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Magnetic dipole moments of High-K isomeric states in Hf isotopes

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Abstract

It is proposed to make precision measurements of the magnetic moments of 5 multiquasiparticle K-isomers in Hf nuclei by the Nuclear Magnetic Resonance of Oriented Nuclei (NMR/ON) technique using the NICOLE on-line nuclear orientation facility and exploiting the unique HfF₃ beams recently available at ISOLDE. Results will be used to extract single-particle and collective g-factors of the isomeric states and their excitations and to shed new light on their structure.

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1 Introduction

The hafnium isotopes are notable for possessing a series of long-lived high-K isomers. It is the aim of this proposal to make precise measurements of the magnetic dipole moments of several high-K, multi-quasiparticle states in Hf nuclei by the technique of On-Line Nuclear Magnetic Resonance of Oriented Nuclei (On-Line NMR/ON) using the NICOLE dilution refrigerator system. These measurements will take advantage of the unique hafnium fluoride beams recently developed at ISOLDE, to implant the Hf isotopes and isomers into iron foils, at ~ 10 - 20 millikelvin temperatures, in which they experience a high magnetic internal field, become polarized, and can be subject to nuclear resonance study. Precise values of the magnetic dipole moments will yield essential information on intrinsic g_K of the isomeric states and hence their single-particle make-up. In combination with data from independent experiments on rotation bands built on the isomeric states, collective g_R will be deduced, shedding light on how the orbit occupation influence nuclear superfluidity.

In the $A=180$ region collective rotation coexists with intrinsic quasiparticle excitation modes. In axially symmetric deformed nuclei the quasiparticle excitations arise from a coupling of several quasiparticle orbitals with a large angular momentum projection Ω onto the the nuclear symmetry axis. The projection of the total single-particle angular momentum \mathbf{J} to this axis, $K(=\sum_i \Omega_i)$ is conserved to a good approximation. Transitions between states with different K values are theoretically only allowed if the multipolarity of the transition λ is higher or equal to ΔK . In reality, transitions with lower multipolarity occur, but are significantly hindered, leading to formation of metastable, long-lived multi-quasi-particle isomeric states, so called the K-isomers. K-isomers are of considerable interest because they form reservoirs of energy in atomic nuclei [1] and are sometimes thought to be potential candidates for development of devices based on laser stimulated energy release.

From the nuclear structure point of view K-isomers are rather pure and well defined deformed multiparticle systems that can be studied using a relatively simple single-particle models, like the Nilsson model. However, collective degrees of freedom are equally important. There is no collective rotation of an axially deformed nucleus about the nuclear symmetry axis because it would result in a system which is not distinguishable from the original one (before the rotation started) and the projection of the rotational angular momentum \mathbf{R} onto the symmetry axis is zero. The conserving non-zero value of K arises from the sum of momenta of individual orbiting nucleons which themselves do not have axial symmetry. An axially symmetrical nucleus rotates about an axis perpendicular to the symmetry axis and, due to the presence of pairing correlations, it is generally accepted, it rotates like a superfluid rather than a rigid body. In rapidly rotating nuclei with high spins the pairing correlations can be quenched and single particle orbitals perturbed. However, in slowly rotating K-isomers, in which the pairing breaking effects due to collective rotation are small, nucleon pairs are broken mainly due to internal excitations and their effect on nuclear superconductivity can be studied step-by-step. The total angular momentum \mathbf{I} , nuclear spin, is used to identify which pairs are broken. Here, measurement of other observables, in addition of its spin, such as magnetic dipole moments, becomes extremely important in determination of the quasiparticle structure of the isomer.

Earlier measurements of magnetic dipole moments of hafnium multi-quasiparticle isomers include 2- and 3-quasiparticle nanosecond isomers [2] by time-differential perturbed angular distributions (TDPAD), and the 4-quasiparticle, 31-year isomer in ^{178}Hf [3] by laser spectroscopy. The magnetic moments have been used to determine intrinsic g_K factors and hence quasiparticle configurations, with particular interest in high-K neutron-proton admixtures [2].

In the present work, however, it is proposed also to determine collective g_R factors. The magnetic moment of the K-isomer (for which $J=I=K$) is defined as

$$\mu = gI = g_R I + (g_K - g_R) K^2 / (I + 1). \quad (1)$$

Experimentally, values of $|(g_K - g_R)/Q_0|$ can be deduced from γ -ray energies and the magnitude of in-band quadrupole/dipole mixing ratios for bands built on K-isomers. For example, very recent investigation of collective rotation and vibration in $^{180,182}\text{Hf}$ nuclei [5] yielded the value of 0.10(1) for the $|(g_K - g_R)/Q_0|$ ratio for the two-quasiparticle 8^- state in ^{180}Hf . This result is based on the value of the intrinsic quadrupole moment Q_0 for well deformed nuclei, such as the hafnium isotopes under consideration, estimated from the spectroscopic quadrupole moment of low-lying states, or calculated theoretically [4]. A typical value, usually taken in $A \sim 180$ region is about 7 eb (see Ref. [5] and references therein). So far, the g_K value is obtained either from known single-particle moments of orbitals contributing to the isomeric state or theoretical calculations using Nilsson model. It is clear that a combination of the experimental values of $|(g_K - g_R)/Q_0|$ and the precise value of the measured magnetic dipole moment (1) will yield a better determined value of g_R than is available at present. Starting from

$$\begin{aligned} \frac{g_K - g_R}{Q_0} &= A \\ \frac{\mu}{I} &= g_K \frac{I}{I+1} + g_R \frac{1}{I+1} = B \end{aligned} \quad (2)$$

(taking positive sign of A), g_K and g_R are given separately as

$$\begin{aligned} g_K &= B + \frac{1}{I+1} A Q_0 \\ g_R &= B - \frac{I}{I+1} A Q_0 \end{aligned} \quad (3)$$

To date there is little knowledge of how the collective g_R value depends on the structure of the multi-quasiparticle configurations, yet this is of basic importance for understanding the influence of pairing correlations, and how pairing is blocked by quasiparticle occupations [6]. The hafnium isomers provide an excellent testing ground for investigating this aspect of the pairing phase transition, as more and more orbits are blocked. The importance of this aspect is highlighted by the recent work of Bissell et al. [7]. They find systematic charge radius reductions for multi-quasiparticle states, which may be related to the blocking of pairing correlations.

2 Experimental background.

2.1 Magnetic dipole moments and resonance frequencies

We propose to make accurate ($\sim 1\%$) measurement of the magnetic moments of the states, detailed in Table 1, recently made accessible to experiment at ISOLDE. All have been studied by a variety of methods and their quasi-particle composition suggested as summarized in Table 1 [8, 9, 10]:

Magnetic dipole moments of states in Table 1 have been estimated by seeking the best empirical g -factors for the single particles composing the multiparticle state from neighbouring measured odd- A moments. Several applications of the odd-odd moment coupling relation for a

Table 1: Isotopes and isomers of interest.

A	level energy [keV]	I^π	$T_{1/2}$	suggested configuration	ISOLDE yield [ions per μC]
177	1315	$23/2^+$	1.1 s	n $7/2^-$ [514], p $7/2^+$ [404], p $9/2^-$ [514]	$6.0 \cdot 10^5$ fed from $37/2^-$
	2740	$37/2^-$	51.4 m	n $5/2^-$ [512], n $9/2^+$ [624], n $7/2^-$ [514], p $7/2^+$ [404], p $9/2^-$ [514]	$6.0 \cdot 10^5$
179	1106	$25/2^-$	25.1 d	n $9/2^+$ [624], p $7/2^+$ [404], p $9/2^-$ [514]	$1.5 \cdot 10^7$
180	1183	8^-	5.5 h	p $7/2^+$ [512], p $9/2^-$ [514]	$2.4 \cdot 10^7$
182	1173	8^-	62 m	p $7/2^+$ [512], p $9/2^-$ [514]	$2 \cdot 10^4$

state based on particles of angular momenta j_1 and j_2 , having g-factors g_1 and g_2 , coupled to total single-particle angular momentum J

$$\mu_J = J \left[\frac{g_1 + g_2}{2} + \frac{[j_1(j_1 + 1) - j_2(j_2 + 1)](g_1 - g_2)}{2J(J + 1)} \right] \quad (4)$$

have then been used to obtain the given estimates. For example, the moment of the $23/2^+$ state in ^{177}Hf is estimated by first coupling the two protons [$7/2^+$ and $9/2^-$] to spin 8^- , then coupling this to the $7/2^-$ neutron to reach $J = 23/2^+$. These moments, in combination with the known hyperfine field at Hf nuclei in iron, allow determination of the expected search range of resonance frequencies in the NMR/ON experiments. The moments, estimated in this model, and the corresponding resonance frequencies, are summarized in Table 2.

2.2 The hyperfine field at Hf nuclei in iron

The hyperfine field at Hf in iron has been accurately measured by an NMR/ON experiment on ^{175}Hf for which the ground state magnetic moment is $-0.677(9)$ n.m. [11]. The observed resonance at 139.0(1) MHz yields the hyperfine field for Hf in iron as $67.4(9)$ T [12]. The proposed NMR/ON experiment will determine the magnetic moments with accuracy limited by the magnetic field result, currently 1.4%.

2.3 Spin-lattice relaxation of the Hf nuclei in the iron matrix

An essential of standard On-Line Nuclear Orientation experiments is that the lifetime of the parent, implanted isotope be comparable or longer than the spin-lattice relaxation time with which the nuclei cool to the iron lattice temperature. For a series of isotopes of the same element the relaxation time constants depend inversely upon the squares of the nuclear g-factors. There are no direct relaxation time measurements for Hf isotopes, however an empirical relation, $C_k T_{\text{int}}^2 = 1.4 \times 10^{-4} \text{ sK}^3$, where T_{int} is the nuclear interaction strength, $T_{\text{int}} = gB_{\text{hf}}/k$, can be used to give estimates of the Korringa constant, C_k , usually found reliable to better than a factor of 2. The relaxation time, T_1 , at a specific temperature T is given at temperatures above T_{int} by $T_1 = C_k/T$. At lower temperatures T_1 reaches a maximum value of approximately $3.3C_k/(I + 1/2) T_{\text{int}}$ [13].

Table 2: Estimated magnetic dipole moments, NMR frequencies and relaxation times for the proposed Hf K-isomers.

A	I^π	suggested configuration	Estimated/measured μ [n.m.]	NMR/ON ν [MHz]	T_1 at 10 mK [sec]
177	$23/2^+$	n7/2 ⁻ [514],p7/2 ⁺ [512], p9/2 ⁻ [514]	est. 8.04(6)	358.9(27)	7.5
	$37/2^-$	n5/2 ⁻ [512], n9/2 ⁺ [624], n7/2 ⁻ [514],p7/2 ⁺ [404], p9/2 ⁻ [514]	est. 8.14(17)	255.8(47)	18.8
179	$25/2^-$	n9/2 ⁺ [624],p7/2 ⁺ [512], p9/2 ⁻ [514]	meas. 7.43(34)	333.8(41)	8.9
180	8^-	p7/2 ⁺ [512], p9/2 ⁻ [514]	est. 8.4(7)	539(45)	3.0
182	8^-	p7/2 ⁺ [512], p9/2 ⁻ [514]	est. 8.4(7)	539(45)	3.0

The NICOLE dilution refrigerator reaches temperatures as low as 10 milliKelvin on-line. At this temperature estimated relaxation times for the proposed isotopes are given in Table 2. It is clear that for all except the $23/2^+$ state in ^{177}Hf the condition for thermal equilibrium before decay is fully satisfied. The case of the $23/2^+$ state is fortunate however, since it is populated in the decay of the longer lived $37/2^-$ state and will ‘inherit’ a large orientation from its parent isotope. This will allow observation of NMR/ON of the $23/2^+$ state.

2.4 Production of Hf beams

Production of intense Hf beam has been tested recently during the successful $^{180}\text{Hf}^m$ parity non-conservation experiment. The yield was constant during three days of run with an average proton beam intensity of 1 to 2 μA . No radioactive beam contaminations were detectable. The same technology has been shown to produce other Hf beams of adequate strength for NMR/ON experiments. A mixed tantalum/tungsten target (43 g/cm² Ta and 7 g/cm² W) is made from rolled foils and bombarded with 1.4 GeV protons. A flow of $8 \cdot 10^{-6}$ mbar l/s CF₄ is leaked into the 1900°C hot target to react with the radiogenic Hf atoms and transport them in form of HfF₄ molecules to the ion source. During electron impact ionization in an ISOLDE type FEBIAD ion source the molecules are partly dissociated and appear dominantly in the HfF₃⁺ molecular sideband. $^{180m}\text{HfF}_3^+$ was separated with a yield of $2.4 \cdot 10^7$ ions per μC . Table 1 shows the yields measured with the last Ta/W target (No. 312) and the yield extrapolated for a pure W foil target for ^{182m}Hf , respectively.

The measured beam intensities are given in Table 1. There is an advantage that each isomer emits a succession of gamma transitions of which four (for the 8^- isomers, see example in Fig. 1), seven (for the $25/2^-$ isomer in ^{179}Hf), eight (for the $23/2^+$ isomer in ^{177}Hf) and as many as sixteen (in the decay of the $37/2^-$ isomer in ^{177}Hf) will give signals of an NMR/ON resonance. Thus the count rate per implanted isotope is increased by these useful factors.

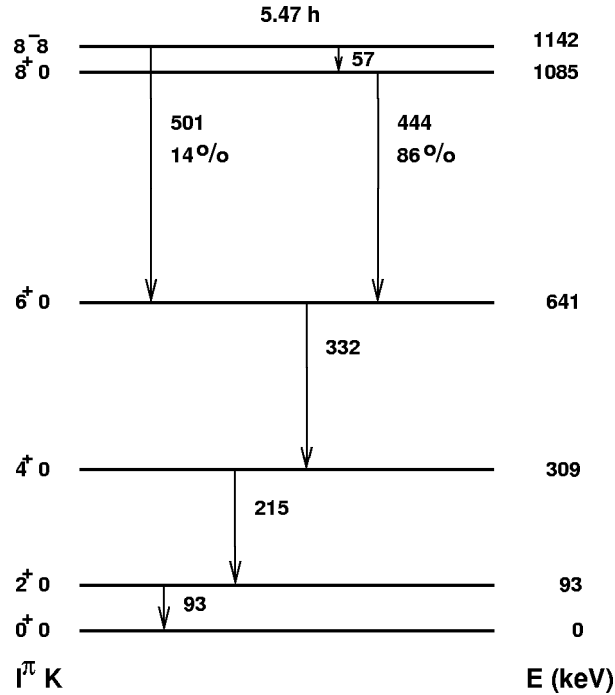


Figure 1: Decay of the 5.47 h ^{180}Hf

3 Nuclear Orientation Experiment

3.1 NMR/ON

In order to achieve high precision of measured moments needed for the most reliable interpretation in terms of the single-particle structure of multiparticle states, we propose to use the NMR/ON technique, detecting destruction of anisotropy of the angular distribution of γ emission from Hf nuclei, implanted at low temperature in a pure iron ferromagnetic host.

The NICOLE $^3\text{He}/^3\text{He}$ dilution refrigerator on line to the general purpose isotope separator will be used. In the standard geometry, three ORTEC/SILENA HP Ge detectors will be used outside the cryostat at 0^0 (two) and 90^0 (one) for detection of the γ radiation. A modulated RF field produced in a resonance coil inside the fridge with axis normal to the nuclear orientation axis is used to excite resonance between the hyperfine-split substates of the oriented nuclei. As the RF frequency is varied, resonant absorption can be detected by reduction in the observed anisotropy. The temperature of the sample will be determined using γ -transitions in an oriented $^{60}\text{Co}(\text{Fe})$ sample soldered to the cold-finger of the dilution refrigerator.

The large magnetic moments of all the Hf isotopes combined with the large hyperfine field will produce close to complete nuclear polarization giving high sensitivity for resonance detection.

3.2 Gamma-ray anisotropy: E2/M1 mixing ratios

In the odd-A decays we will observe many examples of pure E2 and mixed E2/M1 transitions from the same band state. Comparison of the anisotropy of the angular distribution of these transitions will yield accurate values of the E2/M1 multipole mixing ratio δ , which in turn provide good new values of the variable A in Eq. (4). In this way a nuclear orientation experiment offers an

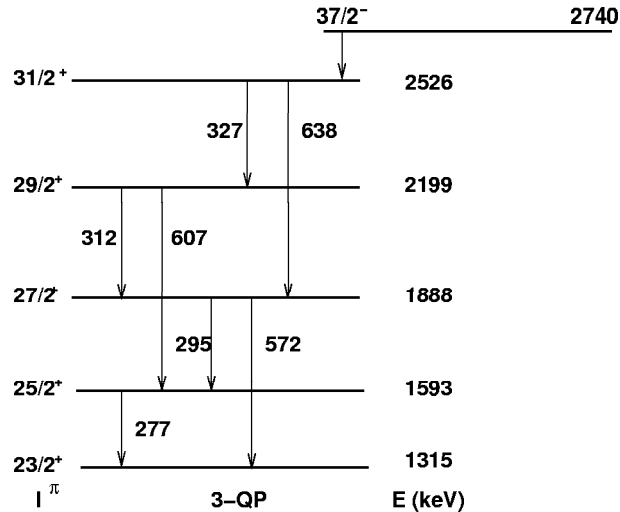


Figure 2: Decay of the $37/2^-$ isomer in ^{177}Hf

alternative way of determining [5]

$$|(g_K - g_R)/Q_0| = 0.933 \frac{E}{\delta \sqrt{I^2 - 1}}, \quad (5)$$

(E is the energy of the $\Delta I=1$ transition from a state with spin I), independent of in-beam spectroscopy data. This situation is illustrated in Fig. 2 for the case of a band built on the 3-quasiparticle $23/2^+$ state populated in the decay of the $37/2^-$ isomer in ^{177}Hf but can be also applied to one-quasiparticle ground states of $^{177,179}\text{Hf}$.

4 Experimental procedure and beam time request

Each isotope to be studied requires time to set up the beam and to observe the anisotropy as the dilution refrigerator is cooled from close to 1 Kelvin in order to get good base temperatures, gamma-ray anisotropies and to establish the sensitivity of the observed gamma transition count rates to resonance. Once this is established the resonance search can be conducted. A reasonable estimate is between 3 and 4 shifts per isomeric level to be resonated, that is **14 shifts** for the $A = 177, 180$ and 182 isomers. We propose to collect a source of the 25.1 d $A = 179$ isomer, implanted into iron, for subsequent off-line NMR/ON measurement. For this collection we request **1 shift**, giving a total of **15 shifts**.

Support from CERN: For the experiments proposed here, we will need liquid nitrogen for the detectors and liquid nitrogen and liquid helium for the $^3\text{He}/^3\text{He}$ dilution refrigerator.

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References

- [1] P. M. Walker and G. Dracoulis, *Nature (London)*, **399**, 35 (1999)
- [2] P. M. Walker et al., *Nucl. Phys.* **A349**, 1 (1980).
- [3] N. Boos et al., *Phys. Rev. Lett.* **72**, 2689 (1994).
- [4] F. R. Xu et al., *Phys. Lett.* **B435**, 257 (1998).
- [5] E. Ngijoi-Yogo et al., *Phys.Rev.* **C75**, 034305 (2007).
- [6] G. D. Dracoulis, F. G. Kondev and P. M. Walker, *Phys. Lett.* **B419**, 7 (1998).
- [7] M. L. Bissell et al., *Phys. Lett.* **B645**, 330 (2007).
- [8] S. M. Mullins, A. P. Byrne, G. D. Dracoulis, T. R. McGoram and W. A. Seale, *Phys. Rev.* **C58**, 831 (1998).
- [9] S. M. Mullins et al., *Phys. Rev.* **C61**, 044315 (2000).
- [10] H. Hübel, K. Freitag, E. Schoeters, R. E. Silverans, L. Vanneste and R. A. Naumann, *Phys. Rev.* **C12**, 2013 (1975).
- [11] A.Nieminen et al., *Phys. Rev. Lett.* **88**, 094801 (2002)
- [12] S. Muto, T. Ohtsubo, S. Ohya and K. Nishimura, *Hyp. Int.* **158** 195 (2004).
- [13] T. Shaw and N. J. Stone, *Atomic Data and Nuclear Data Tables*, **42**, 339 (1989).