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Lorentz invariance on trial in the weak decay of polarized atoms

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Abstract One of the most fundamental principles underlying our current understanding of nature is the invariance of the laws of physics under Lorentz transformations. Theories trying to unify the Standard Model with quantum gravity suggest that this invariance may be broken by the presence of Lorentz-violating background fields. Dedicated high-precision experiments at low energies could observe such suppressed signals from the Planck scale. At KVI, a test on Lorentz invariance of the weak interaction is performed searching for a dependence of the decay rate of spin-polarized nuclei on the orientation of their spin with respect to a fixed absolute galactical reference frame. An observation of such a dependence would imply a violation of Lorentz invariance.

Keywords Lorentz invariance · sidereal variations · β^+-decay · optical pumping

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1 Introduction

The invariance of physical laws under rotations in 3-dimensional space and velocity changes (boosts) of the reference frame of a physical system is commonly referred to as Lorentz invariance. Lorentz invariance is a at the basis of the theory of Special Relativity, as well as the local quantum field theories underlying the Standard Model of particle physics. In addition Lorentz invariance is a local symmetry of General Relativity. It is also connected to CPT invariance via the CPT theorem which states that a Lorentz invariant local quantum field theory must also be invariant under CPT-transformations. It has been

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proven that any interacting local quantum field theory which violates CPT also violates Lorentz invariance [1]. Certain theoretical models of quantum gravity contain terms which violate Lorentz invariance [2,3], and this could lead to manifestations of Lorentz invariance violation also in low-energy observables accessible in laboratory experiments. Kostelecký and coworkers have developed a theoretical framework named "Standard Model Extension" (SME) that contains all the properties of the Standard Model and General Relativity, but additionally contains all terms violating Lorentz and CPT symmetry via spontaneous breaking of Lorentz invariance [4]. There are many experimental tests constraining the parameters of the SME [5], most of which are tests of Lorentz violating extensions of QED or gravity and astrophysical observations. The weak sector is tested mostly in CPT tests of neutral meson or neutrino oscillations. Especially decay aspects are up to now largely unexplored.

In a phenomological description, the differential decay rate of a nucleus decaying via an allowed Gamow-Teller transition can be written as [1]

$$\frac{d\Gamma}{dEd\Omega} \sim \left(1 + A\frac{\langle\mathbf{I}\rangle}{I}\cdot\frac{\mathbf{p}}{E}\right) + t + \mathbf{w}_1\frac{\langle\mathbf{I}\rangle}{I} + \mathbf{w}_2\frac{\mathbf{p}}{E} + T_1^{ij}\frac{\langle\mathbf{I}\rangle}{I}^i\frac{\langle\mathbf{I}\rangle}{I}^j + T_2^{ij}\frac{\langle\mathbf{I}\rangle}{I}^i\frac{\mathbf{p}}{E}^j + S^{ijk}\frac{\langle\mathbf{I}\rangle}{I}^i\frac{\langle\mathbf{I}\rangle}{I}^j\frac{\mathbf{p}}{E}^k \quad (1)$$

where we have integrated over neutrino momentum and summed over β-particle spin. $\mathbf{p}$ and E are the momentum and energy of the β-particle, $\mathbf{I}$ is the nuclear spin and the quantities t, $\mathbf{w}_{1,2}$, $T_{1,2}^{ij}$ and S^{ijk} contain the hypothetical fields that violate Lorentz invariance by defining a "preferred" reference frame. The first term in eq. (1) describes the Standard Model contribution to the decay rate including the parity-violating parameter A of the weak interaction. The quantity $\mathbf{w}_2$ can be accessed in experiments detecting the decay electron direction, while $\mathbf{w}_1$ and T_1^{ij} require a non-zero average polarization of $\mathbf{I}$ along a quantization axis. To test the tensors T_2^{ij} and S_1^{ijk}, both the detection of the decay electron and a nuclear polarization are required. The quantity t is not affected by rotations, it can only be probed by boosting the experimental system. A non-zero value for any of these quantities would indicate a violation of Lorentz invariance. Precise measurements of this decay rate as a function of $\mathbf{p}$ or $\mathbf{I}$ can therefore be used to probe a possible violation of Lorentz invariance by looking for changes in the decay rate while the experimental system rotates on the earth (daily variations), while the experimental system rotates with the earth around the sun (annual variations), or by deliberately reorienting the experimental system on shorter timescales (i.e. by periodical reorientation of the nuclear spin $\mathbf{I}$). Previous attempts focussed on tests of Lorentz invariance in forbidden β decays (see [6,7]). In the present experiment, we access $\mathbf{w}_1$ by looking for a change in the decay rate of allowed β decays when reversing the orientation of the nuclear spin $\langle\mathbf{I}\rangle$ via optical pumping.

[1] J. P. Noordmans, R. G. E. Timmermans, paper in preparation.

2 Testing Lorentz symmetry at KVI

At KVI, Lorentz invariance is tested using a beam of short-lived alkali isotopes produced with the AGOR cyclotron at KVI. The isotopes are stopped in a buffer gas cell, where their spins are subsequently oriented via optical pumping using a weak magnetic field and circularly polarized laser light. Changing the circular polarization of the laser light will reverse the nuclear polarization. Detecting a change in the decay lifetime when changing the direction of nuclear polarization by 180^o would indicate a non-zero value of $\mathbf{w}_1$. A change in lifetime can be looked for detecting the rates of β-particles (or the corresponding annihilation photons at 511 keV for β^+ decays) or prompt gamma rays from decays of excited daughter particles. In general, alkali isotopes are good candidates because their hyperfine structure makes them ideally suited for efficient optical pumping. A preference is given to candidates decaying via a pure Gamov-Teller transition. This choice reduces the number of Lorentz-violating quantities in the decay rate description. The degree of nuclear polarization is monitored using the parity-violating asymmetry in the emission of the β-particle. While initial studies considered using ^{80}Rb atoms ($\tau_{1/2} = 33.4$ s) [8], the availability of a strong pumping laser for sodium atoms at the KVI allowed to study Lorentz invariance in the decay of ^{20}Na ($\tau_{1/2} = 0.448$ s).

2.1 Production and stopping

^{20}Na is produced via a ^{20}Ne(p,n)^{20}Na reaction by colliding a ^{20}Ne beam with a hydrogen gas target. The resulting isotopes pass through the TRIμP isotope separator facility to obtain a clean ^{20}Na beam which is stopped in a buffer gas cell filled with 2 atm of neon gas. Up to 10^6 decays/s can be obtained in this way. Adjustable aluminum degrader foils in the beamline allow to position the beam's stopping distribution in the center of the cell. The neon buffer gas is cleaned with a cryo-trap filled with liquid nitrogen and a gas purifier cartridge. A heatable dispenser with natural sodium is mounted inside the buffer gas cell. The natural sodium binds residual chemically active contaminants in the gas and prevents that the radioactive sodium forms molecules, and thus can't be polarized with optical pumping.

2.2 Polarization

Stopped ^{20}Na atoms in the center of the buffer gas cell are optically pumped into a "stretched" state in which the electronic and nuclear spins are both aligned along the direction of the magnetic holding field provided by two Helmholtz coils. To achieve this, a circularly polarized laser beam with 589 nm wavelength is sent through the buffer gas cell. A mirror above the buffer gas cell reflects the light back into the cell. The reflected light pumps the atoms into the same state as the incoming laser beam. This configuration allows for

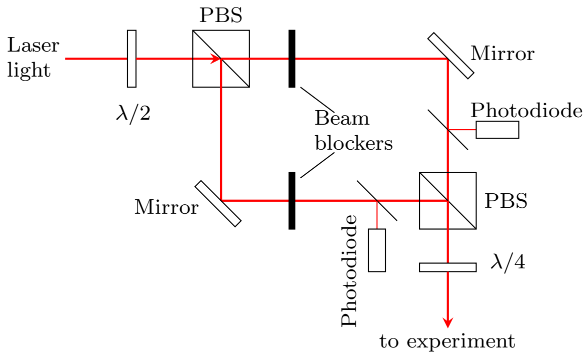


Fig. 1: Setup to create circularly polarized laser beams. Two polarizing beam splitters (PBS) are used to create vertically and horizontally polarized beams which are sent through a $\lambda/4$-waveplate to produce right and left circular light (σ^- and σ^+ light).

an efficient use of laser power. As shown in Fig. 1, circular polarization is obtained by splitting the laser light into a vertically and horizontally polarized beam using a polarizing beam splitter cube. The two beams are recombined by a second beam splitter. Switchable beam blockers select the desired linear polarization state. A $\lambda/4$-plate then converts the linear polarization into circular polarization. A $\lambda/2$-plate in front of the first beam splitter allows to balance the laser power in the two linearly polarized beams. Two photodiodes are used to monitor the laser power. Depending on the helicity of the light that enters the buffer gas cell, the atoms will be pumped into a state with the spins aligned or anti-aligned to the direction of the magnetic field [9]. Therefore the spins (nuclear and electronic) follow the helicity of the laser light.

2.3 Measurement of polarization

The polarization is verified by measuring β^+ particles emitted in the upward direction with a plastic scintillator detector positioned right above the upper mirror (see Fig. 2). From the β^+-rates detected there for different laser light helicities, an asymmetry a can be built:

$$a = \frac{W_{\sigma^-} - W_{\sigma^+}}{W_{\sigma^-} + W_{\sigma^+}}. \tag{2}$$

Due to the parity-violating nature of the weak interaction, the angular distribution of β radiation is proportional to

$$W(\theta) \propto 1 + \frac{\nu}{c} \cdot A \cdot P \cdot \cos\theta \,, \tag{3}$$

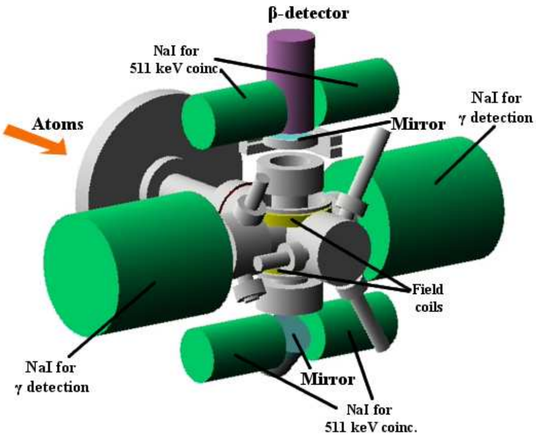
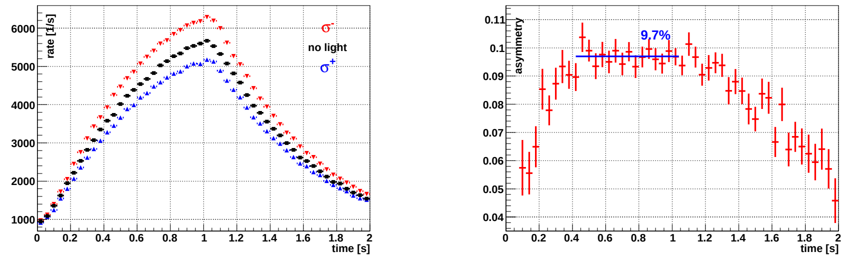


Fig. 2: Sketch of the experimental setup to test Lorentz invariance at KVI. The two pairs of NaI detectors to detect 511 keV γ coincidences from β^+ particles above and below the setup were present in the setup, but the high rate of accidental coincidences strongly reduced their sensitivity for polarization measurements.

with ν/c the β^+ velocity in units of the speed of light c, $A = +1/3$ is the parity-violating parameter of the weak interaction for ^{20}Na, P is the degree of polarization of the atoms and θ is the β emission angle with respect to the orientation axis of the nuclear spins. $\nu/c \simeq 1$ for β particles from ^{20}Na decay (endpoint energy $E \simeq 11.2$ MeV). A deviation from the maximum asymmetry $a = A = +1/3$ is measured due to background from decays of unpolarized atoms as well as the presence of 2 atm of neon buffer gas (which limits the maximum degree of polarization to 80%). The cyclotron was pulsed with a 1s "on" - 1s "off" period, and the laser light helicity was switched after each "on"-"off" period. In addition, a period in which no laser light entered the buffer gas cell was recorded. In this last period, no polarization of nuclei is expected. These "no light" measurements are very important to evaluate systematic effects. Fig. 3a shows the β^+ rates measured by the β detector for different helicity states of the laser light used for optical pumping. A preferred emission of β^+ radiation in the upward direction is observed when shining right circularly polarized light (σ^-) into the buffer gas cell. This corresponds to an alignment of the nuclear spins along the upward direction ($A > 0$ in eq. 3, see also [10]). Fig. 3b shows the corresponding asymmetry a from eq. 2. After a quick rise to a plateau of approximately 10%, the asymmetry starts to decrease after the isotope beam is switched off. Reasons for this decrease are the diffusion of the ^{20}Na atoms out of the laser light and possibly the molecule formation of sodium with residual chemically active contaminants in



(a) (b)

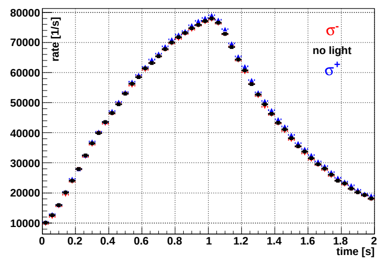
Fig. 3: (a) β^+ rates detected with the PHOSWICH detector for different helicity states of the laser light with a pulsed beam of ^{20}Na (1s “on”, 1s “off”). Rates have been averaged over a data taking period of 35 min. (b) Asymmetry a from eq. 2 for β^+ rates detected in the PHOSWICH detector.

the buffer gas. From the asymmetry shown in fig. 3b it can be concluded that at least 40% of the maximally reachable polarization has been achieved.

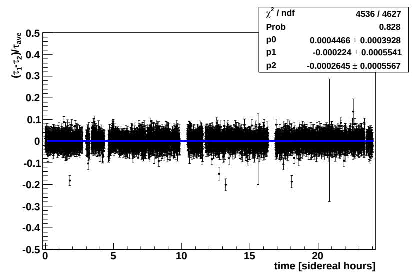
2.4 Measurement of the ^{20}Na lifetime

The lifetimes of ^{20}Na for the two polarization directions are measured by detecting the γ-radiation from the decay of the ^{20}Ne daughter nucleus with two NaI-detectors placed perpendicularly to the polarization axis (see fig. 2). ^{20}Na decays with a branching fraction of 80% to the first excited state at 1.6 MeV in ^{20}Ne. The subsequent γ decay does not violate parity, and therefore its emission distribution does not change under reversal of the spin orientation. Since many precise tests have been performed for Lorentz invariance in the electromagnetic interaction [5] with no hint for violation of Lorentz invariance, we assume that the electromagnetic interaction conserves Lorentz symmetry to a much better degree than the weak interaction. Because the ^{20}Ne γ decay is “prompt”, it allows to access and measure the lifetime information of the ^{20}Na nucleus.

Fig. 4a shows the rates of 1.6 MeV γ radiation detected by one of the NaI-detectors for different helicity states of the laser light. The small but finite rate changes can be attributed to the quadrupole emission pattern of the γ radiation and geometrical imperfections of the setup. We test Lorentz invariance of ^{20}Na searching for a difference in the lifetimes for different orientations of the nuclear polarization. This is done by fitting the rate spectra in fig. 4a for $t > 1$s with an exponential decay function. A difference in the lifetimes for different nuclear spin directions due to Lorentz invariance violation would be confirmed if the difference showed an oscillation period of the sidereal day because the earth rotates with respect to a fixed galactical reference frame [11]. The lifetime



(a)



(b)

Fig. 4: (a) γ rates detected with a NaI detector for different helicity states of the laser light with a pulsed beam of ^{20}Na (1s "on", 1s "off"). Rates have been averaged over a data taking period of 35 min. (b) Preliminary result on $\varDelta\tau$ for two consecutive pulses of the isotope beam when no light was entering the buffer gas cell.

difference

$$\varDelta\tau = \frac{\tau_{\sigma^-} - \tau_{\sigma^+}}{\tau_{\text{ave}}} = \frac{\tau_{\text{up}} - \tau_{\text{down}}}{\tau_{\text{ave}}} \tag{4}$$

is constructed from two consecutive pulses of the isotope beam, resulting in a timescale of approximately 4s. While this reduces the statistics available for the individual values of $\varDelta\tau$, it prevents systematic effects from ambient temperature and pressure changes in the laboratory, which are assumed to be negligible on these timescales. In a first step, $\varDelta\tau$ has been evaluated for two consecutive pulses in which no light entered the buffer gas cell. In this case, there is no net polarization of the ^{20}Na atoms, and one expects no significant contribution from Lorentz symmetry breaking effects. It provides for a cross check of systematic uncertainties of the experimental setup, and doubles as a test-case for the actual analysis using polarized atoms. Fig. 4b shows $\varDelta\tau$ plotted against the time t_{sid} in sidereal hours. The function

$$\varDelta\tau(t_{\text{sid}}) = C + A_S \sin(\omega_\oplus t_{\text{sid}}) + A_C \cos(\omega_\oplus t_{\text{sid}}) \tag{5}$$

has been fitted to the data, where $\omega_\oplus = 2\pi/(23\text{h}56\text{m}04\text{s})$. The parameters A_S and A_C parameterize the sidereal variations of $\varDelta\tau$ due to Lorentz symmetry breaking effects. While a small deviation from zero of the constant term C is observed (which can be explained by a slow change of buffer gas pressure leading to different diffusion properties in the gas cell during the experiment), the parameters A_S and A_C are found to be compatible with zero in fig. 4b. One can therefore conclude that systematic effects from pressure- or temperature changes are well under control for the present experimental setup. It can also be seen that the statistical sensitivity of the experiment on A_S and A_C is on the order of $10^{-3} - 10^{-4}$. To further investigate possible systematic effects which could mimic a Lorentz violating signal, the whole setup has been modeled using the GEANT4 toolkit [12,13]. This is an important tool to determine detector acceptances and to estimate the effect from detector misalignment and variations of the stopping distribution of the ^{20}Na atoms in the buffer gas cell. The estimate of systematic errors is in progress.

3 Conclusions and outlook

At the KVI in Groningen, we have carried out a first experiment to test Lorentz invariance in the weak decays of polarized atoms. A beam of ^{20}Na is stopped in a buffer gas cell. Subsequently the atoms are polarized by optical pumping. Lorentz invariance is tested by searching for a dependence of the lifetime of the ^{20}Na β^+ decay on the orientation of the nuclear spins with respect to a fixed galactical reference frame. Preliminary results from the analysis of unpolarized decays show that a statistical sensitivity on sidereal variations of lifetime changes for different nuclear polarization directions of $10^{-3} - 10^{-4}$ can be reached, and that systematic effects from ambient temperature and pressure changes are well under control. Next steps include the extraction of the degree of polarization from the emission direction of the β^+ particle and the lifetime analysis for the case when the atoms are polarized. In addition, further systematic checks are performed using a GEANT4 simulation of the experimental setup. At the same time, the corresponding theoretical development for interpreting the observables within the framework of the Standard Model Extension is underway.

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