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Testing Lorentz invariance in β decay

using polarized sodium atoms

A. Sytema[1,a] for the "Fundamental Interactions and Symmetries" group

[1] *KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*

Abstract. In theories aiming to unify the Standard Model with gravity, Lorentz invariance may be broken. Although Lorentz symmetry appears to hold well, few experiments have been performed that consider its violation in the weak interaction. We have started a theoretical and experimental research program to this effect. We consider a Lorentz violating correction of the W-boson propagator, characterized by a tensor. With this extension of the Standard Model the β-decay rate will depend on how the spin of the parent nucleus and the emission direction of the β and ν particles are oriented in absolute space. We explore the consequence for allowed Fermi and Gamow-Teller transitions and the spin degrees of freedom in the latter.

Experimentally we exploit the Gamow-Teller transition of polarized ^{20}Na, where we can test the dependence of the β-decay rate on the spin orientation of ^{20}Na. The polarization degree is measured using the β asymmetry, while the decay rate is measured by the γ yield. A change in the γ rate, when reversing the spin, implies Lorentz invariance violation. The decay rate should depend on sidereal time and the polarization direction relative to the rotation axis of the earth. The method of the measurement will be presented, together with the first results.

1 Introduction

Lorentz symmetry is the fundamental basis of two of the most successful theories of modern physics, General Relativity (GR) and the Standard Model of particle physics (SM). It is the symmetry group of rotation and boost transformations. For obtaining a theory incorporating the four fundamental forces, effort is made to unify GR and quantum mechanics in a 'theory of everything'. Several candidate theories exist, referred to as quantum gravity models. In some of these models Charge-Parity-Time (CPT) symmetry breaking and / or Lorentz Invariance Violation (LIV) is possible [1, 2].

Many experiments testing LIV in the electromagnetic interaction have been performed [3], however only few have considered the weak interaction. This despite the fact that the theoretical description of the weak interaction has played an important role in developing the SM. One can look at the violation of rotational invariance, since there is no *a priori* reason why angular momentum would be conserved [4]. Previously such tests were performed using forbidden β decays [5, 6].

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[a] e-mail: sytema@kvi.nl

Table 1. Expressions for ξ_i in terms of $\chi^{\mu\nu}$. r and i denote the real and imaginary parts of the tensor.

ξ	Fermi	Gamow-Teller
$\xi_1 \hat{n}_1^l$	$2\chi_r^{0l}$	$\frac{2}{3}(\chi_r^{l0} + \epsilon^{lmk}\chi_i^{mk})$
$\xi_2 \hat{n}_2^l$	n.a.	$A\epsilon^{lmk}\chi_i^{mk}$
$\xi_3 \hat{n}_3^l$	$\mp \sqrt{(1-(\alpha Z)^2)(1-\beta^2)}\epsilon_1 \hat{n}_1$	$\mp \sqrt{(1-(\alpha Z)^2)(1-\beta^2)}\epsilon_1 \hat{n}_1$

2 LIV in the weak decay

The Lorentz-violating extension of the SM, developed by V. A. Kostelecky and coworkers [7], is an effective quantum field theory that includes all possible Lorentz-violating operators. In the theory developed at KVI, the consequence of LIV in the weak decay is parametrized as the modification of the W-boson propagator

$$\langle W^{\mu+}(p) W^{\nu-}(-p) \rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2} , \tag{1}$$

where $g^{\mu\nu}$ is the Minkowski metric and $\chi^{\mu\nu}$ is a (complex, possibly momentum dependent) LIV tensor [8]. This leads to a modification of the SM decay width Γ_0. There could be an anisotropy with respect to the direction of the β-particle $\vec{\beta}$, the nuclear spin of the parent nucleus $\vec{J}$ or the spin of the β particle $\vec{\sigma}$. The relative decay width is then given by

$$\frac{d\Gamma}{\Gamma_0} = 1 + \vec{\beta} \cdot \left[A \frac{\langle \vec{J} \rangle}{J} + \xi_1 \hat{n}_1 + G\vec{\sigma} \right] + \xi_2 \frac{\langle \vec{J} \rangle}{J} \cdot \hat{n}_2 + \xi_3 \vec{\sigma} \cdot \hat{n}_3 , \tag{2}$$

where ξ_i ($i = 1, 2, 3$) are Lorentz-invariance violating parameters that relate to $\chi^{\mu\nu}$ and $\hat{n}_i$ are the preferred directions in absolute space. The SM parity violation is given by the β-asymmetry parameter A, and G, the parameter associated with the longitudinal polarization of the β particles. Other terms than those in Eq. (2) are also possible [8] but are not measured in our experiment. Boost effects are not considered because of the low velocity of the nuclei. Table 1 summarizes which parts of $\chi^{\mu\nu}$ can be obtained by measuring the various ξ_i using an allowed Fermi or Gamow-Teller decay.

3 Experiment performed at KVI

At the KVI an experiment was designed to measure the term $\xi_2 \hat{n}_2$. We look for a change in the decay rate if the nuclear spin orientation changes with respect to $\hat{n}_2$ in terms of daily or yearly variation caused by the motion of the Earth around its axis and around the sun, and for variation as a consequence of deliberately changing the nuclear spin direction.

The experiment uses ^{20}Na, a Gamow-Teller β^+ emitter with a half life of 0.45 s and a β asymmetry $A = 1/3$. The daughter nucleus of ^{20}Ne subsequently undergoes an electromagnetic (EM) quadrupole transition, emitting a 1.63 MeV photon. The decay scheme is shown in Fig. 1. A 27 MeV/nucleon ^{20}Na beam is provided by the AGOR cyclotron facility, using the ^{1}He(^{20}Ne,^{20}Na)n reaction and the TRIμP isotope separator. The beam of ^{20}Na ions is stopped in a cell containing a buffer gas of 7 atm. neon, where the ions neutralize. The position of the stopping distribution of the ^{20}Na can be tuned by adjustable aluminum degrader foils. The measurement setup, schematically shown in Fig. 2, consists of two plastic scintillator detectors for detecting β particles on the left and right – the West and East direction, respectively – and two NaI γ detectors above and below the buffer gas cell. The atoms are polarized with a solid state laser at the D_1 line frequency of ^{20}Na, using the technique of optical pumping in a weak magnetic field with circularly polarized light [9].

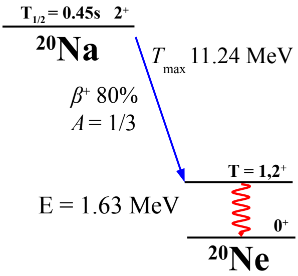

Figure 1. Decay scheme of ^{20}Na.

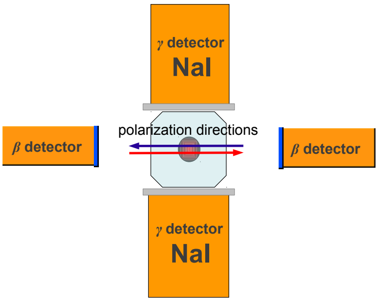

Figure 2. Schematic drawing of the buffer gas cell and detectors.

In our experiment the deliberate reorientation of nuclear spin is repeatedly done in two opposite directions and from this an asymmetry is constructed. Therefore, of the LIV parameters only $\xi_2\hat{n}_2$ is measured. To reduce systematic effects the count rate variation is obtained by measuring γ instead of β^+ particles, the NaI detectors are covered by 20 mm thick Al plates to block β^+ particles and an electronic threshold at 1 MeV suppresses counts from electron-positron annihilation photons. Using the γ yield assumes, of course, Lorentz invariance in the EM decay. Upon writing $\tilde{\chi}_i^l = \epsilon^{lmk}\chi_i^{mk}$, the relative decay width and the asymmetry can thus be written as

$$\frac{d\Gamma_\gamma}{\Gamma_{\gamma,0}} = 1 + AP\left[\vec{\tilde{\chi}}_i \cdot \hat{I}\right] \quad \text{and} \quad \Delta_y(t) = \frac{\Gamma_\gamma^{+\hat{y}}(t) - \Gamma_\gamma^{-\hat{y}}(t)}{\Gamma_\gamma^{+\hat{y}}(t) + \Gamma_\gamma^{-\hat{y}}(t)} = AP(t)\tilde{\chi}_i^2(t)\,, \tag{3}$$

where we have defined $\frac{\langle\vec{J}\rangle}{J} = P\hat{I}$ with P the average polarization of the sample and $\hat{I}$ the average polarization direction, chosen to be in the East-West i.e. $\pm\hat{y}$ direction in the lab frame[1]. $\Gamma_\gamma^{\pm\hat{y}}$ denotes the (total) γ decay rate for polarization in the $\pm\hat{y}$ direction. Assuming a fixed LIV tensor in the Sun-Centered frame [3], transforming to the lab frame leads to a sinusoidal variation as a function of sidereal time ($T_{\text{sid.}} \approx 23^{\text{h}}56^{\text{m}}$).

The ultra-relativistic β^+ particles are measured parallel and antiparallel to the spin direction $\hat{I}$, and are used to measure the polarization degree P from the parity violating term. The laser light helicity is changed every four seconds from σ^+ to σ^- and back. The beam of ^{20}Na is pulsed "on" and "off" every two seconds. As a result we collect decay-rate histograms of an unpolarized sample and of polarized samples for σ^+ and σ^- light, where each histogram has a 2 s beam "on" followed by a 2 s beam "off" time period.

4 Analysis

A typical decay-rate histogram for one of the β detectors is shown in Fig. 3. The asymmetry due to parity violation can be seen for the polarized cases (upper and lower graph) compared to the unpolarized case (middle graph). A β asymmetry of about 17% was achieved, which corresponds to a polarization degree of $P \approx 53\%$.

The corresponding graphs for one of the γ detectors is given in Fig. 4. An enhancement of the count rates for the polarized samples with respect to the unpolarized sample, due to the quadrupole

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[1] In the first such experiment performed, $\hat{I}$ was perpendicular to the earth's surface [10, 11].

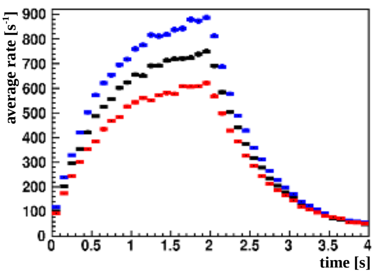

Figure 3. β detector pulsed count rates.

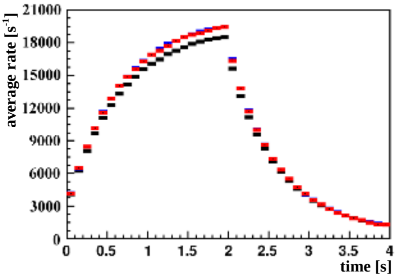

Figure 4. γ detector pulsed count rates.

nature of the radiation can be seen but the effect is similar for both spin directions. Note that these results are from the on-line analysis using half an hour of data. During the experiment, several 24 hour periods of data were taken. For an earlier experiment with polarization in the up and down direction, the statistical sensitivity is of the order 10^{-4} for the γ asymmetry [12]. For the present experiment the polarization, the effective detector area and the measuring time have been increased. Systematic errors have been eliminated or reduced. A one order of magnitude improvement is now feasible.

To conclude, the theory for LIV in the weak decay sector is being developed, some aspects are still being unraveled. Our experiment provides a unique test of LIV in the weak decay. Polarization of nuclei is achieved and several 24h-periods of data are on disk. The analysis is in progress.

5 Acknowledgements

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References

[1] V. A. Kostelecky and S. Samuel: Phys. Rev. D **39**, 683 (1989)
[2] V. A. Kostelecky and R. Potting: Phys. Lett. B **381**, 89 (1996)
[3] V. A. Kostelecky and N. Russell, Rev. Mod. Phys. **83**, 11 (2011)
[4] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956)
[5] R. Newman and S. Wiesner, Phys. Rev. D **14**, 1 (1976)
[6] J. D. Ullman, Phys. Rev. D **17**, 1750 (1978)
[7] D. Colladay and V. A. Kostelecky, Phys. Rev. D **58**, 11602 (1998)
[8] J. P. Noordmans, H. W. Wilschut and R. G. E. Timmermans, Phys. Rev. C **87** 055502 (2013)
[9] E. A. Dijck, Master’s Thesis and added notes, University of Groningen (2012)
[10] S. E. Müller *et. al.*, Hyperfine Interact. **215**, 31 (2013)
[11] H. W. Wilschut *et. al.*, Ann. Phys. (Berlin) (2013), DOI: 10.1002/andp.201300076
[12] S. E. Müller *et. al.*, *submitted for publication*