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Possibilities for Lorentz violation in nonleptonic decays

K. Keri Vos[*]
Van Swinderen Institute for Particle Physics and Gravity, University of Groningen
E-mail: `k.k.vos@rug.nl`

H. W. Wilschut
Van Swinderen Institute for Particle Physics and Gravity, University of Groningen

R. G. E. Timmermans
Van Swinderen Institute for Particle Physics and Gravity, University of Groningen

The weak interaction offers an interesting portal to search for Lorentz symmetry breaking. We explore the possibilities to study Lorentz violation in nonleptonic decays, focusing on the recent measurement of the KLOE collaboration of the directional dependence of the lifetime of the neutral kaon meson. We study Lorentz-violating effects by adding a tensor $\chi^{\mu\nu}$ to the W-boson propagator, and interpret the KLOE data in this general framework.

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[*] Speaker.

1. Introduction

Lorentz symmetry, a key element in both the Standard Model (SM) of particle physics and the theory of General Relativity, can be spontaneously broken in unifying theories of Quantum Gravity [1, 2]. This realization led to an increased effort, both experimentally and theoretically, to search for Lorentz symmetry breaking. The natural scale for unification, the Planck scale (10^{19}GeV), lies far out of reach of present day experiments, but Lorentz violation can become manifest at low energies, hence providing a "window on Quantum Gravity".

The weak interaction, which separately violates the three discrete symmetries P, C, and T, offers an interesting portal to search for Lorentz symmetry breaking [3, 4, 5, 6, 7, 8]. The effects of Lorentz violation in the weak gauge sector are described in a theoretical framework developed in particular to study β decay and electron capture [3, 4, 5]. The framework describes all Lorentz-violating effects on the W boson by adding a general Lorentz-violating tensor $\chi^{\mu\nu}$ to the Minkowski metric. It includes a wide class of corrections, such as modifications of the low-energy W-boson propagator

$$\langle W^{\mu+}W^{\nu-}\rangle = \frac{-i(g^{\mu\nu}+\chi^{\mu\nu})}{M_W^2} , \tag{1.1}$$

and vertex corrections

$$\Gamma^{\mu} = (g^{\mu\nu}+\chi^{\mu\nu})\gamma_{\nu} . \tag{1.2}$$

This framework has been used to search for Lorentz violation in several weak interaction processes. Besides limits from forbidden β decay [5] and allowed β decay [9, 10, 11], bounds on $\chi^{\mu\nu}$ have been derived in pion [12, 13] and muon decay [14]. These bounds can be translated into bounds on the gauge and Higgs parameters of the Standard Model Extension (SME), the most general effective field theory that describes Lorentz violation at low energy [15, 16]. Bounds on the various SME parameters can be found in Ref. [17].

In this talk, we explore the possibilities for nonleptonic decays by considering neutral-kaon decay [18]. We take the recent measurement of the KLOE Collaboration, which searched for the directional dependence of the neutral K_S meson lifetime, as an example to explore to which extent nonleptonic decays can compete with current bounds in semileptonic decays [18].

2. KLOE life-time asymmetry

In addition to the precision measurement of the short-lived neutral K_S^0 lifetime, the KLOE Collaboration searched for the direction dependence of the lifetime with respect to the K_S^0 direction [19, 20]. This dependence was studied by measuring the lifetime asymmetry

$$\mathscr{A} = \frac{\tau^{+}-\tau^{-}}{\tau^{+}+\tau^{-}} , \tag{2.1}$$

where $\tau^{+(-)}$ is the life-time parallel (anti-parallel) to a specific direction in space. The momenta were transformed to galactic coordinates $\{\ell, b\}$ [21], where ℓ is the galactic longitude and b is the galactic latitude. Measurements were done in three direction, for which the results are given in Table. 1. In this Table, CMB0 is the direction of the dipole anisotropy in the CMB and CMB2 and CMB1 are two direction perpendicular to that. The subscript cone refers to the fact that only events inside a cone of 30° opening angle were used [18]. Using this data, we determine limits on $\chi^{\mu\nu}$.

$\{\ell, b\}$	$\mathscr{A}_{\text{cone}} \times 10^3$
CMB0 = $\{264^\circ, 48^\circ\}$	-0.2 ± 1.0 [19]
CMB0 = $\{264^\circ, 48^\circ\}$	-0.13 ± 0.4 [20]
CMB1 = $\{174^\circ, 0^\circ\}$	0.2 ± 1.0 [19]
CMB2 = $\{264^\circ, -42^\circ\}$	0.0 ± 0.9 [19]

Table 1: Measurements of the K_S^0 lifetime asymmetry [19, 20], in three specified directions. CMB0 is the direction of the dipole anisotropy in the CMB, and CMB1 and CMB2 are two perpendicular directions, expressed in galactic coordinates $\{\ell, b\}$. The asymmetries are limited by statistics.

3. Theoretical model

Theoretical calculations in nonleptonic decays are more challenging than semileptonic decays, as the QCD (gluon) corrections are not fully understood (see Ref. [22] for the SM description). The enhancement of decays with $\Delta I = 1/2$ might be cause by penguin-diagrams, although recent lattice calculations find that these diagrams might be of less importance than previously thought [23]. As our goal is to explore if nonleptonic decays can be of importance to the search for Lorentz violation in the weak interaction, we do not derive the full effective Lorentz-violating Hamiltonian. Instead we work in a theoretical model, in which we calculate the contributions of three-level W-boson exchange. Lorentz violation is incorporated by using the modified W-boson propagator in Eq. (1.1). In Ref. [18] we show that the penguin diagram does not contribute to the Lorentz-violating decay rate, which reduces the sensitivity to Lorentz-violating effects.

We derive the decay rate of a K_S^0 into $\pi^+\pi^-$, treating this process naively as being semileptonic, such that

$$\left\langle \pi^+\pi^- | \mathscr{H} | K^0 \right\rangle = 2\sqrt{2} G_F \cos\theta_c \sin\theta_C \left\langle \pi^+ | \bar{u}_L \gamma^\mu d_L | 0 \right\rangle (g_{\mu\nu} + \chi^*_{\mu\nu}) \left\langle \pi^- | \bar{s}_L \gamma^\nu u_L | K^0 \right\rangle , \qquad (3.1)$$

where G_F is the Fermi constant and θ_C is the Cabibbo angle. The complete differential K^0 decay rate in the laboratory frame is given in Ref. [18]. The decay asymmetry is

$$\mathscr{A}_{\vec{n}} = \frac{\frac{4}{3} + \frac{2}{3}\frac{m_\pi^2}{m_K^2}}{\left(1 - \frac{m_\pi^2}{m_K^2}\right)} \gamma^2 \chi_S^{i0} \beta_K^i = 0.34 \chi_S^{i0} \hat{\beta}_K^i , \qquad (3.2)$$

where $\chi_S^{i0} \equiv \chi_r^{i0} + \chi_r^{0i}$, $\beta_K = 0.217$, $\gamma = 1.02$ and $\hat{\beta}_K$ is the direction of the kaon velocity. Important is that the γ^2 enhancement is a general result, which could be exploited in fast-moving decaying particles. In this way, nonleptonic or semileptonic decays could compete with the strong bounds obtain in forbidden β decay [5], which benefited from high-intensity sources. Theoretically, semileptonic decays are preferred for Lorentz violation tests, because nonleptonic decays have a reduced sensitivity due to the penguin diagram that does not contribute and because of theoretical uncertainties related to the unsolved $\Delta I = 1/2$ rule.

For our final results we transform $\chi_{\mu\nu}$ to the sun-centered reference frame[17] and find at 95% confidence level[18],

$$|X_{10}^r + X_{01}^r| < 3.3 \times 10^{-3} ,$$

$$\begin{aligned} |X^r_{20}+X^r_{02}| &< 6.3\times 10^{-3} \,, \\ |X^r_{30}+X^r_{03}| &< 6.0\times 10^{-3} \,. \end{aligned} \tag{3.3}$$

4. Conclusion and Outlook

In this talk we summarized the results of Ref. [18], in which the possibilities to test Lorentz violation in nonleptonic decays are explored. Recent measurements of the lifetime asymmetry of neutral kaons were taken as an example. We work in a general framework that parametrizes Lorentz-violating effects on the W boson by a tensor $\chi^{\mu\nu}$. To first order, this tensor can be related to the SME coefficients [3],

$$\chi^{\mu\nu} = -(k_{\phi\phi})^{\mu\nu} - \frac{i}{2g}(k_{\phi W})^{\mu\nu} \,, \tag{4.1}$$

where $k_{\phi\phi}$ and $k_{\phi W}$ are SME parameters [15]. Our results give at 95% C. L. [18]

$$\begin{aligned} |(k_{\phi\phi})^{XT}_S| &< 3.3\times 10^{-3} \,, \\ |(k_{\phi\phi})^{YT}_S| &< 6.3\times 10^{-3} \,, \\ |(k_{\phi\phi})^{ZT}_S| &< 6.0\times 10^{-3} \,. \end{aligned} \tag{4.2}$$

We discussed that nonleptonic decays are theoretically more challenging than semileptonic or leptonic decays, which are therefore at this point prefered for the study of Lorentz violation. Possibilities to compete and/or complement the strong bounds from forbidden β decays [5], mainly lie in exploiting the γ^2 enhancement, which offers a range of opportunities for LHC experiments. Besides, β decay also offers an interesting portal to further study the effects of Lorentz violation in both the W-boson sector [6] as the neutrino sector [8]. Completely new would be to test Lorentz violation in electron capture. Interesting isotopes and possible experiments have been listed in Ref. [4].

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