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PARITY NON-CONSERVATION OBSERVED IN NUCLEAR γ-DECAY OF ^{180m}Hf*

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This paper presents results of experiment which studied (using the Nuclear-Orientation technique) the γ-decay of isomeric ^{180m}Hf. The described experiment used the newly developed mass-separated ^{180m}Hf beam at ISOLDE, CERN which was implanted into an iron foil polarized at millikelvin temperatures. The observed irregular admixture of E2 to M2/E3 multipolarity in 501 keV $8^- \longrightarrow 6^+$ γ-transition was the clear experimental evidence for parity mixing in nuclear states. The temperature dependence of the forward–backward asymmetry of the angular distribution has been measured over extended range of temperatures (and therefore nuclear polarizations), proving a parity mixing of the 8^- and 8^+ nuclear levels. The value found for the E2/M2 mixing ratio $\varepsilon = -0.032(2)$ of this transition is in close agreement with averaged value of all previously published results $\varepsilon = -0.030(2)$.

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1. Motivation

Parity is one of the most fundamental symmetries of physics. Proving that parity is being conserved or not forms basic constraints upon physical theories. The discovery of parity non-conservation (PNC) in the weak interaction was one of the most important discoveries of modern physics.

In 2006 it was exactly 50 years since Lee and Yang suggested that the invariance under mirror reflection might be violated on the microscopic scale by the weak interaction [1]. Very soon (in January 1957) this suggestion had been experimentally confirmed by observing parity non-conservation in the β-decay of a polarized sample of the radioactive ^{60}Co nucleus in a famous experiment of Wu [2]. Parity non-conservation has since then become a basis of formulation of the weak interaction and the Standard Model. However, whether parity is conserved in nuclear phenomena remains a challenge to both experiment and theory. Parity violation is characteristic for the weak nuclear force, while the strong nuclear force and the electromagnetic force do preserve parity. Parity mixing in bound nuclear systems is understood as a consequence of weak (parity violating) interaction terms in the nuclear Hamiltonian and precise calculations of this phenomenon are not yet available.

The measurement of an irregular E2/M2 mixing in the $8^- \longrightarrow 6^+$, highly K-forbidden 501 keV γ-decay of the 5.47 h isomer of ^{180m}Hf provides a unique opportunity to study PNC in the electromagnetic and strong sectors due to a very large amplification of the observable effect. This amplification arises from the details of the nuclear structure, namely the proximity of the 8^+ and 8^- levels and the very different structure of the 8^- level with respect to the sequence of positive parity levels below to which it decays (Fig. 1) which causes a strong hindrance of the regular transition.

Parity mixing in the decay of ^{180m}Hf was established already in 1970s when a forward–backward asymmetry of about 1% was observed in the emission of the 501 keV γ-transition — the only clear demonstration of this type of parity violation until now [3, 4]. No other nucleus has been found where the parity non-conserving effect (stronger than two standard deviations) was observed [5]. It is, therefore, very important to check the validity of this significant result. This paper describes a re-measurement of the ^{180m}Hf isomeric decay, using the up-to-date techniques of on-line nuclear orientation. Developments of nuclear orientation technique over 30 years have enabled us to achieve higher and stable degrees of polarization and the possibility to use radioactive beam in online experiment made it possible to measure continuously with steady source strength instead of offline measurements on a series of decaying samples. Previous experiments used a series of samples which were cooled by adiabatic demagnetization method and then were steadily warming (hence slowly changing degree of nuclear polarization) and were also decaying with the 5.47 h half-life (hence variable dead-time and electronic pile-up correction).

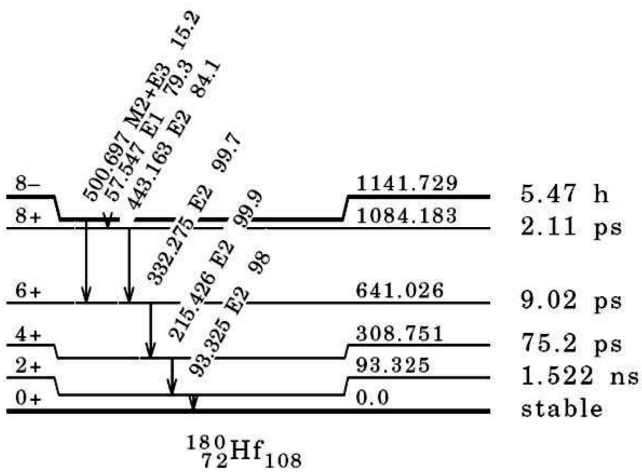

Fig. 1. The level scheme of ^{180}Hf. The 8^-–8^+ doublet, separated by 57 keV, and the γ-decay modes are indicated. The 8^- level is isomeric with a long half-life of 5.5 h, due to its $K = 8$ angular momentum projection quantum number. The 501 keV line exhibits the PNC effect, shown via the parity violating mixing E2/M2 in addition to the "normal" M2/E3 mixing. The other lines exhibit a null effect.

2. Experiment

The experiment was performed at the ISOLDE isotope separator facility, CERN, using the NICOLE on-line nuclear orientation ^{3}He–^{4}He dilution refrigerator. The ^{180m}Hf isomer beam was produced by bombarding thick Ta/W target with 1.4 GeV protons and then extracting the beam of $(HfF_3)^+$ ions with energy 60 keV. The Hf nuclei were implanted into the pure (99.99%) iron foil in the dilution refrigerator which was cooled to millikelvin temperatures and oriented in external magnetic field of 0.5 T. The direction of this magnetic field, defining the direction of the polarization axis of the sample, was periodically reversed during the experiment.

Gamma radiation was detected by 3 large HPGe detectors, two on the magnetic field axis at 0° and 180° (depending upon the field direction — "L" = Left, "R" = Right) and one at 90° to the axis of polarization. The spectra were accumulated in files of 300 s duration throughout the experiment, pulses from a regular pulser sent to the pre-amplifiers were used to correct for pile-up in detectors and dead-time in the electronics. The gamma ray spectrum contained six strong, fully resolved, transitions at 501 keV, 444 keV, 332 keV and 215 keV from ^{180m}Hf, and at 137 keV and 122 keV from the ^{57}Co nuclear orientation thermometer.

The aim of the experiment was simple. The sample was cooled to achieve high degrees of nuclear polarization and the polarizing magnetic field was reversed periodically. For parity conserving transitions there should be no change in anisotropy — therefore any observed change would be proportional to the parity non-conserving transition amplitude. The main objective of the experiment was to observe the temperature dependence of the parity non-conserving amplitude reported in the 501keV transition over a wider range of temperature, and hence to higher degrees of nuclear polarization, than had been possible in the previous studies. The forward–backward asymmetry of the 501 keV γ-rays measured as a ratio of the count rates in two horizontal γ-detectors (at 0° and 180°) — a direct consequence and a direct proof of the PNC effect — has been looked for.

3. Results

Since in online experiment the source strength changes in time depending on the intensity of incoming beam, all anisotropy and asymmetry measurements are in the form of ratios of counts in detectors at different angles to the polarizing field. Furthermore, to eliminate effects of variable dead-time and pile-up during different counting periods, each raw peak count is divided by the pulser peak count for the same file and detector (pulser-normalized count). The quantity $W_{\rm exp}(\theta)$ is the ratio of the pulser normalized count in a specific gamma peak in a detector at angle θ to the polarization axis, to the pulser normalised counts in that peak from an unpolarized sample, the 'warm' counts. The measured value of anisotropy $a(T)$ is given by the ratio $[W_{\rm exp}(0)/W_{\rm exp}(90) - 1]$ from which temperatures are deduced and the measured asymmetry $A(T)$ is given by $2[W_{\rm exp}(0) - W_{\rm exp}(180)]/[W_{\rm exp}(0) + W_{\rm exp}(180)]$, sensitive to the degree of parity non-conservation.

When the applied external magnetic field (and hence the direction of nuclear polarization) is reversed, the asymmetry, and with it any difference in this ratio from unity, must change sign. Eight magnetic field reversals have been made within the temperature range of 7–60 mK. The data show variation about unity which reverses at every field reversal. The asymmetry A was evaluated for each field reversal for all transitions observed. The analysis shows that there is a clearly established non-zero result of between 0.9% and 1.5% for the 501 keV γ-transition in every reversal in which the nuclear sample was polarized depending on the temperature (and hence the degree of polarization) of the sample. The analysis yields the value of asymmetry at 20 mK as $A_{501\mathrm{keV}}(20\mathrm{mK}) = 1.21(8)$. All other γ-transitions show zero asymmetry within statistical error.

The asymmetries measured for the 501 keV transition are plotted *versus* $1/T$ in Fig. 2 where they may be compared with theoretical calculations of the asymmetry obtained for selected values of the E2/M2 mixing ratio ε. The analysis gives value of the weighted average value of this mixing ratio as $\varepsilon = -0.032(2)$.

The results we obtained (presented in Fig. 2) show the parity-violating effect in the 501 keV γ-transition and the value of the asymmetry of the order of 1% (see details in [7]) confirms the previous experiments [3, 4, 6]. We clearly observe PNC effect (15σ) for the 501 keV γ-transition while no effect is observed for the reference γ-transitions 443, 332 and 215 keV.

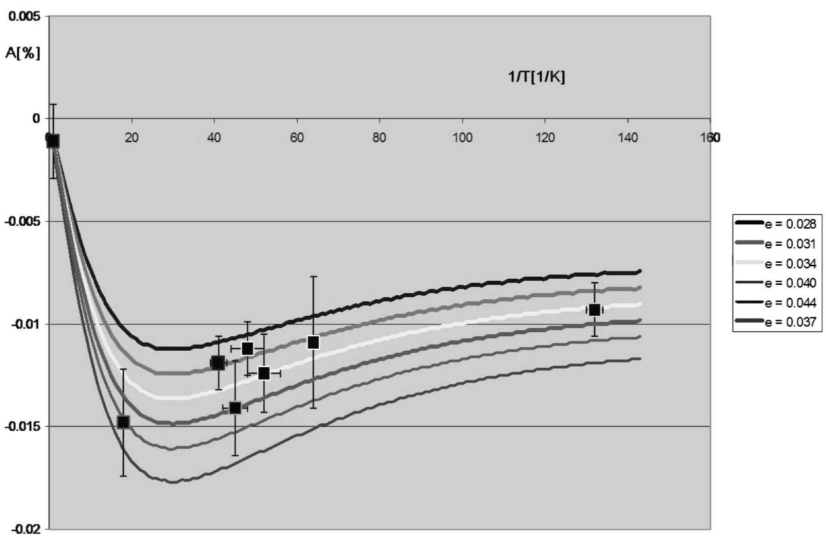

Fig. 2. Measured asymmetry A of the 501 keV γ-transition as a function of inverse temperature $1/T$ compared with calculations using a range of values of the E2/M2 mixing ratio ε.

4. Discussion

Our experiment aimed to eliminate possible systematic errors. Magnetic field reversals were carried out from different initial field directions, pile-up and dead-time corrections were checked via measurements with and without pulser. The Left/Right ratio of parity conserving transitions 332 keV/444 keV was looked at to prove the absence of any spurious effect. The temperature was varied in wide range in order to change significantly the degree of polarization of the hafnium nuclei and therefore observe the temperature variation of the asymmetry. The result for the irregular E2/M2 mixing ratio in the 501 keV transition, $\varepsilon = -0.032(2)$, is in a good agreement with the long accepted best value $-0.030(2)$ [4]. So the present work fully confirms the older results and extends them by checking some sources of systematic errors and observing the temperature dependence of the asymmetry, which fully agrees with expected behaviour.

Unfortunately, the relation between the observed experimental value of asymmetry A, the corresponding value of (PNC enabled) irregular mixing ε and the amount of admixture of irregular parity state in the decaying state of ^{180m}Hf is not straightforward. On the one hand, specific structure of the involved nuclear levels (mainly the high degree of K-forbiddeness of the 8^- decay) causes the strong hindrance of normal decay matrix elements and therefore enables us to experimentally observe a PNC effect. On the other hand, this complexity prevented up to now effective theoretical calculation of the expected degree of parity non-conservation in this case. Therefore the theory should come now with understanding and interpretation of this confirmed experimental result.

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