

Concurrent tests of Lorentz invariance in β -decay experiments

K. K. Vos, H. W. Wilschut, and R. G. E. Timmermans

Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

(Received 12 August 2015; published 23 November 2015)

Modern experiments on neutron and allowed nuclear β decay search for new semileptonic interactions, beyond the left-handed electroweak force. We show that ongoing and planned β -decay experiments, with isotopes at rest and in flight, can be exploited as sensitive tests of Lorentz invariance. The variety of correlations that involve the nuclear spin, the direction of the emitted β particle, and the recoil direction of the daughter nucleus allow for relatively simple experiments that give direct bounds on Lorentz violation. The pertinent observables are decay-rate asymmetries and their dependence on sidereal time. We discuss the potential of several asymmetries that together cover a large part of the parameter space for Lorentz violation in the gauge sector. High counting statistics is required.

DOI: [10.1103/PhysRevC.92.052501](https://doi.org/10.1103/PhysRevC.92.052501)

PACS number(s): 24.80.+y, 11.30.Cp, 12.60.Cn, 23.40.-s

Motivation. β decay is a recognized probe of symmetry violation in the electroweak interaction. Because of the wide choice of β emitters and the various observables that can be measured with high precision, one can select isotopes that are tailored to specific searches for particle physics beyond the standard model (SM) [1–4]. Over the years, strong limits were put on scalar, right-handed vector and axial vector, and tensor contributions to the semileptonic process $d \rightarrow u + e^- + \bar{\nu}_e$. Recently, it was shown that β decay is moreover a unique laboratory for testing Lorentz invariance in the weak gauge [4–7] and neutrino [8,9] sectors. Such studies are strongly motivated by ideas how to unify the SM and general relativity in a theory of quantum gravity [10,11]. We demonstrate here that ongoing and planned β -decay experiments can, with moderate modifications in the setup and data analysis, be exploited to improve the existing limits on Lorentz violation.

We base our studies on the theoretical framework for Lorentz and CPT violation developed in Refs. [5,6] for β decay and in Ref. [7] for orbital electron capture. It covers effects from, e.g., a modified low-energy W -boson propagator $\langle W^{\mu+} W^{\nu-} \rangle = -i(g^{\mu\nu} + \chi^{\mu\nu})/M_W^2$. The tensor components $\chi^{\mu\nu}$ were limited with data on allowed [12–15] and forbidden [6] β decay, pion decay [16,17], nonleptonic kaon decay [18], and muon decay [19]. The best upper bounds were derived from experiments on forbidden β decays [6], while a first experiment on allowed β decay with polarized nuclei gave additional, partly complementary information [13,14]. These results were translated into bounds on Higgs- and W -boson parameters of the standard model extension (SME) [20–22], the general effective field theory for Lorentz and CPT violation at low energies.

The allowed- β -decay rate with Lorentz violation was derived in Ref. [5]. Compared to ordinary β decay, it contains additional, frame-dependent correlations between the momenta and spins of the nuclei and leptons and the tensor χ . The correlations involve linear combinations of the components $\chi^{\mu\nu}$, depending on the type of β decay: Fermi, Gamow-Teller, or mixed. While many of these correlations are hard to measure, a few appear relatively straightforward. We discuss a number of experiments on neutron and allowed

nuclear β decay that can give competing bounds on Lorentz violation. The pertinent observables are all rather simple asymmetries recorded with sidereal time stamps. We also consider the β decay of nuclei in flight, e.g., at proposed β -beam facilities, as a way to increase the sensitivity. We end with recommendations on how to further explore Lorentz violation in weak decays.

Decay rate. We assume that Lorentz violation comes from propagator corrections and neglect momentum-dependent terms in χ , which are suppressed by powers of the W -boson mass. Hermiticity of the Lagrangian then implies that $\chi^{\mu\nu} = (\chi^*)^{\nu\mu}$. We also neglect here terms with only neutrino-momentum or neutrino-spin correlations, which are important in electron capture [7] but in β decay do not contain more information than the easier to measure β -particle correlations. In addition, we ignore for the moment terms proportional to the spin factor $\Lambda^{(2)}$ [5], which is associated with higher-order spin correlations ($\Lambda^{(2)} = 0$ for unpolarized and spin-1/2 nuclei).

With these simplifications the β -decay rate [5], in the rest frame of the parent nucleus, reduces to ($\hbar = c = 1$)

$$dW = dW_0 \left\{ 1 + 2a\chi_r^{00} + 2(-a\chi_r^{0l} + \check{g}\check{\chi}_l^l) \frac{p_e^l}{E_e} + ([a + 2\check{a}\chi_r^{00}]\delta_{lm} - 4\check{g}\chi_r^{lm}) \frac{p_e^l p_v^m}{E_e E_v} + 2a\chi_i^{0k} \frac{(\vec{p}_e \times \vec{p}_v)^k}{E_e E_v} + \frac{\langle J^k \rangle}{J} \left(-2\check{L}\check{\chi}_i^k + [(A + B\chi_r^{00})\delta_{kl} - B\chi_r^{kl}] \frac{p_e^l}{E_e} \right) - A\chi_i^{0k} \frac{(\langle \vec{J} \rangle \times \vec{p}_e)^k}{J E_e} \right\}, \quad (1)$$

where $dW_0 = |\vec{p}_e| E_e (E_e - E_0)^2 dE_e d\Omega_e d\Omega_\nu F(E_e, \pm Z) \xi / (2\pi)^5$, $\vec{p}_{e(v)}$, $E_{e(v)}$ are the momentum and energy of the β particle (electron or positron) and neutrino, and $\langle \vec{J} \rangle$ is the expectation value of the spin of the parent nucleus. $F(E_e, \pm Z)$ is the usual Fermi function, with Z being the atomic number of the daughter nucleus, and the upper (lower) sign holds for $\beta^{-(+)}$ decays; $\xi = 2C_V^2 \langle 1 \rangle^2 + 2C_A^2 \langle \sigma \rangle^2$. The subscripts r and i denote the real and imaginary parts of $\chi = \chi_r + i\chi_i$, $\check{\chi}_i^k = \epsilon^{klm} \chi_i^{lm}$, and k, l, m are spatial directions. The coefficients $a, A,$

TABLE I. Statistical precision for the components $X^{\mu\nu}$ required to compete with the existing upper bounds from forbidden β decay [6]. The components X_i^{0l} are unconstrained at present.

X_r^{00}	X_r^{0l}	X_r^{kl}	X_i^{0l}	\tilde{X}_i^k
10^{-6}	10^{-8}	10^{-6}	–	10^{-8}

and B are standard in β decay [23,24], while \check{a} , \check{g} , and \check{L} multiply correlations that are Lorentz violating [5]. They are defined by

$$a = (1 - \frac{1}{3}\varrho^2)/(1 + \varrho^2), \quad (2a)$$

$$A = (\mp\lambda_{JJ'}\varrho^2 - 2\delta_{JJ'}\sqrt{J/(J+1)}\varrho)/(1 + \varrho^2), \quad (2b)$$

$$B = (\pm\lambda_{JJ'}\varrho^2 - 2\delta_{JJ'}\sqrt{J/(J+1)}\varrho)/(1 + \varrho^2), \quad (2c)$$

$$\check{a} = (1 + \frac{1}{3}\varrho^2)/(1 + \varrho^2), \quad (2d)$$

$$\check{g} = \frac{1}{3}\varrho^2/(1 + \varrho^2), \quad (2e)$$

$$\check{L} = \pm\frac{1}{2}\lambda_{JJ'}\varrho^2/(1 + \varrho^2), \quad (2f)$$

where $\varrho = |M_{GT}|C_A/(|M_F|C_V)$ is the ratio between the Gamow-Teller and Fermi matrix elements. The value of the spin factor $\lambda_{JJ'}$, where J (J') is the initial (final) nuclear spin, is $\lambda_{JJ'} = 1$ for $J' = J - 1, 1/(J + 1)$ for $J' = J$, and $-J/(J + 1)$ for $J' = J + 1$.

Observables. There are 15 independent tensor components $\chi^{\mu\nu}$. It is standard to translate the tensor χ to the Sun-centered reference frame, in which it is denoted by X , and report limits for the components $X^{\mu\nu}$ [22]. The best upper bounds on (linear combinations of) $X^{\mu\nu}$ are $O(10^{-6})$ – $O(10^{-8})$, derived [6] from pioneering forbidden- β -decay experiments [25,26] that used strong sources. In case there are accidental cancellations, the bounds on the individual components could be significantly weaker and range from $O(10^{-4})$ to $O(10^{-6})$ [27]. The order-of-magnitude precision required to improve the existing bounds on the various components $X^{\mu\nu}$ is summarized in Table I. A statistical precision of 10^{-n} requires at least $O(10^{2n})$ events. This would require one year of data collection with a source of 1 Curie for an experiment of the type performed in Ref. [25]. An alternative option is electron capture, which allows experiments at high rates and low doses [7]. We focus here on the possibilities to improve the existing bounds in allowed β decay.

From Eq. (1) we derive asymmetries that are proportional to specific components $\chi^{\mu\nu}$. Asymmetries are practical to measure and ideal to control systematic errors. Expressed in terms of $X^{\mu\nu}$, they oscillate in time with the sidereal rotation frequency $\Omega = 2\pi/(23\text{ h } 56\text{ m})$ of Earth and depend on the colatitude ζ of the site of the experiment. These sidereal-time variations of the observables are a unique feature of Lorentz violation and help to separate the desired signal from systematic errors. They also distinguish Lorentz violation from effects due to, e.g., scalar or tensor interactions, which would produce deviations from SM predictions that are independent of Earth's orientation.

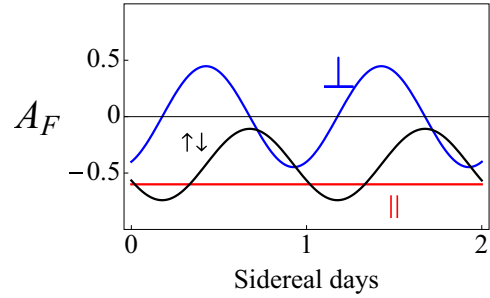


FIG. 1. (Color online) The sidereal time dependence of the asymmetry A_F in Eq. (3), for $X_r^{0x} = 0.1, X_r^{0y} = 0.2, X_r^{0z} = 0.3$, and colatitude $\zeta = 45^\circ$. For β particles observed parallel (\parallel) to Earth's rotation axis, A_F is constant. Observation in the $\uparrow\downarrow$ (up-down) direction or perpendicular (\perp) to the rotation axis results in an oscillation of A_F with sidereal time.

(i) The simplest way to study Lorentz violation is to integrate over the neutrino direction and measure the dependence of the decay rate on the direction of the β particle. The highest sensitivity can be reached in pure Fermi or Gamow-Teller decays. For Fermi decays, the experimental observable is the asymmetry

$$A_F = \frac{W_F^+ - W_F^-}{W_F^+ + W_F^-} = -2\chi_r^{0l}\beta\hat{p}_e^l, \quad (3)$$

where $\beta = |\vec{p}_e|/E_e$ and W_F^\pm is the rate of β particles measured in the $\pm\hat{p}_e$ direction. For Gamow-Teller decays of unpolarized nuclei, the analogous asymmetry is

$$A_{GT} = \frac{W_{GT}^+ - W_{GT}^-}{W_{GT}^+ + W_{GT}^-} = \frac{2}{3}(\chi_r^{0l} + \tilde{\chi}_i^l)\beta\hat{p}_e^l. \quad (4)$$

These two asymmetries are complementary and give direct bounds on χ_r^{0l} and $\tilde{\chi}_i^l$. Mixed decays are slightly less sensitive; e.g., for neutron β decay, with $\varrho = \sqrt{3}C_A/C_V$, where $C_A/C_V \simeq -1.275$ [28,29], the asymmetry is $A_n = (0.21\chi_r^{0l} + 0.55\tilde{\chi}_i^l)\beta\hat{p}_e^l$.

Figure 1 illustrates the sidereal-time dependence of the asymmetry A_F for three different observation directions. When the β particles are detected parallel to Earth's rotation axis, no oscillation is observed. Observation of the β particles perpendicular to the rotation axis, i.e., east-west, gives a sidereal-time variation. When the β particles are observed in the up-down ($\uparrow\downarrow$) direction, this oscillation has a constant offset. Systematic errors can result in a finite offset, and therefore observation in the direction perpendicular to the rotation axis is favored. The asymmetries should preferably be measured in a rotating setup [25] to reduce systematic errors. Alternatively, a multidetector setup with appropriate symmetry can exploit the full polar and azimuthal dependence as shown in Fig. 1, while reducing the counting rates of the individual detectors. An experiment with a duration of one year can use diurnal variations to reduce systematic errors.

There are ongoing efforts to improve the bounds on tensor currents in β decay. A promising observable for this purpose is the energy spectrum of the β particles [30]. The Gamow-Teller decays of ${}^6\text{He}$ [31,32] and ${}^{45}\text{Ca}$ [30] are under consideration.

Such experiments require high statistics and accuracy. The ^6He facility promises to produce 10^{10} particles/s, but it remains to be seen how such a beam can be used for Lorentz-violation measurements [32]. Isotopes such as ^{32}P , ^{33}P , ^{35}S , and ^{63}Ni are also of interest, because they have clean ground-state-to-ground-state β^- transitions and low Q values. For example, conveniently shaped ^{63}Ni sources of 1 GBq are commercially available. Such sources have minimal contributions of secondary radiation that can complicate the measurements. Moreover, strong sources can be produced in reactors. For the Fermi asymmetry A_F , any of the superallowed $0^+ \rightarrow 0^+$ decays [33,34] can be considered. We recommend that in these experiments the asymmetries A_F of Eq. (3) and A_{GT} of Eq. (4) are measured concurrently, with sidereal-time stamps.

(ii) With polarized nuclei one can measure the correlations that involve the nuclear spin. The simplest of these is the spin asymmetry

$$A_J = \frac{W^\uparrow - W^\downarrow}{W^\uparrow + W^\downarrow} = -2\check{L}\check{\chi}_i^k P \hat{J}^k, \quad (5)$$

where \hat{J} is the unit vector in the direction of the parent spin, P is the degree of nuclear polarization, and $W^{\uparrow(\downarrow)}$ is the integrated decay rate in the $\pm\hat{J}$ directions. For pure Gamow-Teller decays, $\check{L} = \frac{1}{2}B = -\frac{1}{2}A$. Isotopes for which $\lambda_{JJ'} = 1$ are optimal.

The first dedicated experiment to search for Lorentz violation in allowed β decay measured A_J in the β^+ decay of ^{20}Na [13]. The result of the most recent measurement is $|\check{\chi}_i^{x,y}| < 5 \times 10^{-4}$ with 90% confidence [14]. Data for polarized-neutron decay are currently being analyzed [15,35]. When the sidereal-time dependence of A_J is measured, it is not necessary to know A and P with high precision. If the polarization is not exactly equal in the two directions, A_J will show an offset, which is independent of the sidereal frequency as long as the polarization can be kept independent of Ω . Still, a measurement of the β asymmetry A_{GT} , as discussed above, is probably preferable for improving the bounds on $\check{\chi}_i^k$.

(iii) The components χ_i^{0k} , for which there are no bounds available yet, can be accessed through the correlations of $\hat{J} \times \hat{p}_e$ or $\hat{p}_e \times \hat{p}_\nu$ and a component of χ . The first correlation can be measured with the asymmetry

$$A_{\beta\nu} = \frac{W_L^\uparrow W_R^\downarrow - W_R^\uparrow W_L^\downarrow}{W_L^\uparrow W_R^\downarrow + W_R^\uparrow W_L^\downarrow} = 4(a\chi_i^{0k} \epsilon^{klm} - 2\check{g}\chi_r^{lm})\beta \hat{p}_e^l \hat{p}_\nu^m, \quad (6)$$

where $W_{L,R}$ is obtained by measuring the β particles in the opposite left (L) and right (R) \hat{p}_e directions, while the recoiling nucleus is detected in the perpendicular \uparrow (\downarrow) direction. For this asymmetry, pure Fermi decays, with $a = 1$ and $\check{g} = 0$, are preferred. Experiments that measure both the β and the neutrino direction are thus of interest. For example, Ref. [36] reports a search for a deviation from the SM prediction $a = 1$ for the β - ν correlation in ^{38m}K , with an error on a of order $O(10^{-3})$, which would be the corresponding limit for χ_i^{0k} .

With polarized nuclei, χ_i^{0k} can be measured from the asymmetry between the nuclear spin and the β particle,

$$A_{J\beta} = \frac{W_L^\uparrow W_R^\downarrow - W_R^\uparrow W_L^\downarrow}{W_L^\uparrow W_R^\downarrow + W_R^\uparrow W_L^\downarrow} = -2(A\chi_i^{0m} \epsilon^{mkl} + B\chi_r^{kl})P \hat{J}^k \beta \hat{p}_e^l, \quad (7)$$

where now $W_{L,R}$ is the rate with the β particles in the opposite left (L) and right (R) \hat{p}_e directions and the nuclei polarized in the perpendicular \uparrow (\downarrow) \hat{J} direction. Equation (7) holds for Gamow-Teller and mixed decays. Gamow-Teller decays with $\lambda_{JJ'} = 1$ are preferred.

The bounds from forbidden β decay give $|\chi_r^{kl}| < O(10^{-6})$ [6]. A measurement of $A_{J\beta}$ or $A_{\beta\nu}$ with a precision lower than 10^{-6} , therefore, translates to a bound on χ_i^{0k} . The sidereal-time variation of $A_{J\beta}$ and $A_{\beta\nu}$ is similar to that shown in Fig. 1. To reduce systematic errors $\hat{J} \times \hat{p}_e$ or $\hat{p}_e \times \hat{p}_\nu$ should point perpendicular to Earth's rotation axis. $A_{J\beta}$ can possibly be obtained in polarized-neutron decay by reanalyzing the data of Ref. [15]. Measuring the asymmetries better than 10^{-6} requires coincident event rates exceeding 3×10^4 /s for a year, but will then also improve the bounds on χ_r^{kl} .

Exploiting Lorentz boosts. So far we discussed β decay of nuclei at rest. The required event rate in these measurements is a challenge. In forbidden β decays one can benefit from an enhancement of Lorentz violation of one order of magnitude [6]. A much larger enhancement can be obtained when the decaying particle is in flight. Consider specifically the total decay rate, which in the rest frame depends only on the isotropic term in Eq. (1),

$$W/W_0 = 1 + 2a\chi_r^{00}, \quad (8)$$

where W_0 is the SM decay rate and $a = 1(-1/3)$ for Fermi (Gamow-Teller) decays. The component χ_r^{00} can be measured, e.g., from the ratio between the longitudinal β polarization, $P_\beta = (1 + 2a\chi_r^{00})G\beta$, for Fermi and Gamow-Teller decays, where $G = \mp 1$ [23,24]. Comparing the best value $P_F/P_{GT} = 1.0010(27)$ [37,38] to the SM prediction $P_F/P_{GT} = 1$ gives $-1.3 \times 10^{-3} < \chi_r^{00} < 2.0 \times 10^{-3}$ with 90% confidence, which is a much weaker bound than the one obtained for forbidden β decay [6] and hard to improve with nuclei at rest.

The decay rate in flight depends on the velocity $\vec{v} = v\hat{v}$ of the nucleus that results from a Lorentz boost. In terms of the components $X^{\mu\nu}$ in the Sun-centered frame one has $\chi_r^{00} = \gamma^2(X_r^{00} - 2vX_r^{0l}\hat{v}_l + X_r^{kl}v^2\hat{v}_k\hat{v}_l)$, where $\gamma = 1/\sqrt{1-v^2}$ is the Lorentz factor. When the velocity \hat{v} is perpendicular to Earth's rotation axis (east-west) one finds

$$\begin{aligned} \chi_r^{00} = & \gamma^2(X_r^{00} + \frac{1}{2}v^2[X_r^{xx} + X_r^{yy}] + 2vX_r^{0x} \sin \Omega t \\ & - 2vX_r^{0y} \cos \Omega t - v^2X_r^{xy} \sin 2\Omega t \\ & - \frac{1}{2}v^2[X_r^{xx} - X_r^{yy}] \cos 2\Omega t), \end{aligned} \quad (9)$$

which is enhanced by a factor γ^2 . The components $X_r^{\mu\nu}$ can be fitted to the sidereal-time dependence of the measured decay rate. Alternatively, one can measure the decay rate at time t and 12 h later, and isolate X_r^{0l} via the

asymmetry

$$A_t = \frac{W(\Omega t) - W(\Omega t + \pi)}{W(\Omega t) + W(\Omega t + \pi)} \\ = 4a v \gamma^2 (X_r^{0x} \sin \Omega t - X_r^{0y} \cos \Omega t), \quad (10)$$

while X_r^{kl} can be obtained by measuring at intervals of 6 h , with

$$A_{2t} = \frac{W(\Omega t) - W(\Omega t + \frac{1}{2}\pi) + W(\Omega t + \pi) - W(\Omega t + \frac{3}{2}\pi)}{W(\Omega t) + W(\Omega t + \frac{1}{2}\pi) + W(\Omega t + \pi) + W(\Omega t + \frac{3}{2}\pi)} \\ = -a v^2 \gamma^2 ([X_r^{xx} - X_r^{yy}] \cos 2\Omega t + 2X_r^{xy} \sin 2\Omega t), \quad (11)$$

which oscillates only with the double frequency 2Ω .

The γ^2 enhancement in Eqs. (9), (10), and (11) can be exploited at a β -beam facility planned for neutrino physics [39]. A good nucleus for such a facility is ${}^6\text{He}$, for which the production rates are estimated at $10^{12}/\text{s}$ with $\gamma = 100$ [40]. A possible setup for a β -beam facility that uses the proton synchrotrons at CERN is discussed in Refs. [39,40].

Of course, any weakly decaying particle in flight can be used, provided the coefficient a in Eq. (8) can be calculated reliably. Nonleptonic decays of strange hadrons such as kaons are problematic [18] but decays of heavy quarks do not have this drawback. Leptonic and semileptonic decays are clearly preferable. For fast-moving pions [41] bounds of $O(10^{-4})$ on $\chi^{\mu\nu}$ were obtained [16]. Semileptonic kaon decays have been studied at the SPS at CERN [42] with $\gamma \simeq 150$ and will be part of the background in the NA62 experiment. LHCb, designed to observe decays at $\gamma \gtrsim 10$, is serendipitously oriented perpendicular to Earth's rotation axis. For all accelerator studies, the precise normalization of the decay rate as function of sidereal time is necessary for a concurrent test of Lorentz invariance.

β - γ correlations. We have only considered cases where the anisotropic decay rate is observed in the emission direction of the β particles and/or is associated with the polarization direction of the parent nucleus. The anisotropy can also be observed from γ rays when an excited state in the daughter nucleus is populated. In Gamow-Teller transitions the daughter

nucleus is left in a polarized state that reflects the degree of anisotropy of the emission. When measuring the γ -decay angular distribution this anisotropy can be observed as a residual alignment. Inspection of Eq. (1) shows that this will be the case for the term $-2\tilde{\chi}_i^k \hat{J}^k$. Clearly, such a measurement will have lower sensitivity compared with the direct measurements discussed above. The last line of Eq. (1) can also be accessed by measuring β - γ correlations. The last term is relevant because it contains the missing components χ_i^{0k} . In this case the lower sensitivity may be compensated by an efficient setup. To obtain the actual expressions and the corresponding asymmetries, the terms proportional to $\Lambda^{(2)}$ [5] have to be added to Eq. (1). The evaluation depends on the particular details of detection method and will be considered when the need arises.

Conclusion. The breaking of Lorentz invariance in the weak interaction can be probed in relatively simple allowed- β -decay experiments. We propose to measure a number of decay-rate asymmetries as function of sidereal time, which together can constrain all Lorentz-violating gauge components. Measurements of the β -decay asymmetry in Fermi and Gamow-Teller decays, Eqs. (3) and (4), give direct bounds on χ_r^{0l} and $\tilde{\chi}_i^k$. The most complicated experiments require the measurement of a correlation between two observables, as in Eqs. (6) or (7). The components χ_i^{0k} are still unconstrained and these measurements will give the first bounds. In addition, we point out the potential of β beams and LHCb for tests of Lorentz invariance. Ultimately, the experiments should aim to improve the existing forbidden- β -decay limits starting at $O(10^{-6})$, which requires high-intensity sources and excellent control of systematic uncertainties. As we have shown, this can go hand-in-hand with high-precision allowed- β -decay experiments that search for new semileptonic physics. Such efforts are, therefore, of considerable general interest.

Acknowledgments. This investigation grew out of discussions at the 33rd Solvay Workshop on β -Decay Weak Interaction Studies in the Era of the LHC (Brussels, September 3–5, 2014). We thank J. Noordmans for helpful discussions. The research was supported by the Dutch Stichting voor Fundamenteel Onderzoek der Materie (FOM).

-
- [1] N. Severijns and O. Naviliat-Cuncic, *Ann. Rev. Nucl. Part. Sci.* **61**, 23 (2011).
 [2] V. Cirigliano, S. Gardner, and B. Holstein, *Prog. Part. Nucl. Phys.* **71**, 93 (2013).
 [3] O. Naviliat-Cuncic and M. González-Alonso, *Ann. Phys. (Berlin)* **525**, 600 (2013).
 [4] K. K. Vos, H. W. Wilschut, and R. G. E. Timmermans, *Rev. Mod. Phys.* (to be published).
 [5] J. P. Noordmans, H. W. Wilschut, and R. G. E. Timmermans, *Phys. Rev. C* **87**, 055502 (2013); In Eq. (18) it should read $w_3^l = -x\chi_r^{0l} + \tilde{g}(\chi_r^{0l} + \tilde{\chi}_i^l)$; this also corrects Eq. (38).
 [6] J. P. Noordmans, H. W. Wilschut, and R. G. E. Timmermans, *Phys. Rev. Lett.* **111**, 171601 (2013).
 [7] K. K. Vos, H. W. Wilschut, and R. G. E. Timmermans, *Phys. Rev. C* **91**, 038501 (2015).
 [8] J. S. Díaz, V. A. Kostelecký, and R. Lehnert, *Phys. Rev. D* **88**, 071902(R) (2013).
 [9] J. S. Díaz, *Adv. High Energy Phys.* **2014**, 305298 (2014).
 [10] S. Liberati, *Class. Quant. Grav.* **30**, 133001 (2013).
 [11] J. D. Tasson, *Rept. Prog. Phys.* **77**, 062901 (2014).
 [12] H. W. Wilschut *et al.*, *Ann. Phys. (Berlin)* **525**, 653 (2013).
 [13] S. E. Müller, E. A. Dijck, H. Bekker, J. E. van den Berg, O. Böll, S. Hoekstra, K. Jungmann, C. Meinema, J. P. Noordmans, M. Nuñez Portela, C. J. G. Onderwater, C. Pijpker, A. P. P. van der Poel, B. Santra, A. Sytema, R. G. E. Timmermans, O. O. Versolato, L. Willmann, H. W. Wilschut, and K. Yai, *Phys. Rev. D* **88**, 071901(R) (2013).
 [14] A. Sytema *et al.* (unpublished).
 [15] K. Bodek *et al.*, *PoS XLASNP*, 029 (2014).
 [16] B. Altschul, *Phys. Rev. D* **88**, 076015 (2013).

- [17] J. P. Noordmans and K. K. Vos, *Phys. Rev. D* **89**, 101702(R) (2014).
- [18] K. K. Vos, J. P. Noordmans, H. W. Wilschut, and R. G. E. Timmermans, *Phys. Lett. B* **729**, 112 (2014).
- [19] J. P. Noordmans *et al.* (unpublished).
- [20] D. Colladay and V. A. Kostelecký, *Phys. Rev. D* **55**, 6760 (1997).
- [21] D. Colladay and V. A. Kostelecký, *Phys. Rev. D* **58**, 116002 (1998).
- [22] V. A. Kostelecký and N. Russell, *Rev. Mod. Phys.* **83**, 11 (2011); updated 2015 version: [arXiv:0801.0287v8](https://arxiv.org/abs/0801.0287v8) [hep-ph].
- [23] P. Herczeg, *Prog. Part. Nucl. Phys.* **46**, 413 (2001).
- [24] N. Severijns, M. Beck, and O. Naviliat-Cuncic, *Rev. Mod. Phys.* **78**, 991 (2006).
- [25] R. Newman and S. Wiesner, *Phys. Rev. D* **14**, 1 (1976).
- [26] J. D. Ullman, *Phys. Rev. D* **17**, 1750 (1978).
- [27] J. P. Noordmans, Ph.D. thesis, University of Groningen, 2014 (unpublished).
- [28] M. P. Mendenhall *et al.*, *Phys. Rev. C* **87**, 032501 (2013).
- [29] D. Mund, B. Markisch, M. Deissenroth, J. Krempel, M. Schumann, H. Abele, A. Petoukhov, and T. Soldner, *Phys. Rev. Lett.* **110**, 172502 (2013).
- [30] N. Severijns, *J. Phys. G* **41**, 114006 (2014).
- [31] A. Knecht *et al.*, *Nucl. Instrum. Meth. A* **660**, 43 (2011).
- [32] O. Naviliat-Cuncic and F. Wauters, talks at the 33rd Solvay Workshop on Beta Decay Weak Interaction Studies in the Era of the LHC, Brussels, September 3–5, 2014 (private communication).
- [33] J. C. Hardy and I. S. Towner, *Phys. Rev. C* **79**, 055502 (2009).
- [34] J. C. Hardy and I. S. Towner, *Phys. Rev. C* **91**, 025501 (2015).
- [35] A. Kozela *et al.*, *CPT and Lorentz Symmetry* **V**, 174 (2011).
- [36] A. Gorelov *et al.*, *Phys. Rev. Lett.* **94**, 142501 (2005).
- [37] V. A. Wichers, T. R. Hageman, J. van Klinken, H. W. Wilschut, and D. Atkinson, *Phys. Rev. Lett.* **58**, 1821 (1987).
- [38] A. S. Carnoy, J. Deutsch, T. A. Girard, and R. Prieels, *Phys. Rev. Lett.* **65**, 3249 (1990).
- [39] M. Lindroos and M. Mezzetto, *Ann. Rev. Nucl. Part. Sci.* **60**, 299 (2010).
- [40] B. Autin *et al.*, *J. Phys. G* **29**, 1785 (2003).
- [41] B. Altschul, *Phys. Rev. D* **87**, 096004 (2013).
- [42] J. R. Batley *et al.*, *Eur. Phys. J. C* **50**, 329 (2007).