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ACCELERATOR DEPARTMENT
Informal Report

A TEST OF CPT AT VERY SMALL DISTANCES

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January, 1972

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A TEST OF CPT AT VERY SMALL DISTANCES

Jay N. Marx
Yale University
January 1972

The invariance of physical laws under the combined transformation of spacial reflection, charge conjugation, and time reversal (CPT) has formed the cornerstone of our view of nature. It has been proven, for example, that any field theory which satisfies Lorentz invariance and local causality is invariant under CPT transformations. To my knowledge no one has been able to construct a field theory which, in fact, violates this symmetry. From the experimentalist's point of view we must ask ourselves how this fundamental principle has been tested; that is, what are the observable consequences of CPT invariance? First, the CPT theorem implies the usual connection between spin and statistics - no exception has yet been found. CPT invariance also predicts the equality of masses, total decay rates and form factors (e.g. anomalous magnetic moment) of elementary particles and their antiparticles. Representative limits of these ratios are given in Table I for masses, Table 2 for lifetimes and Table 3 for gyromagnetic ratios. CPT invariance also plays a role in the Wu-Yang analysis of CP violation. Their assumption of CPT invariance results in a triangular relation between the CP violating parameters Σ , η^{+-} , η_{00} . An accurate measurement of these complex parameters would result in a sensitive test of CPT. Unfortunately, the history of measurements of η_{00} is quite discouraging as the results have fluctuated over many standard deviations. Until this number is really pinned down this test of CPT cannot be done with high credibility. In addition, if the explanation of CP violation lies in a Superweak Interaction, then there is only one CP violating parameter- the amplitude for direct $K^0 \rightarrow \bar{K}^0$

transitions. In this case the triangular equality of Wu and Yang reduces to a point in the complex plane.

The more basic problem with the aforementioned tests of CPT invariance comes from the fact that they are sensitive only at low Q^2 - a few hundred MeV for the decays and possibly up to the nucleon mass for the mass equalities. If one is to really test the assumptions of the CP^T theorem, especially local causality, it is important to reach as high a Q^2 as is possible. Only then does one probe for extremely microscopic granularity in the structure of space-time through the violation of local causality at very small distances. In the following I would like to propose an experiment which can be done at ISABELLE to test the CPT theorem at distances less than 7×10^{-16} cm.

This proposal hinges on the possibility of implementing a rather exotic ISABELLE-option storage of positrons in a lepton storage ring and antiprotons in a baryon ring. The positrons should present no serious problem if it is decided to proceed with the e-p option suggested by Mel Schwartz. The storage of $\bar{p}$'s is another matter. This possibility has been discussed by R. Palmer in CRISP #71-10 and so I refer the reader to that paper for details. Palmer claims that by using the AGS to produce $\bar{p}$'s it is possible to collect and store 5×10^{12} $\bar{p}$ /week by using electron cooling to reduce the phase space volume of the stacked antiprotons or 10^{10} $\bar{p}$ /week with no such tricks. To calculate the expected luminosity for $e^+ \bar{p}$ colliding beams I take the current and beam cross section for the lepton ring from the SLAC lepton-lepton colliding beam feasibility study. There it is proposed to store about 100ma with a beam area of 3mm x 3mm. For the $\bar{p}$ beam I assume 10^{10} antiprotons in a beam of area 1cm x 1cm. The resulting specific luminosity is 3×10^{26} $\text{cm}^{-2} \text{sec}^{-1} / \text{meter}$. Electron cooling increases the specific luminosity to 1.5×10^{29} $\text{cm}^{-2} \text{sec}^{-1} / \text{meter}$.

The proposed experiment consists of a comparison of electron-proton scattering with positron-antiproton scattering at large Q^2 . The most probing results will probably come from inelastic rather than elastic events for two reasons. First we can study inelastic processes to much higher Q^2 (we assume that scaling persists at these high energies). The larger the momentum transfer the smaller the interaction distance probed. Also, when viewed from a frame of reference reached by an infinite longitudinal boost, the impulse approximation is valid for deep inelastic scattering and so one probes small interaction times. In addition, at large Q^2 exotic two photon channels may contribute significantly thus enlarging the kinds of amplitudes probed for CPT violation. Thus, to best test causality at small space-time intervals (near the light cone) one must study the deep inelastic region. [Any difference in the e^+p and e^-p cross sections is a direct measure of CPT noninvariance.]

To make specific arguments let me assume that the experiment is performed using the Impactometer (Fig. 1) designed by Willis. This 4π solid angle detector consists of wire proportional chambers and total absorption calorimeters surrounding a 2 meter colinear interaction region. The device has adequate energy and spacial resolution to compete with magnetic spectrometers for studying deep inelastic scattering. The calorimeters have an energy resolution of about 5% for 10 GeV electrons and positrons and for 200 GeV protons and antiprotons. The inelastic cross sections must be studied as a function of $\nu = E - E_0$ the energy loss of the lepton and $Q^2 = 2EE_0(1 - \cos\theta)$ the momentum transfer. The resolution in both Q^2 and ν is about 5% since both errors are dominated by the energy resolution of the scattered lepton rather than the beam momentum spread or angular resolution of the detectors.

In Fig. 2 I have plotted the e^-p (or e^+p) elastic and inelastic cross sections as a function of $\log_{\sqrt{e}} \Omega$ for $s_{\perp} \propto$ where Ω is the momentum transfer.

Scaling (and of course CPT) are assumed so that the fall-off of cross section with momentum transfer is due solely to the photon propagator in the inelastic case. The inelastic structure function is assumed to be .2 resulting in an inelastic cross section which behaves like 1/5 of the Mott scattering cross section. The variable $\log_{\sqrt{e}} \Omega$ is used because it gives bins of constant resolution for the Impactometer. To determine the value of Ω to which one is sensitive, I assume an event rate of 1 event/day in a resolution bin as the minimum acceptable sample. The horizontal line marked A corresponds to a luminosity of $6 \times 10^{26} \text{ cm}^{-2} \text{ sec}^{-1}$. The line marked B corresponds to the case where electron cooling of the antiproton beam is used to produce a luminosity of $3 \times 10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$. In the first case it is possible to detect elastic scattering to a momentum transfer of .8 GeV/c and inelastic scattering to 1.6 GeV/c. In the second case the limiting momentum transfer is 2.0 GeV/c for elastic and 30 GeV/c for inelastic scattering. The line marked C corresponds to a luminosity of $4 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ for the e^-p option. Thus, the limiting factor is the rate at high Q^2 for e^+p scattering. If no electron cooling is attempted, the maximum momentum transfer for 1 event/day is low enough to make the experiment marginal. With the use of electron cooling the sensitivity is increased to 30 GeV/c thus allowing a comparison of e^-p and e^+p deep inelastic scattering to distances of as small as $7 \times 10^{-16} \text{ cm}$. In one year of running time one could thus test Lorentz invariance and local causality at distances of less than 10^{-15} cm with an accuracy in the cross section of 5% (about 400 events) for e^+p at $Q^2 \leq (30 \text{ GeV/c})^2$ and with a 5% resolution in ν and Q^2 . Systematic biases are reduced by the use of the same apparatus to measure both e^-p and

e^+p cross sections. The resolution in energy and angle of the Impactometer allows the determination of the missing mass of the final state hadronic system in lepton scattering to better than 50 MeV. This is adequate to separate elastic from inelastic events.

We note that the limiting value of Q^2 is determined by luminosity rather than the energy of the leptons. The horizontal lines in Fig. 2 marked 5 GeV and 15 GeV indicate the kinematic boundaries for lepton energies of 5 GeV and 15 GeV, respectively, on 200 GeV protons (antiprotons). Thus from the point of view of this proposal it is best to concentrate one's efforts on the intensity of the lepton and antiproton stored beams rather than the energy of the lepton ring.

Should a positron-antiproton facility come into being one can then consider second generation experiments to search for violations of CPT invariance in specific amplitudes. The next step might be, for example, a detailed study of the hadronic final state.

I thank W. J. Willis for extremely enlightening discussions about calorimeter resolutions and the applicability of the Impactometer to the study of deep inelastic electron-proton scattering

From Lectures by Jan Nilsson
CERN SUMMER SCHOOL 1987

Particle	$\frac{m_{\bar{p}}}{m_p} - 1$
$u^\pm$	10^{-4}
$\pi^\pm$	0.002 ± 0.002
$K^\pm$	0.00 ± 0.01

Table 1: The mass ratio for some particle-antiparticle systems

Particle	$\frac{\tau_+}{\tau_-} - 1$
$u^\pm$	0.000 ± 0.001
$\pi^\pm$	0.0018 ± 0.0040
$K^\pm$	-0.0009 ± 0.0008

Table 2: Lifetime Ratio for some particle-antiparticle systems

Particle	$\frac{1}{2}(g_+ - g_-)$
e^+, e^-	$(1.5 \pm 2) \alpha^2 / \pi^2$
u^+, u^-	$(0 \pm 1.5) \alpha^2 / \pi^2$

Table 3: Gyromagnetic Ratio for electrons and muons

Figure 2

$$\frac{d\sigma}{d\Omega^2}$$

$$\frac{d\sigma}{d\Omega^2}$$

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SECTION B-B

Figure 1:

IMPACTOMETER

FOR 200 GEV PROTONS ON P OR C,
MEASURES $\pi_\psi = \sum E_z \sin \theta_L$

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