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Measuring the gravitational free-fall of antihydrogen

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Abstract Antihydrogen holds the promise to test, for the first time, the universality of free-fall with a system composed entirely of antiparticles. The AEgIS experiment at CERN's antiproton decelerator aims to measure the gravitational interaction between matter and antimatter by measuring the deflection of a beam of antihydrogen in the Earths gravitational field ($\bar{g}$). The principle of the experiment is as follows: cold antihydrogen atoms are synthesized in a Penning-Malberg trap and are Stark accelerated towards a moiré deflectometer, the classical counterpart of an atom interferometer, and annihilate on a position sensitive detector. Crucial to the success of the experiment is the spatial precision of the position sensitive detector. We propose a novel free-fall detector based on a hybrid of two technologies: emulsion detectors, which have an intrinsic spatial resolution of 50 nm but no temporal information, and a silicon strip / scintillating fiber tracker to provide timing and positional information. In 2012 we tested emulsion films in vacuum with antiprotons from CERN's antiproton decelerator. The annihilation vertices could be observed directly on the emulsion surface using the microscope facility available at the University of Bern. The annihilation vertices were successfully reconstructed with a resolution of 1–2 ∝mon the impact parameter. If such a precision can be realized in the final detector, Monte Carlo simulations suggest of order 500 antihydrogen annihilations will be sufficient to determine $\bar{g}$with a 1 % accuracy. This paper presents current research towards the development of this technology for use in the AEgIS apparatus and prospects for the realization of the final detector.

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1 The AEgIS experiment

The principal of equivalence between gravitational mass and inertial mass is a cornerstone of general relativity. The universality of free-fall (UFF), the experimental evidence on which the weak equivalence principle is based, has been tested to be valid to a very high precision (1 part in 10 trillion) by many experiments using a variety of techniques [1]. However, the UFF has never been tested directly with antimatter. The scientific goal of the AEgIS experiment is to measure, in the first instance, the acceleration of antihydrogen in the Earths gravitational field with a 1 % accuracy [2].

The conceptual design of the AEgIS experiment is shown in Fig. 1. Details of the design and current status of the AEgIS experiment are described elsewhere in these proceedings [3]. The production of the antihydrogen beam will require many technical problems to be overcome. It is therefore highly desirable that the flux of antihydrogen required for the gravity measurement is minimized. Emulsion based detectors offer the opportunity to reduce the antihydrogen flux required for a measurement of $\overline{g}$ with a 1 % relative error by enabling the reconstruction of the antihydrogen annihilation vertex with micron-level precision [4].

2 Antihydrogen flux requirement for gravity measurement with 1 % accuracy

The experimental challenge is to produce and accelerate antihydrogen atoms through the moiré deflectometer and onto the free-fall detector. For an antihydrogen atom to reach the free-fall detector it must have a radial temperature less than 100 mK. To produce such

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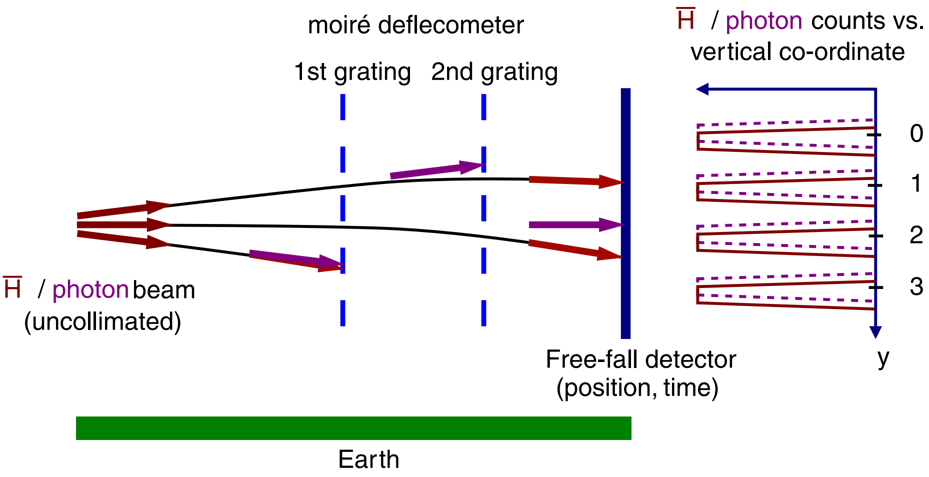

Fig. 1 Conceptual design of the AEgIS experiment. The divergent antihydrogen beam traverses a pair of identical gratings with horizontal slits (moiré deflectometer) and annihilates on the position and time sensitive free-fall detector. The free-fall detector is based on a hybrid of three detector technologies: nuclear emulsions, a scintillating fiber tracker and a silicon strip detector. Emulsion based detectors provide unrivaled positional information but no time information. Therefore, a scintillating fiber tracker and silicon strip detector are used to measure the arrival time of each antihydrogen anti-atom on the free-fall detector with a 1 ∝m time resolution. The time of flight (TOF) of each anti-atom is inferred from the arrival time on the free-fall detector and the (known) time at which the pulsed antihydrogen beam is produced. A *light pattern* is produced by illuminating the gratings homogeneously with an incoherent light source (LED with spatial diffuser) and is recorded directly on the emulsion film. The *shadow-like spatial* distribution of the annihilation vertices (*solid line*) is displaced relative to that of light (*dashed lines*) by an amount which depends on the time of flight between the gratings and the gravitational strength $\overline{\mathrm{g}}$ between the antihydrogen atom and the Earth

atoms two experimental approaches will be pursued: the production of antihydrogen which is as cold as possible and the synthesis of as many anti-atoms as possible. Since there are considerable technical difficulties to be overcome, it is illuminating to investigate the absolute antihydrogen flux required for a measurement of gravity with a 1 % accuracy and the dependency of this flux on the spatial resolution of the free-fall detector.

The influence of the spatial resolution of the free-fall detector on the flux of antihydrogen required for a measurement of $\overline{\mathrm{g}}$ with a 1 % precision has been studied with a Monte Carlo Simulation. Antihydrogen atoms were uniformly generated in a cylinder of 3 mm transverse radius and 2 cm axial length, with initial velocities distributed according to a Maxwell-Boltzmann distribution with a mean temperature of 100 mK. The atoms were then accelerated towards the moiré deflectometer (pitch d=40 ∝m between horizontal slits of 12 ∝m width) and the free-fall detector. A Gaussian smearing was then applied to the annihilation vertex to simulate the detector resolution. Figure 2 left, shows the expected intensity distribution as a function of the phase $\phi = (2\pi/d)\Delta x$, where $\Delta x = \overline{\mathrm{g}}\mathrm{T}^2$ and T is the time of flight between the 2 gratings. The contrast of the shadow-like image is greatly improved by a higher spatial resolution. The benefit of the improved contrast is shown in Fig. 2 right, which shows the dependency of the relative $\overline{\mathrm{g}}$ precision on the antihydrogen flux for various spatial resolutions. A free-fall detector with a $\sim$ 2 ∝m spatial resolution requires $\sim$ 600 fully reconstructed and time tagged antihydrogen atoms for a 1 % relative error on $\overline{\mathrm{g}}$, which compared to a 10 ∝m spatial resolution is an order of magnitude reduction in the required antihydrogen flux.

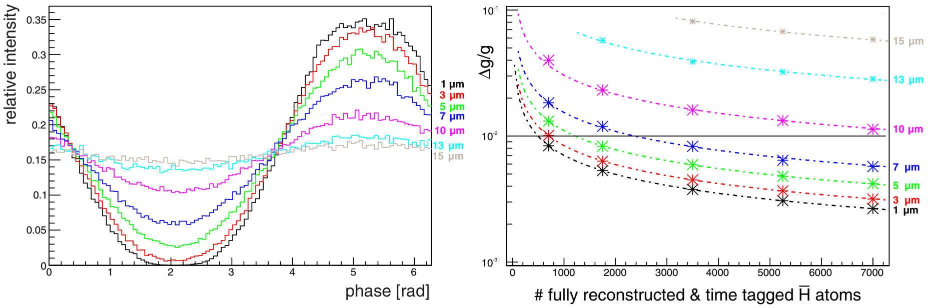

Fig. 2 *Left*: Simulated distribution of reconstructed annihilation vertices on the free-fall detector over one grating period for vertex resolutions between 1 and 15 µm for an antihydrogen beam with a velocity of 700 m/s. The contrast of the shadow-like image increases with improved vertex resolution. *Right*: Simulation of the relative precision on $\bar{g}$ vs. the number of fully reconstructed and time tagged antihydrogen atoms for vertex resolutions between 1 and 15 µm. The horizontal black line indicates a 1% relative error on $\bar{g}$ [5]

3 Reconstruction of $\overline{\mathrm{H}}$ annihilation vertices with micron level spatial resolution

In light of the considerable benefit to AEgIS of a free-fall detector with a 1–2 µm spatial resolution, a detector based on nuclear emulsions is currently under development. Nuclear emulsions are photographic films which are optimized for use as particle tracking detectors and are still the most precise particle tracking detector technology currently available [6]. A typical detector consists of a gel with a suspension of silver bromide crystals, in which a track is formed after the passage of an ionizing particle. After chemical development silver grains along the path of the track, with dimensions of 1 µm or less, are visible with an optical microscope. With just a single 50 µm layer it is possible for the full three-dimensional reconstruction of the particle track and a measurement of the energy loss. The intrinsic resolution for tracks in a nuclear emulsion is a mere 50 nm [5].

In order to evaluate the suitability of an emulsion based free-fall detector for AEgIS, a series of measurements were performed during the 2012 antiproton decelerator (AD) run at CERN. The 5 MeV antiprotons from the AD were directed onto a nuclear emulsion the surface of which was partially covered with a 20 µm stainless steel foil. The foil simulates the separation window which will be used in the actual experiment to isolate the emulsion detector from the ultra high vacuum region. After passing through a series of degrading foils and vacuum separation windows, the average energy of the antiprotons reaching the emulsion was $\approx$ 150 keV.

Images of the antiproton annihilations in the bare emulsion are shown in Fig. 3. A full 3D image of the annihilation star is constructed by focusing the microscope at different depths in the emulsion. The nuclear fragments and charged pions from the antiproton annihilation are clearly discernible in the emulsion as black (heavily ionising) and thin (minimum ionising) tracks respectively.

In order to determine the vertex resolution that is achievable for the $\bar{g}$ experiment, the vertex position was determined by finding the coordinates of the point which minimised the quadratic sum of distances to all tracks. Figure 4 left, shows the distribution of the vertex position in the direction of the antiproton beam axis. For the bare sample the distribution has a sharp peak at the surface of the emulsion, while the distribution for the stainless steel sample is much broader due to the fact that the foil was not in perfect contact with the

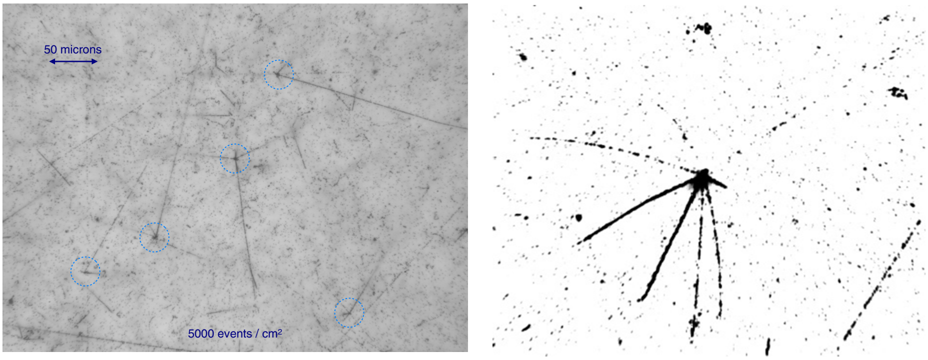

Fig. 3 *Left*: Antiproton annihilations in a bare emulsion. *Blue circles* indicate the location of the annihilations. *Right*: 3D image of antiproton annihilation in a new emulsion prepared at LHEP from a gel produced by the University of Nagoya. The size of the 3D image is 150x120x50 ∝m

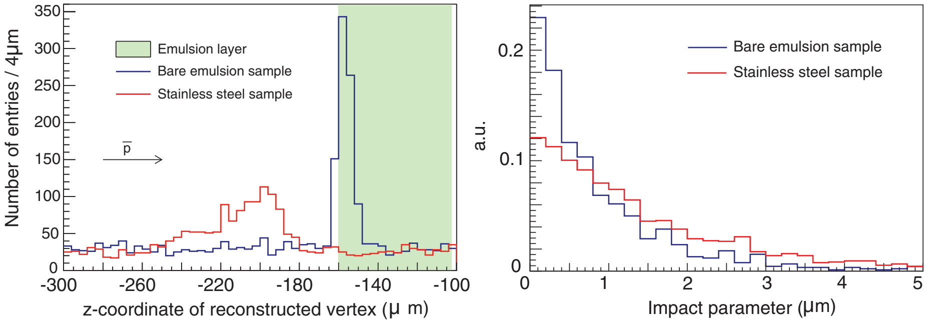

Fig. 4 *Left*: Annihilation vertex resolution in the direction of the antiproton beam (perpendicular to the emulsion surface). *Right*: Impact parameter distribution for annihilations [5]

emulsion surface. Figure 4 right, shows the distribution of the distance between the reconstructed vertex and the tracks (impact parameter). This demonstrates that an r.m.s resolution of $\sigma \simeq 1$ ∝m on the vertical position of the annihilation can, in principal, be achieved with an emulsion based detector.

4 Conceptual design for a free-fall detector

Emulsion based detectors provide spatial but no temporal information. To measure the time of flight of the antihydrogen atom requires that the time of the annihilation on the emulsion is also measured. A conceptual design for a hybrid detector that combines the emulsion detector with timing information from a scintillating/silicon tracker and silicon strip detector is shown in Fig. 5. The time of the annihilation is determined from information from both the silicon strip detector and the downstream tracker. The tracker will also be used to seed the search for annihilation vertices in the emulsion by reconstructing the annihilation pions.

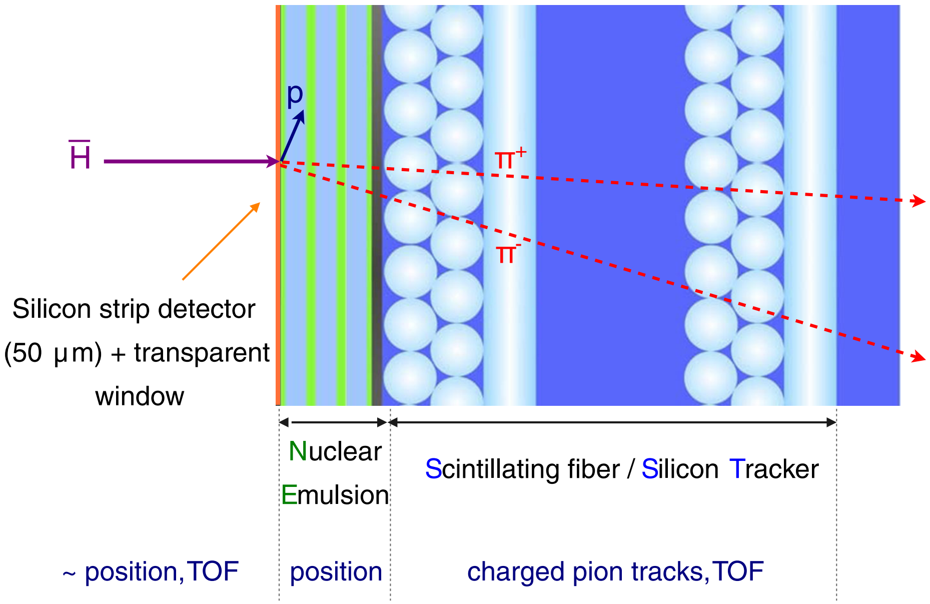

Fig. 5 Conceptual design for a free-fall detector for AEgIS. The emulsion detector is used to identify the precise location of the annihilation vertex and the downstream tracker and silicon strip detector are used to measure the time of the annihilation

5 Summary

Emulsion based detectors can be used to reconstruct the annihilation vertex position with an r.m.s resolution of $\sigma \simeq 1$ ∝m on the vertical position of the annihilation. If such a precision can be realised in the final free-fall detector, a measurement of $\overline{g}$ with 1 % relative error will require the reconstruction of $\sim$ 600 antihydrogen atoms. A hybrid detector which combines the spatial precision of emulsion detectors with temporal information from silicon/scintillating fiber technologies is currently under investigation.

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