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THEORETICAL STUDIES OF LORENTZ AND CPT SYMMETRY

Final Report: Summary of Research

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INTRODUCTION

This Final Report summarizes the principal research supported in whole or in part by NASA grant NAG8-1770 issued at Marshall Space Flight Center.

The Principal Investigator is A. Kostelecký. Other personnel supported in part during the grant lifetime include three graduate students, Q. Bailey, M. Mewes (now a professor at Carleton College), and J. Tasson, and one undergraduate student, A. Picking. Other scientists collaborating on some of the research described below but not supported by the grant include Professors R. Bluhm (Colby College), C. Lane (Berry College), M. Perry (Cambridge University, England), and N. Russell (Northern Michigan University), and Dr. R. Lehnert (Vanderbilt University).

The focus of this effort is ground-based scientific research, with as objective the theoretical study of possible violations of certain fundamental symmetries of nature and the identification of suitable experimental tests.

During the reporting period, 12 papers have been prepared. Eleven have already been published. Three are in *Physical Review Letters,* which is widely regarded as the top refereed physics journal for letter-length communications. Eight have appeared in *Physical Review D,* a leading refereed physical journal for regular articles, while the remaining one is currently undergoing the refereeing process. Several of these works have received coverage in the media, including the press, radio, television, the internet, and popular scientific magazines. Also during this period, the P.I. has delivered about two dozen invited talks at conferences and research institutions.

RESEARCH SUMMARY

The fundamental symmetries studied here are Lorentz and CPT invariance, which form a cornerstone of the relativistic quantum theories used in modern descriptions of nature. The results obtained during the reporting period focus on the idea, originally suggested by the P.I. and his group in the late 1980s, that observable CPT and Lorentz violation in nature might emerge from the qualitatively new physics expected to hold at the Planck scale. What follows is a summary of results obtained during the period of this grant.

Background. Lorentz violation is a promising candidate signal for Planck-scale physics [1]. For instance, it could arise in string theory [2] and is a basic feature of noncommutative field theories [3]. In quantum field theory at attainable energies, small violations can be incorporated into the Standard Model to yield a general Lorentz-violating Standard-Model Extension (SME) [4]. Its lagrangian consists of all possible observer Lorentz scalars formed from Standard-Model and gravitational fields while allowing for coupling coefficients with Lorentz indices. All renormalizable and gauge invariant terms relevant at low energies are explicitly known.

Spectropolarimetry. The SME predicts definite experimental signals. In the fermion sector of the theory, various experiments have bounded coefficients for Lorentz violation. However, prior to the research performed under the present auspices, relatively little had been known experimentally about the implications of the SME for the properties of light. In particular, no bounds existed on the 19 CPT-even coefficients for Lorentz violation in the photon sector. During the period of this grant, these terms were studied in a paper published in *Physical Review Letters* [5]. Spectropolarimetry of cosmological sources was used to obtain stringent bounds on Lorentz violation comparable to the best current limits in the fermion sector. Ten of the 19 independent coefficients for Lorentz violation were bounded to less than 3×10^{-32}.

Clock-comparison experiments. Among the sharpest tests of Lorentz symmetry in matter are clock-comparison experiments. These search for spatial anisotropies by studying the frequency variation of a Zeeman hyperfine transition as the quantization axis changes orientation. Traditionally, the frequencies of two different co-located clocks are compared as the laboratory rotates with the Earth. Experiments of this type are sensitive to suppressed effects from the Planck scale [6]. During the period of this grant, a paper published in *Physical Review Letters* [7] showed that clock-comparison experiments on satellites and other spacecraft can provide wide-ranging tests of Lorentz and CPT symmetry with Planck-scale sensitivity. Space experiments were analyzed in a general theoretical context. Tests for some specific orbital and deep-space missions were studied, including several (PARCS, RACE, ACES, SUMO) approved for the International Space Station (ISS). The orbital configuration of a satellite platform and the relatively large velocities attainable in a deep-space mission could permit a broad range of tests with Planck-scale sensitivity.

Laboratory searches with cavity oscillators. During the period of this grant, a comprehensive study was performed to investigate the astrophysical and laboratory implications of all 19 CPT-even coefficients for Lorentz violation in the photon sector. This work was published in *Physical Review D* [8]. Limits on the dispersion of light produced by galactic and extragalactic objects were used to provide bounds of 3×10^{-16} on certain coefficients for Lorentz violation. A refinement of the comparative spectral polarimetry of light from cosmologically distant sources was used to extract improved constraints of 2×10^{-32} on ten of the 19 coefficients for Lorentz violation. It was shown that all nine remaining coefficients in the photon sector are measurable in high-sensitivity laboratory tests involving cavity-stabilized oscillators. Experimental configurations in Earth- and space-based laboratories were considered that involve optical or microwave cavities and that could be implemented using existing technology. This work has since led to several experiments performed by three independent research groups, one based at Stanford University, one based in Germany, and one based in France and Australia [9].

Spacetime-varying couplings. A study was performed of the possible connections between spacetime-varying couplings and relativity violations. This work was published in *Physical Review D* [10]. It showed that spacetime-varying couplings can be associated with Lorentz and CPT violation, demonstrating that these effects can arise naturally even when the dynamics of the underlying theory is Lorentz invariant and contains only constant couplings. An explicit example was constructed, involving an analytical cosmology in a supergravity theory that is a limit of M theory, and estimates were made for some experimental constraints.

Space-based experiments. During the period of this grant, a detailed investigation was performed of space-based experiments offering sensitivity to Lorentz and CPT violation. This work has been published in *Physical Review D* [11]. It provides a classification of clock sensitivities and presents explicit formulae for time variations arising in space-based experiments from nonzero coefficients in the SME. Specific emphasis was placed on forthcoming experiments on the ISS. Expressions were derived for observable effects in the PARCS, ACES, and RACE missions, thereby complementing the detailed photon-sector analysis [8] performed in the previous reporting period for the planned SUMO experiment with microwaves on the ISS.

Searches for boost-dependent effects. An analysis of data was performed from a clock-comparison experiment performed by Ron Walsworth's group at the Harvard-Smithsonian Center for Astrophysics. The results are reported in a paper written in collaboration with the Walsworth group and published in *Physical Review Letters* [12]. This work presents the results of a search for sidereal annual variations in the frequency difference between xenon-129 and helium-3 masers. The analysis uses boost effects to yield several stringent new limits on a number of coefficients for Lorentz and CPT violation involving the neutron.

Neutrino sector. A comprehensive study of the neutrino sector of the SME was undertaken. This resulted in three papers published in *Physical Review D* [13,14,15]. In these papers, a general formalism for violations of Lorentz and CPT symmetry in the neutrino sector is developed, and the behavior and properties of the neutrinos are determined. Possible signals in existing and future experiments are analyzed. A specific example is given of a theory consistent with observed data but having oscillations driven by Lorentz and CPT violation instead of neutrino mass differences. Applications to short-baseline experiments are developed.

Gravitational couplings. During the period of this grant, a detailed study of the role of the gravitational sector in the SME was performed. This work is published in *Physical Review D* [16]. The paper develops a framework for studying this topic in the context of Riemann-Cartan spacetimes, which include as limiting cases the usual Riemann and Minkowski geometries. The incorporation of arbitrary Lorentz and CPT violation into Einstein's General Relativity and other theories of gravity based on Riemann-Cartan geometries is discussed. The dominant terms in the effective low-energy action for the gravitational sector are provided, thereby completing the formulation of the leading-order terms in the SME with gravity. Explicit Lorentz symmetry breaking is found to be incompatible with generic Riemann-Cartan geometries, but spontaneous Lorentz breaking evades this difficulty. Various possibilities for applications to ground- and space-based experiments are suggested.

Electromagnetostatics. An investigation of the static limit of Lorentz-violating electrodynamics was performed in vacuum and in macroscopic media. This work is published in *Physical Review D* [17]. Features of the general solution include the need for unconventional boundary conditions and the mixing of electrostatic and magnetostatic effects. Explicit solutions are obtained for some simple cases, and electromagnetostatics experiments are proposed for improving existing sensitivities to parity-odd coefficients in the photon sector.

Nambu-Goldstone modes. In followup work to the detailed study of the role of the gravitational sector in the SME [16], an investigation of the massless Nambu-Goldstone modes arising from spontaneous Lorentz violation was performed. This work is currently under review [17]. It shows that up to 10 Lorentz and diffeomorphism Nambu-Goldstone modes can appear and that they are contained within the 10 modes of the vierbein associated with gauge degrees of freedom in a Lorentz-invariant theory. A general treatment of spontaneous local Lorentz and diffeomorphism violation is given for various spacetimes. The results are illustrated within the general class of bumblebee models involving vacuum values for a vector field. In Minkowski and Riemann spacetimes, the bumblebee model provides a dynamical theory generating a photon as a Nambu-Goldstone boson for spontaneous Lorentz violation. Associated effects of potential experimental relevance include Lorentz-violating couplings in the matter and gravitational sectors of the Standard-Model Extension and unconventional Lorentz-invariant couplings. In Riemann-Cartan spacetime, the possibility also exists of a Higgs mechanism for the spin connection, leading to the absorption of the propagating Nambu-Goldstone modes into the torsion component of the gravitational field.

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