Search for Time-Reversal Violation in the $\beta$-Decay of Polarized $^8\text{Li}$ Nuclei

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The transverse polarization of electrons emitted in the $\beta$-decay of polarized $^8\text{Li}$ nuclei has been measured. For the time reversal violating triple correlation parameter we find $R = (0.9\pm2.2) \times 10^{-3}$. This result is in agreement with the standard model and yields improved constraints on exotic tensor contributions to the weak interaction. It also provides a new limit on the mass of a possible scalar leptoquark, $m_{LQ} > 560 \text{ GeV}/c^2$ (90% C.L.).

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Following the surprising discovery of the small violation of the $CP$ symmetry in the neutral kaon system almost 40 years ago [1], larger signatures have been observed more recently in the decay of neutral $B$ mesons [2]. According to the $CPT$ theorem any violation of the combined particle-antiparticle and space inversion symmetries ($CP$) is equivalent to a violation of time reversal symmetry ($T$). However, only recently a measurement of a difference between the rate of a process and its inverse and thus the first direct confirmation of a time reversal violation has been published [3]. All the observations performed so far could be accommodated within the standard model (SM) through Cabibbo - Kobayashi - Maskawa mixing of the quark states. It is not yet clear whether the small direct $CP$ violation measured in the decay of the $K^0$ (the $\epsilon'/\epsilon$-parameter) [2] can also be explained by the same mechanism, since hadronic corrections cannot be calculated with sufficient precision. Furthermore, the amplitude of $CP$ violation due to mixing of the quark states is by several orders of magnitude too small to explain the matter-antimatter asymmetry of the Universe. Despite huge efforts during the past three decades, no $T$ or $CP$ violation has ever been observed outside the $K^0$ or $B^0$ systems. If the only source of $CP$-violation would be the one offered by the standard model, effects in $\beta$-decay would be second order in the weak interaction and therefore vanishingly small. Thus any observation of a time reversal violation in such a process would be the first unambiguous signal of new physics beyond the SM.

It has been shown in Refs. [2,4] that the accurate determination of the transverse polarization of the electrons emitted in the decay of polarized nuclei can provide such a precision test. An appropriate experiment could yield a new limit for a possible time reversal ($T$) non-invariant tensor-coupling. In renormalizable gauge-theories the only mechanism that could generate such a coupling at the tree level is the exchange of a spin-0-leptoquark [4].

We present here the final result of a measurement of the transverse polarization of electrons emitted in the decay of polarized $^8\text{Li}$ nuclei. A detailed description of the measuring principle and of the experimental setup have been reported previously [5]. We describe here the modifications of the experimental setup which allowed to obtain a considerably higher precision. The most important improvements are a doubling of the $^8\text{Li}$ polarization and an order of magnitude reduction in background events.

The terms in the allowed $\beta$-decay rate function which are relevant for the following discussion are the ones given by the usual parity violating $\beta$ asymmetry parameter $A$ and the parity and time reversal violating triple correlation coefficient $R$ [6].

$$W \propto \left( 1 + A \frac{\vec{J} \cdot \vec{p}_e}{E_e} + R \frac{\vec{J} \cdot (\vec{p}_e \times \vec{\sigma}_e)}{E_e} + ... \right).$$  \hspace{1cm} (1)

In this expression $\vec{J}$ denotes the initial nuclear polariza-
tion whereas \( \vec{p}_e, E_e \) and \( \vec{\sigma}_e \) correspond to the momentum, energy and spin of the electron, respectively.

The experiment was performed at the Paul Scherrer Institute, Villigen, Switzerland. Polarized \(^8\)Li nuclei were produced in the reaction \(^7\)Li(\(\vec{d}, p\))\(^8\)Li using a 0.9 \(\mu\)A beam of 10 MeV vector-polarized deuterons from a polarized-ion source based on the atomic-beam method. Compared to the earlier experiments, the beam polarization was improved by use of radio-frequency transitions on the atomic beam which, ideally, yield reversible vector polarizations of \( \pm 1 \) \(\sigma\). The transitions were adjusted by optimizing the asymmetry in the \(^{12}\)C(\(\vec{d}, p\))\(^{13}\)C reaction. The target, a 5 mm diameter rod of 99.9 \% enriched \(^7\)Li metal, was cooled with liquid helium and placed in a magnetic field of \( B_y = 7 \) mT (c.f. fig. 1) to achieve a long polarization relaxation time (\( T \geq 20 \) s), an order of magnitude longer than the mean decay time (\( \tau = 1.21 \) s).

![FIG. 1: Simplified view of the \(^7\)Li target cryostat. The horizontal access of the beam is indicated on the right. The outer diameter of the cryostat is 40 mm](image)

The polarization of the \(^8\)Li target was deduced from the beta decay asymmetry detected by plastic scintillator telescopes placed at \( \theta = 45^\circ \) and \( 135^\circ \) with respect to the \(^8\)Li polarization axis. The Li target was viewed by the detectors through small holes in the shielding. The evolution of the asymmetry during the experiment as measured by one of the telescopes is shown in fig. 2. From the super-ratios of the counting rates of the two telescopes and the value of the asymmetry parameter for a \( J_i = J_f \) pure Gamow-Teller transition (\( A = -1/3 \)) the value of the \(^8\)Li polarization, averaged over the whole measurement period, was found to be \( |J| = 0.21 \pm 0.01 \), which represents a factor 2 improvement over the earlier experiment \( \& \).

The transverse polarization of the electrons emitted in the decay \(^8\)Li \( \rightarrow ^{8}\)Be(2.9 MeV)\(+\)e\(^-\)+\(\vec{\nu}_e\) was deduced from the measured asymmetry in Mott scattering at backward angles. A lead foil of 105 mg/cm\(^2\) thickness was used as analyzer. To obtain a large solid angle the asymmetry detectors were arranged in a cylindrical geometry around the \(^8\)Li polarization axis (c.f. fig. 3). In practice, the detector was made of four separate azimuthal segments, each containing an upper and a lower telescope, which provided four independent measurements of the electron polarization. The telescopes consisted of two thin transmission scintillators (\( \delta, \Delta \)) followed by a stopping scintillator (\( E \)). Much attention was paid to the passive shielding of the detectors against background radiation produced in the target neighborhood. In the central part of the apparatus, additional cylindrical electron skimmers were mounted on the brass collimators. They reduced significantly multiple scattering of electrons on the collimator plates. All other shieldings with large atomic numbers have been covered with plastic to reduce the scattering of electrons.

![FIG. 2: Beta asymmetry measured with the \(^8\)Li polarization monitor as a function of file (run) number](image)

![FIG. 3: Vertical cross section through the Mott polarimeter. The direction of the incident polarized deuteron beam is perpendicular to the figure. The central arrow indicates the direction of the \(^8\)Li spin in the target. A trajectory of an electron scattered on the lead foil is also shown. The diameter of the analyzer foil ring is 1.1 m.](image)
TABLE I: Deduced values of the R-coefficient including applied corrections in units of $10^{-3}$ for the present and five former results.

| Series     | I Ref. [10] | II Ref. [10] | III Ref. [8] | IV Ref. [8] | V Ref. [14] | VI present |
|------------|-------------|--------------|--------------|-------------|-------------|------------|
| Raw data   | 12 $\pm$ 34 | 9 $\pm$ 12   | $-13 \pm 7$ | $-8 \pm 4$  | $-3.6 \pm 6.1$ | 0.7 $\pm$ 2.6 |
| Decay background | $-39 \pm 26$ | $-13 \pm 8$  | 6 $\pm$ 4    | 0 $\pm$ 2   | 2.5 $\pm$ 1.1 | $-0.5 \pm 0.9$ |
| Gain shifts | $-1 \pm 3$  | $-1 \pm 2$   | $-1 \pm 1$  | $-1 \pm 1$  | $-0.7 \pm 1.6$ | 0.0 $\pm$ 0.4 |
| Accidental  | $-7 \pm 8$  | $-1 \pm 2$   | 2 $\pm$ 2    | 1 $\pm$ 1   | $-1.6 \pm 1.1$ | $-0.4 \pm 0.5$ |
| Beta asymmetry | 11 $\pm 5$  | 13 $\pm 2$   | 10 $\pm 1$   | 6 $\pm 1$   | 5.5 $\pm 0.5$  | 2.5 $\pm 0.7$  |
| Result     | $-24 \pm 44$ | 7 $\pm 15$   | 4 $\pm 8$    | $-2 \pm 5$  | 2.1 $\pm 6.5$  | 2.3 $\pm 2.9$  |

The modifications of the apparatus mentioned above led to a signal-to-background ratio between 75 and 150 in the different segments of the polarimeter. This is an improvement of an order of magnitude compared with the conditions in the earlier stage of the experiment [8, 10].

The measurement was performed in a cyclic fashion with a 0.33 s activation of the target followed by a measuring period divided into 32 intervals of 33 ms each. The sign of the beam polarization $p_y$ was reversed every four activation/measurement cycles. The data were accumulated separately for eight telescope sectors in form of two-dimensional spectra (time vs. energy) and stored for off-line analysis. 24 runs of 2 hours duration with the scattering foil in place (foil-in) and 2 runs with foil removed (foil-out) were taken. The foil-out runs provided the information on the intensity and asymmetry of the background that affected each telescope.

It has been shown previously [8] that different methods of analyzing the data lead to virtually the same results. The data collected in the current experiment were analyzed twice. In the first procedure, the polarization of the $^8$Li source was assumed to be constant in time. In the second one, each file of raw data, corresponding to a single run, was associated with the polarization value measured for this particular run. Again, the final results and their statistical consistency are almost identical which indicates that the asymmetry variations shown in Fig. 2 have no significant effect. In both analyses the correlation coefficient $R$ was calculated file-by-file, separately for four pairs of telescopes and then the weighted average of the four telescopes was calculated.

Table I summarizes the evolution of the improvements achieved during this project. The table includes in columns I-IV the results obtained previously [8, 10]. Series V and VI were obtained with the modified setup presented here, except that for series V only some of the improvements had been implemented.

The most important steps in the treatment of the data and the corrections were the following:

*Analyzing power.* The spin dependence (analyzing power or Sherman function) in the scattering of 14 MeV electrons from Pb as a function of scattering angle and foil thickness was investigated in a separate experiment at the Mainz Microtron, c.f. Ref. [14]. In order to minimize background and multiple scattering effects in the lead foil, the lower threshold for the energy of scattered electrons was set to 4 MeV. (The $\beta$-endpoint energy is 13.1 MeV). The thickness of the lead foil was chosen to optimize the count rate while limiting the decrease in effective analyzing power by multiple scattering in the foil. In the present experiment the mean value of the analyzing power was $A = 0.08 \pm 0.01$.

*Cuts in time.* The first time channel (33 ms) after each activation period was disregarded since the rate recorded by all detectors in this time interval was higher by an order of magnitude than that in the next channel. This excess was attributed to short lived background activities after irradiation.

*Gain corrections and energy cuts.* The amplification of the detectors was monitored with LED flashes fired at the beginning of each time channel. The amplifications were always observed to be about 5 % larger at the beginning of each time channel. This effect is very similar for the two polarization states of the $^8$Li source. As a consequence, the gain variation contribution to the uncertainty of the R-coefficient is strongly suppressed.

*Decay background.* The fraction of events not originating from electrons scattered by the analyzer foil was assumed to be constant in time. It was deduced from the measurements with removed scattering foil. The corresponding correction was calculated for each pair of telescopes separately.

*Accidentals, dead time and pile up.* The rate of accidental coincidences was determined by inserting delay lines into the input channels of the master coincidence unit. The rate of accidentals compared to the regular foil-in rate was only $\approx 0.0009$. The correction was applied separately for each pair of telescopes. The effects from dead time and pile up are very small and are combined in Tab. I with accidentals.
**Beta asymmetry.** This nonstatistical effect is associated with the nonuniform illumination of the scattering foil. It arises from an interplay between the asymmetric angular distribution of decay electrons from polarized nuclei and the finite geometry of the apparatus, in particular, the scattering foil. (see Ref. [8]). This is a small but measurable effect which does not cancel under inversion of the nuclear spin $J$ (see Eq. 4). Since the magnitude of this effect is proportional to the square of the height $h^2$ of the scattering foil, it was reduced in series V and VI by using a lead foil with a smaller height (40 mm and 25 mm, instead of 50 - 70 mm as in the previous experiments). The associated correction was determined by replacing the regular scattering foil used during the measurement by one of smaller size which was moved over the region covered by the regular foil [11].

The weighted average value of the $R$-correlation deduced from all the six runs including the last two with the modified setup is

$$R_M = (1.6 \pm 2.2) \times 10^{-3}$$  \hspace{1cm} (2)

**Final state interaction.** The effects of the final state interaction (FSI), which can mimic the genuine time reversal violation in the $R$ correlation, are exceptionally small for the $^8\text{Li}$ decay. An average value of the FSI correction over the energy range of detected electrons amounts to $R_{FSI} = 0.7 \times 10^{-3}$ and is known with 10% accuracy. This accuracy is adequate for our experiment although more precise calculations of the FSI correction are possible [12, 13].

Taking into account the FSI effects we obtain the time reversal violating part $R$ from the measured correlation $R_M$:

$$R = R_M - R_{FSI} = (0.9 \pm 2.2) \times 10^{-3}.$$  \hspace{1cm} (3)

This result is consistent with time reversal invariance.

One of the distinct advantages of the decay $^8\text{Li} \to ^7\text{Be}(2.9\text{MeV}) + e^- + \bar{\nu}_e$ is its simple spin-isospin structure ($\Delta J = 0, \Delta T = 1$). The Fermi matrix elements vanish and one has an essentially pure, allowed Gamow-Teller transition. In this case the $R$-parameter depends only on the tensor interaction:

$$R = -\frac{4}{3} \Im \left( \frac{g_T}{g_A} a_{RL}^T \right) = \frac{1}{3} \Im \left( \frac{C_T + C_F^2}{C_A} \right)$$  \hspace{1cm} (4)

We use the helicity projection constants $(g_T, g_A, a_{RL}^T)$ as defined in Ref. [8]. They are analogous to the ones used in the Review of Particle Properties for pure leptonic transitions [14]. $C_T, C_F^2$ are the unknown tensorial coupling constants and $|C_A| \approx 1.26$ is the axial-vector coupling constant as defined in Ref. [8]. If we use the same normalization as Ref. [8] for the tensorial coupling constant, $g_T/g_A = 1$, we get the new limit

$$\Im \left( a_{RL}^T \right) = -0.0007 \pm 0.0016$$ \hspace{1cm} (1σ)  \hspace{1cm} (5)

which has roughly the same precision as the best determination of the real part, $|\Re (a_{RL}^T)| < 0.0035$ (90% C.L.) [15]. We therefore also obtain an improved limit for

$$|a_{RL}^T| < 0.0044$$ \hspace{1cm} (90% C.L.)  \hspace{1cm} (7)

Finally, for a possible coupling with scalar leptoquarks, we obtain using a relation from Ref. [8]:

$$\frac{m_{LQ}}{h_R h_L^\frac{1}{2}} = \frac{\sqrt{2}}{8 G_F a_{RL}^T} > 1.8 \text{GeV} \text{ at } 90\% \text{ C.L.}$$  \hspace{1cm} (8)

$h_R$ and $h_L$ are the (unknown) coupling constants of the leptoquarks and $G_F$ the Fermi coupling constant. If we assume “canonical” values for $h_{L,R} = \sqrt{\frac{1}{4 \alpha_{em}}} \approx 0.3$ we get an estimate for the mass of a possible scalar leptoquark with charge $Q = \pm 2/3e$ of $m_{LQ} > 560 \text{ GeV}/c^2$. This has to be compared to limits from high energy experiments, which yield in general lower limits of approx. 300 GeV/c² [10].