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PARITY NON-CONSERVATION IN NUCLEI: THE CASE OF ^{180m}Hf REVISITED

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1 Abstract

The technique of low temperature nuclear orientation (LTNO) [1] has been used frequently to observe parity (P) nonconservation in weak interactions [2]. The strongest effect reported so far has been observed in the 501 keV $8^- \rightarrow 6^+$ transition in ^{180m}Hf [3]–[12]. The techniques used were circular polarisation of gamma-rays from an unoriented source [3]–[8] and LTNO [9]–[12] in late 1960's and early 1970's. However, careful examination of these thirty year old results indicates that the considerable improvements in technique of the experiment, available now at ISOLDE, should be applied to the ^{180m}Hf system to confirm or deny results of these landmark experiments.

2 Introduction

The technique of LTNO is well suited for observation of fundamental symmetry violating effects in nuclear processes [13, 14] and has made a strong contribution to the search for parity, time (T) and sumultaneous PT non-conservation detected through nuclear gamma-decay. The experiments were supported by extensive theoretical work exploring the implication of finding non-zero P, T, and PT non-conserving terms in the nucleon-nucleon potential. It has been argued that the presence of a strong parity non-conserving (PNC) effect in a nuclear gamma-transition might be an indication of the presence of T non-conservation in that transition [15, 16]. Thus searches for cases of P non-conservation potentially select suitable systems for testing the CPT theorem [17]. Data on the strength of PNC mixing are ultimately used for derivation of parity non-conserving terms H_{PNC} in the nuclear hamiltonian.

PNC effects in bound nuclear systems have been found in several nuclei (for review see e.g. [13, 14]). However, only three PNC measurements to date lead to H_{PNC} differing from zero by more than two standard deviations (see Table 1 and [18, 19]).

^{180m}Hf, the first measured PNC case in nuclear gamma-decay using the LTNO technique [9, 10, 12], is by far the most accurate and statistically significant result. The LTNO experiment was performed twice by the same group [9, 12]. The same ^{180m}Hf system was studied by several groups using measurement of the circular polarisation of gamma rays from an unoriented source [3]–[8] with different types of polarimeter. The results are summarised in Table. 2 and most of them indicate a PNC effect on the 501 keV transition in the decay of ^{180m}Hf (see Fig. 1).

The gamma-ray circular polarisation experiments suffer from low polarisation detection efficiency and require strong radioactive sources. This in turn worsens their energy resolution and the effect, measured for a particular gamma-ray, is diluted by the presence of other gamma-rays in the spectrum of the studied isotope. Complicated corrections needed to be made to the data to extract the desired effect. The polarisation is dependent on three multipole mixing ratios (see below) and in principle another independent measurement is needed to analyse the data fully. LTNO experiments performed so far suffer from several potentially serious problems with ^{180m}Hf sample preparation, cooling technique and data reduction which we will discuss in the next section in more detail. We therefore propose a new LTNO measurement, taking advantage of the most advanced technology now available at ISOLDE.

3 Angular distribution of gamma-rays from oriented nuclei.

The angular distribution of gamma-radiation from nuclei oriented at low temperatures by hyperfine interaction in a ferromagnetic host is expressed as

$$W(\theta) = \sum_{k=0}^{k_{max}} B_k U_k A_k Q_k P_k(cos\theta) \tag{1}$$

where all symbols have the usual meaning in the LTNO context [20]. B_k are orientation parameters, describing the mechanism of orientation of nuclear spins via hyperfine interaction at low temperatures. θ is measured with respect to the orientation axis, defined by the direction of the applied external magnetic field acting on the ferromagnetic host containing the atoms of nuclei of interest. U_k are deorientation coefficients, taking into account the effect of all unobserved radiation between the oriented state and the initial state of the studied gamma-ray. A_k are angular distribution coefficients of the observed gamma-rays, Q_k are geometrical factors and P_k are ordinary Legendre polynomials. All the coefficients in (1) are normalised to 1 at k=0. The summation goes over even values of k for parity conserving radiation. If parity is not conserved in a transition in question, contributions from terms with k odd to (1) are non-vanishing. The effect of these terms is measured by comparing intensities of the emitted radiations at angle θ and θ+180^o, which is dependent on the k-odd terms only, as

$$\begin{aligned}\mathcal{A}(\theta) &= \frac{W(\theta) - W(\theta + 180^o)}{\frac{1}{2}(W(\theta) + W(\theta + 180^o))} && (2)\\ &= \frac{\sum_{k=odd} 2B_k U_k A_k Q_k}{\sum_{k=even} B_k U_k A_k Q_k} && (3)\end{aligned}$$

The usual choice of angle is θ=0^o where the effect is maximum. The angular distribution coefficients A_k are dependent on spins I_i and I_f of the initial and

Table 1: Magnitude of the PNC matrix element between states of the same spin and opposite parity.

Nucleus	$\langle H_{PNC} \rangle$
^{19}F	380(100) meV
^{93}Tc	0.59(0.19) meV
^{180m}Hf	1.0(0.1) meV

final states of a gamma-transition and the multipolarity of the radiation L. For a parity conserving transition between states of the same (opposite) parity the possible multipole structure is M1,E2,M3,E4,..., (E1,M2,E3,M4,...). The parity non-conserving contributions to the multipole make-up will be of a 'irregular' multipolarity, e.g. M1+E1+... or E2+M2+....The multipole order L is limited by the condition $|I_i - I_f| \leq L \leq I_i + I_f$. In practice, usually only the first two most intense multipole components are taken into account and the multipole mixing ratio δ is defined as [13]

$$\delta = \frac{\gamma(\sigma' L')}{\gamma(\sigma L)} \tag{4}$$

where $\gamma(\sigma L)$ is the amplitude of the transition matrix element and L$'$ = L+1. The measure of the 'irregular' contributions is given by the mixing ratios

$$\epsilon = \frac{\gamma(\sigma' L)}{\gamma(\sigma L)} \tag{5}$$

and

$$\epsilon' = \frac{\gamma(\sigma L')}{\gamma(\sigma' L')} \tag{6}$$

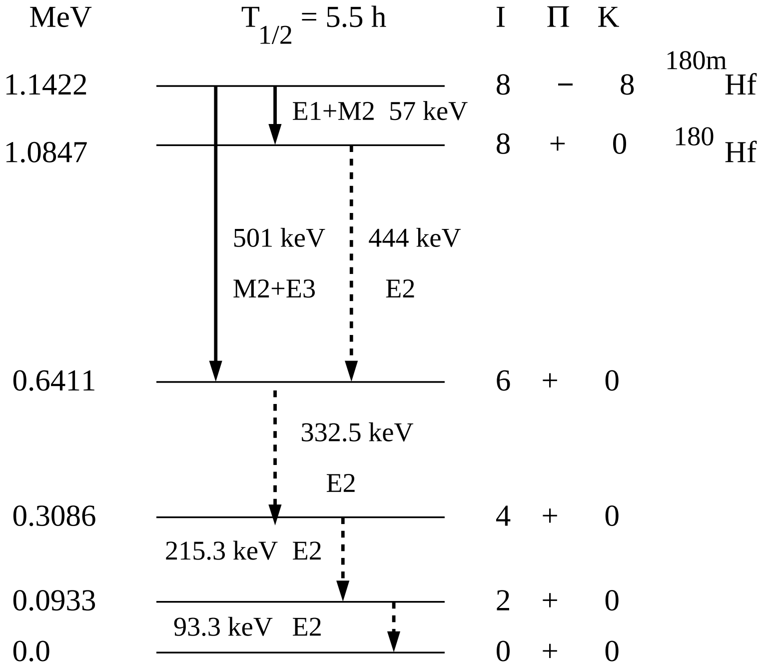
where for σ'=E σ=M and vice versa.

In order to determine the value of $\mathcal{A}$ from (3), standard methods for determination of B_k, Q_k and U_k are applied. If parity mixing is present, evaluation of the angular distribution coefficients A_k requires knowledge of the regular mixing ratio δ as well as the 'irregular' mixing ratios ϵ and ϵ'. δ can be determined by some other suitable method like angular correlation, electron conversion or gamma-ray linear polarisation. Thus the unknowns in (3) are ϵ and ϵ' which are to be extracted from the measured value of the asymmetry $\mathcal{A}$. If both are non-zero, a second, independent, measurement, such as gamma-ray circular polarisation, dependent on the mixing ratios as [13],

$$P_\gamma = \frac{2(\epsilon + \epsilon' \delta^2)}{(1+\epsilon^2) + \delta^2(1+\epsilon'^2)}, \tag{7}$$

is needed to obtain independent values of ϵ and ϵ'. Thus in principle reliable LTNO and circular polarisation results are required input for full analysis of the ^{180m}Hf system. However, usually one of the irregular mixing ratios can be regarded as small on the basis of known γ-ray transition rates. Taking the Weisskopf estimates as a scale, the transition rates for for constant photon energy decrease by a factor of order 10^5 for a unit increse in L, with ML-transitions a factor of order 10^2 slower compared to EL-transitions. For example, ϵ(E2/M2) will be considerably larger than ϵ'(M3/E3).

Figure 1: Decay Scheme of ^{180m}Hf.



4 The case of ^{180m}Hf.

Parity non-conservation studies in gamma-decay of the isomeric 8^- state in ^{180}Hf have been described in detail several times (see [13] and references therein). The parity mixing, arising because of the proximity in energy of the two I=8 states (ΔE=57 keV) with opposite parity at 1142 and 1085 keV (see Fig. fig1) is significantly enhanced due to large K-forbiddness (ΔK=8) which slows down the 'regular'gamma-transitions and allows the 'irregular' components to be seen. Thus although the PNC matrix element is rather small (see Table 1), the total enhanced effect is unusually large.

4.1 Present status

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The reported nuclear orientation experiments [13] were conducted using technology available in early 1970's. The low temperature necessary to polarize Hf nuclei was produced by adiabatic demagnetization of a chromium potassium sulfate salt pill, cooled to 1K and demagnetized to a temperature of ~10 mK. The ^{180m}Hf was prepared by neutron irradiation either of a sample of $HfZrFe_2$ or of ^{180}Hf alone, which was then used to prepare the alloy with $ZrFe_2$. The effective hyperfine field acting on the dilute Hf impurities in $ZrFe_2$ was deduced to be 20(2)T. The temperature of the sample was between 16 to 30 mK rising

Table 2: Experimental data on gamma-ray circular polarisation of the 501 keV transition. $P_\gamma=\epsilon.\delta$ where ϵ is the polarisation detection efficiency and δ is the experimental asymmetry.

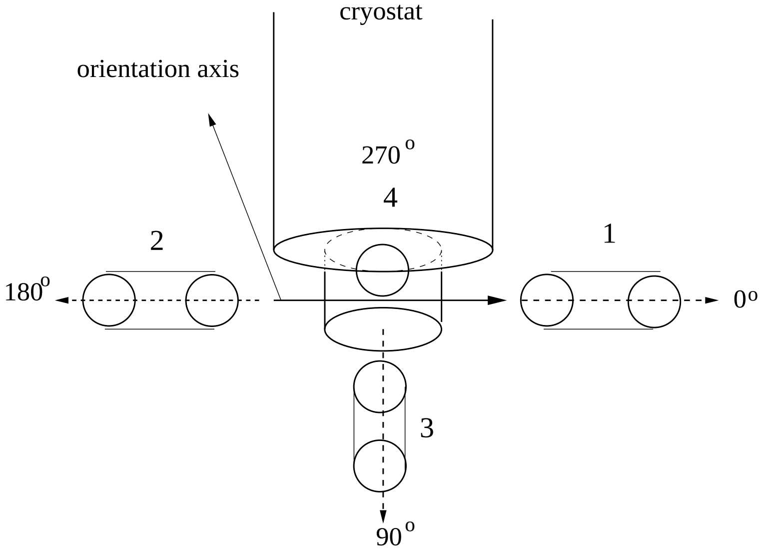
$\delta\times 10^{-5}$	P_γ [%]	Ref.
0.9±2.9	≤2%	[3]
-4.2±2.6	-1.4±0.9	[4]
-5.0±0.8	-0.28±0.05	[5]
-4.6±1.1	-0.23±0.06	[6]
-2.0±0.4	-0.20±0.04	[7]
-0.49±0.16	-0.19±0.06	[8]

slowly during the measurement as the salt pill warmed up. Steady, controled temperature was not available in the 1970's. The external polarising magnetic field, defining the orientation axis, was produced by two pairs of perpendicularly oriented Helmholtz coils and rotated in a controled way by 90^o or 180^o degrees during the course of the experiment. Two (four in some experiments) 40 cm^3 Ge(Li) detectors were used to collect data. Typical duration of one measurement was about 10 hours due to the short life-time of ^{180m}Hf ($T_{1/2}$=5.5 h) and warm-up characteristics of the salt pill. Two lines in the gamma-ray spectrum were monitored (see Fig. 1): the 444 and 501 keV transitions. In order to achieve significant statistics, rather strong samples were used [11], ∼200-400 counts/sec in the 444 keV photopeak and ∼40-80 counts/sec in the 501 keV photopeak at the beginning of the experiment. These count rates were reduced by a factor of ∼3-4 by the end of the measurement. As the source decayed, with initially very high total counting rates, both the width of the peaks and the peak-to-background ratio were continuously changing. In order to compensate for changing efficiency (dead-time corrections) of the small detectors with increasing count rate, empirical correction factors were introduced with no explicit definition [11]. These factors were different for each detector at a given count rate.

The observable measured was the forward-backward (0^0 - 180^0) asymmetry of the angular distribution of the 501 keV E3+M2 gamma transition searching for the 'irregular' E2 component, assuming that the irregular M3 contribution will be negligibly small. The angular distribution of the 444 keV transition, with the assumptions that it is of pure E2 multipolarity and that the unobserved 57 keV transition is of pure E1 multipolarity, was used to determine the temperature of the Hf sample. This was different from the temperature of the salt pill, measured by a ^{60}Co(Fe) thermometer. No other transition in the decay of ^{180m}Hf was monitored for the elimination of possible systematic errors.

The 'irregular' E2/M2 mixing ratio ϵ for the 501 keV transition has been extracted using expression (5), taking the 'regular' mixing ratio δ=+5.3(3) [9].

Figure 2: Detector arrangement for measurement of angular distribution of gamma radiation of oriented ^{180m}Hf(Fe).



It was argued that circular polarisation data showed that it was sufficient to take into account only the lowest order 'irregular' multipole E2, neglecting any M3 components.

4.2 Proposed improvement of the experiment.

The new LTNO experiment at the NICOLE facility will take advantage of the unique ^{180m}Hf beam, provided by the GP isotope separator at ISOLDE. Hf atoms will be implanted directly into a cold Fe host attached to the cold finger of the ^{3}He+^{4}He dilution refrigerator at temperatures down to 10-12 mK which can be held steady as a long as required. The temperature will be measured by a ^{191m}Ir(Fe) thermometer which has sufficient sensitivity at the high temperatures at which ^{180m}Hf ($\mu \sim 9$ n.m.) will orient in iron. ^{191m}Ir has just one strong γ-ray at 129 keV and will not interfere with the transitions measured in the decay of ^{180m}Hf. The continuous implantation of ^{180m}Hf will build up a sample in equilibrium allowing measurement of the angular distribution of the emission probability of relevant gamma-rays without interruption until sufficient statistics of the results is reached. In comparison with the previous experiment, the hyperfine field of Hf in Fe ~65 T [21]) is more than three times higher than that of HfZrFe$_2$. This allows higher degrees of polarisation and a more sensitive measurement.

Gamma radiation will be detected by 4 high efficiency Ge detectors arranged as shown in Fig. 2. Three of the detectors (1,2,4) will be in the plane of the incoming beam and the orientation axis at angles 0^o, 180^o, and 270^o and one of them (3) perpendicular to the plane below the cryostat at 90^o to the orientation axis. A special frame will be built to support these detectors at adjustable positions to prevent systematic errors due to detector misalignment and to determine the position of the orientation axis from measurement of the angular distribution.

This arrangement of detectors will allow the measurement of the main experimental fingerprint of the presence of a PNC effect, the forward-backward asymmetry $\mathcal{A}(0^o)$. The detectors placed at 90^o and 270^o will be used to measure details of the angular distribution, determine temperature of the sample and serve as an additional check on systematic errors as $\mathcal{A}(90^o)$ is exactly equal to zero. Data at fixed temperature will be taken for both orientations of the polarizing magnetic field (+,-) which will be changing periodically during the experiment. The change will be controled electronically and integrated into the data acquisition system to assure reproducibility of the field change procedure. In this way two sets of counting rates $\mathrm{N}^+ = \mathrm{W}(0^o)$ and $\mathrm{N}^- = \mathrm{W}(180^o)$ will be available for each detector. The anisostropy $\mathcal{A}(0^o)$ will be evaluated for each of the detectors 1 and 2 separately using standard statistical averaging procedures over the full set of data taken during the run for both orientations of the magnetic field.

It is essential for the success of the experiment to identify major sources of systematic errors which would mimic the 'true' effect. In the previously reported LTNO experiments no full numerical account of monitoring for spurious effect was given. In the present experiment one concern is a possible movement of the implanted source during the course of the experiment, introduced by the magnetic field reversals. This effect is co-ordinated in time with data taking. However, ion beam deflection will be perpendicular to the orientation axis, giving only a small, second order, change in count rate. Nevertheless such effects could cause artificial asymmetry by changing the effective solid angle of detectors or by affecting the gamma-ray absorption in the material of the cryostat between the source and the detectors. These effects may be energy dependent. Another possible cause of source movement, instability in the beam optics, will not be co-ordinated with field reversals and will tend to average out over several data taking cycles.

The tool for detection and elimination of these effects is the presence of 'control' γ-rays, emitted from the same source as close in energy as possible to the γ-ray of interest. In the case of ^{180m}Hf the transitions $8^+ \rightarrow 6^+$ 444 keV, $6^+ \rightarrow 4^+$ 332 keV and $4^+ \rightarrow 2^+$ 215 keV are available to monitor spurious effects. A double ratio for two lines p,q (one the monitoring line and one the 505 keV line) can be calculated [19] which is practically independent of all spurious processes considered above. If it differs from unity, one of the transitions p or q shows 'true' asymmetry.

Another control available is measurement of the the asymmetry $\mathcal{A}(0^o)$ not only at the base temperature of the cryostat, but also as function of temperature.

In summary, the continues sample production by implantation of the ^{180m}Hf beam leading to emission of γ-rays with a stable intensity during the course of the experiment, use of a superior LNTO apparatus with a lower sample base temperature and full control of the temperature regime of the experiment, together with detailed monitoring and analysis of sources of possible spurious effects should form a basis for a successful experiment.

5 Beam time request

The previous experiment reported $\mathcal{A}(0^o)$ values of order of 1%. The ^{180m}Hf beam has been measured to be 2.8×10^6 atom/μC. With estimated transmission efficiency to the refrigerator, detector solid angle and detector efficiency, a double ratio measurement of $\mathcal{A}(0^o)$ to 0.1% should take two and a half shifts.

Three temperature points, each repeated, of this precision – 15 shifts

A dummy control experiment with the sample unoriented — 3 shifts

gives a total request of 18 shifts for the actual measurement.

In addition, we request 8 shifts for beam and set-up testing prior to the actual measurement, giving the total of 26 shift.

Table 3: Summary of beam time request.

Beam	Min Intensity	Target material	Ion source	Shifts
^{180m}Hf	10^6	Ta metal foil	Hot plasma	26

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