EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of the β-asymmetry parameter in the decay of ^{133}Xe.

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Abstract: We propose to measure the emission asymmetry in the pure Gamow-Teller β^- decay of the isotope ^{133}Xe with the NICOLE low-temperature nuclear orientation setup, to search for a tensor component in the weak interaction. The transition was selected for its large sensitivity which is due to the low beta-endpoint energy, the large nuclear polarization that can be obtained and the possibility for a precise calibration of this polarization. Furthermore, we present improvements of the detection setup, the data acquisition, and the Geant4-based simulation routine used in the analysis. A total precision of about 1% is anticipated rendering this experiment sensitive to a value of $(C_T + C'_T)/C_A = 0.03$ (90% C.L.).

Requested shifts: 9 shifts, (split into 3 runs over 2 years)

Introduction

Whereas the standard model can explain all experimental data obtained till now, it contains many parameters that have been fixed by experiments as well as a number of features that had to be inserted *ad hoc*. Finding new physics, not included in the standard model, would indicate in which direction the model is to be extended towards a more encompassing theory of particles and their interactions. This can be done at colliders, such as the LHC, where one can search for the direct production of e.g. new gauge bosons and supersymmetric particles. An alternative and complementary approach [1] are precision measurements at lower energies, i.e. in nuclear β decay, muon decay and meson decays, where one then searches for the small deviations such new particles would cause in the value of experimental observables. In muon and pion decay new results were recently reported by respectively the TWIST [2] and the PIBETA collaborations [3]. In nuclear β decay new results were reported from measurements with ^{21}Na [4], ^{37m}K [5], ^{60}Co [7], ^{80}Rb [8], ^{114}In [6] and ^{6}He [12].
Here we focus on a possible tensor contribution to the weak interaction. Under very general assumptions, the most recent global fit [13] yielded the following limits on the amplitudes of tensor couplings relative to the axial vector ones (95.5% C.L.)

$$|C_T^{(\prime)}/C_A| < 0.09 \tag{1}$$

This leaves sizable room for such exotic contributions to the weak interaction in β decay. Similar limits are obtained from results in muon decay and pion decay.
This proposal constitutes the second phase of our β-asymmetry project IS431 [14] which produced results already for ^{114}In [6] and ^{60}Co [7] (both from measurements performed at Leuven) while data taken at ISOLDE/NICOLE with ^{67}Cu are currently being analyzed. With ^{114}In we found $-0.082 < (C_T + C_T')/C_A < 0.139$ (90% C.L.) while the measurement with ^{60}Co resulted in $-0.094 < (C_T + C_T')/C_A < 0.018$ (90% C.L.). With many conditions being improved with respect to these previous measurements, both in the experiment itself as well as in analysis and simulations, a sensitivity of 0.03 (90% C.L.) for the quantity $(C_T + C_T')/C_A$ is aimed at in the experiment with ^{133}Xe that is proposed here.

Proposal: β-asymmetry measurement of $^{133(m)}$Xe

Physics case

The β-asymmetry parameter $\widetilde{A}$ of a pure Gammov-Teller decay is independent of the nuclear matrix element, making this observable an excellent probe for tensor-type weak currents. As the 3/2+ ground state of ^{133}Xe decays via a pure Gammov-Teller transition to the 81 keV 5/2+ exited state of ^{133}Cs (99 % branching ratio), the β-asymmetry parameter $\widetilde{A}$ becomes (using the formalism of Ref. [15])

$$\widetilde{A} \cong 0.6 + \frac{\alpha Z m}{p} Im\left(\frac{C_T + C_T'}{C_A}\right) + \frac{\gamma m}{E_e} Re\left(\frac{C_T + C_T'}{C_A}\right) \quad . \tag{2}$$

Here, α is the fine structure constant, Z the charge of the daughter nucleus, m the rest mass of the electron, p and E_e the momentum, respectively the total energy of the β-particle and $\gamma = \sqrt{1-(\alpha Z)^2}$. The last term in Eq. 2 is the so-called Fierz interference term.
As the R-correlation measurement of ^{8}Li [16] severely constrains a time-reversal violating

tensor-type interaction, a measurement of $\widetilde{A}$ will mainly be sensitive to the real term in Eq. 2. The factor $\underbrace{(\gamma m/E_e)}$ is rather large, viz. 0.55 at the β endpoint energy for ^{133}Xe (i.e. 346 keV). As a consequence, $\widetilde{A}$ of ^{133}Xe is very sensitive to non-zero values of C_T and C'_T.

Recoil terms, such as weak magnetism, slightly modify the SM expectation value of 0.6. However, for the fast, allowed β transition we are dealing with here (with log ft = 5.6) this correction can be calculated to be only 0.003(2) (see also [6]) so that it does not play a significant role for the interpretation of the result to be obtained.

Experiment: measurement of the β-asymmetry parameter in the decay of ^{133}Xe

The experiments will be carried out with the NICOLE low-temperature nuclear orientation setup. The $^{133(m)}$Xe nuclei will be implanted into a 99.99 % pure Fe foil, soldered onto a Cu sample holder, which is at a temperature between 5 mK and 4 K. Implanting into a cold Fe foil significantly improves the implantation quality [17].

The ^{133}Xe and ^{133m}Xe nuclei produced at ISOLDE will be polarized by the combination of millikelvin temperatures, which can be reached with the NICOLE dilution refrigerator, and the large magnetic hyperfine field ($\approx$ 160 T) which Xe impurities experience in a Fe host foil [18, 19]. At temperatures below 10 mK, the polarization of both ^{133}Xe and ^{133m}Xe will approach saturation. An external magnetic field of 0.1 T is used to magnetize the Fe foil and to define the polarization axis. The sample temperature will be determined with a calibrated ^{57}Co(Fe) nuclear orientation thermometer, attached to the back side of the sample holder.

The **angular distribution of the β-particles** is obtained as

$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + f\,\widetilde{A}\,P\,\frac{v}{c}Q_1\cos\theta \quad , \tag{3}$$

with $N(\theta)_{pol/unpol}$ the count rate in the detector at angle θ with respect to the magnetization (polarization) axis when the nuclei are polarized, i.e. *cold* or millikelvin data, respectively unpolarized, i.e. *warm* or 4 K data. The fraction f is an overall, temperature independent attenuation of the anisotropy, which is related to the site distribution of the implanted ions in the Fe foil. Further, P is the degree of nuclear polarization, v/c is the initial velocity of the β particles relative to the speed of light and Q is a solid angle correction factor that takes into account the finite dimensions of the source and the detector but also the effects of scattering and of the magnetic field.

The β particles will be observed by three Si **particle detectors** mounted inside the 4K thermal shield of the refrigerator, thereby directly facing the sample so as to minimize energy loss and scattering effects. Compared to the Ge detectors that were used in the previous experiments [9, 10, 14, 6], Si detectors cause less backscattering.

In the first run we will use the 500 μm thick Si p-i-n diode detectors, which have shown good performance under the conditions of low temperatures and high magnetic field [11, 20]. In addition, their response function is understood very well using our GEANT4-based simulation code [21], which is crucial to control systematic effects. In the second run we will use custom

1.5 mm thick fully-depleted planar Si detectors from Micron Semiconductor©. Performing two measurements with two different detector types will help to better control systematic effects.

To determine the **fraction** f, the anisotropy of the 223 keV γ line in the decay of ^{133m}Xe (100 % branching ratio), $t_{1/2}$ = 2.19 d, will be observed with three high-efficiency HPGe detectors. As this is a pure M4 transition, the expected γ-ray anisotropy is well understood, thus providing a very clean way to determine the fraction. In addition, no separate calibration measurement is required as this measurement can be done in parallel with the β-asymmetry measurement. The yield of ^{133m}Xe is expected to be about several to 10% of that for ^{133}Xe, which is largely sufficient.

The **degree of polarization** depends on the temperature and the magnetic hyperfine interaction μB, μ being the nuclear magnetic moment and B the total magnetic field experienced by the Xe nuclei, i.e. the sum of the hyperfine field, the external field and a small demagnetization field. Values above 90 % can be expected at temperatures below 10 mK (Table 1).
The temperature will be obtained from the anisotropy of the 136 keV γ transition in the decay of the ^{57}Co(Fe) nuclear thermometer that will be mounted on the back side of the sample holder. As two major sites can be populated simultaneously when implanting Xe in Fe, with different values for the magnetic hyperfine field, i.e. 130(5) T and 160(5) T [19], we will determine the interaction μB in our samples by performing additionally a nuclear magnetic resonance experiment on the oriented Xe nuclei (NMR/ON; see further).

Table 1: Expected β and γ anisotropies for the relevant transitions. At a few millikelvin, de degree of polarization is close to saturation for both values of the magnetic hyperfine field.

	$t_{1/2}$ (d)	μ (μ_N)	P@5mK (%) B_{hf} = 130 T	P@5mK (%) B_{hf} = 160 T	W($\theta = 0$)@5mK (%) B_{hf} = 160 T
^{133}Xe $3/2^+ \rightarrow 5/2^+$ β transition	2.19	+0.8129	99.6	99.9	60
^{133m}Xe $11/2^- \rightarrow 3/2^+$ γ transition	5.24	-1.0825	96.7	98.0	-98

The relevant properties for the β transition of ^{133}Xe and the 223 keV γ line of the isomer ^{133m}Xe, together with the anisotropies expected at a sample temperature of 5 mK, are listed in Table 1.

Besides the beneficial properties of the β transition, several **improvements** in the detection setup and the analysis methods will help us to reach the 1 % precision which is being aimed for.

As the experimental β anisotropy is extracted from a comparison of data-sets taken over a period of several hours, the stability of our **detection setup** is a crucial factor in these type of measurements. In order to improve stability of the detection setup, we will use a fast fully digital data acquisition system, FASTER, developed at the LPC-CAEN [24], reducing dead-time and pile-up effects by a factor of 10 and improving gain stability. In addition, to further reduce possible gain shifts and reduce the electronic noise in the detection chain, part of the pre-amplifier will be mounted on the 77 K radiation shield of NICOLE, close to the particle detectors.

The factor $v/c\ Q\ \cos\theta$ in Eq. 3 depends on the response function of the particle detectors, on scattering and energy loss of the β particles in the experimental setup, as well as on the influence of the external magnetic field. In the course of the last few years, we have developed a **GEANT4-base simulation code** to deal with these effects [21][25] for both Si and HPGe detectors, as well as to quantify a series of systematic effects [6][7].
Currently, we are working on optimizing the performance of this code. New reference data, which is to be compared with the simulation output, was taken with the new 1.5 mm thick Si detectors, so as to better understand the response of these detectors. The redesign of the low-energy physics package and the release by the GEANT4 collaboration of new electromagnetic physics packages, including more realistic models for electron scattering [26][27], offers good perspectives to improve the quality of the simulation results obtained. The performance of the different new physics packages and the optimization of several physics parameters are currently under investigation. Electron backscattering probabilities on Si will be measured at Leuven as reference data for the simulation code.
We will use this upgraded simulation code to analyze the ^{133}Xe data, thereby decreasing the systematic error contribution on $\widetilde{A}$ related to the quality of the simulation code. Further, a significant increase of the CPU-power available will allow us to run more detailed simulations in order to better control systematic effects.

NMR/ON on ^{133}Xe

As was mentioned already, two sites have been observed for Xe impurities in Fe. It will therefore be necessary to determine the total magnetic field experienced by the nuclei in our samples in a NMR/ON measurement after every β-asymmetry measurement. Since the β-asymmetry measurements will depend on the average magnetic field (averaged over the different lattice sites that might be populated), while NMR/ON measurements yield the field at a specific lattice site, the total magnetic field will additionally also be extracted from a two-parameter fit of the 223 keV γ line (fitting the magnetic field B and the fraction f). Agreement of both magnetic field values thus obtained will give confidence that we are dealing with only one dominant lattice site, as is to be expected based previous measurements performed under similar conditions (see e.g. Table III in Ref. [23]).
In addition, a dedicated NMR/ON run will be performed so as to investigate the hyperfine field and a possible site distribution in detail. As can be seen from Table 1, the expected β anisotropy is not much influenced by the exact value of the hyperfine field. Determining the site distribution with a precision of about 10 % will be sufficient to keep the systematic error related to this distribution at the permille level.
For all three experiments three identical foils (from the same supplier and prepared simultaneously) will be used, thus avoiding foil dependent effects and allowing to compare results from the three measurements.

Beam-time request

We request a total of nine shifts. We plan three experimental runs:

- Two runs of three shifts, collecting a $^{133(m)}$Xe sample to measure the $\beta-$asymmetry parameter of ^{133}Xe, combined with a short NMR/ON scan to determine the hyperfine interaction.
- Three shifts to collect a $^{133(m)}$Xe sample for a dedicated NMR/ON experiment.

The beam of 133Xe will come pretty pure from a UCx + W converter + VD7 ion source.

For a beam intensity of 10^7/s arriving into the sample inside NICOLE (for a given gate setting of the separator and taking into account the beam transport efficiency to NICOLE) and assuming a spot diameter of 5 mm (which means a spot surface of 20 mm^2, so that implanted yields have to be multiplied by a factor 5 to convert them into a dose/cm^2), we get a ^{133}Xe dose of 5 x 10^7/cm^2/s. If we further assume a stable beam (^{133}Cs) contamination of a factor 10, the total dose will be 5.5 x 10^8/cm^2/s. Setting then for the total accumulated dose after the implantation an upper limit of a few 10^{13}/cm^2, we get a total implantation time of 10 hours. Therefore, 1 shift for stable beam tuning and 1 to 2 shifts to collect a $^{133(m)}$Xe source will be sufficient for one single run.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
NICOLE	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT : Hazards named in the document relevant for the NICOLE installation.