Search for Time-Reversal Violation in the β Decay of Polarized ^{8}Li Nuclei

R. Huber, J. Lang, S. Navert,* and J. Sromicki
Institut für Teilchenphysik, Eidgenössische Technische Hochschule, CH-8093 Zürich, Switzerland

K. Bodek, St. Kistryn, and J. Zejma
Instytut Fizyki, Uniwersytet Jagielloński, PL-30059 Kraków, Poland

O. Naviliat-Cuncic
Laboratoire de Physique Corpusculaire de Caen, ISMRA-IN2P3, 14050 Caen, France

E. Stephan
Instytut Fizyki, Uniwersytet Śląski, PL-40007 Katowice, Poland

W. Haeberli
University of Wisconsin, Madison, Wisconsin 53706, USA

(Received 6 January 2003; published 20 May 2003)

The transverse polarization of electrons emitted in the β decay of polarized ^{8}Li nuclei has been measured. For the time-reversal violating triple correlation parameter we find $R = (0.9 \pm 2.2) \times 10^{-3}$. This result is in agreement with the standard model and yields improved constraints on exotic tensor contributions to the weak interaction. Combined with other experimental results and using a model for the coupling constants, a new limit for the mass of a possible scalar leptoquark, $m_{\mathrm{LQ}} > 560\ \mathrm{GeV}/c^2$ (90% C.L.), is obtained.

DOI: 10.1103/PhysRevLett.90.202301 PACS numbers: 24.80.+y, 11.30.Er, 23.40.Bw, 24.70.+s

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 ϵ'/ϵ parameter) [4] 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 [5]. 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 β 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. [6,7] 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 [7].

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

The terms in the allowed β-decay rate function which are relevant for the following discussion are the ones given by the usual parity violating β asymmetry parameter A and the parity and time-reversal violating triple correlation coefficient R [9].

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

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

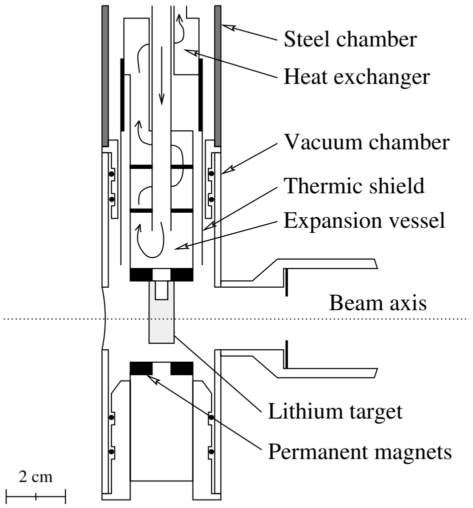

FIG. 1. Simplified view of the ^{7}Li target cryostat. The horizontal access of the beam is indicated on the right. The outer diameter of the cryostat is 40 mm.

The experiment was performed at the Paul Scherrer Institute, Villigen, Switzerland. Polarized ^{8}Li nuclei were produced in the reaction $^{7}\mathrm{Li}(\vec{d},p)^{8}\vec{\mathrm{Li}}$ using a 0.9 μA 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 ± 1 [10]. The transitions were adjusted by optimizing the asymmetry in the $^{12}\mathrm{C}(\vec{d},p)^{13}\mathrm{C}$ 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 (cf. 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).

The polarization of the ^{8}Li target was deduced from the beta decay asymmetry detected by plastic scintillator telescopes placed at $\theta = 45°$ and $135°$ 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 superratios 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 $|\vec{J}| = 0.21 \pm 0.01$, which represents a factor of 2 improvement over the earlier experiment [8].

The transverse polarization of the electrons emitted in the decay $^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be}(2.9\ \mathrm{MeV}) + e^{-} + \bar{\nu}_e$ 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 (cf. 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 (δ, Δ) 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.

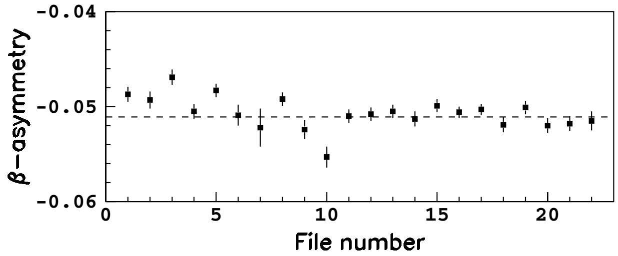

FIG. 2. Beta asymmetry measured with the ^{8}Li polarization monitor as a function of file (run) number.

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 [8,11]. 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

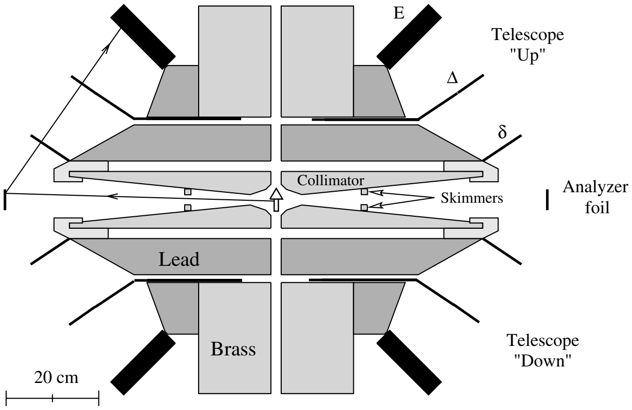

FIG. 3. Vertical cross section through the Mott polarimeter. The direction of the incident polarized deuteron beam is perpendicular to the figure. The central arrow indicates the direction of the ^{8}Li spin in the target. A trajectory of an electron scattered on the lead foil is also shown. The diameter of the analyzer foil ring is 1.1 m.

four activation/measurement cycles. The data were accumulated separately for eight telescope sectors in the form of two-dimensional spectra (time vs energy) and stored for off-line analysis. Twenty-four runs with the scattering foil in place (*foil in*) and two 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 [8,11]. 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; cf. Ref. [13]. 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 β–end-point 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 $\mathcal{A} = 0.08 \pm 0.01$.

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 light-emitting diode flashes fired at the beginning of each time channel. The amplifications were always observed to be about 5% larger at the beginning of the counting interval. 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 0.008 ± 0.002. 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 pileup.—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 ≈ 0.0009. The correction was applied separately for each pair of telescopes. The effects from dead time and pileup are very small and are combined in Table 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 $\vec{J}$ [see Eq. (1)]. 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 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

TABLE I. Deduced values of the R coefficient including applied corrections in units of 10^{-3} for the present and five former results. All the errors are random and dominated by counting statistics. To get the results they are added in quadrature.

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

covered by the regular foil [12]. This test was carried out separately for each series. Thus the uncertainties in the correction are statistically independent.

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

$$R_M = (1.6 \pm 2.2) \times 10^{-3}. \tag{2}$$

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}Li decay (see Sec. VII B in Ref. [8]). An average value of the FSI correction over the energy range of detected electrons and calculated in the point nucleus approximation [9] amounts to $R_{\mathrm{FSI}} = 0.7 \times 10^{-3}$ and is known with 10% accuracy.

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

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

This result is consistent with time-reversal invariance.

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

$$R = -\frac{4}{3}\mathrm{Im}\left(\frac{g_T}{g_A} a_{RL}^T\right) = \frac{1}{3}\mathrm{Im}\left(\frac{C_T + C_T'}{C_A}\right). \tag{4}$$

We use the helicity projection constants (g_T, g_A, a_{RL}^T) as defined in Ref. [6]. They are analogous to the ones used in [14] for pure leptonic transitions. C_T, C_T' are the unknown tensorial coupling constants and $|C_A| \approx 1.26$ is the axial-vector coupling constant as defined in Ref. [9]. Since the transition from quark states to nucleons is not trivial [15], we use the same, rather conservative normalization as Ref. [6] for the tensorial coupling constant, $g_T/g_A = 1$, and get the limit

$$\mathrm{Im}(a_{RL}^T) = -0.0007 \pm 0.0016 \qquad (1\sigma), \tag{5}$$

$$|\mathrm{Im}(a_{RL}^T)| < 0.0029 \qquad (90\%\ \mathrm{C.L.}), \tag{6}$$

which has roughly the same precision as the best determination of the real part, $|\mathrm{Re}(a_{RL}^T)| < 0.0035$ (90% C.L.) [6]. We therefore also obtain an improved limit for

$$|a_{RL}^T| < 0.0044 \qquad (90\%\ \mathrm{C.L.}). \tag{7}$$

Indirect limits on the tensor interaction from atomic dipole moments and from radiative corrections in π decay are discussed in Ref. [16]. A Fierz transformation shows that this tensor interaction can be explained by the exchange of spin-0 leptoquarks. We obtain, using the same Hamiltonian as Ref. [7], Eq. (159) [17]:

$$\frac{m_{LQ}}{|h_L h_R^*|^{1/2}} = \left|\frac{\sqrt{2}}{8G_F a_{LR}^T}\right|^{1/2} > 1.8\ \mathrm{TeV} \quad \text{at } 90\%\ \mathrm{C.L.} \tag{8}$$

h_R and h_L are the (unknown) coupling constants of the leptoquarks and G_F is the Fermi coupling constant. If we assume "canonical" values for $h_{L,R} = \sqrt{4\pi\alpha_{elm}} \approx 0.3$ we get an estimate for the mass of a possible scalar leptoquark with charge $Q = \pm 2/3e$ of $m_{LQ} > 560\ \mathrm{GeV}/c^2$. This has to be compared to limits from high energy experiments, which yield in general lower limits of $\approx 300\ \mathrm{GeV}/c^2$ [18].

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*Permanent address: Swiss Nuclear Safety Inspectorate, CH-5232 Villigen HSK, Switzerland.

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