EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

ISOLDE and Neutron Time-of-Flight Experiments Committee

Status Report

β-asymmetry measurements in nuclear β-decay as a probe for non-Standard Model physics

IS431

N. Severijns1), F. Wauters1), V. De Leebeeck1), V.V. Golovko1,*), P. Herzog2), U. Köster3,&),
V.Yu. Kozlov1,#), I.S. Kraev1), M. Tandecki1), E. Traykov1), S. Van Gorp1),
and D. Zákoucký4)

Spokesperson : N. Severijns
Contact person: U. Köster

Abstract

A status report is given on the measurements of the β asymmetry parameter and the development and validation of a dedicated simulation code, performed in the framework of experiment IS431 to search for possible tensor type contributions to the weak interaction. The measurements have provided the most precise results for the β asymmetry parameter in nuclear β decay to date and provide new limits for tensor type charged current weak interactions.

---

1) Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium
2) Helmholtz-Institut für Strahlen- und Kernphysik , Universität Bonn, D-53115 Bonn, Germany
3) ISOLDE - EP Division, CERN, CH-1211, Geneva 23, Switzerland
4) Nuclear Physics Institute, Academy of Sciences of the Czech Republic, 250 68 Rez, Czech Republic
*) now at Department of Physics, Queen's University, Kingston, Canada
#) now at Institut Laue-Langevin, Grenoble, France
&) now at Karlsruhe Institute for Technology, Karlsruhe, Germany

Introduction

In the proposal P189/IS431 we proposed to measure the β asymmetry parameter, *A*, for a number of pure Gamow-Teller β-decays, with the NICOLE low temperature nuclear orientation set-up at ISOLDE. The β asymmetry parameter determines the correlation between the spin of a polarized nucleus and the momentum of the β particle emitted in its decay [1]. Precision measurements of this parameter provide new information on the possible presence of tensor type contributions to the weak interaction. The amplitude of the coupling constants, $C^{(')}_T$, for a tensor interaction could be as large as about 9% of that of the known axial vector type weak interaction (C_A) [2].

Previously, we had already gained experience with the determination of the β asymmetry parameter in the framework of the experiment IS381 ("Isospin mixing in $N \approx Z$ nuclei" [3]). This time, however, our goal was to reach a precision and accuracy at the 1% level, compared to about 5% in the isospin mixing project. At this level of precision the traditional method to determine the correction for the finite solid angle [4] is not applicable anymore. In addition, the effects of (back)scattering of the β particles, as well as deviations in their trajectories caused by the applied magnetic field have to be dealt with in far more detail. We have therefore developed and validated a GEANT4 based Monte Carlo code that is able to simulate the complete experiment, including anisotropic emission of the β particles, to be used in the analysis of our measurements.

In the measurements performed, several isotopes, as well as different source preparation techniques and polarization methods were used. In this way the systematic errors were also different, so that the results of the measurements would cross check and complement each other. Three experiments have been performed, two in Leuven (with ^{60}Co and ^{114}In) and one at ISOLDE (with ^{67}Cu).

In the following sections we will first give a brief overview of the relevant formalism, then discuss the GEANT4 based Monte Carlo code, focus on the different experiments that were performed and the results obtained, and, finally, end with a conclusion and outlook.

Formalism

The technique of low temperature nuclear orientation (LTNO) was used. This combines temperatures in the millikelvin region with high (up to several tens of Tesla) magnetic fields. The angular distribution of β particles is experimentally obtained as

$$W(\theta) = \frac{\mathrm{N}(\theta)_{pol}}{\mathrm{N}(\theta)_{unpol}} = 1 + A_{GT}^{\beta^{\mp}}\, k\, P\, Q \frac{v}{c} \cos\theta \qquad (1)$$

with $\mathrm{N}(\theta)_{pol\,/\,unpol}$ the count rate in the detector at angle θ with respect to the magnetic field axis when the nuclei are polarized, respectively unpolarized. An unpolarized ensemble is obtained by heating the sample to a temperature of about 4K. Further, *k* is a factor determining the implantation quality, *v/c* is the velocity of the β-particles relative to the speed of light, *P* is the degree of nuclear polarization 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 (back)scattering and of the magnetic field.

In the Standard Model one has for a J → J' pure Gamow Teller transition $A_{GT}^{\beta^{\mp}} \equiv \mp\lambda_{\mathrm{J'J}}$ with $\lambda_{\mathrm{J'J}} = 1$ for $\mathrm{J} \rightarrow \mathrm{J}-1$ and $\lambda_{\mathrm{J'J}} = -\mathrm{J/J{+}1}$ for $\mathrm{J} \rightarrow \mathrm{J{+}1}$. Note that J→J transitions are not considered here as they can contain small but non-negligible Fermi contributions due to isospin impurities (which we studied in the ISOLDE experiment IS381 [3]) that would mask non-Standard Model contributions. Allowing for tensor currents in the weak interaction and assuming Standard Model vector (V) and axial-vector (A) interactions, the β-asymmetry parameter $A_{GT}^{\beta^{\mp}}$ becomes [1,2]:

$$A_{GT}^{\beta^{\mp}} \cong \lambda_{\mathrm{J'J}}\left[\ \mp 1 + \frac{\alpha Z m}{p}\,\mathrm{Im}\left(\frac{\mathrm{C_T}+\mathrm{C_T'}}{\mathrm{C_A}}\right) + \frac{\gamma m}{E}\,\mathrm{Re}\left(\frac{\mathrm{C_T}+\mathrm{C_T'}}{\mathrm{C_A}}\right)\right] \qquad (2)$$

with $\mathrm{C_T}$ and $\mathrm{C'_T}$ the coupling constants for a parity conserving/violating tensor type interaction and $\mathrm{C_A} = -1.27\ \mathrm{C_V}$ the axial vector coupling constant. Further, α is the fine structure constant, Z is the charge of the daughter nucleus, m is the rest mass of the electron, p and E are the momentum, respectively the total energy of the β-particle and $\gamma = \sqrt{1-(\alpha Z)^2}$. For simplicity recoil terms have been neglected in the above equation, but they were duly taken into account in the final results (see below). For the β decays observed in our experiments the recoil effects on the β asymmetry parameter were calculated (using the formalism of ref. [5] and nuclear matrix elements provided by I.S. Towner) to be about 0.3 % to 0.4 %. This is to be compared to the final precisions of 1% to 2% that were finally obtained (see below). Radiative corrections are about one order of magnitude smaller [6] and could therefore be neglected.

Recently, a very stringent limit was obtained for a time reversal violating tensor type interaction, i.e. $-0.008 < \mathrm{Im}(\mathrm{C_T}+\mathrm{C'_T} / \mathrm{C_A}) < 0.014$ (90% C.L.), from a precise determination of the so-called *R*-correlation in the decay of polarized ^{8}Li at the Paul Scherrer Institute [7]. We therefore focused in our experiments on a time reversal invariant tensor type interaction, i.e. the last term in Eq. (2), viz. $\mathrm{Re}(\mathrm{C_T}+\mathrm{C'_T}/\mathrm{C_A})$, which enters the expression for *A* via the so-called Fierz interference term [1]. In order to assure a good sensitivity to this combination of coupling constants β transitions with low endpoint energy should preferably be used.

GEANT4 simulation code

The following effects tend to modify the observed angular distribution pattern of the β radiation:

- scattering of the β particles in the host foil material;
- backscattering on the layer of solder with which the foil is attached to the sample holder;
- backscattering on the sample holder;
- backscattering on the β detector;
- magnetic field influence on the β particle propagation;
- possible Compton background from γ rays accompanying the β decay and/or γ rays emitted by the nuclear orientation thermometer source.

All these effects modify the value of the factor $Q(v/c)\cos\theta$ in Eq. (1). The GEANT4 based simulation code we developed (having at regular moments contact with the GEANT team at CERN) allows for a Monte-Carlo simulation of the complete experiment. It thus provides simulated β spectra for both isotropic (i.e. no nuclear polarization) and anisotropic (i.e. when the sample is polarized) emission. The anisotropic data are simulated using the Standard Model value for the β asymmetry parameter, A_{SM}, and for exactly the same degree of nuclear polarization, P, (see Eq. (1)) as obtained in the experiment. The experimental polarization P is deduced from a calibration measurement, i.e. from the anisotropies of γ rays in the decay of the same isotope, or from a measurement with a different isotope of the same element.

The data are analyzed in exactly the same way as the experimental data. The β asymmetry parameter, A_{exp}, is then obtained from the ratio:

$$\frac{[W(\theta)-1]_{\text{exp}}}{[W(\theta)-1]_{\text{sim}}} = \frac{A_{\text{exp}}}{A_{\text{sim}}} \qquad (3)$$

where $W(\theta)_{\text{exp}}$ and $W(\theta)_{\text{sim}}$ are the anisotropy functions (Eq. (1)) obtained experimentally and from the simulations, respectively.

The development and validation of the simulation code was performed in several steps, where each time the simulation results were compared with experimental data obtained in well-controlled conditions. A brief description will be given here. Detailed reports can be found in Ref. [8].

Firstly, a simple simulation routine was built to generate electron backscattering coefficients. With this routine the influence of the different tunable physics parameters in GEANT4 on the calculated backscattering fractions was studied, i.e., the cut-for-secondaries (CFS) parameter and the so-called f_r parameter. The CFS parameter determines the production threshold for secondary particles, while the f_r parameter limits the step size for tracking of electrons at the boundary between two materials. These two parameters were then fixed at the values that provide the best match with the reference data obtained from the literature (the value for the f_r parameter was later fixed by the GEANT team at our value).

As a second step, β spectra were measured for a series of isotopes in simple and well controlled experimental conditions, and compared to simulations. Two types of particle detectors were used for this, i.e. Si PIN diodes and planar HPGe detectors. A comparison of the experimental β spectrum with the simulated one is shown in Fig.1 for ^{60}Co and in Fig.2 for ^{85}Kr, respectively. These simulations showed that our code was able to reproduce very well the upper half of β spectrum. To put our simulation code even more to the test, the scattering conditions were modified by adding copper foils of different thickness behind the source.

As a last step, experimental spectra were taken in the real setup, with a strong magnetic field being present as well. These spectra were again compared to the simulated ones, showing good results on the condition that all relevant details of the experimental setup were properly included in the Monte-Carlo code.

Concluding, a GEANT4 based Monte-Carlo simulation routine was developed and validated for the experimental conditions of LTNO β asymmetry measurement. The code is able to take the different effects that tend to disturb the experimental β anisotropies into account to a sufficiently high degree of precision, thus enabling to analyze the experimental data as will be shown in the next section. The remaining imperfections and uncertainties related to this simulation code, e.g. the underestimation of the Compton electron tail shown in Fig. 1, will be translated into a systematic error.

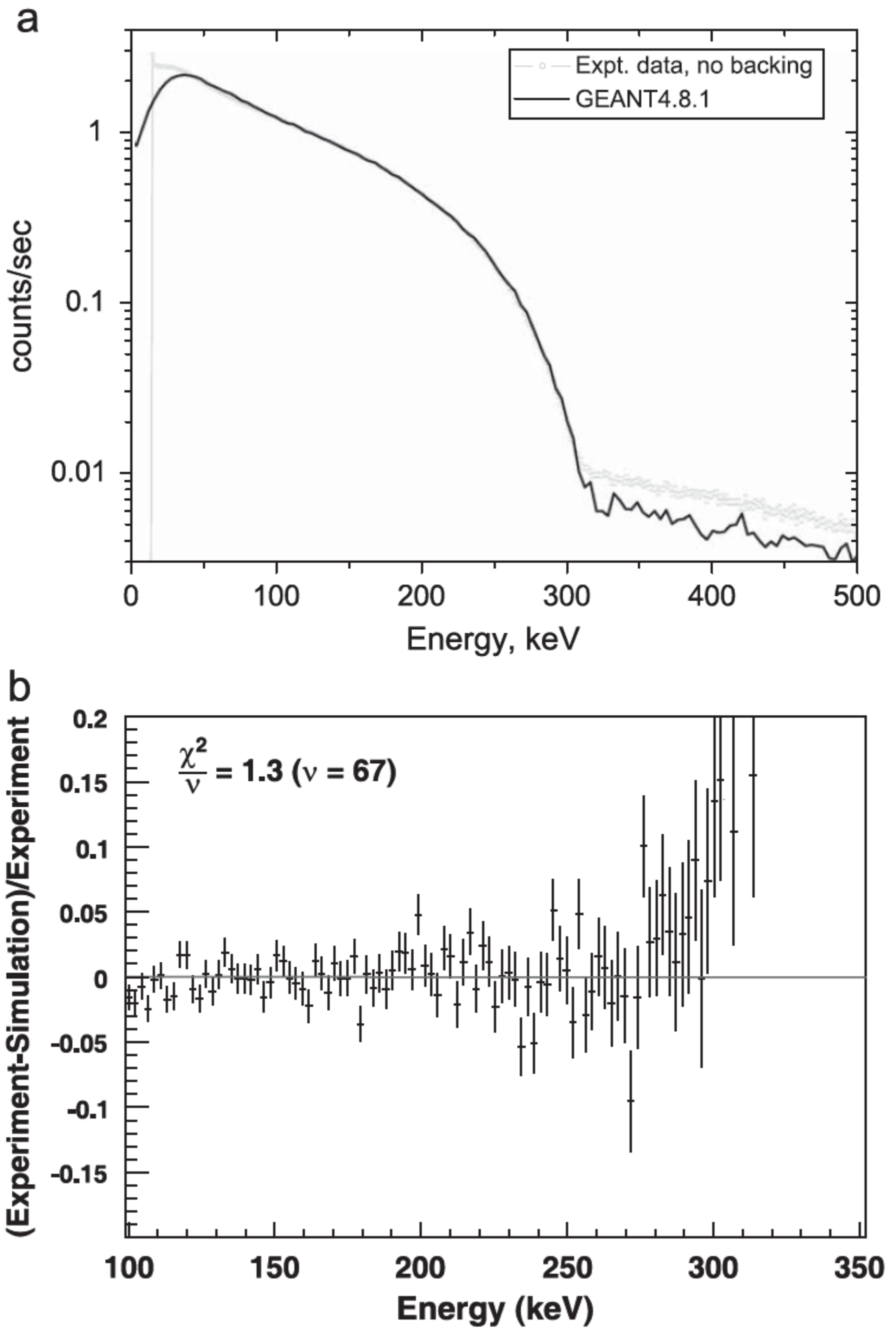

Fig. 1. (a) Comparison of the experimental β spectrum of ^{60}Co (measured with a Si PIN diode) with the simulated one. Gray dotted line: experimental data (error bars are smaller than the size of the data points). Black solid line: GEANT4.8.1 simulations with $f_r = 0.02$ and CFS = 10μm. (b) Relative difference between simulated and experimental spectra. In the region of interest, i.e. from 150 to 300 keV, the difference is well within 2 %. It is larger near the β spectrum endpoint where the relative contribution of Compton background from the gamma-rays of ^{60}Co is more important. The value $\chi^2/\nu = 1.3$ for 67 degrees of freedom (which is within the 95% confidence level) refers to the energy region from 150 to 300 keV.

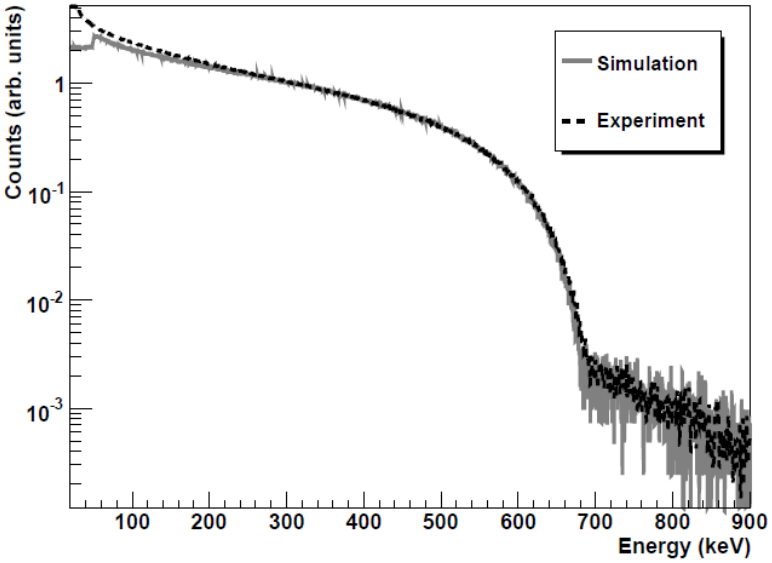

Fig. 2. Comparison of a simulated and measured ^{85}Kr spectrum, using a planar HPGe detector. The two spectra were normalized in the region 300 - 600 keV. For this energy region, $\chi^2/\nu = 1.4$ with $\nu = 74$ and simulated and experimental agree within 2 %. The counts above the β spectrum endpoint at 687 keV are due to pile-up events.

Experiments performed

Three experiments have been performed, two in Leuven (with ^{60}Co and ^{114}In) and one at ISOLDE (with ^{67}Cu).

a) ^{60}Co experiment

The isotope ^{60}Co was diffused into a pure Cu foil mounted on a Cu sample holder at a temperature of about 10 mK inside the Leuven nuclear orientation system. Nuclei were oriented in the Cu foil by the combination of the low temperature and a 9 T, respectively 13 T magnetic field provided by a superconducting solenoid. To detect the β particles a Si PIN photodiode (Hamamatsu Photonics, type S3590-06) with a thickness of 500 μm and an active surface of 9 x 9 mm^2 was used. The behavior of this at low temperatures (i.e. about 10 K) and in magnetic fields up to 11 T had been extensively studied on beforehand [9].

We choose to perform first these measurements with ^{60}Co being polarized 'brute-force' in high external magnetic fields, in order to provide a strong test for the simulation code. Indeed, in these high fields about 50% of all β particles (with energies up to 318 keV in the case of ^{60}Co) are focussed as a very narrow beam onto the detector. The simulation code has to take care of the effect of this high magnetic field, i.e. its effect on the β particle trajectories, as well as of the (back)scattering of the particles, which is also affected by the magnetic field. In order to limit scattering of the β particles in the sample foil this was placed perpendicular to the magnetic field and detector axes.

A total of four measurements were performed, three in a field of 13 T (at temperatures of 7.5 mK, 10.4 mK and 17.1 mK) and one in a field of 9 T (at 7.4 mK). Fig. 3 shows the anisotropies obtained as a function of energy for these four measurements. Fig.4 shows, for the measurement at 7.5 mK in a field of 13 T (i.e. the lower curve in Fig. 3), the result for the asymmetry parameter as a function of energy after the same analysis as shown in Fig. 3 was also applied to the simulated spectra and the ratio defined by Eq.(3) was calculated. As can be seen, no energy dependence is observed, indicating that the GEANT4 based simulation code perfoms well at the attained level of precision.

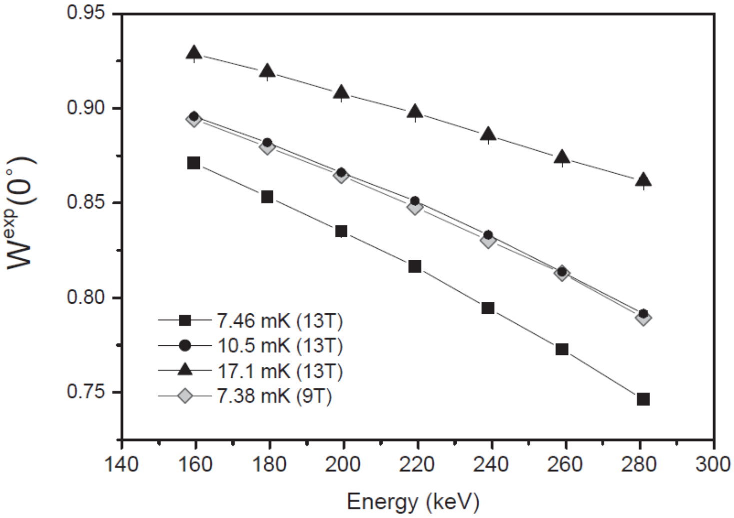

Fig. 3: Experimental β anisotropies as a function of energy for ^{60}Co. The error bars are smaller than the size of the symbols.

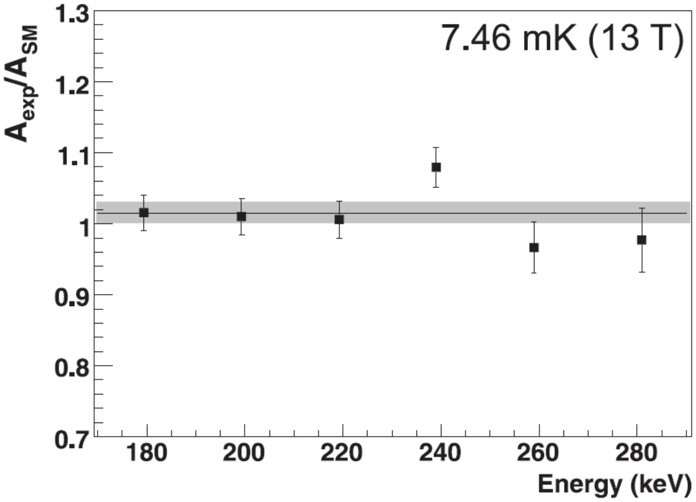

Fig. 4: Ratio between experimental and Standard Model values for *A* obtained with Eq.(3) for the lowest curve in Fig. 3. The grey band is the one standard deviation error on the weighted average.

Combining the results of all four measurements and taking into account systematic effects, the final result $A = -1.014 \pm 0.012stat \pm 0.016syst$ is obtained, in good agreement with the Standard Model value (including recoil order corrections related to contributions from higher order nuclear matrix elements, calculated using the formalism of Ref. [5] and matrix elements provided by I.S. Towner), i.e. $A = -0.987(9)$. The largest contributions to the systematic errors are due to the incomplete knowledge of the distribution of the Co activity inside the Cu foil, the normalization of the degree of nuclear polarization (i.e. the factor *k* in Eq. (1)) and the Geant simulations. A paper is being prepared for publication [10]. Our precision is similar to the result previously obtained by Chirovsky et al., i.e. $A = -1.01$ (2) [11].

b) ^{114}In experiment

The isotope ^{114}In was implanted with the Leuven isotope separator into a pure (99.99 %) Fe host foil and measured with the Leuven nuclear orientation setup. The nuclei were polarized by means of the large magnetic hyperfine field of -28.7 T they experienced in the magnetized Fe foil.

The β particles emitted in the decay of the polarized ^{114}In nuclei were observed with two thin (thickness 2 mm and 3 mm) HPGe detectors installed at angles of 20° and 108.5° with respect to the polarizing magnetic field (quantization axis). Ge instead of Si detectors had to be used because of the rather large endpoint energy of the ^{114}In β spectrum, i.e. 1.990 MeV. The detectors were installed out of the plane of the Fe host foil in order to minimize the effect of scattering of the β particles in this foil. The sample temperature was determined with a calibrated ^{57}Co$\underline{\text{Fe}}$ nuclear orientation thermometer attached to the back side of the sample holder, and that was observed with three large volume HPGe detectors installed outside the refrigerator.

After the simulation code had shown to perform very well at the few percent precision level in the measurements with ^{60}Co that were performed in very high magnetic fields [8], we choose to perform the experiment with ^{114}In in low magnetic fields. The corrections to be taken care of by the simulation code would then be smaller leading to smaller systematic errors and an overall higher precision and accuracy.

Three measurements were carried out, in external fields of 0.046 T, 0.093 T and 0.186 T. These fields served to maintain the magnetization of the Fe foil in which the nuclei were implanted, with the nuclei being polarized by the internal magnetic hyperfine field they experienced in the foil. As the backscattering on the Ge detectors was rather important [12], the analysis was limited to the highest energy part of the β spectrum, i.e. to energies above 1.700(10) MeV. An example of an experimental β anisotropy is shown in Fig. 5.

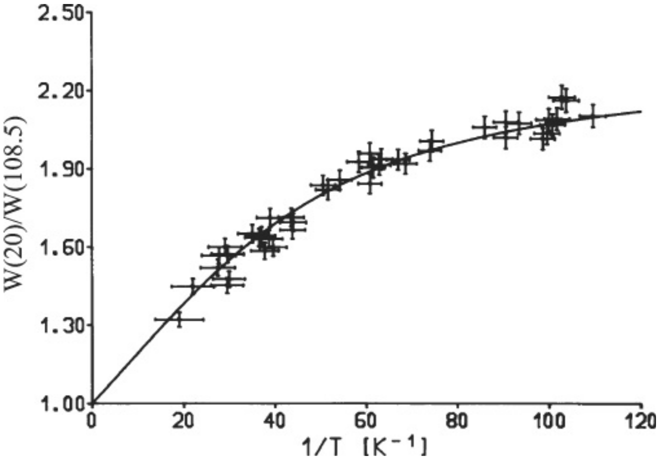

Fig. 5. Experimental *β* anisotropy of ^{114}In for the energy region from 1.700 to 1.830 MeV, in a magnetic field of 0.046 T ($\chi^2/\nu = 0.71$).

Combining the results of all three measurements and taking into account systematic effects, the final result is obtained as A = -0.990 ± 0.010*stat* ± 0.010*syst*, in agreement with the Standard Model value (again including recoil order terms) of A = -0.996(3). The largest contributions to the systematic errors are due to the Geant simulations and the normalization of the degree of nuclear polarization (i.e. the factor k in Eq. (1)). This result was recently published [12].

c) ^{67}Cu experiment

The isotope ^{67}Cu was implanted with the ISOLDE isotope separator into a pure (99.99 %) Fe host foil and measured with the NICOLE nuclear orientation setup. The nuclei were polarized by means of the large magnetic hyperfine field of -21.8 T they experienced in the magnetized Fe host foil. As there is no γ ray in the decay of ^{67}Cu to determine the factor k in Eq. (1), this normalization factor for the nuclear polarization of the ^{67}Cu nuclei was obtained from a measurement of the β asymmetry for the isotope ^{68}Cu, performed in the same Fe host foil and during the same experimental run.

Two runs were performed. In the first one we were the last user of the target. It later turned out that the beam intensity was too low already to collect enough statistics for a precision experiment. Indeed, in this case only the upper 93 keV of the ^{67}Cu β spectrum (endpoint energy 562 keV; Fig. 6) can be used to obtain weak interaction information. The lower parts of the β spectrum are contaminated by β particles from other branches and from other isotopes. The average result for the A parameter from four measurements, without correcting for the effects of scattering and of the magnetic field, is $A = 0.573(8)$. Comparing this with the Standard Model value for this pure Gamow-Teller $3/2^- \rightarrow 5/2^-$ transition, i.e. $A = 0.600$, shows that corrections are most probably small, as should indeed be the case since only the region close to the spectrum endpoint is used (where disturbing effects from scattering, the magnetic field, etc. are small), and the external magnetic was only 0.1 T. As only the statistical precision obtained was already about 1.5 %, which is not competitive with the measurements with ^{60}Co and ^{114}In, a second run was required to gather enough statistics. In this second run about four times more statistics was finally obtained. The analysis of these data is still in progress as we decided to first completely finish the analysis of the ^{60}Co and ^{114}In experiments. The analysis of the first run provided valuable information that was used to create more favorable conditions in the second run.

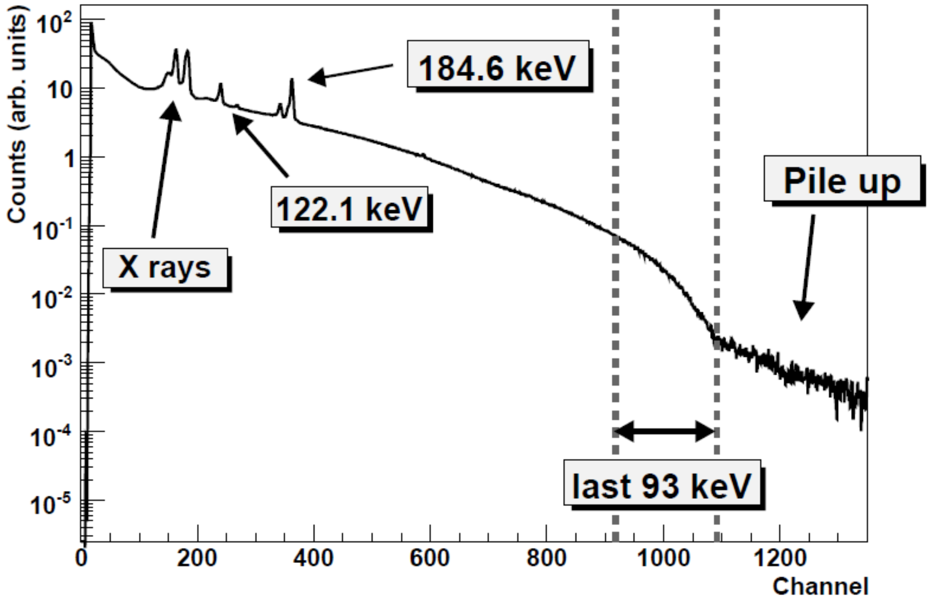

Fig. 6: Experimental β spectrum of ^{67}Cu. The ^{67}Cu β spectrum endpoint (at 562 keV) is at about channel 1100. The γ rays are from the ^{57}CoFe nuclear orientation thermometer (122 keV) and from the decay of ^{67}Cu itself (184.6 keV).

Limits on tensor currents

The results of the experiments with ^{60}Co and ^{114}In, i.e. A = -1.014 ± 0.012*stat* ± 0.016*syst,* respectively A = -0.990 ± 0.010*stat* ± 0.010*syst*, both agree with their respective Standard Model values (see above). These are the two most accurate results for the β asymmetry parameter in a nuclear β decay to date. Only in neutron decay (a mixed Fermi/Gamow-Teller transition, which is therefore less sensitive to tensor contributions) a slightly higher precision has been obtained [13]. As no indication for a non-zero tensor contribution to the charged current weak interaction is observed our results provide new limits for the presence of such a contribution. These are shown in Fig. 7 and compared to those from the best other experiments. As can be seen, our limits are competitive to the ones from these other experiments. Note that the limits from ^{60}Co are more stringent than the ones from ^{114}In. This is due to the higher sensitivity (i.e. the factor $\gamma m/E$ in Eq. (2)) in the case of ^{60}Co caused by the lower endpoint energy.

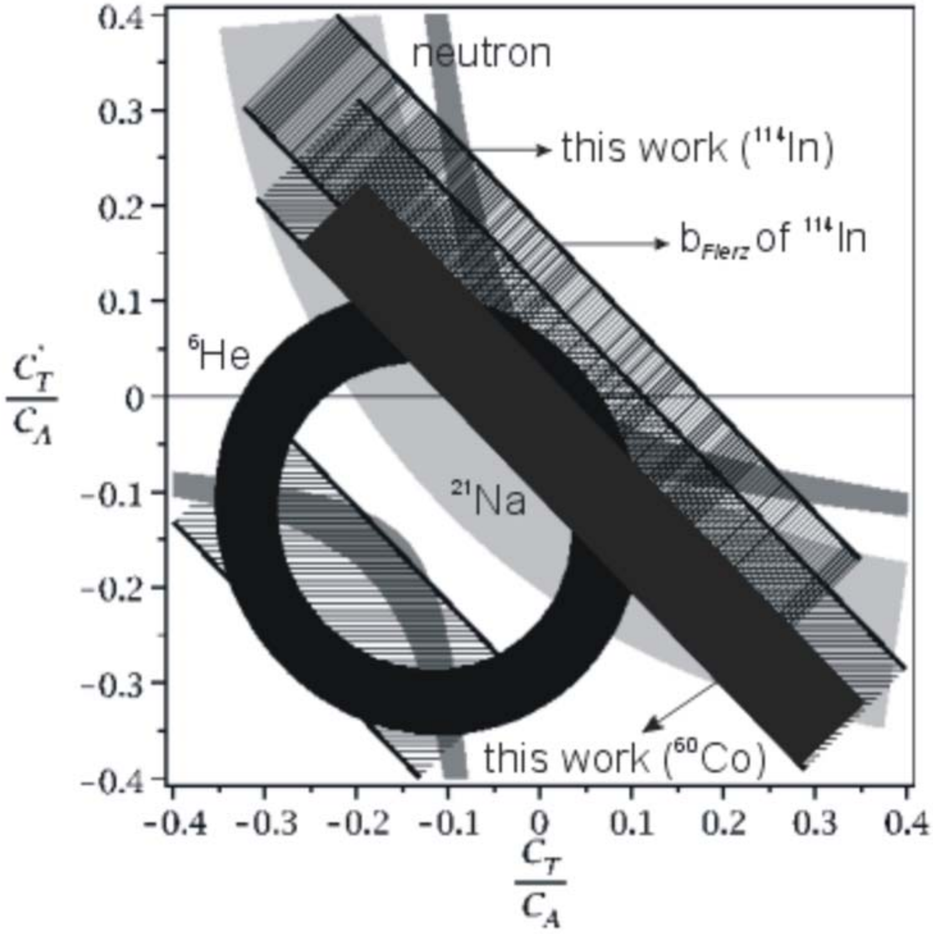

Fig.7. Limits (90% C.L.) on time-reversal-invariant tensor couplings from correlation measurements in nuclear β decay: the Fierz interference term b_{Fierz} from a spectrum shape measurement for ^{114}In (with only statistical errors quoted) [14], the β-asymmetry parameter A in the decays of ^{60}Co and ^{114}In (this work) and in free neutron decay [15], and the β-ν correlation coefficient a in the decays of ^{6}He [16, 17] and ^{21}Na [18]. Limits for the mixed Fermi/Gamow-Teller transitions of the neutron and ^{21}Na are for scalar coupling constants $C_S = C'_S = 0$.

Conclusion and outlook

We have perfomed three precision measurements of the β asymmetry parameter in nuclear β decay. The analysis makes extensive use of a dedicated Monte Carlo code for β spectroscopy measurements, including anisotropic β particle emission, that was developed and validated as part of this project. The two results obtained so far (with ^{60}Co and ^{114}In) constitute the most precise and most accurate ones of this type in nuclear β decay to date. A third experiment (with ^{67}Cu) is still being analysed.

As only 17 out of the originally requested 28 shifts had been allotted and two runs were required to obtain sufficient statistics for the experiment with ^{67}Cu (including the normalization measurement with ^{68}Cu), only one out of three experiments that were originally planned could be performed. However, two experiments with long lived isotopes (i.e. ^{60}Co and ^{114}In) were additionally performed, at Leuven, thereby still reaching the physics goals that were set out for this proposal. The results of the experiment performed at ISOLDE with ^{67}Cu will complement these. Note finally also that the originally planned measurements with ^{82}Rb and ^{118}Sb to optimize the GEANT Monte Carlo code were replaced by the measurements with ^{60}Co that were reported in Ref. [8].

Based on the knowledge gained in the measurements performed till now, we are at present preparing a number of upgrades of our experimental and analysis method, in order to reach an even higher precision in the second phase of this project, i.e.

- switch to a more stable (in time) and digital data acquisition system (in preparation),
- install cooled pre-amplifiers to improve the energy resolution (already available),
- develop a compact and dedicated β spectrometer to perform more accurate measurements of multiple scattering than the ones that are presently available in the literature (these new data can then be used to improve the performance of the simulation code),
- investigate the so-called recoil effects in more detail, to be able to calculate these effects with better precision, or even determine them experimentally with the new spectrometer,
- search the nuclear data base to find the best suited isotopes for a new measurement.

This will lead to a new proposal to be submitted at a later stage.

References

[1] J. D. Jackson, S. B. Treiman and H.W. Wyld, Nucl. Phys. 4 (1957) 206.
[2] N. Severijns, M. Beck and O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991.
[3] P. Schuurmans et al., Nucl. Phys. A672, 89 (2000).
N. Severijns et al., Phys. Rev. C 71 (2005) 064310.
N. Severijns et al., 'Isospin mixing in N ≈ Z nuclei', ISOLDE experiment IS381, CERN-INTC-99-5 and CERN-INTC-2002-032 (addendum).
[4] N.J. Stone, H. Postma (Eds.), Low-Temperature Nuclear Orientation, North-Holland, Amsterdam, 1986 (Chapter 2).
[5] B.R. Holstein, Rev. Mod. Phys. 46 (1974) 789 and 48 (1976) 673 (err.).
[6] F. Glück, Comp. Phys. Comm. 101 (1997) 223 and private communication.
[7] R. Huber et al., Phys. Rev. Lett. 90 (2003) 202301.
[8] F. Wauters et al., Nucl. Instr. & Meth. A609 (2009) 156.
F. Wauters, Ph.D. thesis, University of Leuven (2009).

[9] F. Wauters et al., Nucl. Instr. & Meth. A604 (2009) 563.

[10] F. Wauters et al., to be published.

[11] L.M. Chirovsky, et al, Nucl. Instrum. Methods. A 219, 103 (1984).

[12] F. Wauters et al., Phys. Rev. C 80 (2009) 062501.

[13] H. Abele, Prog. Part. Nucl. Phys. 60 (2008) 1.

[14] H. Daniel and P. Panussi, Z. Phys. 164 (1961) 303.
H. Daniel, G. T. Kaschl, H. Schmidtt, and K. Springer, Phys. Rev. 136 (1964) B1240.

[15] C. Amsler et al., Phys. Lett. B667 (2008) 1.

[16] C. H. Johnson, F. Pleasonton, and T. A. Carlson, Phys. Rev. 132 (1963) 1149.

[17] F. Glück, Nucl. Phys. A628 (1998) 493.

[18] P. A.Vetter, J. R. Abo-Shaeer, S. J. Freedman and R.Maruyama, Phys. Rev. C 77 (2008) 035502.