g factors of the $^{7+}_2$ and $^{14+}$ isomers in $^{175,176}$W

M. Ionescu-Bujor$^{a,*}$, A. Iordachescu$^a$, F. Brandolini$^b$, M. De Poli$^c$, N. Mărginean$^{a,c}$, N.H. Medina$^d$, Zs. Podolyak$^e$, P. Pavan$^b$, R.V. Ribas$^d$, S.M. Lenzi$^b$, A. Gadea$^c$, T. Martinez$^c$

$^a$ 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 Física, Universidade de São Paulo, São Paulo, Brazil
$^e$ Department of Physics, University of Surrey, Guildford, UK

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Abstract

The $g$ factors of the $^{7+}_2$ 235 keV isomer in $^{175}$W and the $^{14+}$ 3746 keV isomer in $^{176}$W have been measured by observing the precession of the decay $\gamma$-ray angular distribution in an external magnetic field as $g\left(^{7+}_2, ^{175}$W$\right) = -0.187(6)$ and $g(14^+, ^{176}$W$) = +0.475(15)$. A pure wave function has been assigned to the $K^\pi = 14^+$ isomer from comparison with predictions based on experimental $g$ factors of deformed single-particle orbitals in this mass region. The value $g_R = 0.27(2)$ has been deduced for the rotational $g$ factor by using the measured $g$ factor of the $14^+$ state and the branching ratios in the associated band. © 2000 Elsevier Science B.V. All rights reserved.

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In the midshell deformed nuclei of the $A \approx 180$ region high-spin states of high-seniority intrinsic configurations are able to compete with rotational structures as both proton and neutron Fermi surfaces are close to nucleon orbits with large projections $\Omega$ on the prolate symmetry axis. The study of these high-$K$ states has attracted in recent years much experimental and theoretical work aiming to elucidate interesting aspects as the dependence of pairing correlations and nuclear shapes on the multi-quasiparticle configurations, and the mechanisms which govern their decay to lower-lying states. A large number of high-$K$ multi-quasiparticle intrinsic states and associated rotational bands have been identified in isotopes of Hf, Ta, W, Re and Os [1–5]. In most cases the underlying quasiparticle configurations were assigned on the basis of experimental in band branching ratios, from which $|\Delta g_k|/Q_k$ were derived. These analysis are, however, dependent on the assumptions concerning the quadrupole deformation and the effects associated with the reduction of the pairing correlations on both the rotational $g$ factor $g_R$ and the alignment.

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

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In this respect the knowledge of the static magnetic dipole and electric quadrupole moments is of crucial importance, as they are providing independent information on the composition of the wave-function and on the nuclear deformation, respectively. Up to now static electromagnetic moments have been measured only for few high-$K$ isomeric states of seniority $\geq 4$ in the $A \approx 180$ region: $16^+$ in $^{178}$Hf [6], $\tfrac{4^+}{3}$ in $^{179}$W [7], $16^-$ in $^{182}$Re [8] and $25^+$ in $^{182}$Os [9,10].

The investigation of decay properties of the high-$K$ states is another subject of large interest. Due to the approximate conservation of the $K$ quantum number, direct decays via electromagnetic transitions of multipolarity $\lambda < \Delta K$ are hindered, thus leading to high-$K$ isomers with half-lives ranging from a few nanoseconds up to several years. Usually isomeric transitions were observed to be hindered by factors of 20–100 per degree of $K$-forbiddenness $\nu = \Delta K - \lambda$. Anomalous transitions with apparently large $\Delta K$ values and reduced-hindrance values lower than 5 were however observed in few nuclei of the region. In order to explain these unexpected decays various models of $K$-mixing have been developed, which include tunneling through $\gamma$-degree of freedom [11,12], Coriolis mixing and band coupling with Fermi-aligned configurations [13,14], statistical mixing with states with lower $K$ values in the structure of the high-$K$ multi-quasiparticle state [15] and the onset of triaxial shapes in the multi-quasiparticle structures [4,16]. It is worthwhile to mention that the proposed mechanisms describe only in part the experimentally determined features.

Our interest focused on the $K^\pi = 14^+$ isomeric state in $^{176}$W [17,18]. This isomer shows in its decay a severe breakdown of the normal $K$-selection rules, as it deexcites predominantly to states with $\langle K \rangle \simeq 0$, bypassing levels of intermediate $K$. This feature appears at difference with most of the known decays of high-$K$ isomers in neighbouring nuclei, where the highly $K$-violating branches represent only small fractions of the total decay. To understand the unusual character of the $^{176}$W isomer decay, it is important to have as much information as possible regarding its underlying structure. The lifetime $T_{1/2} = 35(10)$ ns [18] is well suited for applying the time-differential perturbed angular distribution (TD-PAD) method in static moment investigations. In the present paper we report on the $g$-factor measurements for the $14^+$ isomer in $^{176}$W, as well as for the $\tfrac{27}{2}^+$ $235$ keV isomer bandhead with $T_{1/2} = 216$ ns in $^{175}$W.

The isomeric states were populated in the $^{164}$Dy($^{16}$O,4$n$)$^{176}$W and $^{164}$Dy($^{16}$O,5$n$)$^{175}$W reactions using an 83 MeV $^{16}$O beam delivered by the XTU-Tandem at Laboratori Nazionali di Legnaro. 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 inbetween the beam bursts of $\approx 10^5$. In view of the very low population of the $14^+$ isomer (about 2% of the 4$n$ channel), this good suppression was essential for a proper observation of the isomeric decay $\gamma$ lines. The target consisted of 0.5 mg/cm$^2$ metallic Dy, enriched in $^{164}$Dy to 95.6%, on thick Pb backing in which both the recoiling W nuclei and the projectiles were stopped. In order to reduce the dealignment effects due to the interaction with the radiation induced defects, the target was heated at a temperature of 410 K in a special oven. Two planar Ge detectors and two Ge detectors of 25% efficiency positioned at the angles $\pm 135^\circ$ and $\pm 45^\circ$ with respect to the beam direction, respectively, were used. The target was placed between the pole tips of an electromagnet. A magnetic field $B = 27.2(6)$ kG was applied perpendicular to the beam-detection plane and its direction was periodically reversed. Inside the magnet a soft-iron beam tube was used to keep deviations of the beam spot on target to less than 1 mm when the field direction was changed. Data were registered by using the acquisition system of the GASP multi-detector array, adapted for the specific configuration of the TD-PAD experiments.

In off-line analysis, two-dimensional matrices of energy versus time for each detector were formed. From these matrices time-gated energy spectra and energy-gated time spectra were created. A sample delayed $\gamma$ spectrum registered inbetween the beam bursts is illustrated in the upper part of Fig. 1. It is dominated by the 240, 351, 440, 508 and 558 keV $\gamma$ lines of the $^{176}$W yrast band which collects practically all the $14^+$ isomeric decay branches [18]. The delayed spectrum also shows the 131 keV $\gamma$ ray which deexcites the $\tfrac{27}{2}^+$ $235$ keV isomer in $^{175}$W [19]. The background subtracted summed time spectrum of delayed $\gamma$ rays in $^{176}$W is shown in Fig. 1. A value of $T_{1/2} = 41(1)$ ns was determined for the half-life of
Fig. 1. (a) Partial energy spectrum gated by the time interval 30–110 ns after the beam burst, registered with a 25% efficiency Ge detector. The γ lines belonging to the decay 14⁺ isomer in 176W are labelled by energy. The background due to long-lived activities has been subtracted. (b) Summed time spectrum for the 240, 351, 440 and 558 keV γ rays in 176W.

The time spectra $I(t, \theta)$ obtained for each of the two magnetic field directions were used to form the experimental modulation ratio $R(t) = [I^1(t, \theta) - I^2(t, \theta)]/[I^1(t, \theta) + I^2(t, \theta)]$. The 131 keV transition of E1 multipolarity in 175W was analysed with the planar Ge detectors, while the 240, 351, 440 and 558 keV transitions of E2 multipolarity in 176W were analysed in all detectors. For each detector the $R(t)$ ratios revealed Larmor oscillations. The modulation ratios corresponding to the total accumulated statistics are illustrated in Fig. 2 and exhibit oscillations with an amplitude attenuated in time. The observed damping of the anisotropy is attributed to the interaction of the electric quadrupole moment $Q$ of the isomeric state with the average electric field gradient $V_{zz}$ due to radiation damage near the W impurity in the cubic lattice of the metallic Pb host. Similar effects have been previously reported for Po isomers implanted in Pb [20]. In the least-squares fit we used the expression

$$R_{\text{theo}}(t) = \frac{3}{4} A_2 E_{zz}^2 (\omega Q t) \cos 2(\phi - \omega_L t)$$  \hspace{1cm} (1)
derived in [21] for the combined interaction of the externally applied magnetic field and the weak electric field gradients. The angular distribution coefficient \( A_2 \), the Larmor frequency \( \omega_L = g \beta \mu_N / h \), the quadrupole interaction frequency \( \omega_Q = Q V_{zz} / 4 \), and the phase \( \phi \) depending on the detector position angle and the beam bending in the magnetic field were free parameters. The values
\[
g(\frac{7}{2}^+, 175 \text{W}) = -0.187(6) \quad \text{and} \quad g(14^+, 176 \text{W}) = +0.475(15)
\]
were determined for the isomeric state \( g \) factors. The diamagnetic and Knight shift corrections were not applied, as they are small (about 1%), similar in magnitude and opposite in sign. From the derived quadrupole interaction frequencies an estimate of the ratio of the quadrupole moments of the investigated isomers has been obtained as \( Q(\frac{7}{2}^+, 175 \text{W}) / Q(14^+, 176 \text{W}) = 0.54(21) \).

The \( g \) factor of states with well defined \( K \) is given by
\[
g = g_R + (g_K - g_R) \frac{K^2}{I(I + 1)} \quad (2)
\]
For \( I = K \) and large \( I \), \( g \) approaches \( g_K \), which is calculated from \( K g_K = \sum \Omega g_{\Omega} \). In the calculations of \( g \) factors for multi-quasiparticle states, \( g_{\Omega} \) deduced from experimental \( g \) factors of low-lying states in deformed neighbouring odd-mass nuclei are generally used. A good knowledge of these quantities is required for reliable high-\( K \) state \( g \)-factor evaluations. In Table 1 we present the adopted \( g_{\Omega} \) values for the single proton and neutron states, obtained from experimental \( g \) factors of low-lying states in odd-mass nuclei [22]. For the neutron \( \frac{7}{2}^- \) [633] orbital the \( g \) factor measured in the present work for the \( \frac{7}{2}^+ \) state in \( 175 \text{W} \) has been taken. So far \( g \) factors for the \( \frac{7}{2}^- \) [633] neutron state were determined only in three rare-earth nuclei with \( N = 99 \) and they show an increase with \( Z \) number: \( g(\frac{7}{2}^- \text{65Dy}) = -0.148(2) \), \( g(\frac{107}{88}\text{Er}) = -0.161(10)(4) \), \( g(\frac{7}{2}^- \text{67Yb}) = -0.181(2) \) [22]. The presently measured \( g \) factor in \( 175 \text{W} \) provides a reliable \( g_{\Omega} \) value for the Coriolis mixed \( \frac{7}{2}^- [633] \) neutron state to be used in the \( g \)-factor calculations for multi-quasiparticle isomers in the \( A \approx 180 \) region.

<table>
<thead>
<tr>
<th>State</th>
<th>Shell</th>
<th>( g ) factor(^a)</th>
<th>Nucleus</th>
<th>( g_{\Omega} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{7}{2}^- ) [404]</td>
<td>( g7/2 )</td>
<td>+0.649(13)</td>
<td>( 175 \text{Ta} )</td>
<td>+0.763(22)</td>
</tr>
<tr>
<td>( \frac{7}{2}^- ) [402]</td>
<td>( d5/2 )</td>
<td>+1.309(17)</td>
<td>( 181 \text{Ta}, 181 \text{Re} )</td>
<td>+1.733(31)</td>
</tr>
<tr>
<td>( \frac{7}{2}^- ) [514]</td>
<td>( h11/2 )</td>
<td>+1.173(20)</td>
<td>( 181 \text{Ta} )</td>
<td>+1.378(26)</td>
</tr>
<tr>
<td>( \frac{7}{2}^- ) [505]</td>
<td>( h11/2 )</td>
<td>+1.129(2)</td>
<td>( 187 \text{Ir} )</td>
<td>+1.289(9)</td>
</tr>
</tbody>
</table>

\( a \) Values taken from Ref. [22].
\( b \) Present work.

The calculated values of the \( g \) factor for the four-quasiparticle configurations proposed for the \( 14^+ \) isomer in \( 176 \text{W} \) [18] are listed in Table 2. The \( g \) factors for high \( K \) isomers depend weakly on the \( g_R \) value. In the present evaluations \( g_R = 0.25 \) has been used, based on the values \( g(2^+) = 0.25(5) \) and \( 0.25(4) \) measured in \( 168 \text{W} \) and \( 180 \text{W} \) nuclei, respectively [22]. The comparison of the experimental \( g \) factor with the calculated ones leads to the assignment of the configuration composed by two protons occupying the \( \frac{7}{2}^- \) [404] and \( \frac{5}{2}^- \) [514] orbitals and two neutrons occupying the \( \frac{5}{2}^- \) [633] and \( \frac{3}{2}^- \) [512] orbitals. We note that this configuration is also predicted by Woods–Saxon calculations for the lowest-lying \( 14^+ \) state in \( 176 \text{W} \) [18]. The remarkable agreement between the measured and calculated \( g \) factor points to a pure wave function for the anomalously decaying \( 14^+ \) isomer in \( 176 \text{W} \). In Table 2 are also presented the experimental \( g \) factors and the assigned configurations for the \( 16^+ \) isomer with \( T_{1/2} = 31 \) years in \( 178 \text{Hf} \) [6] and the \( 25^+ \) isomer with \( T_{1/2} = 150 \) ns in \( 182 \text{Os} \) [9], as well as the \( g \)-factor values calculated by using the adopted \( g_{\Omega} \) from Table 1. In both cases the calculated values reproduce very well the measured \( g \) factors. For the \( 16^+ \) isomer in \( 178 \text{Hf} \) a similar value, \( g_{\text{cal}} = +0.511 \), has been reported in Ref. [6]. As concerns the \( 25^+ \) isomer in \( 182 \text{Os} \), a value \( g_{\text{cal}} = +0.38 \), somewhat smaller compared to the measured one, has been previously
moments we deduced the ratio of the intrinsic quadrupole what points, within the errors, to axial symmetric different decays, involving strongly hindered transi-
tate to be determined by the structure of the populated configurations, their different decay properties seem are characterized by rather pure multi-quasiparticle are experimentally determined in Ref. [18]. We have been experimentally determined in Ref. [18]. We have used these ratios to evaluate the \(|g_K - g_R|/Q_\circ\) values in the band according to the relation
\[
\frac{|g_K - g_R|}{Q_\circ} = \frac{1}{K} \left( \frac{5}{12} \frac{B(M1)}{B(E2)} \left| \frac{IK20}{IK10} - 1 \right| \right)^2
\]
and weighted average value \((g_K - g_R)/Q_\circ = 0.030(2)\) has been derived. This value and the presently measured \(g\) factor then have been used in the expression (2) to obtain the relation between \(g_R\) and the intrinsic quadrupole moment \(Q_\circ\) for the \(14^+\) isomer, which is illustrated in Fig. 3. No quadrupole moment measurement has been reported so far for \(176\)W. From the systematics of measured \(B(E2)\) in the ground state bands of neighbouring even–even nuclei [24], as well as from recent configuration-constrained potential-energy-surface calculations with Lipkin–Nogami pairing and diabatic blocking performed for the neighbouring \(178\)W [16], one can assume \(Q_\circ = 7.5\ e\) for the intrinsic quadrupole moment of the \(14^+\) state. As seen in Fig. 3, this value corresponds to \(g_R = 0.27(2)\). The rotational \(g\) factor of multi-quasiparticle configurations is expected to be affected by the changes in pairing due to the blocking of orbitals near the Fermi

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>(J^+)</th>
<th>Proton orbitals</th>
<th>Neutron orbitals</th>
<th>(g_{calc})</th>
<th>(g_{exp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(176)W</td>
<td>(14^+)</td>
<td>(\frac{1}{2}^+ [404], \frac{3}{2}^- [514])</td>
<td>(\frac{1}{2}^- [512], \frac{3}{2}^+ [633])</td>
<td>+0.462(11)</td>
<td>+0.475(15)</td>
</tr>
<tr>
<td>(\frac{1}{2}^+ [404], \frac{3}{2}^+ [402])</td>
<td>(\frac{1}{2}^- [633], \frac{3}{2}^+ [624])</td>
<td>+0.342(10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\frac{1}{2}^- [512], \frac{3}{2}^- [514], \frac{3}{2}^- [633], \frac{1}{2}^- [624])</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(178)Hf</td>
<td>(16^+)</td>
<td>(\frac{3}{2}^+ [404], \frac{5}{2}^- [514])</td>
<td>(\frac{5}{2}^- [514], \frac{3}{2}^+ [624])</td>
<td>+0.521(10)</td>
<td>+0.510(3)(^a)</td>
</tr>
<tr>
<td>(182)Os</td>
<td>(25^+)</td>
<td>(\frac{5}{2}^- [514], \frac{3}{2}^- [505])</td>
<td>(\frac{5}{2}^- [503], \frac{3}{2}^- [514], \frac{5}{2}^- [633], \frac{3}{2}^- [624])</td>
<td>+0.427(7)</td>
<td>+0.425(8)(^b)</td>
</tr>
</tbody>
</table>

\(^a\) Ref. [6].
\(^b\) Ref. [9].


Table 2
Experimental and calculated \(g\) factors for multi-quasiparticle isomeric states: \(14^+\) in \(176\)W, \(16^+\) in \(178\)Hf and \(25^+\) in \(182\)Os (see text)

shapes in the isomeric states. We note that recently a significant triaxiality has been suggested for the ground state band of \(176\)W by calculations within the triaxial projected shell model approach in order to reproduce the experimental moment of inertia [23].

The knowledge of the static moments of a high-
K isomeric state and of the branching ratios in its associated band allows to derive the rotational \(g\) factor \(g_R\). The \(K^\pi = 14^+\) isomer in \(176\)W is the bandhead of a \(\Delta I = 1\) band for which the \(B(M1)/B(E2)\) ratios have been experimentally determined in Ref. [18]. We have used these ratios to evaluate the \(|g_K - g_R|/Q_\circ\) values in the band according to the relation
\[
\frac{|g_K - g_R|}{Q_\circ} = \frac{1}{K} \left( \frac{5}{12} \frac{B(M1)}{B(E2)} \left| \frac{IK20}{IK10} - 1 \right| \right)^2
\]
and weighted average value \((g_K - g_R)/Q_\circ = 0.030(2)\) has been derived. This value and the presently measured \(g\) factor then have been used in the expression (2) to obtain the relation between \(g_R\) and the intrinsic quadrupole moment \(Q_\circ\) for the \(14^+\) isomer, which is illustrated in Fig. 3. No quadrupole moment measurement has been reported so far for \(176\)W. From the systematics of measured \(B(E2)\) in the ground state bands of neighbouring even–even nuclei [24], as well as from recent configuration-constrained potential-energy-surface calculations with Lipkin–Nogami pairing and diabatic blocking performed for the neighbouring \(178\)W [16], one can assume \(Q_\circ = 7.5\ e\) for the intrinsic quadrupole moment of the \(14^+\) state. As seen in Fig. 3, this value corresponds to \(g_R = 0.27(2)\). The rotational \(g\) factor of multi-quasiparticle configurations is expected to be affected by the changes in pairing due to the blocking of orbitals near the Fermi
Fig. 3. Relation between $g_R$ and $Q_\alpha$ for the $14^+$ isomer, derived from experimental $g$ factor and $B(M1)/B(E2)$ ratios. The $g$ factor of the $2^+$ states in light W isotopes and $g_R = Z/A$ for $^{170}$W are also depicted.

In summary, we have measured the $g$ factors of the $7^+$ $235$ keV isomer in $^{175}$W and the $14^+$ $3746$ keV isomer in $^{176}$W. A pure wave function composed by two protons occupying the $\frac{7}{2}^+ [404]$ and $\frac{9}{2}^- [514]$ orbitals and two neutrons occupying the $\frac{7}{2}^- [633]$ and $\frac{5}{2}^- [512]$ orbitals has been assigned to the $14^+$ isomer. The measured bandhead $g$ factor and the branching ratios in the associated band have been used in order to obtain the rotational $g$ factor of a multi-quasiparticle state. In this analysis the value of the intrinsic quadrupole moment was taken from systematics. Shape polarisation effects induced by specific high-$\Omega$ orbitals are however expected in the multi-quasiparticle configurations. In the case of the $25^+$ isomer in $^{182}$Os the measured static quadrupole moment [10] corresponds to a deformation about 20% lower than that of the ground state band, in extremely good accordance with recent calculations [16]. Further TDPAD experiments are planned for measuring the static quadrupole moment of the $14^+$ state in $^{176}$W, in order to determine the isomer shape and to get a reliable $g_R$ value.

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