-SPIN ISOMERS: TEST OF THE TILTED-AXIS CRANKING MODEL*

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We report the results of recent measurements of the spectroscopic quadrupole moments of high-spin isomers. For the $K^{\pi} = \frac{35}{2}^{-}$ five-quasiparticle isomer in ^{179}W we measured $Q_s = 4.00(^{+0.83}_{-1.06})$ eb. It corresponds to a smaller deformation compared to the ground states of the W isotopes and is in disagreement with the current theoretical predictions. We also measured the quadrupole moment of the $I^{\pi} = 11^{-}$ isomer in ^{196}Pb, $Q_s = (-)3.41(66)$ eb. It has the same proton $(s_{1/2}^{-2} h_{9/2} i_{13/2})$ configuration as the one suggested for the $I^{\pi} = 16^{(-)}$ magnetic bandhead which allows to deduce the quadrupole moment of the 16^{-} state as $Q_s = -0.316(97)$ eb. This small value proves the near sphericity of the bandhead.

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1. Introduction

Several measurements of spectroscopic quadrupole moments of high-spin isomers were performed at the CYCLONE facility at Louvaine-la-Neuve, using the LEvel Mixing Spectroscopy technique (LEMS) [1].

We measured the quadrupole moment of the five-quasiparticle isomer in ^{179}W, addressing the question: is the nuclear deformation of the ground state and of the high-seniority multiquasiparticle excitations the same?

Next, we studied the isomers in $N = 82$ nucleus ^{196}Pb, for which several bands with enhanced M1 transitions have been established [2]. They are built on states which result from the coupling of high-spin particle to high-spin hole excitations. In the Pb nuclei, high-spin particle states are formed by proton excitations into the $\pi h_{9/2}$ and $\pi i_{13/2}$ orbitals and the high-spin hole states result from neutron excitations in the $\nu i_{13/2}$ shell. The specific coupling of the spin vectors of these two excitations causes a magnetic dipole moment with a large component perpendicular to the total spin. Its rotation around the spin axis gives rise to enhanced M1 radiation. Our study addresses the question: what is the deformation of the magnetic bandhead?

These experiments are related to the tilted-axis cranking (TAC) model, since both excitations, the high-K states and the magnetic rotation are described within this approach [3, 4]. In the former case the quenching of pairing is studied. The usual approach is to deduce the moments of inertia of the bands built on the high-K states and compare them 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 is determined experimentally. In the case of magnetic rotation, the measured weak B(E2) transition probabilities are an indication for small deformation [6]. However, the measurement of the spectroscopic quadrupole moment will provide the stringent test.

2. Experimental details

The LEMS set-up consists of a split-coil 4.4 T superconducting magnet, a target holder, allowing precise temperature control in the interval 4–600 K, and 4 Ge detectors, positioned at 0° and 90°, which monitor the target through the holes of the magnet. The magnetic field is oriented along the beam axis. The anisotropy of the γ-radiation is measured as a function of the external magnetic field. At small magnetic fields the initial anisotropy is perturbed due to the interaction of the quadrupole moment of the isomer of interest, Q_s, with the Electric-Field Gradient (EFG) of the LEMS host, V_{zz}. It is restored at high fields. The transition between the two regimes depends on the ratio of the quadrupole frequency $\nu_Q = \frac{e}{h} Q_s V_{zz}$ and the magnetic moment of the isomer [1].

2.1. The case of ^{179}*W*

The ^{170}Er(^{13}C,4n) reaction at 63 MeV was used to populate high-spin states in ^{179}W. The target was 500 μg/cm^2 self-supporting, enriched ^{170}Er, which allowed an in-beam implantation of the ^{179}W recoils into a Tl foil at T = 473(1) K, serving as a LEMS host. The obtained LEMS curve is presented in Fig. 1. A quadrupole frequency ν_Q = 53(8) MHz was deduced. A more complete report of this experiment was published elsewhere [7].

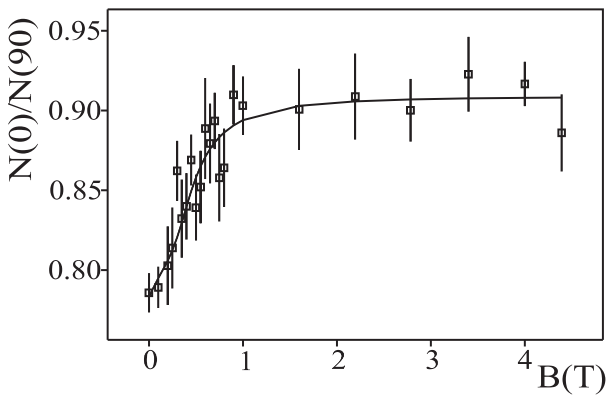

Fig. 1. LEMS curve for the $I = K = \frac{35}{2}^-$ isomer in ^{179}W. The recoiling nuclei were implanted into a Tl polycrystalline foil at a temperature of 473(1) K.

In order to determine the EFG of W<u>Tl</u> we performed band-structure calculations based on density functional theory using the full-potential Linearized Augmented Plane Wave (LAPW) method as implemented in the WIEN97 package [8]. A value of V_{zz}(W<u>Tl</u>) = 2.54 × 10^{21} V/m^2 at 0 K was obtained. The EFGs in Tl decrease strongly with temperature. The temperature dependence of the EFGs in non-cubic metals follows the $T^{3/2}$ law: $V_{zz}(T) = V_{zz}(0) \times [1 - bT^{3/2}]$ [9]. In a dedicated experiment the temperature dependence factor $b = 7.6(^{+0.2}_{-0.4}) \times 10^{-5}$ K$^{-3/2}$ was derived, resulting in a value V_{zz}(W<u>Tl</u>) $= 0.55(^{+0.12}_{-0.08}) \times 10^{21}$ V/m^2 at 473 K [10]. Thus, the spectroscopic quadrupole moment of the $K^\pi = \frac{35}{2}^-$ isomer in ^{179}W is found to be $Q_s = 4.00(^{+0.83}_{-1.06})$ eb. This value is smaller than the ground state quadrupole moments of the Z=74 nuclei, which were derived from the reduced transition probabilities [11], and is about 2σ off the current theoretical estimates.

A critical reader might question the reliability of this result, as it relies on a calculated EFG for W<u>Tl</u>, as well as on the assumption for a $T^{3/2}$ temperature dependence of V_{zz}. However, in a parallel experiment Ionescu–Bujor *et al.* measured the quadrupole moment of the $K^\pi = 14^+$ isomer in ^{176}W [12]. The experiment was performed under similar conditions as our measurement (in-beam implantation of W in Tl at 464 K) and yields a quadrupole frequency $\nu_Q = 92(10)$ MHz for the isomer. This frequency corresponds to a ratio of the quadrupole moments of the two isomers:

$$\frac{Q_s(^{176}\mathrm{W})}{Q_s(^{179}\mathrm{W})} = 1.6 \pm 0.3\,, \tag{1}$$

and to value for the quadrupole moment of the 14^+ isomer, which is close to the ground-state values. This is in disagreement with the current theoretical predictions and leads to the logical question: do we understand the deformations of the high-K excitations?

2.2. The case of ^{196}Pb

High-spin isomers in ^{196}Pb (as well as in ^{194}Pb) have been populated in the $^{\mathrm{nat}}$Re(^{14}N,5n) reaction. The 50 μm $^{\mathrm{nat}}$Re foil served as a target and a LEMS host. Quadrupole frequencies of $\nu_Q = 38(3)$ MHz and $\nu_Q = 199(32)$ MHz were measured for the $I^\pi = 12^+$ and the $I^\pi = 11^-$ isomers, respectively. This study is discussed in more detail elsewhere [10]. The LEMS curve for the $I^\pi = 11^-$ isomer is displayed in Fig. 2. The quadrupole moment of the 12^+ isomer is known, $Q_s = 0.65(5)$ eb [13]. Also the magnetic moments of both isomers are known [13, 14]. This provides the possibility for an internal calibration and allows us to deduce the quadrupole moment of the 11^- isomer from the ratio of the measured frequencies:

$$Q_s(11^-) = \frac{\nu_Q(11^-)}{\nu_Q(12^+)}\, Q_s(12^+) = (-)3.41 \pm 0.66\,\mathrm{eb}\,. \tag{2}$$

The negative sign comes from systematics. The quoted uncertainty includes the uncertainties of the magnetic moments as well. Assuming an axial symmetry for this state ($K = I = 11$), the quadrupole deformation is $\beta = (-)0.16(3)$, which is in a perfect agreement with the theory [15].

The $I^\pi = 11^-$ and the $I^\pi = 12^+$ isomers have the $\pi(s^{-2}_{1/2}h_{9/2}i_{13/2})$ and the $\nu(i^{-2}_{13/2})$ configurations, respectively, and the $\pi(s^{-2}_{1/2}h_{9/2}i_{13/2})_{11^-} \otimes \nu(i^{-2}_{13/2})_{12^+}$ $2p$–$2h$ configuration is suggested for the $I^\pi = 16^{(-)}$ magnetic bandhead [2]. It is possible to derive the quadrupole moment of this state, $Q_s(16^-) = -0.32(10)$ eb, using the additivity of the quadrupole operator, $Q^0_2 = Q^0_2(\pi) + Q^0_2(\nu)$:

$$Q_s(16^-) = \langle 16, 16|Q^0_2(\pi) + Q^0_2(\nu)|16, 16\rangle\,. \tag{3}$$

This value proves the small deformation of the $16^{(-)}$ state, which supports the concept of magnetic rotation.

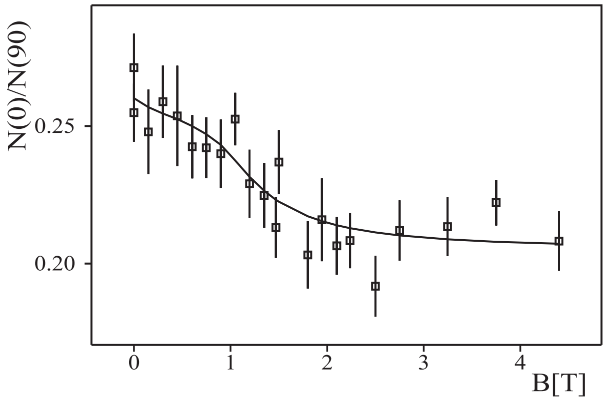

Fig. 2. LEMS curve for the $I^\pi = 11^-$ isomer in ^{196}Pb. The recoiling nuclei were implanted into a Re polycrystalline foil at room temperature.

3. Conclusions

We have measured the spectroscopic quadrupole moments of high-spin isomers in ^{179}W and ^{196}Pb using the LEMS technique. These experiments were performed to test the predictions of the TAC model [3,4]. We find that the deformation of the $K = \frac{35}{2}$ isomer in ^{179}W is smaller than the ground-state deformation, which questions the current understanding of these excitations. For the $I^\pi = 16^{(-)}$ magnetic bandhead in ^{196}Pb we derive a small quadrupole moment, which is in agreement with the concept of magnetic rotation.

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