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g factors of the $\frac{7}{2}^+$ and 14^+ isomers in ^{175,176}W

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Abstract

The g factors of the $\frac{7}{2}^+$ 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 γ-ray angular distribution in an external magnetic field as $g\left(\frac{7}{2}^+, {}^{175}\mathrm{W}\right) = -0.187(6)$ and $g(14^+, {}^{176}\mathrm{W}) = +0.475(15)$. 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 Ω 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 $|g_K - g_R|/Q_\circ$ 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.

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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 $\geqslant 4$ in the $A \approx 180$ region: 16^+ in ^{178}Hf [6], $\frac{35}{2}^-$ 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 ΔK 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 γ-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 $K^\pi = 14^+$ 3746 keV 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 many 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 (TDPAD) 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 $\frac{7}{2}^+$ 235 keV isomer bandhead with $T_{1/2} = 216$ ns in ^{175}W.

The isomeric states were populated in the ^{164}Dy(^{16}O, 4n)^{176}W and ^{164}Dy(^{16}O, 5n)^{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 $\approx 10^4$. In view of the very low population of the 14^+ isomer (about 2% of the 4n channel), this good suppression was essential for a proper observation of the isomeric decay γ 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 $\pm 135°$ and $\pm 45°$ 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 TDPAD 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 γ 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 γ 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 γ ray which deexcites the $\frac{7}{2}^+$ 235 keV isomer in ^{175}W [19]. The background subtracted summed time spectrum of delayed γ 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

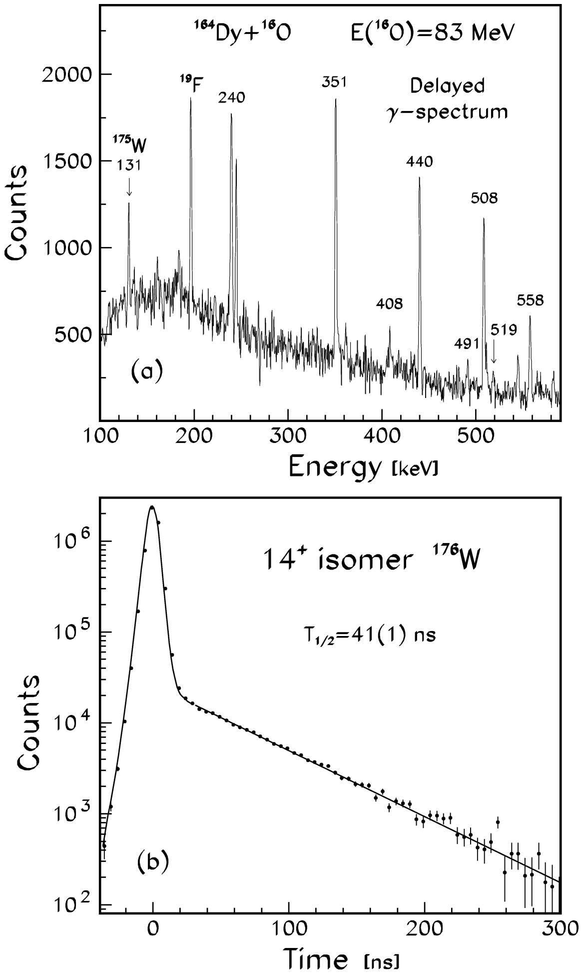

Fig. 1. (a) Partial energy spectrum gated by the time interval 30–110 ns after the beam burst, registered with a 25% efficiency Ge detector. The γ lines belonging to the decay 14^{+} isomer in ^{176}W are labelled by energy. The background due to long-lived activities has been subtracted. (b) Summed time spectrum for the 240, 351, 440 and 558 keV γ rays in ^{176}W.

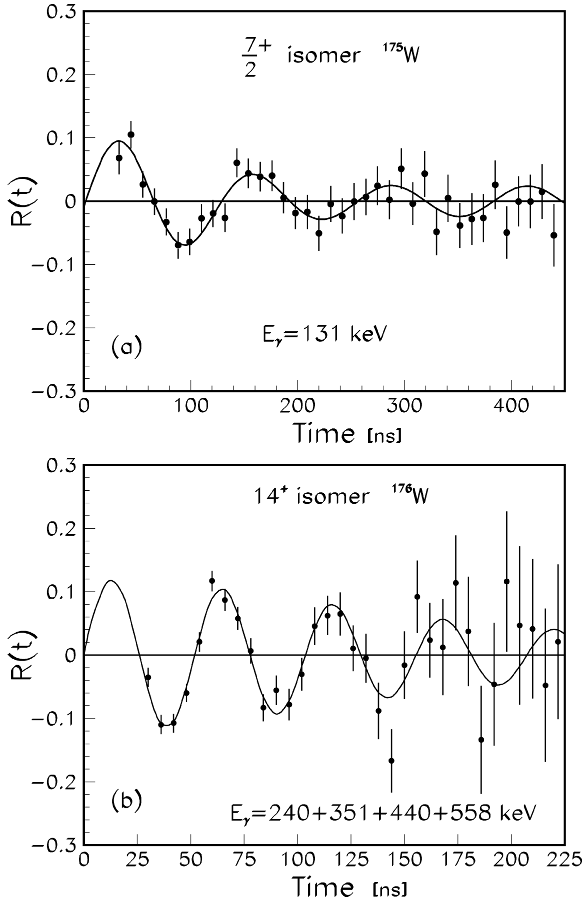

Fig. 2. Modulation spectra for ^{175}W (a) and ^{176}W (b) in Pb, in an external magnetic field of 27.2 kG.

14^{+} 3476 keV isomer, in agreement with the value reported earlier [18], however, with an improved accuracy.

The time spectra $I(t,\theta)$ obtained for each of the two magnetic field directions were used to form the experimental modulation ratio $R(t) = [I^{\uparrow}(t,\theta) - I_{\downarrow}(t,\theta)]/[I^{\uparrow}(t,\theta) + I_{\downarrow}(t,\theta)]$. The 131 keV transition of E1 multipolarity in ^{175}W was analysed with the planar Ge detectors, while the 240, 351, 440 and 558 keV transitions of E2 multipolarity in ^{176}W 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

$$R_{\text{theo}}(t) = \frac{3}{4} A_2 E_{22}^{22}(I\omega_Q t)\cos 2(\phi - \omega_L t) \tag{1}$$

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 $\omega_L = gB\mu_N/\hbar$, the quadrupole interaction frequency $\omega_Q = QV_{zz}/4I(2I-1)\hbar$, and the phase ϕ depending on the detector position angle and the beam bending in the magnetic field were free parameters. The values

$$g\left(\tfrac{7}{2}^+, {}^{175}\mathrm{W}\right) = -0.187(6) \quad \text{and}$$
$$g\left(14^+, {}^{176}\mathrm{W}\right) = +0.475(15)$$

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 $\left|Q\left(\tfrac{7}{2}^+, {}^{175}\mathrm{W}\right)/Q(14^+, {}^{176}\mathrm{W})\right| = 0.54(21)$.

The g factor of states with well defined K is given by

$$g = g_R + (g_K - g_R)\frac{K^2}{I(I+1)}. \tag{2}$$

For $I = K$ and large I, g approaches g_K, which is calculated from $Kg_K = \sum \Omega_i g_{\Omega_i}$. In the calculations of g factors for multi-quasiparticle states, g_Ω 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_Ω 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 $\tfrac{7}{2}^+[633]$ orbital the g factor measured in the present work for the $\tfrac{7}{2}^+$ state in ^{175}W has been taken. So far g factors for the $\tfrac{7}{2}^+[633]$ neutron state were determined only in three rare-earth nuclei with $N = 99$ and they show an increase with Z number: $g({}^{165}_{66}\mathrm{Dy}) = -0.148(2)$, $g({}^{167}_{68}\mathrm{Er}) = -0.16110(4)$, $g({}^{169}_{70}\mathrm{Yb}) = -0.181(2)$ [22]. The presently measured g factor in ${}^{175}_{74}$W provides a reliable g_Ω value for the Coriolis mixed $\tfrac{7}{2}^+[633]$ neutron state to be used in the g-factor calculations for multi-quasiparticle isomers in the $A \approx 180$ region.

Table 1
Experimental g factors of low-lying states in deformed odd-mass nuclei and corresponding g_Ω values deduced by using $g_R = 0.25(5)$

State	Shell	g factor[a]	Nucleus	g_Ω
$\pi\frac{7}{2}^+[404]$	$g_{7/2}$	+0.649(13)	^{175}Ta	+0.763(22)
$\pi\frac{5}{2}^+[402]$	$d_{5/2}$	+1.309(17)	^{181}Ta, ^{181}Re	+1.733(31)
$\pi\frac{9}{2}^-[514]$	$h_{11/2}$	+1.173(20)	^{181}Ta	+1.378(26)
$\pi\frac{11}{2}^-[505]$	$h_{11/2}$	+1.129(2)	^{187}Ir	+1.289(9)
$\nu\frac{7}{2}^-[514]$	$h_{9/2}$	+0.227(1)	^{177}Hf	+0.220(14)
$\nu\frac{7}{2}^-[503]$	$f_{7/2}$	−0.183(3)	^{157}Yb	−0.307(15)
$\nu\frac{5}{2}^-[512]$	$f_{7/2}$	−0.242(7)	^{175}Hf	−0.439(22)
$\nu\frac{9}{2}^+[624]$	$i_{13/2}$	−0.142(3)	^{179}Hf	−0.229(14)
$\nu\frac{7}{2}^+[633]$	$i_{13/2}$	−0.187(6)[b]	^{175}W	−0.312(16)

[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}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 $g(2^+) = 0.250(5)$ and $0.254(17)$ measured in ^{168}W and ^{180}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 $\tfrac{7}{2}^+[404]$ and $\tfrac{9}{2}^-[514]$ orbitals and two neutrons occupying the $\tfrac{7}{2}^+[633]$ and $\tfrac{5}{2}^-[512]$ orbitals. We note that this configuration is also predicted by Woods–Saxon calculations for the lowest-lying 14^+ state in ^{176}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}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}Hf [6] and the 25^+ isomer with $T_{1/2} = 150$ ns in ^{182}Os [9], as well as the g-factor values calculated by using the adopted g_Ω from Table 1. In both cases the calculated values reproduce very well the measured g factors. For the 16^+ isomer in ^{178}Hf a similar value, $g_{\mathrm{cal}} = +0.511$, has been reported in Ref. [6]. As concerns the 25^+ isomer in ^{182}Os, a value $g_{\mathrm{cal}} = +0.38$, somewhat smaller compared to the measured one, has been previously

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)

Nucleus	I^π	Proton orbitals	Neutron orbitals	g_{calc}	g_{exp}
^{176}W	14^+	$\frac{7}{2}^+[404]$, $\frac{9}{2}^-[514]$	$\frac{5}{2}^-[512]$, $\frac{7}{2}^+[633]$	+0.462(11)	+0.475(15)
		$\frac{7}{2}^+[404]$, $\frac{5}{2}^+[402]$	$\frac{7}{2}^+[633]$, $\frac{9}{2}^+[624]$	+0.342(10)	
			$\frac{5}{2}^-[512]$, $\frac{7}{2}^-[514]$, $\frac{7}{2}^+[633]$, $\frac{9}{2}^+[624]$	−0.147(8)	
^{178}Hf	16^+	$\frac{7}{2}^+[404]$, $\frac{9}{2}^-[514]$	$\frac{7}{2}^-[514]$, $\frac{9}{2}^+[624]$	+0.521(10)	+0.510(3)[a]
^{182}Os	25^+	$\frac{9}{2}^-[514]$, $\frac{11}{2}^-[505]$	$\frac{7}{2}^-[503]$, $\frac{7}{2}^-[514]$, $\frac{7}{2}^+[633]$, $\frac{9}{2}^+[624]$	+0.427(7)	+0.425(8)[b]

[a] Ref. [6].
[b] Ref. [9].

calculated for the assigned six-quasiparticle configuration, what was interpreted as indication of a possible modification of the wave function [9]. Our recalculated value (see last line of Table 2) indicates a pure configuration for the 25^+ isomer too. It is worthwhile to point out that these high-K isomers show very different decays, involving strongly hindered transitions in ^{178}Hf, a weak branch highly K-violating transition in ^{182}Os and a severe breakdown of the normal K-selection rules in ^{176}W. As the isomeric states are characterized by rather pure multi-quasiparticle configurations, their different decay properties seem to be determined by the structure of the populated states.

A recent analysis of the K-forbidden transitions from multi-quasiparticle states has revealed a strong correlation of declining K hindrance with increasing excitation energy [15]. It has been shown that statistical mixing of low-K states in the structure of high-K four-quasiparticle states located well above their respective yrast lines could be at least partly responsible for the observed reduced hindrances. The configuration mixing due to the high density-of-states, expected for the 14^+ isomer in ^{176}W which is situated far from yrast [15], is however not reflected by the presently measured g factor.

The occurrence of triaxial shapes could also explain the observed decay pattern. Assuming the strong coupling scheme, from the presently determined ratio of the spectroscopic quadrupole moments for the $\frac{7}{2}^+$ and 14^+ isomers in ^{175}W and ^{176}W, respectively, we deduced the ratio of the intrinsic quadrupole moments $Q_\circ(\frac{7}{2}^+, {}^{175}\mathrm{W})/Q_\circ(14^+, {}^{176}\mathrm{W}) = 0.94(37)$, what points, within the errors, to axial symmetric 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^π=14^+ isomer in ^{176}W is the bandhead of a $\Delta I = 1$ band for which the $B(\mathrm{M1})/B(\mathrm{E2})$ 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

$$\frac{|g_K - g_R|}{Q_\circ} = \frac{1}{K}\sqrt{\frac{5}{12}\frac{B(\mathrm{M1})}{B(\mathrm{E2})}\frac{\langle IK20|I-2K\rangle^2}{\langle IK10|I-1K\rangle^2}}, \qquad (3)$$

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 $B(\mathrm{E2})$ 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 $Q_\circ = 7.5\ e\,\mathrm{b}$ 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

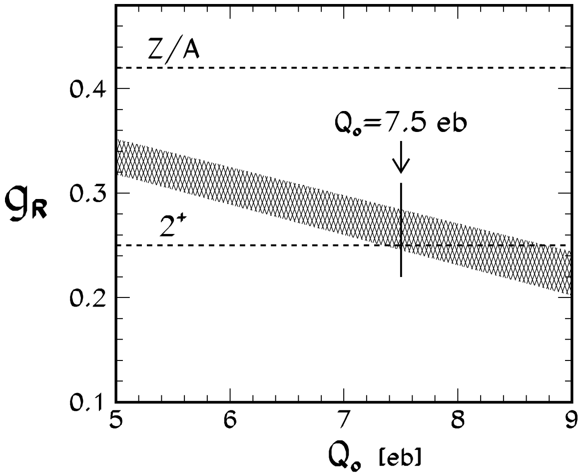

Fig. 3. Relation between g_R and $Q_\circ$ for the 14^+ isomer, derived from experimental g factor and $B(\mathrm{M1})/B(\mathrm{E2})$ ratios. The g factor of the 2^+ states in light W isotopes and $g_R = Z/A$ for ^{176}W are also depicted.

surface. In the presently investigated case the proton and neutron pairing reduction appears to compensate each other in the two proton–two neutron configuration, and therefore the g_R is very close to the rotational value $g(2^+)$.

In summary, we have measured the g factors of the $\frac{7}{2}^+$ 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-Ω 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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