EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ADDENDUM TO PROPOSAL IS460

To the ISOLDE and Neutron Time-of-Flight Committee

MAGNETIC DIPOLE MOMENTS OF HIGH-K ISOMERIC STATES IN Hf ISOTOPES

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CERN-INTC-2009-005 / INTC-P-229-ADD-1
19/01/2009

Abstract

Results of an experimental run carried out on the NICOLE facility August 14 - 19, 2008 include the first successful on-line NMR/ON resonance of a Hf isotope – the $37/2^-$ five-quasi-particle K-isomer in ^{177}Hf – using the unique ISOLDE HfF_3 beam. The measured magnetic dipole moment, $\mu(37/2^-$ 2740 keV state in ^{177}Hf) = 7.33(7) n.m., leads to a preliminary value for the collective g_R factor of the band built on this state of 0.22(3). The $37/2^-$ state is the highest seniority isomer for which data of this kind have been obtained. Additionally valuable precise E2/M1 mixing ratios in both the ground state band of ^{177}Hf and the band built on the $23/2^+$ three-quasi-particle isomer were obtained from measurement of the anisotropic gamma ray distributions from the highly oriented sample. Less success was achieved in measurements on other Hf isotopes. The reasons for the difficulties experienced are summarized and indications of how they may be overcome are given. Request is made for a second experiment, of 15 shifts, to complete the work by measuring the magnetic moments of the 8^- isomers in ^{180,182} Hf, the $23/2^+$ isomer in ^{177}Hf and the $25/2^-$ isomer in ^{179}Hf.

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I. Introduction

In this addendum request a status report on the experiment IS 460 is given in the form of a description of the run carried out at ISOLDE in August 2008 and its present state of analysis. Successes achieved and problems found are discussed.

Please refer to the original proposal [1] for details of the physics case for these experiments. The main objective is the precise measurement of magnetic dipole moments of high-K isomers in Hf isotopes using the unique HfF_3 beam at ISOLDE and the On-Line Nuclear Orientation Facility NICOLE. An overview of the isomers to be studied in given in Table 1.

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]	$6.0\cdot10^5$ 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]	$6.0\cdot10^5$
179	1106	$25/2^-$	25.1 d	n$9/2^+$[624], p$7/2^+$[404], p$9/2^-$[514]	$1.5\cdot10^7$
180	1183	8^-	5.5 h	p$7/2^+$[512], p$9/2^-$[514]	$2.4\cdot10^7$
182	1173	8^-	62 m	p$7/2^+$[512], p$9/2^-$[514]	$2\cdot10^4$

Table 1. Isomers to be studied in IS 460 experiment at the NICOLE facility.

II. The experiment of August 2008.

<u>The HfF_3 beam</u>

A very adequate beam was produced, giving excellent counting rates for the desired isomers in ^{177,179,180} Hf at the NICOLE dilution refrigerator.

A problem which emerged during the experiment was the strong accompanying Hf ground state beam, which gave rise to large total implant dose in times far shorter than is usual for on-line orientation experiment beam strengths. A high dose makes NMR/ON observation more difficult as discussed in more detail below.

A further problem, which was significant at mass A=182, was the presence of oxyfluoride ions at a relative concentration five times higher than had been seen previously. This gave rise to a beam involving a proton rich isotope, $^{166}LuOF_3$ which was strong enough, at mass A=182, to overwhelm the desired ^{182}Hf 8^- isomer beam. Strong positron annihilation radiation at 511 keV from this contaminant activity made study of the 8^- ^{182}Hf isomer impossible as shown below.

Low Temperatures

The low temperature aspects of the experiment went well, with fully on-line temperatures in the range 15-20 mK throughout, low enough to produce almost complete polarization of the implanted Hf isotopes that experienced the full hyperfine field of 67 T in the iron sample.

III Results and status of the analysis

The isomers studied

$^{177}Hf^{m2}$ and $^{177}Hf^{m1}$

The first high-K isomer implanted was the $37/2^-$, 2740 keV state in ^{177}Hf, which decays through a series of E2 and mixed E2/M1 transitions to the lower isomer $23/2^+$ at 1315 keV. This in turn decays through a similar series of transitions to the $9/2^+[624]$ state at 321 keV and to the $7/2^-$ [514] ground state. Data were taken on all accessible transitions - 21 in all - a few being lost through overlap with transitions in the nuclear orientation thermometers, ^{192}IrFe and ^{60}CoFe, used to measure the temperature of the sample.

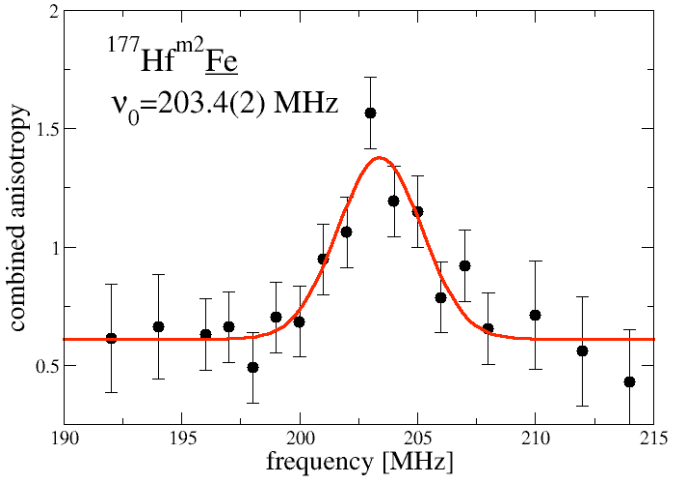

Fig.1 NMR/ON on the $37/2^-$ state, $^{177}Hf^{m2}$, in Fe.

NMR/ON was observed in transitions from the $^{177}Hf^{m2}$ isomer at 203.4(2) MHz as shown in Fig.1. The centre frequency gives the magnetic moment of this isomer as

$$\mu(37/2^-\ 2740\ \text{keV state in}\ ^{177}\text{Hf}) = 7.33(7)\ \text{n.m}\ .$$

Using this value for the magnetic moment combined with the value for $|g_K - g_R|/Q_0$ for the band built on this level (inaccessible to our experiment) from Mullins et al.

[3] gives a preliminary value for g_R of 0.22(3). This value is small compared to collective model (0.41) or valence-space model [4] (0.32) estimates and apparently indicates a dominating role for neutrons in the generation of collective angular momentum. This will need to be compared to realistic model calculations, but it presumably arises due to the relatively large quenching of neutron pairing correlations by the three neutron quasiparticles that contribute to the structure of the 5-quasiparticle isomer. This is the highest seniority isomer (i.e. with the largest quasiparticle number) for which data of this kind have been obtained. The data are expected to lead to an improved understanding of the pairing phase transition. Further data (using the same method) for lower quasiparticle numbers will be very valuable in obtaining a consistent physical interpretation.

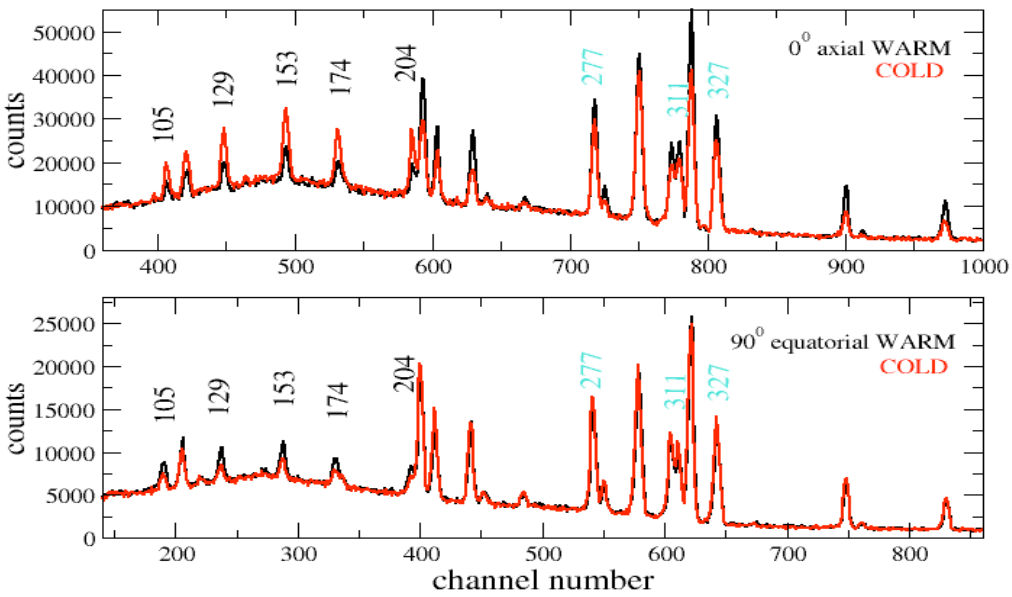

Fig. 2. Cold and Warm spectra from mass A=177 in detectors on the axis of polarization (above) and normal to it (below). Note in particular the strongly anisotropic distribution of the series of E2/M1 mixed transitions below 200 keV.

Angular distribution anisotropies of all transitions have been observed. Fig.2 shows the lower energy part of the spectrum in two detectors, one on the polarization axis and one normal to it. Strikingly large anisotropy $\mathcal{A}$ defined by

$$\mathcal{A} = \left(\frac{C}{W}\right)_{o^o} / \left(\frac{C}{W}\right)_{90^o}$$

is seen in the series of E2/M1 transitions, of opposite sign to the anisotropy of the 214 keV E3 transition which de-excites the $^{177}Hf^{m2}$ isomer. The analysis, which is still in progress to give final values, will yield E2/M1 mixing ratios in three transitions involving levels in the collective band built on the $23/2^+$ three-quasi-particle isomer and five transitions involving levels of the band built on the

$9/2^+[624]$ state. These mixing ratios δ yield the parameter $A = |g_K - g_R|/Q_0$ through the relationship [3]

$$\delta = \frac{0.993 E_{\gamma,\Delta I=1}}{A\sqrt{I^2-1}},$$

where *I* is the spin of the upper level.

$^{180}Hf^{m1}$

The second isomer implanted was the 8^- 1183 keV state in ^{180}Hf. Strong anisotropy was observed in all decay gamma transitions, however, despite diligent search, no clear evidence for an NMR/ON signal was obtained. Contributory reasons for the lack of success are a large accumulated Hf implant dose in the iron sample and strong power resonances in the radiofrequency line to the RF coil in NICOLE. Ways to overcome these problems are discussed below. The gamma transition anisotropies have been fully studied previously [2] and no new results were expected nor any found.

^{182}Hf

At this point in the experiment the problem of total accumulated dose was recognized and the Fe sample foil was changed, after due negotiation with radioactive safety personnel. The intention was to make measurements on ^{182}Hf, however a test gamma spectrum taken at an ISOLDE collection point, shown in Fig.3, revealed that there was a problem at mass A=182, the Hf spectrum being swamped by much stronger gamma transitions, including annihilation radiation at 511 keV, which could not come from a neutron deficient isotope. This activity not only masked the highest energy ^{182}Hf transition at 507 keV but also gave such strong background under all lower energy transitions as to make useful study of ^{182}Hf impossible with the available beam. The source of the problem was identified as ^{166}Lu, which was present in the ion source and which, combined with oxygen, produced an oxy-trifluoride at the same mass as HfF_3. Oxyfluoride contamination had been observed in previous tests of the Hf source but at a level at least five times lower compared with the trifluoride than in this experiment.

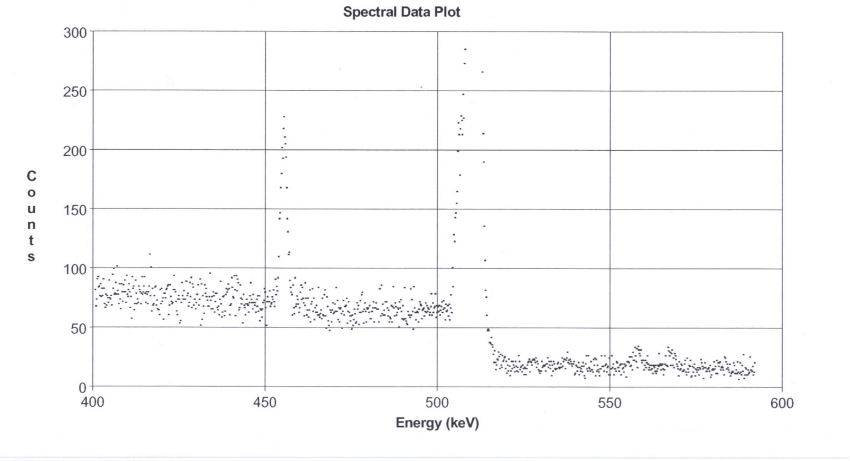

Fig.3. Test gamma spectrum at mass A=182. The strong 511 keV transition dominates the spectrum.

^{179}Hf

A sample of longer-lived activity, $T_{1/2}$ = 25 d, ^{179}Hf, implanted into iron, had been prepared off-line in a room temperature collection. As ^{182}Hf was inaccessible, this was loaded for the last day of on-line running time and was cooled successfully to about 20 mK. However the observed anisotropies were considerably lower than expected, of order 25% compared to greater than 50% for the ^{177,180} Hf activities. This indicated that the total Hf dose was too high and although a resonance search was made, no NMR/ON signal was found.

Measurements of anisotropy of all gamma transitions in the decay were made, including five pairs of pure E2 and mixed E2/M1 transitions from levels in the band built upon the $9/2^+[624]$ ground state of ^{179}Hf. Analysis is in progress, using a two site model with a fraction of implants experiencing the hyperfine field, to extract mixing ratios for the mixed transitions and the associated $|g_K - g_R|/Q_0$ values.

IV. The present situation

The experiment yielded the first on-line NMR/ON result in ^{177}Hf^{m2} and, in ^{177,179} Hf , three series of E2/M1 mixing ratios giving valuable measurements of properties of the bands and their band heads. Problems were identified which made observation of further NMR/ON signals difficult and rendered study of ^{182}Hf impossible with the source as then available.

The problems and their resolution are:

Implant dose

It has been well documented that when the implant dose in the small region of the iron foil in which the implants stop approaches 1 atomic percent then serious overlap of individual implant paths occurs leading to drop of observed gamma

anisotropy in on-line nuclear orientation experiments. At 0.1 atomic % or less, interaction between implants and local host lattice distortion is found to broaden NMR/ON resonances, making them more difficult to find.

Usually on-line experiments at NICOLE use beams of $\sim 10^5 - 10^6$ ions s^{-1} into an area of about 0.5 cm^2. This means a total implant dose of $\sim 10^{10} - 10^{11}$ per day. With implant energy of 60 keV the implants distribute over a region $\sim$ 30 nm thick in the iron sample, containing, in the same area, $\sim 10^{17}$ Fe ions. Thus the implant concentration is well below danger level even after a week of running.

However in this experiment there are strong beams of the stable ground states of the Hf isotopes present, at a level of about 10 - 20 pA, that is $\sim 5 \times 10^8$ ions s^{-1}. Such strong contaminant beams, unobserved in the gamma spectra, will reach the critical total dose concentrations after one or two days. We believe this to be one reason why NMR/ON was not observed except in $^{177}Hf^{m2}$, which was implanted into the fresh, undamaged Fe foil at the start of the experiment. The remedy is simple: to change the Fe foil after each isotope. This will allow at least 24 hours to search for resonances, as was demonstrated by the $^{177}Hf^{m2}$ success.

<u>Power resonances in the RF line into the NICOLE refrigerator.</u>

The introduction of RF power at the sample in NICOLE produces unwanted heating through eddy currents at all frequencies as well as the desired NMR signal at the nuclear resonance frequency. The RF input voltage level is adjusted so non-resonant heating is small. When it does not vary appreciably with frequency it causes no problems. However the RF line between the RF generator and the coil at the cold finger of the refrigerator is complex, and not amenable to detailed analysis. The RF field at the sample depends not only upon the input voltage to the line at the generator, but also on the behavior of the line and coil. Thus variations of RF power and non-resonant heating with frequency occur. The group working on this experiment had limited experience of resonant frequencies at NICOLE as high as 500 MHz [many are at 300 MHz and below] and were unprepared for the strong power resonances found, which gave rise to changes of sample temperature of tens of milliKelvin, and hence large changes of observed anisotropy, which disturb the base-line level of anisotropy against which true resonances are observed, and in worst case can simulate nuclear resonance. Such false resonances can be eliminated since they are seen not only in the isotope under study, but also in the nuclear orientation thermometer, but this takes time. Also the refrigerator has a built-in recovery time after such heating which is more than an hour so there is a hysteresis effect in observed anisotropies following a change of heating which depends upon whether the frequency is being raised or lowered. Such effects make observation of NMR/ON more problematic and should be eliminated as far as possible.

Power resonances may be shifted in frequency by adding length to the RF line, so as to avoid the NMR/ON search range for a given isotope. If the range is large, as it was in this work, they need to be studied by a careful survey of temperature vs

frequency at steady RF input voltage level so that, where necessary, the RF level can be adjusted to maintain a steady temperature and anisotropy baseline. This will be done over the higher frequency range before the start of a new experiment.

V. Beam time request.

The experiment in 2008 demonstrated that success can be achieved, whilst revealing problems which can be overcome. To mount a successful experiment on the remaining isotopes detailed in the original proposal a second experiment, again of **15 shifts, is requested**. The length is based on the need to change Fe sample foils after each isotope [$^{177}Hf^{m1}$, ^{180}Hf, ^{182}Hf], which must be done slowly and carefully, with radioactive protection liaison, taking 2-3 shifts each time. This time is added to the time to then cool the refrigerator from around 1 K to mK temperatures and establish the working base-line anisotropy [1 shift] as well as necessary NMR/ON search time of order 3 shifts per isotope. It is hoped that a second Hf source will not exhibit the oxygen contamination problem, which made study of ^{182}Hf impossible during the first experiment, however the other isomers are clearly open to experiment.

The high total dose problem may make it impossible to observe NMR/ON with longer-lived ^{179}Hf, although off-line preparation of a minimum strength source, scanning the beam to spread the dose, will be investigated.
Alternatively a short $\sim$ 1 shift period at the end of the experiment should suffice to make a weak ^{179}Hf sample on-line to be studied off-line after the end of the on-line experiment.

Support from CERN: For this experiment we will need liquid nitrogen for detectors and liquid nitrogen and helium for the dilution refrigerator.

Acknowledgement.

This research has been supported in part by US DOE grants No. DE-FG02-96ER40983 (University of Tennessee), No. DE-FG02-94ER40834 (University of Maryland) and by the EU Sixth Framework - RII3-EURONS (contract no. 506065).

References:

[1] Original proposal Magnetic dipole moments of High-K isomeric states in Hf isotopes, IS 460, 2008

[2] J.R.Stone et al., Phys. Rev. C76, 025002 (2007)

[3] S.M.Mullins et al., Phys.Rev.C58, 831 (1998)

[4] Valence space includes particles or holes (whichever is smaller) relative to the nearest closed shell and $g_R = N_p/(N_p+N_n)$ with $N_p=10$ and $N_n=21$ for this case.