Experimental Search for Lorentz Violation in Antihydrogen

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The advent of precision measurements on antihydrogen has opened new doors for tests of fundamental physics in the antimatter sector. This paper retrospectively analyzes data on locations of antihydrogen annihilations in the ALPHA trap in a search for temporal variation of its charge, which would constitute a violation of Lorentz Invariance.

I. INTRODUCTION

General relativity purports that a particle's charge is independent of the observer's reference frame. Although the theoretical underpinnings of this prediction are strong, experimental verification of fundamental predictions of physics are critical to assessing the axioms necessary to develop such theory. In this spirit, we have performed a retrospective analysis on the data collected during the ALPHA experiment's runs in 2010 and 2011 to examine it for indications of a varying antihydrogen charge as the trap moves through space.

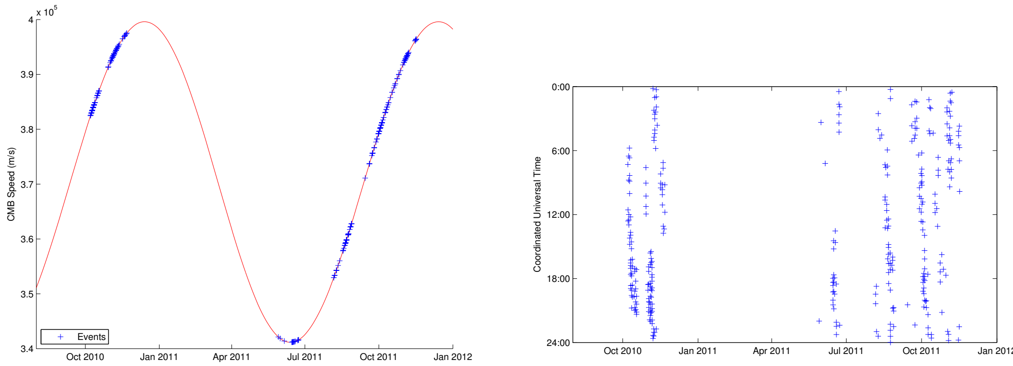
Over 386 antihydrogens in 320 experimental runs passed all detection criteria, hereafter referred to as cuts[1]. Only the antihydrogens that passed the cuts are included in the analysis. The times of these detection events were distributed over 405 days and over all hours of the day (see Fig.1), which is important for the analysis as violations would likely be correlated with the CMB velocity and/or orientation of the trap relative to a preferred frame. With this in mind, we search for a antihydrogen charge oscillation with a period of one year or one sidereal day.

The full data set consists of the times and z-positions (along trap axis) of antihydrogen annihilations after ALPHA's confining magnetic trap is quenched. During the trapping run, a series of axial electric fields called kicks are sequentially applied to the trap to drive unbound antiprotons out and leave only antihydrogen behind. If the antihydrogen atoms have a charge, their trajectories will be perturbed by these fields and the distribution of their annihilations will be shifted. If the charge is time-dependent, then the mean annihilation position will oscillate as well. The Fourier coefficients of the annihilation positions as a function of time are measured experimentally. Simulations are then performed to determine the expected distribution of these Fourier coefficients for charge oscillations of various magnitudes. Comparing the experimental value to these distributions allows bounds to be placed on the magnitude of the charge oscillation.

II. METHODS SUMMARY

A bound on the temporal variation of the antihydrogen charge is performed by comparison of a test statistic S, constructed to approximate the magnitude of a Fourier coefficient, between the collected data and simulated distributions of this statistic. A statistically significant nonzero value of S would indicate a violation of Lorentz Invariance.

The full data set consists of the annihilation times and z-values (position along trap axis) from ALPHA's trapping attempts. Define $f(t)$ to be a function that maps times of $\bar{H}$ annihilations to



(a) Event Dates

(b) Event Times

FIG. 1. (a): The CMB speed of the Earth with the dates of $\bar{H}$ annihilation events marked. (b): The times of day of the antihydrogen events (times are in Coordinated Universal Time).

the z position of those annihilations. To be continued ...

Time Selection

The time of antihydrogen annihilation events where sampled in accordance with estimations of $\sim$ 1900 trial runs which data was collected in 2010 and 2011 to simulate the time of those 386 events which charge was eligible to be detected.

Here we define a run as a operation for one antihydrogen(s) trapping trial. Dozens of runs were conducted within 128 of 4 $\sim$ 17 hours time schedules when ALPHA were able to access the Antiproton Decelerator and actually tried to trap antyhidrogens. Since we have clock time information of the time of annihilation events in order of a second, mili second of time difference between more than one antyhidrogen annihilations in a run were ignored.

Within the 128 time spans, the beginning and the time length of the period we can start running the operation, a standby time period, was predicted, since it usually takes time until we become ready for running apparatus after the given AD schedule has been started. The beginning of the time was estimated by Poisson process, which parameter λ was 9.3289 /day with +8.36 minutes shifted, and the time length was estimated by gaussian distribution where the average being 0.2320+-0.1241 day. The annihilation events can only occur within this time period.

Then the number of runs succeeded in trapping antihydrogen(s) in the standby time span, and the number of the trapped antihydrogens for each run were predicted using Poisson process. Poisson parameters were estimated from the fact that the 386 successful events were observed in 320 runs within 29.6966 days of the total standby time span in the two years of experiment. The

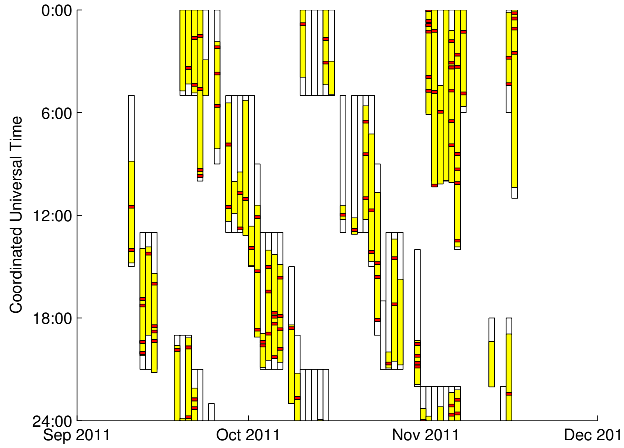


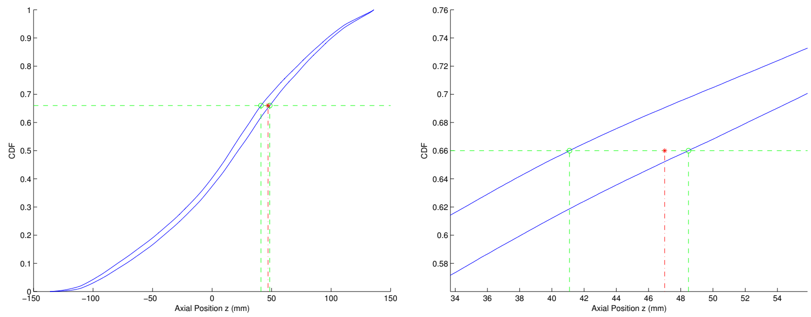
FIG. 2. Time table for one example of time selection in Coordinated Universal Time. The time span when the experiment for trapping antihydrogen are ready to be started (yellow boxes) was chosen regarding to the actual time period when we became able to access to AD (green lines) . Then the number of runs succeeded in trapping antihydrogen, and the starting time of the run as well as the duration time (red boxes) was chosen. At the time the bottom of red box shows, one to several antihydrogen annihilations annihilates.

starting time of the decided number of successful runs was allocated within the standby time span randomly. The annihilation event time was finally decided by adding 10 minutes of deliberately decided operation time until annihilation happens, to the starting time of the run. The example of times selected with this method is shown in Fig.2.

Position Selection

Creation of pseudo-data sets requires an algorithm capable of generating z positions of $\bar{H}$ annihilations for arbitrary charge values. This is achieved by randomly sampling an approximated inverse CDF of the annihilation locations along the trap axis for the given charge.

Using the symplectic integrator discussed in Ref. 1, a list of annihilation z coordinates is created for both quip directions for several different charges $\{q_i\}$, indexed in order of increasing charge. These lists are then adjusted to account for effects from detector smearing and missed detections due to cosmic ray filtering criteria, also discussed in Ref. 1. For each charge q_i, let $D_{q_i}(z)$ denote the linear interpolation of the distribution's normalized CDF for a given direction (either left or right). Two $D_{q_i}(z)$ are depicted in Fig. 3 (blue solid lines). Furthermore, let $D_{q_i}^{-1}(r)$ denote the inverse of $D_{q_i}(z)$. For any one of the q_i, a random annihilation position z_0 is chosen by selecting a random value r_0 in the interval $(0,1)$, then setting $z_0 = D_{q_i}^{-1}(r_0)$.



(a) Full Domain of CDF

(b) Region of Interest

FIG. 3. Graphical depiction of the annihilation z value selection algorithm. Empirical CDFs are generated for several different charges q_i and then linearly interpolated to give $D_{q_i}(z)$. Two such $D_{q_i}(z)$ are shown (blue solid curves). When a z position is desired for a given charge q, a random value r_0, here shown as 0.66, is picked and the values of the inverse CDFs $D_{q_i}^{-1}(r_0)$, which can be read off of the x-axis here, are determined (green dashed lines). The weighted average is then taken to give the sampled z value for q (red dash-dot line). Here q is closer in value to q_{k+1} than q_k.

For a charge q between the discrete q_i, let q_k denote the q_i with the largest value less than q. Then q_{k+1} will be the q_i with the least value greater than q. A random annihilation position for this q is chosen by first selecting a random value r_0 in the interval $(0, 1)$ as before, then calculating z_0 from Eqn. 1. The weights $(q_{k+1} - q)$ and $(q - q_k)$ are chosen to provide a linear interpolation between the two inverse CDFs. The process is summarized in Fig. 3.

$$z_0 = \frac{D_{q_k}^{-1}(r_0) * (q_{k+1} - q) + D_{q_{k+1}}^{-1}(r_0) * (q - q_k)}{q_{k+1} - q_k} \tag{1}$$

ACKNOWLEDGMENTS

To be continued...

III. NOTES

The graphs right now are created in Matlab. In the future they will be made in Origin and should look prettier.

Cite aephem

Look for other papers on charge invariance

Mention this method can be done better in the future

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[1] C. Amole, et al. Experimental limit on the charge of antihydrogen. 2014. in press at Nat. Commun.