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Implications of a matter-antimatter mass asymmetry in Penning-trap experiments

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While there are numerous experiments testing the Charge, Parity, and Time Reversal (CPT) symmetry, it is not clear how these tests are related with one another, and hence, if there is a reasonable way to compare bounds arising from them. In this talk, we focus on the Penning-trap experiment testing the charge-to-mass ratio of protons and antiprotons, and try to compare it with other experiments which also test the matter-antimatter mass asymmetry (MAMA) from a bottom-up approach. This is done with the help of the mass decomposition of hadrons. At the end, we found that the bounds from kaon oscillation experiments are many orders of magnitude above the Penning trap experiment for a set of MAMA parametrization. We also discuss the implications of a CPT violation signal from the Penning trap experiment within the kaon oscillation bounds by tracing back the origins of a non-trivial MAMA, namely the violation of locality and Lorentz invariance in an axiomatic field theory.

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1. Introduction

Building on the fundamental principles: causality, locality and Lorentz invariance, the CPT symmetry will always be conserved in any axiomatic field theory [1, 2]. This is also know as the CPT theorem, and is also what the standard model (SM) of particle physics builds on. On top of simply checking such building blocks, which would change our basic understanding of nature if violated, typical indications of the SM being incomplete motivate CPT symmetry to be not exact. These indications include gravity and the baryon asymmetry of the universe. The former points towards theories such as quantum gravity and extra dimensions. The latter is popularly addressed with models satisfying the Sakharov conditions, under which CPT symmetry is assumed to be conserved. However, if such assumption is lifted, baryon asymmetry can arise in thermal equilibrium when baryon number is violated [3].

Furthermore, since the CPT symmetry features as a mirror between particle and antiparticle, the conservation of it guarantees that their physical properties, such as their mass and life time should be identical. In fact, even without going through CPT symmetry, once locality and Lorentz invariance is established, causality automatically warrants the existence of antimatter with reflected physical properties (identical mass and lifetime, but opposite charge if any) of the corresponding matter field. In this talk, we focus on the testing CPT symmetry through the matter-antimatter mass asymmetry (MAMA). The logic flow would be that if MAMA is nontrivial, not only must the CPT symmetry be broken, but locality and/or Lorentz invariance must be violated in a Hermitian axiomatic field theory. This is illustrated in Fig. 1. There is also the possibility of breaking CPT symmetry through a violation of the weak equivalence principle, but since the measurements we consider, as will be discussed in the next section, are not directly sensitive to such effects, we do not take that into account in this talk.

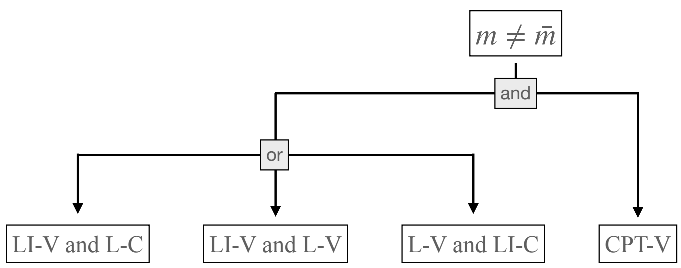

Figure 1: Flow chart for implications of a non-trivial asymmetry between the mass of matter and antimatter ($m \neq \bar{m}$). LI/L/CPT-V(C) means that Lorentz invariance/locality/CPT symmetry is violated (conserved).

2. Precision Tests on MAMA

While one can compare different CPT tests by normalising CPT violating observables of each experiment to dimensionless, it is unclear if different systems are testing the same origins of CPT violation and if they have, e.g. amplification or cancelation, effects compared to one another even with the same origin. By focusing on MAMA testing experiments, we are already narrowing down the arbitrariness of origins, for instance, we do not consider tests, such as [4] or the annual modulation in [5], where the violation of weak equivalence principle could play an important role in the CPT symmetry breaking. In the next section, we will study how to bridge MAMA testing systems from a bottom-top prespective, but before that, we introduce three MAMA testing experiments in this section. These experiments are chosen to represent different approaches/systems of testing MAMA, and give the best precision among similar systems.

The systems taken into account are the proton/antiproton charge-to-mass ratio measured using Penning traps by the BASE collaboration [5]; the mass difference between neutral kaon and antikaon from kaon oscillation experiments; and the mass splitting from neutrino oscillation and anti-neutrino oscillation experiments. In particular, the Penning trap experiment captures an antiproton produced at the large hadron collided and an antihydrogen, then compare their charge-to-mass ratio through measuring the cyclotron frequency (ν_c). This is done by adopting the Brown-Gabrielse invariance theorem: $\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$, where ν_+, ν_z, ν_- are three measured eigenfrequencies, namely, the modified cyclotron frequency, the axial frequency and the magnetron frequency. In addition, $\nu_c = 1/(2\pi)(q/m)B_0$, where B_0 represent the homogeneous magnetic field in the experiment. The resulting MAMA limit for the proton system is set as

$$\left|\frac{m_{\bar{p}}}{m_p} - 1\right| < 3 \times 10^{-12}\,, \tag{1}$$

by the BASE collaboration [5], where $m_p/m_{\bar{p}}$ denote proton/antiproton mass. As for the kaon system, the MAMA lies in the difference between the two diagonal terms of the Hamiltonian of neutral kaon and antikaon ($K^0, \bar{K}^0$) in flavor space. The resulting limit

$$|m_{K^0} - m_{\bar{K}^0}| < 4 \times 10^{-16}\,\text{MeV}\,, \tag{2}$$

is established using the Bell-Steinberger relation (where unitary is assumed) for kaon oscillation experiments [6]. Finally, the MAMA for the neutrino system is provided by fitting the neutrino and antineutrino spectra separately with the different oscillation parameters, namely mass-squared difference ($\Delta m_{jk}^2 = m_j^2 - m_k^2$) and mixing angles. As a result, the analysis using a combination of solar neutrino data, and KamLAND reactor antineutrino data gives [7]

$$\Delta m_{21}^2 - \Delta \bar{m}_{21}^2 < 4.7 \times 10^{-5}\,\text{eV}^2\,, \tag{3}$$

while long-baseline, and short-baseline experiments can set

$$\Delta m_{31}^2 - \Delta \bar{m}_{31}^2 < 3.7 \times 10^{-4}\,\text{eV}^2\,. \tag{4}$$

3. Bridging Different Systems

In order to bride different hadronic systems, we must understand how a violation of CPT can affect the system. This can be done by taking a closer look at the QCD Hamiltonian operator $H_{\text{QCD}} = -\int d^3x\, T_{44}(x)$, and its decomposition: $H_{\text{QCD}} = H_E + H_g + H_m + H_a$ [8]. Here, $T_{\mu\nu}$ is the

QCD energy-momentum tensor and

$$
\begin{aligned}
H_E &= \sum_q \int d^3x\, \bar{\psi}_q (\overrightarrow{D}.\overrightarrow{\gamma})\psi_q\,, &(5)\\
H_g &= \int d^3x\, \frac{1}{2}(B^2 - E^2)\,, &(6)\\
H_m &= \sum_q \int d^3x\, m_q \bar{\psi}_q \psi_q\,, &(7)\\
H_a &= \int d^3x \left[\frac{\gamma_m}{4}\sum_q m_q \bar{\psi}_q\psi_q - \frac{\beta(g)}{4g}(B^2+E^2)\right], &(8)
\end{aligned}
$$

represent the kinetic energy of the quarks, the gluon field energy, the bare quark masses, and the QCD anomaly, respectively. Also, $\overrightarrow{D} = \overrightarrow{\partial}_\mu + igA_\mu$, γ_m is the anomalous mass dimension operator, and $\beta(g)$ is the QCD beta function. At the end, the mass of a single hadron state for a given momentum p would be

$$M = \frac{\langle p|H_{\mathrm{QCD}}|p\rangle}{\langle p|p\rangle}\,. \tag{9}$$

On the other hand, the expression for the corresponding antihadron ($\bar{M}$) would be to replace quark field and corresponding parameters (here, we only have the bare mass m_q) with that for antiquarks, and vice versa, while everything else remain the same. Therefore, CPT breaking (the difference between M and $\bar{M}$) would reflect dominantly on H_m, followed by subdominant contributions from H_a and H_E. Note that the mass decomposition formalism is derived under the assumption that all the fundamental principle are met, hence any violation of it might contribute to the quantum corrections in H_a. Nonetheless, by having the same field structure, the γ and β terms in H_a can be absorbed into H_m and H_g, respectively, by rescaling the coefficients.

Once we realize that a CPT violation reflects primarily on H_m up to zeroth order, we can rewrite Eq. (2) - Eq. (4) using Eq. (9) for some MAMA parametrisation of m_q, namely, $\delta_q = m_{\bar{q}} - m_q$ and $r_q = m_{\bar{q}}/m_q$. We can also define α as $m_x = m_0(1+\alpha)$ for particles and $m_{\bar{x}} = m_0(1-\alpha)$, for antiparticles, such that

$$\alpha \equiv \left|\frac{m_{\bar{x}} - m_x}{m_{\bar{x}} + m_x}\right| \simeq \left|\frac{\sum_j \delta_j}{2m_x}\right|\,. \tag{10}$$

Take the proton system for an example, for estimation purpose, we can set $\delta = \delta_u = \delta_d$ and $r = r_u = r_d$. Furthermore, $C_q = \langle P|\bar{\psi}_q\psi_q|P\rangle$, and would be CPT conserving since it is Hermitian. In addition, the sea quark contribution would also be identical between proton and antiproton, since they come in quark-antiquark pairs, we only need to consider contributions from valance quarks proportional to the respective quark charges, i.e., $C_u : C_d = 2 : 1$. The absolute value of C_q can be estimated through various inputs, including the analogy with the mass splitting between proton and neutron induced by chiral symmetry breaking; the pion-nucleon σ-term from scattering experiments or through lattice calculations (see [9] for a review); and the $\langle H_m\rangle$ contribution of the mass decomposition through lattice calculations [10]. With the purpose of order-of-magnitude comparison between different systems, Table 1 is listed conservatively to a range such that all these inputs are included. Similar parametrisation and estimation method can be carried out for the kaon and neutrino system. For the kaon system, Table 1 includes C_q taken from measurements of

MAMA	Proton	Kaon	Neutrino
$\|\sum_j \delta_j\|$ (MeV)	$O(10^{-10} - 10^{-9})$	$O(10^{-16})$	$O(10^{-9})$
δ (MeV)	$O(10^{-10} - 10^{-9})$	trivial	$O(10^{-9})$
$r - 1$	$O(10^{-11} - 10^{-10})$	$O(10^{-18})$	$O(10^{-1})$
α	$O(10^{-12})$	$O(10^{-19})$	$O(10^{-2})$

Table 1: Limits on the different parameters of CPT violation from different systems. $|\sum_j \delta_j|$ is $|2\delta_u + \delta_d|$, $|\delta_s - \delta_d|$ and ($|\delta_2|$, $|\delta_3|$) from the Penning-trap, neutral kaon oscillation and neutrino oscillation experiments, respectively. δ assumes all δ_js are identical as such value. The other quantities are as defined in the text.

the valance quark contributions [11]. On the other hand, neutrinos are not confined, but there is the uncertainty of what the absolute masses are. Hence, the range in Table 1 include all possible neutrino mass within current bounds [6].

4. Summary and Discussion

From Table 1, it is clear that kaon oscillation set bounds on the MAMA parameters with mass dimension zero and one many orders of magnitude above the Penning trap experiments and the neutrino oscillation fits. Nonetheless, with the Penning trap experiments advancing in leaps and bounds, what would be the indications if they do see a violation in the CPT symmetry? One possibility is if δ_s and δ_d are (nearly) degenerate such that they cancel out each other, as shown in the table as the “trivial" entry. However, in addition to having CPT effects scale with the particle mass (therefore, using the δ instead of the r parametrisation), an addition symmetry between the quarks would be required, such that δ_s and δ_d are identical at least to leading orders. Otherwise, we should trace down to the origins of the MAMA, namely, the fundamental principles. For instance, the sacredness of locality, in a sense, is already challenged through the well-established test of Bell inequality in quantum optics. The description of non-locality in field theory, on the other hand, is another story, which could be a result of non-local interaction motivated by e.g. string theory [12]. In addition, the violation of Lorentz invariance can be motivated by, e.g. quantum gravity, since it is not sufficient before the emergent spacetime [13]. However, genetically speaking, unlike the CP phase being independent for different sectors, a CPT violation should exist in all sectors if there is any, since it roots from a violation of some fundamental principle(s). Still, a measuremnt might be especially sensitive to a particular principle. For instance, since the kaon oscillation involves a one loop box diagram with strangeness violated by two units, it might be more sensitive to non-local interactions; and since neutrinos travel at a large scale, and the MAMA parameter is measured w.r.t. the dispersion relation of the propagating neutrino, it might be more sensitive to the violation of Lorentz invariance. Note that micro-causality would be violated if only one of the two fundamental principles are broken [12, 14], but can be restored if they both break and compensate each other [14]. Therefore, if a UV complete micro-causality is insisted, then there would be a tight connection between the violation of locality and Lorentz invariance. Nonetheless, if the breaking of micro-causality is only required to be confined at high scales, then the breaking of two fundamental principles could be disentangled.

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