Beta asymmetry parameter in the decay of $^{114}$In

F. Wauters, V. De Leebeeck, I. Kraev, M. Tandecki, E. Traykov, S. Van Gorp, and N. Severijns

Instituut voor Kern- en Stralingsfysica,
Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

D. Zákovský
Nuclear Physics Institute, Academy of Sciences of Czech Republic, CZ-25068 Řež, Czech Republic
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Abstract

The $\beta$ asymmetry parameter $\tilde{A}$ for the pure Gamow-Teller decay of $^{114}$In is reported. The low temperature nuclear orientation method was combined with a GEANT4 based simulation code allowing for the first time to address in detail the effects of scattering and of the magnetic field. The result, $\tilde{A} = -0.994 \pm 0.010_{\text{stat}} \pm 0.010_{\text{syst}}$, constitutes the most accurate value for the asymmetry parameter of a nuclear $\beta$ transition to date. The value is in agreement with the Standard Model prediction of $\tilde{A} = -1$ and provides new limits on tensor type charged weak currents.
The historic measurement of the $\beta$ asymmetry parameter $A$ by Wu et al. [1] strikingly showed the violation of parity in weak interactions. Later this parameter was and still is extensively studied in neutron decay, e.g. to test the unitarity of the quark mixing matrix and to constrain the presence of right-handed currents (for reviews see [2, 3, 4, 5]). In nuclear decays only a few measurements of the $\beta$ asymmetry parameter were performed with the aim of testing symmetries of the weak interaction and/or searching for physics beyond the Standard Model (see e.g. [3, 6]). The most accurate result was reported in Ref. [7], i.e. a (purely statistical) precision of 2 % for the case of $^{60}$Co. Still, such measurements can provide interesting information on possible new physics [8]. The best choice are fast ($\log ft \leq 5$) pure Gamow-Teller (GT) transitions and the superallowed mirror transitions between $T = 1/2$ analog states [9, 10], for which nuclear structure and other corrections contribute at most at the permille level. $J^{\pi} \rightarrow J^{\pi}$ transitions between non-analog states should be avoided as they usually contain small isospin-forbidden Fermi contributions that originate from the electromagnetic interaction and modify the value of $A$ (e.g. [11, 12, 13]). For pure Fermi transitions $A \equiv 0$.

Here we report a measurement of the asymmetry parameter for the $1^+ \rightarrow 0^+$ pure GT $\beta^-$ transition of $^{114}$In ($t_{1/2} = 72$ s) with endpoint energy of 1.989 MeV and $\log ft = 4.473(5)$ [14]. Our method combines low temperature nuclear orientation [15] with GEANT4 simulations to address in detail, and for the first time for this method, the effects of scattering and of the magnetic field. The result provides new information on tensor contributions to the charged weak current. Other experiments are pursuing similar goals [16, 17].

The electron angular distribution for $\beta$ decay of nuclei with vector polarization $J$ is written as [8]

$$W \propto \left[ 1 + \frac{m}{E_e} b_{\text{Fierz}} + \frac{p_e}{E_e} \cdot J A \right]$$

with $E_e$ and $p_e$ the total energy and momentum of the $\beta$ particle and $m$ the electron rest mass. Expressions for the Fierz interference term $b_{\text{Fierz}}$ and the asymmetry parameter $A$ are given in Refs. [3, 8]. In the Standard Model $b_{\text{Fierz}} = 0$, while for a $J \rightarrow J - 1$ pure GT transition, $A_{\text{SM,GT}}(\beta^\pm) = \mp 1$. The observable actually determined by experiment is

$$\tilde{A} \equiv A/[1 + (m/\langle E_e \rangle) b_{\text{Fierz}}].$$

A pure $^{114}$In sample was obtained from the internal transition (IT) decay of $^{114m}$In ($t_{1/2} = 49.5$ d). The latter was implanted at 70 kV with a dose of $1 \times 10^{12}$ at/cm$^2$ into a Fe
foil (purity 99.99%, thickness 50 µm). The γ spectrum showed no sign of contamination by another isotope. The foil was soldered at 80 °C (to prevent diffusion of In in the Fe) on the sample holder of a 3He-4He dilution refrigerator. The latter served to polarize the nuclei by cooling them to millikelvin temperatures in a strong magnetic hyperfine field (in the plane of the foil) induced by a superconducting split-coil magnet.

The geometry was similar to the one shown in Fig. 7 of Ref. [18]. The β particles were observed with two planar HPGe detectors [19] with a sensitive diameter of 20 mm and thicknesses of 2 mm and 3 mm, respectively, placed at 0° (axial detector) and 90° (equatorial detector) with respect to the vertical magnetic field (i.e. orientation) axis. They were installed inside the 4 K radiation shield of the refrigerator at (46 ± 1) mm from the sample, and operating at about 10 K with an energy resolution of 4.5 keV. They were directly facing the sample to minimize energy loss and scattering effects. To further minimize the effect of scattering in the foil (a major scattering component) the plane of the foil was tilted 20° towards the axial detector and rotated towards the equatorial detector over 68° (a compromise to permit implantation of the beam). The detectors were then at angles of 20° and 108.5° with respect to the orientation axis. To minimize also the effect of the magnetic field on the β particle trajectories the measurements were performed in low external fields, i.e. $B_{\text{ext}} = 0.046$ T, 0.093 T and 0.186 T.

The γ rays of $^{114m}$In and of the $^{57}$CoFe nuclear orientation thermometer [20] were observed with two large volume HPGe detectors. These were placed outside the refrigerator at angles of 0° and 90° relative to the magnetic field axis, at (70 ± 2) mm from the sample.

The experimental angular distribution was determined as [21] $W(\theta) = N_{\text{cold}}(\theta)/N_{\text{warm}}(\theta)$ with $\theta$ the angle with respect to the magnetization (orientation) direction in the Fe foil and $N_{\text{cold,warm}}(\theta)$ the count rates in a given γ peak, or energy bin in the β spectrum, when the sample is polarized (i.e. at millikelvin temperatures; cold) or unpolarized (i.e. at about 4.2 K; warm). Note that using a ratio of count rates reduces several systematic effects.

The experimental angular distribution of β particles emitted in allowed β decay from polarized nuclei is [21]

$$W(\theta) = 1 + f\frac{v}{c} \bar{A}PQ \cos \theta ,$$

with $v/c$ the initial velocity of the detected β particles relative to the speed of light and $Q$ the solid angle correction factor. Further, $P(J,\mu,T,B)$ is the degree of nuclear polarization of the state with spin $J$ and magnetic moment $\mu$ at temperature $T$ in the polarizing magnetic
field $B = B_{\text{ext}} + B_{hf}$, with $B_{hf} = -28.7$ T the internal hyperfine field which the nuclei feel in the Fe foil. The temperature of the sample which, via the Boltzmann distribution, determines the degree of nuclear polarization is obtained from the anisotropy of the 136 keV $\gamma$ ray of the $^{57}$CoFe thermometer. Finally, the factor $f$ represents the fraction of nuclei that feel the full orienting hyperfine interaction, $\mu B$. In the two-site model used the fraction $(1 - f)$ is supposed to feel no interaction at all. The fraction $f$ was obtained from the anisotropy of the $5^+ \rightarrow 1^+ 190$ keV IT of the implanted $^{114m}$In. This was done for each field value as it was observed [22] that part of the saturation magnetization of the Fe foil obtained at 0.5 T was lost when the field was reduced to a lower value for the measurements. Since emission of the 190 keV $\gamma$ ray does not cause the $^{114}$In daughter nuclei to recoil from their lattice position, the values obtained for the fraction $f$ apply to $^{114}$In as well.

A GEANT4 based Monte-Carlo code [23] was used to calculate the factor $Q_{cos\theta}$ which includes the geometry of the setup, the effect of the magnetic field on the $\beta$ particle trajectories, and (back)scattering in the source, on the sample holder and on the detector. The geometrical $Q_{cos\theta}$ values for zero magnetic field and for the spectrum endpoint (where scattering effects are negligible) were equal to $Q_{cos\theta} = -0.930(6)$ and $+0.314(2)$ for the axial and equatorial detectors, respectively.

For the energy calibration the conversion electrons from $^{114}$In (Fig. 1) and the $\gamma$ rays from a $^{60}$Co source were used. The Ge detectors that were used in view of the high endpoint energy give rise to rather significant scattering effects; the percentage of scattered events was found to increase from 5 % at about 1.75 MeV to 12 % at about 1.60 MeV. Therefore, the analysis was limited to the highest energy part of the $\beta$ spectrum where all disturbing effects are minimal. The lower energy bound for the region for analysis was then set at 1.700(10) MeV as simulations showed that from this energy on the values of $Q_{cos\theta}$ were affected by less than 5 % (relative) by the magnetic field, scattering, etc. (Fig. 1). As the count rate for energies above 1.830(10) MeV was marginal the upper bound for analysis was set at this value, such that $v/c = 0.9744(15)$. Simulations showed the values of $Q_{cos\theta}$ for the region from 1.700 MeV to 1.830 MeV, and for the part of the spectrum above to be identical (see Table I), indicating that the conditions for scattering and magnetic field effects in the region used for analysis are very similar to the ones at the endpoint. The precision to which this holds for both detectors and the three magnetic field values, was found to correspond to a 0.6 % variation of $\tilde{A}$ that was subsequently assigned as a systematic error related to the
Monte-Carlo simulations. This turned out to be the largest systematic error.

![Image of graph showing beta anisotropy](image)

**FIG. 1:** $\beta$ anisotropy of $^{114}$In for the region between 1.700 and 1.830 MeV, in a field of 0.046 T ($\chi^2/\nu = 0.71$). Upper inset: Low energy part of the $\beta$ spectrum with $\gamma$ rays from $^{57}$Co and conversion electrons from $^{114}$In. Lower inset: High energy part of the $\beta$ spectrum.

Fig. shows the $\beta$ anisotropy observed in a field of 0.046 T. Results for $\tilde{A}$ obtained from all three measurements are listed in Table III. An overview of systematic errors is given in Table III. The energy calibration led to a negligible systematic error. The error related to the precision to which the geometry of the setup and the magnetic field map that were used in the simulations are known, was determined by repeating the analysis with one standard deviation modified input for the simulations, leading to systematic errors on $\tilde{A}$ of 0.3 % and 0.4 %, respectively. The magnetic field map was calculated from the magnet’s dimensions and properties provided by the manufacturer. The accuracy of it was checked by a comparison with measured field values. The difference between the calculated and measured values was then used as error bar. The precision to which the geometry of the $\gamma$ detection setup (used to determine the fraction $f$) was known induced a 0.13 %
TABLE I: Differences of the simulated values of $Q\cos\theta$ for the energy region from 1.700 MeV to 1.830 MeV used for analysis (‘anal’), and the region from 1.830 MeV up to the spectrum endpoint at 1.989 MeV (‘end’), for both detectors.

| Magnetic field (T) | $(Q\cos\theta)^{\text{anal}} - (Q\cos\theta)^{\text{end}}$ | axial detector | equatorial detector |
|-------------------|-------------------------------------------------|----------------|---------------------|
| 0.046             | -0.0031(42)                                    | -0.0032(25)    |                     |
| 0.093             | -0.0016(66)                                    | +0.0039(37)    |                     |

systematic uncertainty on $\tilde{A}$. The experimental uncertainty on the magnetic hyperfine interaction strength $\mu B$ used in the analysis translates into an uncertainty in the degree of nuclear orientation. This induces a systematic error of 0.16% from fitting the $\beta$ asymmetry, to obtain $f\tilde{A}$, and an additional 0.15% via the determination of $f$ from the 190 keV $\gamma$ anisotropy. Since both errors are fully correlated they are added linearly.

Finally, analysis also accounted for the facts that $^{114}$In, due to its short half-life, inherits a small part of the polarization from its precursor, $^{114m}$In, and that some nuclei may not yet have reached thermal equilibrium (i.e. the polarization corresponding to the sample temperature) in the Fe lattice when they decay [24, 25, 26]. As the $\mu B$ values for both isotopes that govern these effects are precisely known and, in addition, $\mu B$ for $^{114}$In is very large both effects are small and can be fully accounted for [26, 27]. Varying then all relevant parameters within their error bars translated into a variation of $\tilde{A}$ of at most 0.3%.

To account for the apparent field dependence of $\tilde{A}$ a systematic error of 0.4% was added, determined by the average shift of the $\tilde{A}$ values required to get $\chi^2/\nu = 1.0$.

Taking into account the statistical and systematic errors discussed above (Tables II and III), our experimental result is $\tilde{A} = -0.990 \pm 0.010(\text{stat}) \pm 0.010(\text{syst})$.

At this level of precision a small correction for the effect of recoil order terms [28] is necessary. Since we deal with a $1^+ \rightarrow 0^+$ pure GT transition only the weak magnetism, $b$, in the notation of Holstein [28], and the first class induced tensor term, $d$, are important. Further, from systematics (see e.g. [29, 30]) we estimate $b/Ac = 4.6 \pm 2.7$ and $d/Ac = \pm (1.2 \pm 1.2)$ with $A$ here being the mass of the nucleus and $c$ the GT form factor [28]. One then calculates a recoil correction of $-0.0041(30)$ which leads to $\tilde{A} = -0.994 \pm 0.010(\text{stat}) \pm 0.010(\text{syst})$. 6
TABLE II: Results for $\tilde{A}$. The fraction $f$ was obtained from the anisotropy of the 190 keV IT $\gamma$ ray of $^{114m}$In. Only statistical errors are listed here. The error on $\tilde{A}$ is a combination of the statistics on the $\beta$ anisotropy (from which the product $f\tilde{A}$ was obtained) and the statistical error on the fraction $f$ that was used to extract $\tilde{A}$. The error on the weighted average of $\tilde{A}$ was increased by a factor $\sqrt{\chi^2/\nu} = 1.55$. Systematic errors are listed in Table III.

| $B_{ext}$ [T] | fraction $f$ | $\tilde{A}$ |
|---------------|-------------|------------|
| 0.046         | 0.734(5)    | -1.003(9)  |
| 0.093         | 0.803(8)    | -0.987(13)|
| 0.186         | 0.874(7)    | -0.972(11)|

weighted average -0.990(10)

Being in agreement with the Standard Model value $\tilde{A}_{SM}^{\beta^-} = -1$ this result can now be used to constrain physics beyond. Our value corresponds to a lower limit of $M_2 = 230$ GeV/$c^2$ (90% C.L.) for the mass of the weak boson eigenstate $W_2$ that is mainly related to a $W_R$ boson that couples to right-handed neutrinos [31]. This is less stringent than limits from other experiments in $\beta$ decay [32, 33, 34, 35, 36, 37]. However, our result is of interest for tensor type charged weak currents. Assuming maximal parity violation and time reversal invariance for vector and axial-vector currents, one has for a $J \rightarrow J - 1$ pure GT $\beta^-$ transition [8]:

$$\tilde{A}_{GT}^{\beta^-} \simeq A_{SM} + \frac{\alpha Z m}{p_e} \text{Im} \left( \frac{C_T + C'_T}{C_A} \right) + \frac{\gamma m}{\langle E_e \rangle} \text{Re} \left( \frac{C_T + C'_T}{C_A} \right) + \text{Re} \left( \frac{C_T C'^*_T}{C_A^2} \right) + \frac{|C_T|^2 + |C'_T|^2}{2C_A^2}$$

(3)

with $\alpha$ the fine-structure constant, $Z$ the charge of the daughter nucleus, $\gamma = \sqrt{1 - (\alpha Z)^2}$ and $C_{V,A,T}^{(\ell)}$ coupling constants for vector, axial vector and tensor interactions. Primed (unprimed) coupling constants are for parity violating (invariant) interactions. The term with $\gamma m/\langle E_e \rangle$ comes from the Fierz interference term $b_{\text{Fierz}}$ in Eq. (1).

With an average kinetic energy of about 1.76 MeV for the observed $\beta$ particles, the sensitivity factors in Eq. (3) are $\alpha Z m/\langle p_e \rangle = 0.084$ and $\gamma m/\langle E_e \rangle = 0.209$. Assuming time reversal invariance, i.e. $\text{Im}[(C_T + C'_T)/C_A] = 0$, as was verified at the level of about 1% in a
measurement with $^8$Li, and to first order in $C_T$, Eq. (3) yields for time reversal invariant, real tensor couplings (i.e. the Fierz interference term) $-0.082 < (C_T + C'_T)/C_A < 0.139$ (90 % C.L.). In Fig. 2 this result is compared to limits from other experiments in nuclear $\beta$ decay.

The most accurate measurement of the $\beta$ asymmetry parameter for a nuclear $\beta$ transition to date was reported. Crucial to this was the use of a GEANT based simulation code for this type of measurements. Our result provides limits for time reversal invariant tensor couplings in the weak interaction that are competitive with those from other experiments. A still higher sensitivity can be obtained if $\beta^-$ transitions with a lower endpoint energy are observed. E.g. for $E_e \approx 600$ keV one has $\gamma m/E_e \approx 0.4$ which yields, for the same accuracy, two times more stringent limits. Such measurements are in progress.

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FIG. 2: Limits (90% C.L.) on time reversal invariant tensor couplings from correlation measurements in nuclear $\beta$ decay: the Fierz interference term $b_{\text{Fierz}}$ from a spectrum shape measurement for $^{114}\text{In}$ (with only statistical errors quoted) $^{39, 40}$, the $\beta$ asymmetry parameter $\tilde{A}$ in the decay of $^{114}\text{In}$ (this work) and in free neutron decay $^{31}$, and the $\beta$-$\nu$ correlation coefficient $\alpha$ in the decays of $^6\text{He}$ $^{41, 42}$ and $^{21}\text{Na}$ $^{43}$ (see also ref. $^{17}$). Limits for the mixed Fermi/GT transitions of the neutron and $^{21}\text{Na}$ are for scalar couplings $C_S = C'_S = 0$. 