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LIMIT ON QUARK–ANTIQUARK MASS DIFFERENCE FROM THE NEUTRAL KAON SYSTEM

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We quantify the limits on quark-antiquark mass differences imposed by the neutral kaon mass system. In particular, we find that an upper limit to the mass difference of 10^{-3} eV exists if mass differences across quark flavors are uncorrelated. In the upcoming antihydrogen experiments this limit on quark mass difference would allow a measurement of electron-positron mass difference up to a relative precision level of 10^{-15}.

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The origin of quark and lepton masses remains at present unknown. It is generally presumed that by virtue of CPT symmetry matter and antimatter will always have same fundamental mass parameters. On the other hand, the experimental limits are at present not very good, and in fact the limit on the baryon-antibaryon mass difference [1]:

$$|m_p - m_{\bar{p}}| < 6\,10^{-8} m_p \simeq 60\,\mathrm{eV}$$

is much grater than what would suffice to induce a small baryon-antibaryon abundance asymmetry in the early Universe evolving into present time. At the deconfinement boundary a baryochemical potential of the order of $1.1\,\mathrm{eV} \pm 15\%$ [2] suffices. Consequently, it would seem that our understanding of the early Universe depends sensitively on the implicit assumption about the presence of the mass symmetry for quarks and antiquarks, the constituents of baryons, at a level of two orders of magnitude beyond current experimental knowledge.

Here we show how the properties of the neutral kaon system constrain much more accurately the mass difference between quarks and antiquarks. We also comment on achievable improvement in the measurement of matter-antimatter symmetry in comparisons of hydrogen with antihydrogen.

From a detailed study of the kaon decay rates, it is observed that the mass difference between the K_L and K_S states is $\Delta m \equiv m_{K_L} - m_{K_S} = 3.463 \pm 0.010 \times 10^{-6}$ eV [3]. Because this mass difference is understood within the standard model to arise from second-order weak interactions that mix the K^0 and $\bar{K^0}$ states [4,5], the magnitude of the CPT-violating contribution to particle-antiparticle mass difference is severely restricted by this result.

Recently, it has been demonstrated by Greenberg [6] that CPT breaking implies the violation of coordinate Lorentz invariance. In an extension of the standard model, Lorentz- and CPT-violating operators yielding a satisfactory quantum field theory have been considered [7–9]. Examples include spontaneous Lorentz and CPT violation in the context of string field theory (see, *e.g.*, Refs. [10, 11]) and non-commutative field theories [12]. These models offer a basis for numerous precision experiments placing extremely tight bounds on Lorentz and CPT breaking. In this context, the neutral kaon system has been analyzed both experimentally [13, 14] and theoretically [15–17], while direct CPT violation in the neutrino sector has been explored in Refs. [18–20]. Other work discussing theoretical implications of CPT violation include [21–24].

One may indeed ask if such a hypothesis for a mass difference between particles and antiparticles makes good physical sense, considering the well established principles of quantum field theory. We believe that a search for tacitly assumed limits to accepted physical principles is a very important step in verification of the paradigm which govern our view on the laws of physics. This attitude is more generally shared, and with formation of a large number of antihydrogen atoms, we can look forward to further experimental tests of CPT symmetry to take place at CERN [25, 25]. On a more theoretical side, a momentum-dependent difference between particles and antiparticles is expected [15, 16], should there be a violation of Lorentz invariance, appearing in association with CPT breaking [6].

In the following we describe how the measured mass asymmetry of the neutral kaons limits the mass difference between quarks and antiquarks. We define the K_L and K_S states in the standard formalism [5]:

$$K_L = \frac{1}{\sqrt{2+2\epsilon^2}}\left[(1+\epsilon)K^0 + (1-\epsilon)\bar{K^0}\right] , \tag{1}$$

$$K_S = \frac{1}{\sqrt{2+2\epsilon^2}}\left[(1-\epsilon)K^0 - (1+\epsilon)\bar{K^0}\right] , \tag{2}$$

where $K^0 = |d\bar{s}\rangle$, $\bar{K^0} = |\bar{d}s\rangle$, and $\epsilon \approx 2.3 \times 10^{-3}$ is the CP violation parameter.

We express the (assumed) CPT-violating mass difference between quarks and antiquarks as:

$$m_{s,\bar{s}} = m_s^0 \pm \frac{\delta m_s}{2}, \quad (3)$$

$$m_{d,\bar{d}} = m_d^0 \pm \frac{\delta m_d}{2}, \quad (4)$$

where the signs of δm_s and δm_d are undetermined.

The mass operator for the neutral kaon system, with the quark mass differences, becomes:

$$\hat{M} = \hat{M}_K^0 + \hat{M}_w + \frac{f}{2}\Big[(\delta m_d - \delta m_{\bar{s}})|d\bar{s}\rangle\langle d\bar{s}| + (-\delta m_{\bar{d}} + \delta m_s)|\bar{d}s\rangle\langle\bar{d}s|\Big], \quad (5)$$

where $\hat{M}_K^0$ is the neutral kaon mass excluding weak interactions, $\hat{M}_w$ is the mass contribution due to weak interactions, and the third term is the effect that the change in the current quark masses of Eqs. (3) and (4) would have on the kaon mass.

The form of the third term arises because in a model of hadronic structure (*e.g.*, the bag model), the response of the hadronic mass is linear with respect to the change in quark mass if expanded about a finite quark mass [27]. Note that a similar effect arises in non-relativistic quark models. Furthermore, the scaling factor f is of order unity, as confirmed by the features of hadronic mass splittings.

From Eqs. (1)–(5), the mass difference between K_L and K_S becomes:

$$\begin{aligned}\Delta m &= \langle K_L|\hat{M}|K_L\rangle - \langle K_S|\hat{M}|K_S\rangle \\ &= \Delta m_w + 2\epsilon f\, [(m_{\bar{s}} - m_s) - (m_{\bar{d}} - m_d)]\,, \end{aligned} \quad (6)$$

where $\Delta m_w \equiv \langle K_L|\hat{M}_w|K_L\rangle - \langle K_S|\hat{M}_w|K_S\rangle$ and terms of ϵ^2 or higher have been neglected. Since it is understood that $\Delta m \simeq \Delta m_w$, this immediately yields the result:

$$|(m_{\bar{s}} - m_s) - (m_{\bar{d}} - m_d)| \ll \frac{\Delta m}{2\epsilon f} \approx 10^{-3}\,\mathrm{eV}\,. \quad (7)$$

Equation (7) places rather stringent limits on direct CPT violation in d and s quarks. If the size of the CPT violation across quark flavors is uncorrelated, then an upper limit to the mass difference between quarks and antiquarks of *each* flavor must be much less than 10^{-3} eV. Otherwise, the size of the CPT violation across s and d flavors must be highly correlated, such that $(m_{\bar{s}} - m_s) \simeq (m_{\bar{d}} - m_d)$. This would imply that a CPT violating force does not in effect distinguish between the first and second particle generation. In the following, we assume that this is not the case.

Such a small mass difference between d and $\bar{d}$ quarks allows a thorough study of the possible electron-positron mass difference in the antihydrogen experiments. The wavelengths of atomic transitions in hydrogen scale with the inverse of the reduced mass, $\lambda \propto (m_p + m_e)/m_e m_p$. As a result, the relative shift in wavelength due to a mass difference in hydrogen and antihydrogen atoms comprises also, at a lesser degree, the influence of the atomic nucleus:

$$\begin{aligned} \left|\frac{\delta\lambda}{\lambda}\right| &= \frac{m_p m_e}{m_p + m_e}\left(\frac{\delta m_e}{m_e^2} + \frac{\delta m_p}{m_p^2}\right) \\ &\simeq \left[\frac{1}{m_e}\,\delta m_e \;+\; \frac{m_e}{m_p^2}\,f\;(2\delta m_u + \delta m_d)\right]. \end{aligned} \tag{8}$$

A CPT violation originating in quarks and antiquarks is thus greatly reduced. Indeed, if the mass difference between u and $\bar{u}$ is also limited to be $\ll 10^{-3}$ eV, then the resulting contribution of the atomic nucleus to the shift in wavelength becomes:

$$\left|\frac{\delta\lambda}{\lambda}\right| \ll 2\times 10^{-15}\,. \tag{9}$$

This therefore is in principle the precision with which the relative mass difference of electron and positron can be measured in experiments involving matter and antimatter [25, 26]. Only when this precision is indeed reached we would also become sensitive in these experiments to the possible quark-antiquark mass differences.

In summary, we find that the current upper limit to the mass difference between quarks and antiquarks in the d and s flavors is $\ll 10^{-3}$ eV if the magnitude of the CPT violation is uncorrelated across quark flavors. In this case, the relative precision with which the strange quark mass difference is determined appears to be by far the most precise such value presently known:

$$\left|\frac{m_s - m_{\bar{s}}}{m_s + m_{\bar{s}}}\right| \ll 10^{-11}\,,$$

providing a strong constraint for any CPT model considered, and assuring that a possible quark mass asymmetry is not relevant in the determination of the physical conditions in the early Universe.

A possible d-quark mass difference at this level would have the effect of shifting the wavelengths of the antihydrogen atomic spectrum by $\ll 2\times 10^{-15}$ relative to the hydrogen spectrum, allowing a measurement of the mass difference in the leptonic sector at a yet much higher precision.

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