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Quadrupole moment of the $K^\pi = 14^+$ isomer in ^{176}W

M. Ionescu-Bujor [a], A. Iordachescu [a], F. Brandolini [b], M. De Poli [c], N. Mărginean [a,c], D. Bucurescu [a], S.M. Lenzi [b], N.H. Medina [d], D.R. Napoli [c], Zs. Podolyak [e], P. Pavan [b], R.V. Ribas [d], C. Rossi Alvarez [b], C.A. Ur [a,b]

[a] *National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
[b] *Dipartimento di Fisica dell' Universitá and INFN, Sezione di Padova, Padova, Italy*
[c] *INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy*
[d] *Instituto de Fisica, Universidade de São Paulo, São Paulo, Brazil*
[e] *Department of Physics, University of Surrey, Guildford, UK*

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Abstract

The spectroscopic quadrupole moment of the $I^\pi = K^\pi = 14^+$, $T_{1/2} = 41$ ns isomer in ^{176}W has been measured by observing the time-dependent quadrupole interaction pattern of the decay radiation from the isomer implanted in the polycrystalline metallic Tl host. The result $|Q_s| = 5.99(^{+0.66}_{-0.82})$ eb corresponds to an intrinsic quadrupole moment $Q_0 = 7.37(^{+0.81}_{-1.01})$ eb, similar to the ground-state band quadrupole moment. The value $g_R = 0.269(34)$ has been deduced for the rotational g factor of the 14^+ isomer on the basis of the measured static moments and branching ratios in the associated band. © 2002 Elsevier Science B.V. All rights reserved.

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The structure of high-K states is a subject that has found renewed interest in recent years. High-K multi-quasiparticle configurations abound in the $A \approx 180$ region, where deformed nuclei with axial symmetry have valence nucleons in Nilsson orbitals with large angular momentum projections on the symmetry axis. Due to the approximate conservation of the K quantum number, these states are often isomeric as their decays to states with lower K values are hindered. Much efforts have been paid to understand the K-forbidden transition probabilities, particularly the anomalously low hindrances observed in several cases [1]. High-K multi-quasiparticle states are also sensitive probes of pairing correlations. With increased seniority the nuclear pairing force becomes quenched, what could affect important physical quantities as the excitation energy, the moment of inertia and the collective gyromagnetic ratio [2–5].

The knowledge of the nuclear shape is essential for characterizing the high-K states. Usually it was assumed that the multi-quasiparticle states have the

E-mail address: bujor@ifin.nipne.ro (M. Ionescu-Bujor).

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same deformation as the ground state, however shape polarization effects due to particular orbitals could be present. The quadrupole moment is an observable quantity that can directly determine the nuclear deformation. To date static quadrupole moments have been measured only for few high-K isomeric states in the $A \approx 180$ region: 25^+ in ^{182}Os [6], 16^+ in ^{178}Hf [7], $\frac{23}{2}^-$ in ^{177}Lu [8], $\frac{21}{2}^-$ in ^{173}Ta [9] and $\frac{35}{2}^-$ in ^{179}W [10]. The comparison of the determined quadrupole moments with the ground-state moments shows rather different behaviours indicating that in some cases shape changes could be induced by the multi-quasiparticle orbitals. The most surprising result has been recently reported for the $\frac{35}{2}^-$ state in ^{179}W investigated in a perturbed angular distribution experiment using the polycrystalline metallic Tl as lattice host [10]. In that study an isomeric state quadrupole moment much lower compared to the ground state moment has been determined, in disagreement with the current theoretical predictions.

In the present Letter we report the measurement of the quadrupole moment for the $K^\pi = 14^+$ 3746 keV isomeric state in ^{176}W. To investigate the quadrupole interaction we have chosen the same lattice host as used in the study of the $\frac{35}{2}^-$ state in ^{179}W [10], aiming to obtain a direct comparison of the high-K isomer quadrupole moments, independent of the internal field calibration. The 14^+ isomer in ^{176}W is an interesting high-K isomer whose decay highly violates the normal K-selection rules, as it mostly proceeds directly to $K = 0$ states bypassing available levels of intermediate K [11,12]. In a previous paper [13] we reported a measurement of the g factor for this isomer. On the basis of the obtained value, $g(14^+, {}^{176}\mathrm{W}) = +0.475(15)$, a pure four-quasiparticle configuration, composed by two protons in the $\frac{7}{2}^+[404]$ and $\frac{9}{2}^-[514]$ orbitals and two neutrons in the $\frac{7}{2}^+[633]$ and $\frac{5}{2}^-[512]$ orbitals was assign to this isomer. The main aim of the present study was to determine the shape of this four-quasiparticle state. Another purpose of the work was to look for possible effects of the pairing quenching on the collective g_R factor of the multi-quasiparticle configuration. The 14^+ isomer is the bandhead of a $\Delta I = 1$ band for which the $B(M1)/B(E2)$ ratios have been determined experimentally in Ref. [12]. On the basis of the derived $|g_K - g_R|/Q_0$ value and the measured static electromagnetic moments a reliable g_R value could be deduced. A partial level scheme of ^{176}W showing the decay of the isomer and the $\Delta I = 1$ band developed on it, is presented in Fig. 1.

The quadrupole interaction (QI) of the 14^+ isomeric state with $T_{1/2} = 41$ ns [13] has been investigated in the electric field gradient (EFG) of the polycrystalline lattice of metallic Tl by applying the time-differential perturbed angular distribution (TDPAD) method. The experiment was carried out, as in Ref. [13], at the XTU-Tandem at Laboratori Nazionali di Legnaro. The isomeric state was populated in the ^{164}Dy(^{16}O, 4n)^{176}W reaction using an 83 MeV ^{16}O pulsed beam. The ^{16}O beam has been pulsed with a pulse width of 1.5 ns, a repetition period of 800 ns and a suppression of the continuous beam in-between the beam bursts of $\approx 10^4$. The target consisted of 0.5 mg/cm^2 metallic ^{164}Dy (enriched to 95.6%) on a backing consisting of an evaporated layer of Tl of 10 mg/cm^2 in which the recoiling W nuclei were stopped, followed by a layer of 50 mg/cm^2 Pb that stopped the ^{16}O projectiles and prevented Tl oxidation. The target has been mounted in a special oven which could be electrically heated and allowed the control of the temperature. Two independent measurements, at $T = 404(3)$ K and $T = 464(3)$ K, have been carried out. The γ-rays were detected by Ge detectors of 25% efficiency placed at the angles 0° and 90° with respect to the beam direction.

In off-line analysis of the list-mode stored data, time-gated energy spectra and energy-gated time spectra were created for each detector. An illustrative delayed γ spectrum registered in the time interval 30–110 ns after the beam burst is compared in Fig. 2 with the total γ spectrum. From these spectra one can observe that the 14^+ isomeric state was very weakly populated. An isomer intensity that represents about 2.7% of the ^{176}W reaction channel has been deduced, similar to the isomer yield reported in the spectroscopic study of [12] performed with the ^{150}Nd(^{30}Si, 4n) reaction. In the TDPAD experiments it is convenient to analyze transitions which depopulate the isomeric state, as they have no prompt components in their time spectra. In the present case however the isomeric decay is fragmented over many weak branches (see Figs. 1 and 2), therefore in the analysis we have used the intense 240, 351, 440, and 558 keV delayed γ-rays depopulating the yrast states which are collecting all the isomer intensity. A resolution of about 11 ns has

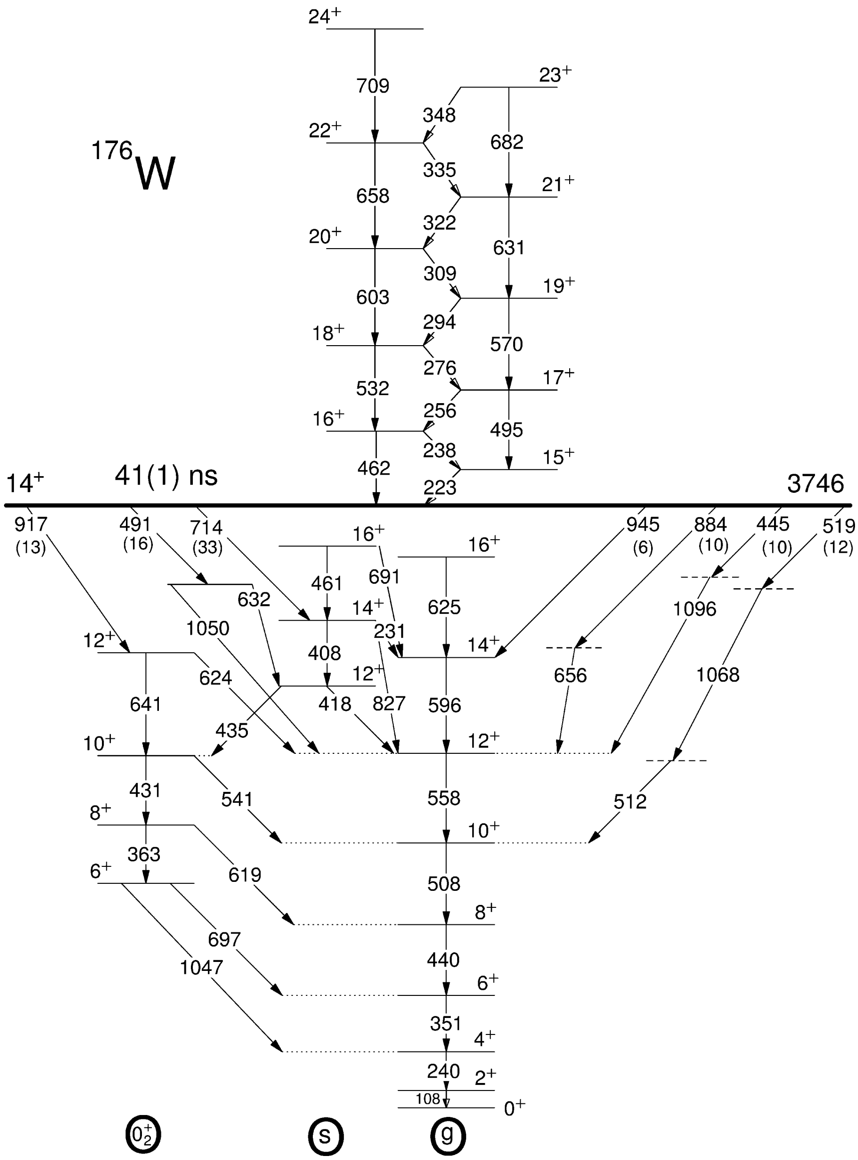

Fig. 1. Partial level scheme of ^{176}W [11,12] showing the decay of the 14^+ isomer, as well as the strongly-coupled band developed on it.

been obtained in the time spectra corresponding to the γ-rays of interest. The summed time spectra for the 240, 351, 440 and 558 keV γ-rays, after background subtraction and proper normalization, were used to construct the experimental ratios $R_{\text{exp}}(t) = [I(t, 0°) - I(t, 90°)]/[I(t, 0°) + I(t, 90°)]$, which were least-squares fitted to the expression:

$$R_{\text{theo}}(t) = \frac{3}{4} A_2 \sum s_{2n} \cos(n\omega_0 t) \quad (1)$$

with the angular distribution coefficient A_2 and the QI frequency ω_0 as free parameters. The quadrupole frequency decreases quadratically with the spin I and, for an integer spin, is given by $\omega_0 = 3\pi\nu_Q/2I(2I-1)$, where $\nu_Q = Q_s V_{zz}/h$ is the quadrupole coupling constant depending on the spectroscopic quadrupole moment Q_s and the EFG strength V_{zz}. The spin-dependent s_{2n} coefficients in the theoretical expression (1) were calculated according to the formulas

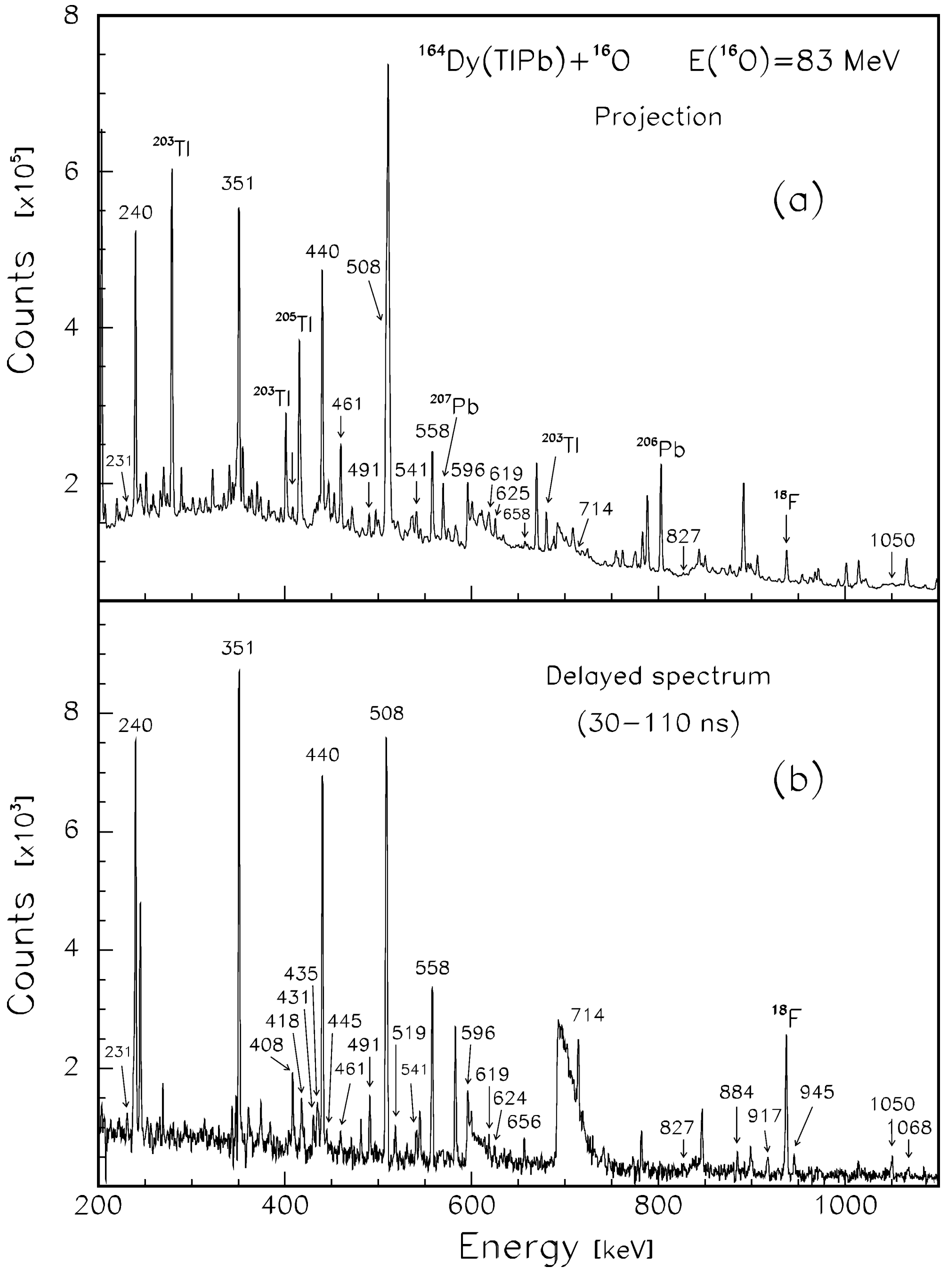

Fig. 2. Total (a) and delayed (b) energy spectra. The γ lines belonging to the decay of the 14^+ isomer in ^{176}W are labelled by energy. The background due to long-lived activities has been subtracted from the delayed spectrum.

in Ref. [14] for an axially symmetric randomly oriented EFG. Due to the high spin value and short lifetime of the isomer, it was not possible to evidence the full quadrupole period $T_0 = 2\pi/\omega_0$ and only the structure at the beginning of the modulation pattern could be observed. The considered γ transitions have intense prompt component in their time spectra and therefore the analysis could be started only at about

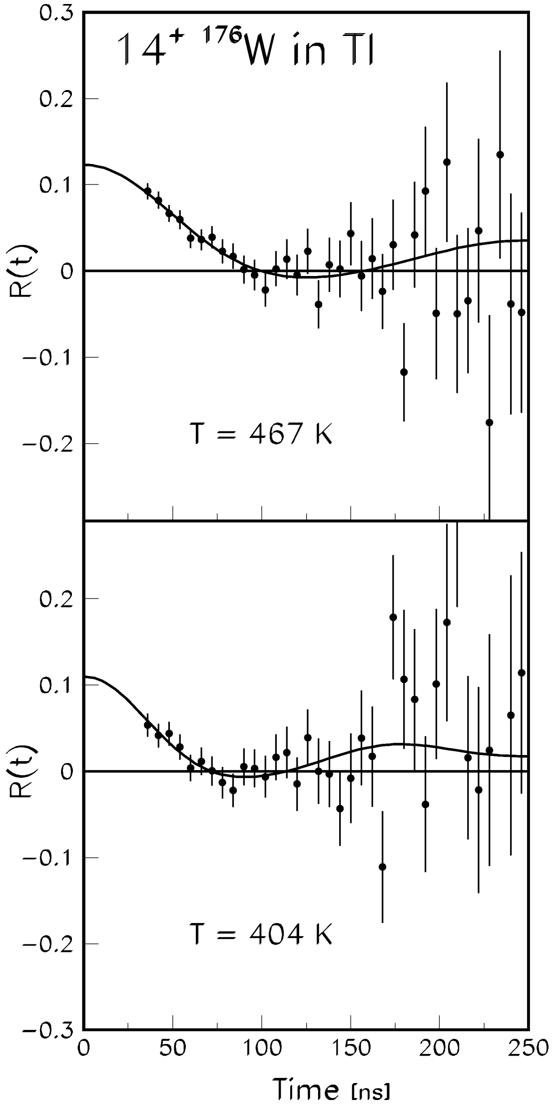

Fig. 3. Experimental quadrupole interaction spectra for the 41 ns 14^+ isomer in ^{176}W implanted in polycrystalline Tl host and the corresponding least-squares fits. The summed time spectra for the 240, 351, 440 and 558 keV γ rays have been used.

35 ns after the isomer population. The experimental modulation ratios obtained in the two QI measurements are illustrated in Fig. 3 together with the theoretical least-squares fits. The observed patterns indicate quite a strong QI temperature dependence, in accordance with the reported EFG temperature dependence for W in Tl (see below). The least-squares analysis of the ratios $R_{\mathrm{exp}}(t)$ led to electric quadrupole coupling constant values of 127(17) MHz and 94(7) MHz for the target temperatures of 404 K and 467 K, respectively.

The metallic Tl host has been recently used to investigate the spectroscopic quadrupole moment of the $\frac{35}{2}^-$ isomer in ^{179}W [10]. In that work a calibration of the EFG strength for the system WTl has been provided based on a calculated value $V_{zz}(\mathrm{WTl}) = 2.54(25) \times 10^{21}$ V/m^2 at $T = 0$ K and an experimentally determined value of $7.6(^{+0.2}_{-0.4}) \times 10^{-5}$ K$^{-3/2}$ for the parameter b of the $T^{3/2}$ temperature dependence law: $V_{zz}(T) = V_{zz}(0)\ (1 - bT^{3/2})$. With this calibration the EFG strengths were derived as $V_{zz}(\mathrm{WTl}) = 0.97(^{+0.13}_{-0.11}) \times 10^{21}$ V/m^2 at $T = 404(3)$ K and $V_{zz}(\mathrm{WTl}) = 0.59(^{+0.12}_{-0.08}) \times 10^{21}$ V/m^2 at $T = 467(3)$ K. Using these values and the measured coupling constants the weighted average value $|Q_s| = 5.99(^{+0.66}_{-0.82}))$ eb has been derived for the spectroscopic quadrupole moment. Assuming that K is a good quantum number, the spectroscopic quadrupole moment is related to the intrinsic quadrupole moment Q_0 through the relation

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

With this relation a value $Q_0 = 7.37(^{+0.81}_{-1.01})$ eb is obtained for the intrinsic quadrupole moment of the $\mathrm{K}^\pi = 14^+$ isomeric state. Note that this is the first quadrupole moment determined in the nucleus ^{176}W. By using the expression: $Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta_2$, with $R = r_0 A^{1/3}$ and $r_0 = 1.2$ fm, a quadrupole deformation $\beta_2 = 0.29(4)$ has been deduced for the 14^+ state.

Available data on intrinsic quadrupole moments for high-K isomers of seniority $\geqslant 3$, derived from spectroscopic quadrupole moments obtained in recent collinear fast beam laser spectroscopy (CFBLS), level mixing spectroscopy (LEMS) and TDPAD experiments, are collected in Table 1. In the same table are given for comparison the corresponding values $Q_0(gs)$ for the ground state bands, obtained from reduced transition probabilities of the first excited 2^+ states [15] and/or from measured spectroscopic quadrupole moments [16]. No direct information concerning $Q_0(gs)$ is available in ^{176,179}W. The existing data in the W isotopic chain, derived from reduced transition probabilities in $^{168\text{–}174}$W and $^{180\text{–}186}$W [15] indicate a smooth dependence on the neutron number

Table 1
Intrinsic quadrupole moments for high-K isomers of seniority $\geqslant 3$ compared to the values of the corresponding ground state quadrupole moments

Nucleus	I^π	$T_{1/2}$	Method	Q_0 (eb)	Q_0(gs)	
					from $B(E2)$ (eb) [15]	from Q_s (eb) [16]
$^{177}_{71}$Lu	$\frac{23}{2}^-$	160.5 d	CFBLS	7.33(6) [8]		7.26(6) [8]
$^{178}_{72}$Hf	16^+	31 yr	CFBLS	7.2(1) [7]	6.96(4)	7.07(7)
$^{173}_{73}$Ta	$\frac{21}{2}^-$	200 ns	TDPAD	8.30(12) [9]		6.67(70)
$^{176}_{74}$W	14^+	41 ns	TDPAD	$7.37(^{+0.81}_{-1.01})^{a}$	$6.6(2)^{b}$	$7.5(15)^{c}$
$^{179}_{74}$W	$\frac{35}{2}^-$	750 ns	LEMS	$4.73(^{+0.98}_{-1.25})$ [10]	$6.6(2)^{b}$	$7.5(15)^{c}$
$^{182}_{76}$Os	25^+	150 ns	TDPAD	4.7(2) [6]	6.19(26)	

[a] Present value.
[b] Interpolated value (see text).
[c] Extrapolated value (see text).

and allow to derive for ^{176}W and ^{179}W an interpolated value of $Q_0(gs) = 6.6(2)$ eb corresponding to a deformation $\beta_2 = 0.26(1)$. A somewhat higher value of $Q_0(gs) = 7.5(15)$ eb ($\beta_2 = 0.30(6)$) is obtained by extrapolating the values of the intrinsic quadrupole moments derived from measured spectroscopic quadrupole moments of 2^+ states in $^{180–186}$W [16]. The quadrupole deformation of the high-K isomer in ^{176}W, determined in the present work, is within errors similar to that of the ground state band. This is at difference to the behavior observed in ^{179}W where the quadrupole moment of the $\frac{35}{2}^-$ isomer was reported to be much smaller than the ground state quadrupole moment (Ref. [10] and Table 1). We note that, as the QI of the isomeric states in ^{176,179}W has been investigated in the same host, the ratio of their quadrupole moments is independent of the EFG calibration. Different shape behaviours are also evidenced for other known multi-quasiparticle states (see Table 1). The intrinsic quadrupole moments for the high-K isomers in ^{177}Lu and ^{178}Hf are practically identical with the corresponding $Q_0(gs)$. The high-K isomer in ^{173}Ta has a higher deformation compared to the ground-state, while Q_0 for the 25^+ isomer in ^{182}Os is about 25% smaller than $Q_0(gs)$.

Realistic treatments of the multi-quasiparticle states were recently achieved by the diabatic blocking method, using a non-axial deformed Woods–Saxon potential and Lipkin–Nogami pairing [17]. Detailed configuration-constrained calculations of this type were performed for several nuclei in the region, such as ^{182}Os [17], ^{178}W [17,18], ^{182,186}Hf [19] and ^{183}Re [20]. In these calculations configuration dependent effects on the deformation parameters β_2, β_4 and γ, as well on the γ-softness, have been predicted. The reduced value of the quadrupole moment for the 25^+ isomer in ^{182}Os compared to the ground state value was remarquable well explained as being due to triaxiality [17]. Such calculations are presently missing for ^{176}W. In the neighbouring ^{178}W nucleus axially symmetric shapes with $\gamma \approx 0°$ have been predicted for all states, and the calculated intrinsic quadrupole moments were found to increase from $Q_0(gs) = 7.1$ eb to a maximum of $Q_0(25^+) = 8.0$ eb and then to decrease at $Q_0(34^+) = 6.2$ eb [17,18]. These shape changes are due to the presence of specific deformation driving orbitals. For a 15^+ state in ^{178}W with the configuration $\pi\frac{7}{2}^+[404]\frac{9}{2}^-[514] \otimes \nu\frac{7}{2}^+[633]\frac{7}{2}^-[514]$ which is similar to that of the 14^+ state in ^{176}W, a value of $Q_0(15^+) = 7.5$ eb was calculated. It agrees very well with the present experimental intrinsic quadrupole moment value, what gives support for the description of the 14^+ isomer as an axially symmetric deformed state with well defined K.

It is worthwhile at this point to make some comments concerning the anomalous decay of the $K^\pi = 14^+$ isomer in ^{176}W. Usually the decay of high-spin isomers in the $A \approx 180$ region proceeds via hindered transitions of multipolarity $\lambda < \Delta K$, and the probabilities of such transitions are correlated with the degree of forbiddenness $\nu = \Delta K - \lambda$. The reduced hindrance factor f_ν, which is defined as $f_\nu = (T^\gamma_{1/2}/T^{\mathrm{W}}_{1/2})^{1/\nu}$, where $T^{\gamma}_{1/2}$ and $T^{W}_{1/2}$ are the partial γ-ray half-life and the corresponding Weisskopf single-particle estimate, has usually values of ≈ 100, however in few nuclei transitions with $f_\nu \ll 100$ have been observed. The 14^+ isomer in ^{176}W is such a case, with transitions of 945, 714 and 917 keV (see Fig. 1) involving large ΔK and very low f_ν values of 3.6, 3.0 and 2.3, respectively [12]. It was recently proposed that the K-forbidden transition probabilities are related to γ-softness, as the f_ν values were found to be correlated with the energies of the γ-vibrational bands [1]. Small reduced hindrance factors $f_\nu < 5$ were observed in nuclei with low energies of 900–1000 keV for γ bands, while in nuclei with energy of γ bands higher than 1100 keV values $f_\nu > 10$ were found. A rather low value of 1042 keV has been very recently determined for the energy of the γ-vibrational band in ^{176}W [21], what indicates, within the systematics discussed in [1], that γ-softness would be partly responsible for the observed small reduced hindrances in this nucleus. This is in accordance with results of γ-tunneling calculations [12,22].

The rotational g_R factor of a multi-quasiparticle configuration is expected to be affected by the changes in pairing due to the blocking of orbitals near the Fermi surface, since it depends on the partition of moments-of-inertia between protons and neutrons. This quantity could be derived if the static moments for the high-K isomeric state and the branching ratios in its associated band are known. Based on the measured $B(M1)/B(E2)$ ratios [12] the weighted average value $(g_K - g_R)/Q_0 = 0.030(2)$ has been deduced for the 14^+ isomeric state in Ref. [13] by using the rotational model formulae. With the experimental values of g [13] and Q_0 (present study), g_R could be calculated from the relationship $g = g_R + (g_K - g_R)K^2/I(I+1)$ as $g_R(14^+, {}^{176}\mathrm{W}) = 0.269(34)$. This value is similar to the collective g-factor $g(2^+)$ in even–even W nuclei [16]. We note that a significant smaller value of the rotational g factor, $g_R(\frac{21}{2}^-) = 0.112(20)$, has been recently derived by the same procedure for the three-quasineutron $K^\pi = \frac{21}{2}^-$ state in ^{179}W [4]. This change of the g_R was explained by the neutron pairing reduction due to neutron blocking, which produces an increase of the neutron moment of inertia and correspondingly a reduction of the proportion on motion attributable to protons. In the presently investigated two-quasiproton–two-quasineutron configuration, the effects of the proton and neutron pairing reduction appear to compensate each other and therefore the $g_R(14^+)$ is very close to the rotational value $g(2^+)$.

In summary, the spectroscopic quadrupole moment of the $K^\pi = 14^+$ 3746 keV isomer in ^{176}W has been measured by TDPAD method. The deduced deformation of this state is similar within errors to the value for the ground state deformation in ^{176}W assigned on the basis of the systematics in the W isotopes. The measured static moments (Ref. [13] and present work) support the description of the 14^+ state by a deformed pure four-quasiparticle configuration with well defined K. The anomalous small hindrances observed in the decay of the isomer could be attributable to γ-softness. Detailed configuration-constrained calculations in ^{176}W would be necessary in order to describe the experimental observed properties of the high-K isomer.

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