A Search for Lorentz Invariance and CPT Violation using Neutrino Interactions in NOvA

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Abstract

CPT symmetry combines the charge conjugation (C), parity inversion (P), and time reversal (T) transformations. Further, CPT symmetry implies that the laws of physics should remain unchanged if these operations are applied sequentially. CPT symmetry is fundamental to the Standard Model, the foundation of particle physics. Lorentz Invariance is another fundamental principle of physics that requires the laws of physics to be the same throughout all of space and time. The potential violation of Lorentz Invariance and CPT symmetry would have profound implications for our understanding of the universe. To search for possible violations, we will examine neutrino interactions from the NuMI Off-Axis ν_e Appearance (NOvA) experiment. This study will search for evidence of Lorentz Invariance and CPT violation by analyzing the variation in the rate of neutrino interactions as a function of sidereal time. Potential detection of sidereal modulations would provide evidence for Lorentz Invariance and CPT violation, fundamentally changing our conception of physics.

Contents

1. Introduction

There are certain fundamental principles in our understanding of physics. For instance, the principle of Lorentz Invariance states that the laws of physics must be the same everywhere in the universe at all times. CPT symmetry is another fundamental principle that states that the laws of physics remain the same under successive operations of charge conjugation (C), parity inversion (P), and time reversal (T). The charge conjugation operation inverts the charge of particles in an interaction. Parity inversion spatially mirrors the orientation of particles in an interaction. Similarly, the time reversal operation reverses the direction of time evolution of the particle interaction. Although its constituent symmetries may be violated, combined CPT symmetry violation has not been observed. The current formulation of the Standard Model of Particle Physics assumes that CPT symmetry holds.

Given how foundational the principles of Lorentz Invariance and CPT symmetry are to physics, we should test them. The Standard Model Extension (SME), which attempts to unite quantum gravity with particle interactions, implies that violations of universal symmetries may occur at the Planck scale, 10^{19} GeV [1]. If found, these deviations from the fundamental symmetries would reshape the landscape of physics.

Neutrinos provide a way to search for Lorentz Invariance violation (LV) and CPT violation (CPTV). Although they are the most abundant fundamental particles in the universe, neutrinos interact extremely weakly with matter. The SME predicts a variation in the rate of neutrino interactions dependent on the propagation direction relative to the Sun-centered inertial reference frame [1]. Each rotation of the Earth, or sidereal day, has a duration of approximately 23 hours and 56 minutes, slightly shorter than one solar day [2]. Detecting a periodic change in the neutrino interaction rate as a function of sidereal time would be evidence of LV and CPTV.

The NOvA experiment, designed to deepen our understanding of neutrino phenomenology, is pivotal to our proposed analysis. By utilizing the NuMI beam and the near detector (ND) located 1 km from the neutrino source, NOvA provides a unique opportunity to investigate neutrino interactions for sidereal modulation. At this distance, neutrino interactions are sensitive to potential effects predicted by the SME. This analysis will be the first to search for LV and CPTV using the NOvA ν_e dataset at a baseline of 1 km and energies of approximately 2 GeV.

2. Methods

The NOvA experiment utilizes a particle accelerator located at Fermilab to accelerate a beam of protons. The accelerated protons impinge on a graphite target to produce hadrons, namely kaons and pions [4]. When these hadrons decay, they produce neutrinos. The number of neutrinos produced is directly proportional to the quantity of protons that strike the target. The generated neutrinos constitute the beam that travels toward the ND. We are interested in the rate at which neutrinos from the beam interact with ions in the ND. We define the ratio of the number of interactions to the quantity of neutrinos generated as the neutrino interaction rate. If LV and CPTV exist, we will observe periodic variations in the rate of neutrino interactions as a function of sidereal time.

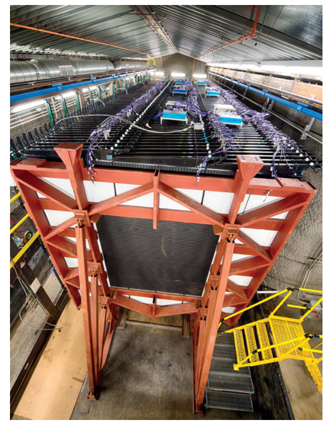

Figure 1. Image of the NOvA near detector. We analyze neutrinos from the NuMI beam after interacting with ions in the detector [3].

The NuMI beam delivers approximately 5×10^{13} protons to the graphite target for a duration of $10\mu s$ every $1.7s$ [5]. Each delivery of protons is tagged using a global positioning system (GPS), which indicates its time signature in Universal Coordinated Time (UTC) [5]. The GPS records when the protons are extracted to the main injector with a pulsed dipole magnet, ensuring the precise event timing necessary for this analysis [5]. We will collate the resulting timing data into a histogram containing the number of neutrino interactions per quantity of protons delivered to the target as a function of sidereal time. To reduce noise, we will use the standard NOvA data quality criteria to select periods of acceptable beam performance. The selection criteria also require that each candidate neutrino interaction within the detector be charged current due to the identifiable lepton signature. The selection scheme and experimental setup allow the NOvA experiment to identify more electron neutrinos and higher energy particles. Improved insight into different neutrino flavors and energies will help us to constrain SME coefficients further than previous measurements.

We will utilize a Fast Fourier Transform (FFT) to decompose the data into integer multiples of the sidereal frequency, $\omega_{\oplus}$. Each frequency will have an associated power that contributes to the distribution. We will restrict our search to the first several harmonics since the powers diminish significantly at higher frequencies. The FFT results in a measurement of the amplitude of sidereal variation in the NOvA data. To interpret these harmonic powers, we will simulate many experiments with identical exposure to the data. Each simulated experiment will assign events at random sidereal time from the distribution. This will result in an event rate as a function of sidereal time containing no sidereal variation. We will use this randomized distribution to establish a signal threshold. If the frequency powers determined from the NOvA data exceed our threshold, there is a significant level of sidereal variation, implying LV and CPTV effects. Conversely, FFT powers within the threshold imply no statistically significant evidence of sidereal variations. In this case, we will perform further simulated experiments to determine the constraints on coefficients related to LV and CPTV from the SME [1]. We will constrain these coefficients by increasing their value and performing an identical FFT analysis to determine the theoretical powers necessary to exceed the signal detection threshold.

3. Timeline

The work will take place over twelve months. The first six months will be dedicated to defining an appropriate harmonic signal threshold, developing the analysis, interpreting the results, and considering systematic effects in the data. The following six months will be used to prepare results for submission to *Physical Review D* for peer review.

4. Conclusion & Future Directions

This work explores violations of fundamental symmetries critical to both experimental and theoretical particle physics. Detecting sidereal modulation would provide evidence for phenomena beyond the Standard Model, developing a new sector for exploration within the field of physics. Contrarily, the absence of sidereal variation would impose tighter constraints on extensions to the Standard Model. Regardless of the results, this research will contribute to the broader effort to probe the limits of modern physics and refine our understanding of fundamental symmetries.

References

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