

## Past Electron-Positron $g$ -2 Experiments Yielded Sharpest Bound on $CPT$ Violation for Point Particles

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In our experiments on a single  $e^-$  and  $e^+$  we measured the cyclotron and spin-cyclotron difference frequencies  $\omega_c^\pm$  and  $\omega_a^\pm = \omega_s^\pm - \omega_c^\pm$  and ratios  $a^\pm = \omega_a^\pm/\omega_c^\pm$  at  $\omega_c/2\pi \approx 141$  GHz and  $e^-$  values also at  $\omega_c/2\pi \approx 164$  GHz. Here we do extract from these data a new figure of merit for violation of  $CPT$  symmetry similar to  $|m_{K_{aon}} - m_{AntiKaon}|/m_{K_{aon}} \lesssim 10^{-18}$  for the  $K$  mesons composed of two quarks. That expression compares experimental relativistic mass energies of particle states before and after the  $C, P, T$  operations have transformed particle into antiparticle. The figure for our *noncomposite* leptons was even smaller:  $|\hbar(\omega_a^-/2) - \hbar(\omega_a^+/2)|/m_0c^2 \lesssim 12 \times 10^{-22}$ .

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In 1962 Dirac wrote, "Recently, new evidence has appeared for the finite size of the electron by the discovery of the muon, having properties so similar to the electron that it may be considered to be merely an excited state of the electron." Finite physical size [1–3] of Dirac's supposed point particles of 1926 may prevent them from obeying [4–6] exact  $CPT$  symmetry simply because this theorem has been proven only for mathematical fictions, true point particles. This has revived interest in the sparse  $CPT$  violation data currently available and their interpretation. In our experiments [7] on a single  $e^-$  and  $e^+$  essentially at rest in free space, and later [8] on  $e^-$  alone, we measured the cyclotron and spin-cyclotron difference frequencies  $\omega_c^\pm$  and  $\omega_a^\pm = \omega_s^\pm - \omega_c^\pm$ . Avoiding the well-known problems of obtaining the small difference between two large quantities with nonvanishing errors we measured  $\omega_a^\pm$  directly. To this end we induced spin flips by a spin-flipping rf field at  $\omega_s^\pm$  synthesized from the free electron-positron cyclotron motion at  $\omega_c^\pm = eB/m_0^\pm$  and an applied rf field at a precisely measured variable frequency. Spin flips thus produced were observed with the help of the continuous Stern-Gerlach effect [9] and counted. A peak in the counting rate as the applied rf field was swept in frequency over  $\omega_a^\pm$  signaled the resonance. To minimize the effects of unavoidable small drifts of the  $B$  field we recorded the anomaly values  $a^\pm = \omega_a^\pm/\omega_c^\pm$ . Our  $g$  value stood for the combination of observed frequency ratios  $g^\pm = 2(a^\pm + 1)$ , and we used  $(g^- - g^+)/2 = a^- - a^+$ , here now called  $\Delta a$ , as a measure of  $CPT$  symmetry violation, where  $g^-$ ,  $g^+$  denote our  $g$  ratios for  $e^-$  and  $e^+$ .

To our experiments on "noncomposite" leptons Bluhm, Kostelecký, and Russell (BKR) [10] have recently applied their impressive formalism that mildly extends the standard model with the help of small, critically selected  $CPT$  breaking perturbations and a perhaps less mild postulated new cosmic axial vector field. In this effort, much appreciated by us, they have been more interested in calling for complex new experimental procedures to test the BKR model than in making full use of our long available data

for the purpose of extracting from them the sharpest possible bound on  $CPT$  violation. Stimulated by their work, we do here extract from our data, as has not been done before, a new and very different figure of merit, one similar to the widely recognized limit

$$|m_{K_{aon}} - m_{AntiKaon}|/m_{K_{aon}} \lesssim 10^{-18} \quad (1)$$

for the  $K$  mesons composed of two quarks [11]. Without reference to the BKR model, that expression may be seen as comparing experimental relativistic mass energies of particle states before and after the  $C, P, T$  operations have transformed particle into antiparticle. Accordingly, in the same constant magnetic field we let the symmetry operations transform an electron in the lowest energy level  $E_{n,s}^-$ ,  $n = 0$ ,  $s = -1$ , into a positron in the lowest energy level  $E_{n,s}^+$ ,  $n = 0$ ,  $s = 1$ , where  $n = 0, 1, 2, \dots$ , is the cyclotron quantum number and  $s = \pm 1$  stands for spin up or spin down. When  $CPT$  symmetry holds we have

$$\begin{aligned} E_{0,-1}^- - E_{0,1}^+ &= (m_0^- c^2 - \hbar\omega_a^-/2) - (m_0^+ c^2 - \hbar\omega_a^+/2) \\ &= 0 \end{aligned} \quad (2)$$

or

$$\begin{aligned} E_{0,-1}^- - E_{0,1}^+ - (m_0^- - m_0^+)c^2 &= -\hbar(\omega_a^- - \omega_a^+)/2 \\ &= 0. \end{aligned} \quad (3)$$

When the right side of the last equation is found not to vanish it becomes a measure of  $CPT$  violation and as a fraction of  $m_0c^2$  a dimensionless figure of merit for the symmetry violation,

$$|\hbar(\omega_a^- - \omega_a^+)/2m_0c^2, \quad (4)$$

that on first sight appears to require the measurement of  $\omega_a^-$ ,  $\omega_a^+$  in more or less exactly the same  $B$  field. Actually, this turns out not to be the case.

Our later experiments [8] have shown that numerical values of  $a^-$  measured at  $\omega_c/2\pi \approx 164$  GHz differed from those at  $\omega_c/2\pi \approx 141$  GHz by no more than  $1.1 \times 10^{-11}$  compared to the measurement error in  $a^\pm$  of

$\approx 10^{-12}$ , and thus the anomaly value is practically constant over a range of 23 GHz. Earlier [7], in the same apparatus with only the trapping potential reversed and therefore in nearly identical fields  $B(e^-)$ ,  $B(e^+)$  with cyclotron frequencies for electron and positron differing by less than 56 kHz, we had measured  $|a^- - a^+| \leq 2 \times 10^{-12}$  at  $\omega_c/2\pi \approx 141$  GHz. Since the  $B$ -field dependent contribution to  $a^-$ , if any, changed by no more than  $1.1 \times 10^{-11}$  over 23 GHz, the effect of not using exactly the same field could have changed the  $e^-$ ,  $e^+$  anomaly values by no more than  $3 \times 10^{-17}$ , a totally negligible amount. Therefore, substituting  $(a_{B(e^-)}^- - a_{B(e^+)}^+)\omega_c^- = \Delta a \omega_c$  for  $(\omega_a^- - \omega_a^+)$  in Eq. (4) is quite legitimate and eliminated the need for the experimental feat of making  $B(e^-)$ ,  $B(e^+)$  more or less exactly equal as proposed in Ref. [10]. Thus we arrive at the final numerical value of the merit figure from our work,

$$|\hbar(\omega_a^+ - \omega_a^-)|/2m_0c^2 = |\Delta a|\hbar\omega_c/2m_0c^2 \leq 12 \times 10^{-22}. \quad (5)$$

Our result is now revealed as the sharpest published bound on  $CPT$  breaking for a ‘‘point’’ particle. Here and everywhere in the paper our error limits are quoted for 1 standard deviation.

Interpreting our result under the BKR model, the only theoretical model currently available, yields the following expression (6), applying exclusively to  $CPT$  violation. Equation (5) is modified to

$$|E_{0,-1}^- - E_{0,1}^+|/m_0c^2 = |\Delta a|\hbar\omega_c/2m_0c^2 \leq 12 \times 10^{-22}, \quad (6)$$

as under the BKR model the small  $CPT$  symmetry violating perturbations leave electron-positron cyclotron frequencies  $\omega_c^\pm$  and rest masses  $m_0^\pm$  identical to  $\omega_c$  and  $m_0$ . While Eq. (6) is even more similar to Eq. (1) than Eq. (5), it must be mentioned that the assumptions underlying the BKR model and Eq. (6) are less general than those underlying Eq. (1). Further, we must now address the unpleasant fact that according to the model the conditions of the 1987 experiment [7] may have been less than optimal for detecting  $CPT$  violation. According to Eq. (8) of Ref. [10] the  $e^-/e^+$  anomaly frequency splitting is not constant as one might expect naively, but varies with sidereal time

$$(\omega_a^- - \omega_a^+) = -4b\hat{b} \cdot \hat{B} = -4b_3, \quad (7)$$

where  $\vec{b}$  is a vector of length  $b$  and direction  $\hat{b}$  fixed with respect to the fixed stars but otherwise unspecified. This vector quantifies the degree of  $CPT$  violation and thereby becomes the all-important parameter of the model that experiment must determine.  $\vec{B}$  is a unit vector along the magnetic field, which in our laboratory is directed vertically upward. Obviously  $\hat{b} \cdot \hat{B}$  changes as the earth rotates around its axis  $\hat{e}$ . To quickly orient ourselves about the range of splittings produced in our laboratory located at about latitude  $\pi/4$  by a given  $\vec{b}$  vector we

discuss the three special cases of the angle between  $\vec{b}$  and  $\hat{e}$  having the values 0,  $\pi/4$ , and  $\pi/2$ . The corresponding value ranges of  $\hat{b} \cdot \hat{B}$  then are  $\text{const} = 1/\sqrt{2}, 0, \dots, 1, -1/\sqrt{2}, \dots, 0, \dots, 1/\sqrt{2}$ . The more or less blind zone where  $\hat{b} \cdot \hat{B}$  drops below  $\frac{1}{4}$  is not negligible, perhaps 30% of the whole sphere. It is widest for the angle between  $\vec{b}$  and  $\hat{e}$  having the value  $\pi/4$ , so we focus on this angle in the following. All 1987  $e^-/e^+$  data were taken in solar not sidereal time over a 42 day period, daily from midnight  $\pm 1$  h to 5 a.m.  $\pm 1$  h in which 16 days of  $e^+$  data taking were followed by a 5 day pause and then by 21 days of  $e^-$  data taking. Each data period is roughly equivalent to one 2:30 a.m. point, one for  $e^+$  at day 8 and one for  $e^-$  at day 33. Combined they effectively yield one  $\Delta a$  point taken at day 21. The odd a.m. time slots were necessitated by conditions in our laboratory. The unfortunate possibility that data taking may have been limited to a partly blind time slot where  $|b_3|/b$  had dropped much below  $\frac{1}{4}$  may in future work be eliminated by repeating an identical series  $\frac{1}{4}$  yr later when it again has reached a large value. The latter occurs because then the Earth has completed one-quarter of its orbit around the Sun and, as seen from our laboratory, the stars appear on the sky 6 h earlier at 8:30 p.m. where they had been at 2:30 a.m. on day 1. We can achieve part of this already with our 1987 data at the price of larger error limits as follows. Combining only the first days of the  $e^+$  and  $e^-$  data we find  $\Delta a = (-2.2 \pm 3) \times 10^{-12}$  at effectively day 12 while combining only the last days of these data gives  $\Delta a = (2.2 \pm 2.2) \times 10^{-12}$  at effectively day 29. For  $\vec{b}$  and  $\hat{e}$  making an angle  $\pi/4$  this implies that if on day 12 in a worst possible case scenario the ratio  $|b_3/b|$  had been 0, at 17 days later by day 29 it would have grown to about 2.5% of its peak value 1. For all possible orientations of  $\vec{b}$  against  $\hat{e}$  this value and Eq. (6) now allow us to roughly bound  $b$ ,

$$b \leq 50 \text{ rad/sec}. \quad (8)$$

By contrast, if our data had been taken when the orientation of  $\vec{b}$  was most favorable, namely,  $\vec{B} \parallel \vec{b}$ , they would have shown that it must be

$$b \leq 0.7 \text{ rad/sec} \quad (9)$$

as it escaped detection. Another result of the BKR model, devastating on first sight, predicts  $g^+ = g^-$  when  $g$  is interpreted not as a ratio of measured frequencies but as a correct theoretical gyromagnetic ratio. Obviously our definition  $g = 2(a + 1)$  is modified by the  $CPT$  violating perturbations here which explains our shift of emphasis from  $g$  to  $a$  values in the introduction.

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- [1] Compare, e.g., P. Dirac, Proc. R. Soc. London A **268**, 57 (1962).
- [2] B. Pullman, *The Atom in the History of Human Thought* (Oxford University Press, New York, 1998).
- [3] H. Dehmelt, Phys. Scr. **T59**, 87 (1995).
- [4] A. Kostelecký and R. Potting, Nucl. Phys. **B359**, 545 (1991).
- [5] A. Kostelecký, in Proceedings of the Conference on CPT Violation, Strings, and Neutral-Meson Systems, 1997 (to be published) [hep-ph/9704264].
- [6] J. Ellis, J. Lopez, N. Mavromatos, and D. Nanopoulos, Phys. Rev. D **53**, 3846 (1996).
- [7] R. Van Dyck, Jr., H. Dehmelt, and P. Schwinberg, Phys. Rev. Lett. **59**, 26 (1987); Phys. Rev. D **34**, 722 (1986).
- [8] R. Mittleman, F. Palmer, and H. Dehmelt, in *Traps for Antimatter and Radioactive Nuclei*, edited by J. D'Auria, D. Gill, and A. Javin (Baltzer, Basel, 1993); Hyperfine Interact. **81**, 105 (1993).
- [9] H. Dehmelt, Proc. Natl. Acad. Sci. U.S.A. **83**, 2291 (1986).
- [10] R. Bluhm, A. Kostelecký, and N. Russell, Phys. Rev. Lett. **79**, 1432 (1997); also hep-ph/9707364; Phys. Rev. D **57**, 3932 (1998).
- [11] C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).