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Measuring GBAR with emulsion detector

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The motivation of the AEgIS experiment is to test the universality of free fall with antimatter. The goal is to reach a relative uncertainty of 1% for the measurement of the earth's gravitational acceleration $\bar{g}$ on an antihydrogen beam. High vertex position resolution is required for a position detector. An emulsion based detector can measure the annihilation vertex of antihydrogen atoms with a resolution of 1-2 μm, which if realized in the actual experiment will enable a 1% measurement of $\bar{g}$ with less than 1000 $\bar{H}$ atoms. Developments and achievements on emulsion detectors for the AEgIS experiment are presented here.

Keywords: Antimatter; gravity; particle tracking detectors; emulsion detectors.

1. The AEgIS Experiment

The universality of free fall has been tested with a precisions down to 10^{-13} for matter, but has never been measured for antimatter. The motivation of the AEgIS experiment is to test the universality of free fall with antimatter.[1] The goal is to reach a relative uncertainty of 1% for the measurement of the earth's gravitational acceleration $\bar{g}$ on an antihydrogen beam.

A sketch of the AEgIS apparatus and the gravity measurement module is shown in Fig. 1. The $\bar{H}$ atoms (~100 mK) will be formed through the charge exchange reaction $Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$ between antiprotons and Rydberg state positronium atoms (Ps^*). A non-uniform electric field is applied along the beam axis to accelerate the $\bar{H}$ atoms to a horizontal velocity of a few 100 m/s. A moiré deflectometer consisting of two gratings placed at a distance L of 40 cm is used to select the propagation directions of the originally diverging beam. Downstream of the gratings, the intensity pattern along the vertical direction y shows the same periodicity as the gratings, shifted by the earth's gravity by $\Delta y = g\tau^2$, where τ is the time of flight between the two gratings.

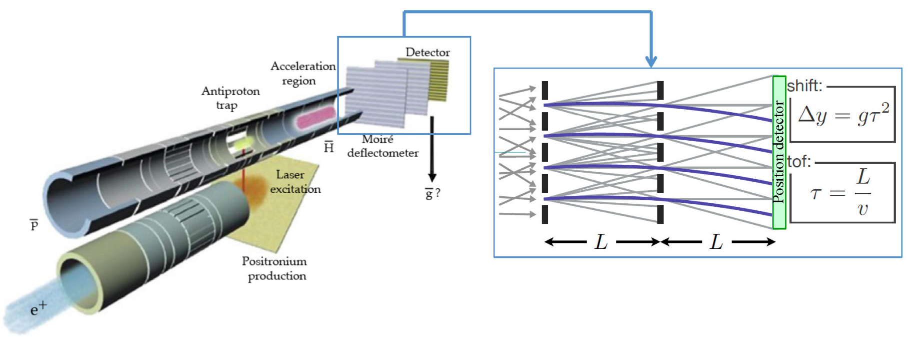

Fig. 1. (Color online) Sketch of the AEgIS apparatus (left) and the gravity measurement module (right).

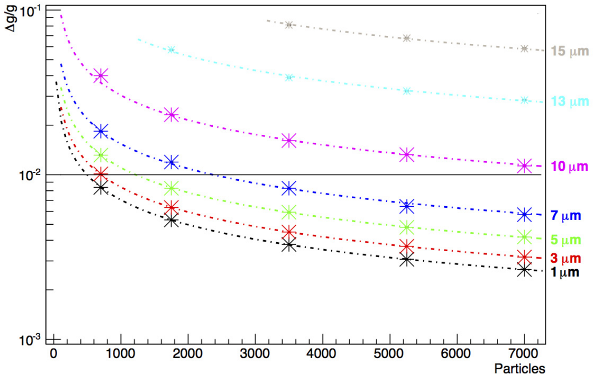

Fig. 2. (Color online) Simulated relative precision on the $\bar{g}$ measurement as a function of the number of detected annihilations for various detector vertex resolutions. The solid line indicates the AEgIS goal $\Delta\bar{g}/\bar{g} = 1\%$.

Figure 2 shows a simulated result on the relative precision on the $\bar{g}$ measurement as a function of the number of detected annihilations for various detector vertex resolutions.[2] The position detector requires the best possible position resolution, which currently is provided by emulsion based detectors. Emulsion detectors which have a vertex resolution of 1-2 μm will enable to reach 1% on the $\bar{g}$ measurement with less than 1000 $\bar{H}$ atoms.

The emulsion detector will measure the shift of the $\bar{H}$ atoms detecting the position of their annihilation in a thin silicon strip detector placed in front of the emulsion detector to separate the ultra high vacuum region of the apparatus to the ordinary vacuum region. A time of flight detector follows the emulsion detector to provide the time information corresponding to each annihilation. More details on the AEgIS experiment are described in Ref. 1.

2. Emulsion Detectors

Nuclear emulsion based particle detectors feature the highest position resolution of any detector technology.

Figure 3 shows the cross-sectional view of a standard so-called OPERA film,[3] and a minimum ionizing track. The emulsion consists of a number of silver bromide (AgBr) crystals suspended in gelatin. The diameter of the AgBr crystal is 0.2 μm. Each crystal works as an independent charged particle detector (micro-detector). An OPERA film consists of two sensitive emulsion layers of 44 μm thickness poured on both sides of a 205 μm thick plastic base and has a surface of about 10 cm $\times$ 10 cm, therefore such an emulsion detector features 1.3×10^{14} micro-detectors. When a charged particle passes through the emulsion, it excites carriers in the AgBr crystals. Electrons are trapped in lattice defects at the surface of the crystal and produce latent images made of silver atoms. Photographic development amplifies the

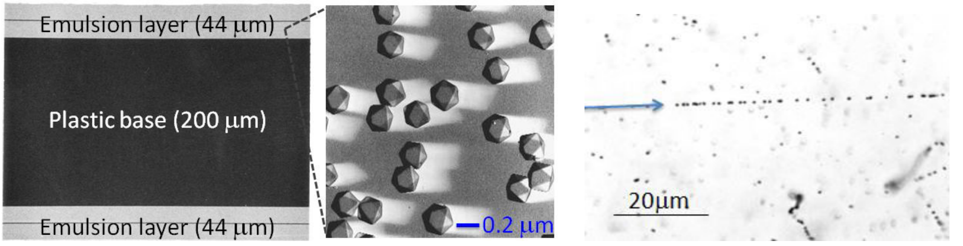

Fig. 3. (Color online) Cross-sectional view of an OPERA film (left) and a minimum ionizing track from a 10 GeV/c π beam (right).

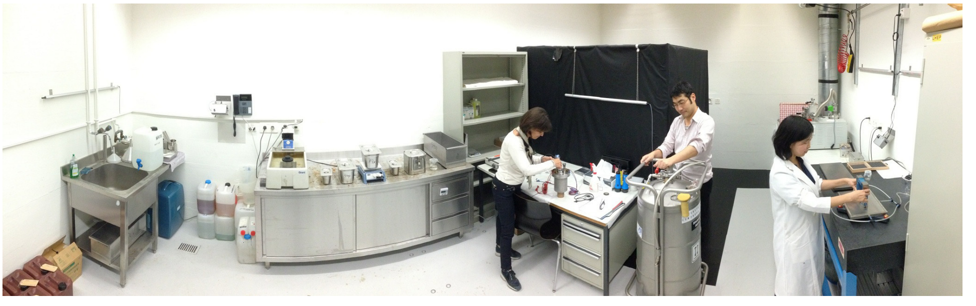

Fig. 4. (Color online) A 30 m deep underground laboratory at the University of Bern.

invisible signal to a silver filament. After development, the tracks can be observed using optical microscopes.

3. Emulsion Detectors in the AEgIS Experiment

The R&D activities on emulsion detectors for the AEgIS experiment are ongoing at the Laboratory for High Energy Physics (LHEP) of the University of Bern. LHEP presently has the largest emulsion scanning laboratory in Europe with six automatic microscopes and R&D activities to improve the scanning system.

Furthermore, LHEP has an underground emulsion facility (Fig. 4). It is located 30 m underground since a low cosmic-ray flux is required for emulsion film production. Custom-made films can then be produced depending on specific experimental requirements, using emulsion gel from Nagoya University in Japan or the Russian company Slavich. Some high precision stages equipped with a vacuum system are operational to pour the emulsion gel on the supporting plastic or glass base. An antiproton annihilation vertex in a new film produced at LHEP using gel produced by Nagoya University is shown in Fig. 5.

There are several technical challenges for emulsion detectors to be used in the AEgIS experiment: operation in vacuum, operation at 77 K, track reconstruction with larger angular acceptance and so on.

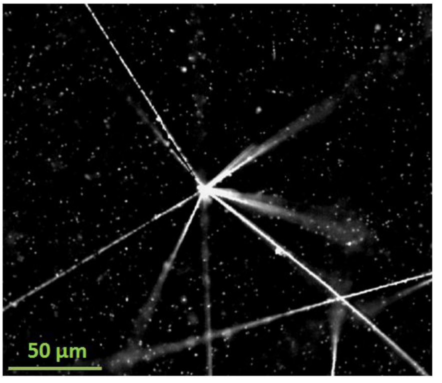

Fig. 5. (Color online) An antiproton annihilation vertex in an emulsion layer. The view is vertical to the antiproton beam direction.

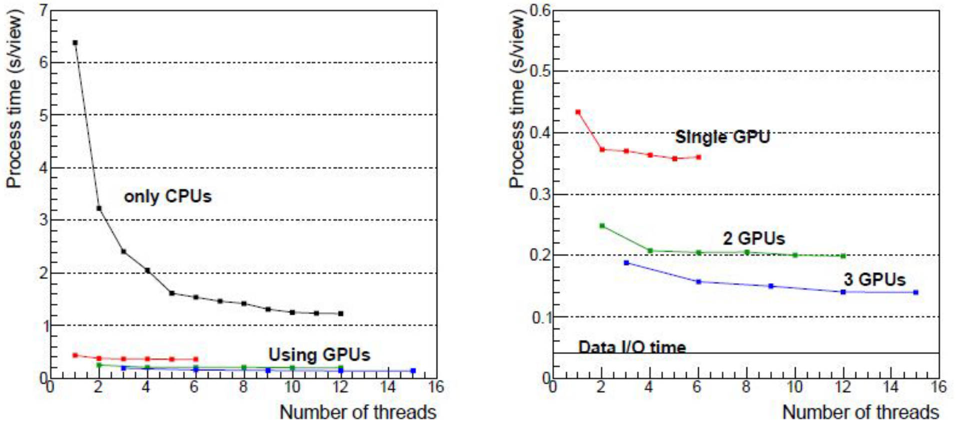

Fig. 6. (Color online) Comparison of processing time per view as a function of the number of threads: processing time for the CPUs and the GPUs-based programs (left) and zoom for the GPUs-based program (right).

We have developed emulsions which can be used in ordinary vacuum (10^{-5}–10^{-7} mbar). In vacuum, water loss leads to cracks of the emulsion layer. Then we have established two ways to avoid cracks: 1) mix glycerin with emulsion gel to replace water by glycerin (glycerin concentration of 1.5% for wet gel) and 2) put gas barrier films on emulsions to keep water in the films. Both works to prevent the appearance of cracks. There was another problem in vacuum due to mechanical stress caused by the drying process, which increases the random noise to unacceptably high values, however this problem was solved by adding glycerin as we reported in Ref. 9.

At 77 K, the performance of emulsion detectors is not well known. A variable temperature cryostat has been designed to measure detector sensitivity and the study is currently underway.

Today's typical scanning systems are optimized for track reconstruction at small angles (tanθ <0.6 rad) since particles in the OPERA experiment are boosted forward , although emulsion detectors themselves can record particles in any direction. At LHEP, we have implemented a new tracking algorithm for full solid angle track reconstruction in emulsion detectors by a GPU-based computing infrastructure[10] since 4π directional track reconstruction is needed to detect annihilation products. Figure 6 shows a comparison of processing time per view as a function of the number of threads. A 60 times faster processing of 3D emulsion detector data, corresponding to processing of 15 cm^2 emulsion surface scanned per hour, has been achieved by GPUs with an excellent tracking performance.

4. Measurements with Antiprotons at CERN

In 2012 we performed tests of emulsion detectors with antiprotons at the CERN-AD to check the performance of emulsion detectors in vacuum and to measure the resolution of reconstructed annihilation vertices.[2] The emulsion detector was installed in a small vacuum chamber at the downstream end of the AEgIS apparatus.

The first tests were performed with standard films, half of the emulsion surface being covered by a $20\mu m$ thick stainless steel foil, while direct annihilations on the emulsion surface could be investigated from the other half (Fig. 7, left). Fig. 7 (right) shows the distribution of minimum distance between reconstructed vertices and tracks (impact parameter) for annihilation on the bare emulsion surface (standard gel) and in the stainless steel foil, demonstrating a resolution of 1 μm on the vertical position can be achieved.

Direct annihilations on the emulsion surface were also studied with new films produced at LHEP and compared to Monte Carlo simulation. Figure 8 shows the multiplicity distribution in antiproton annihilations in emulsion layers for data and for Monte Carlo based on the CHIPS package embedded in GEANT4 (Refs. 11,

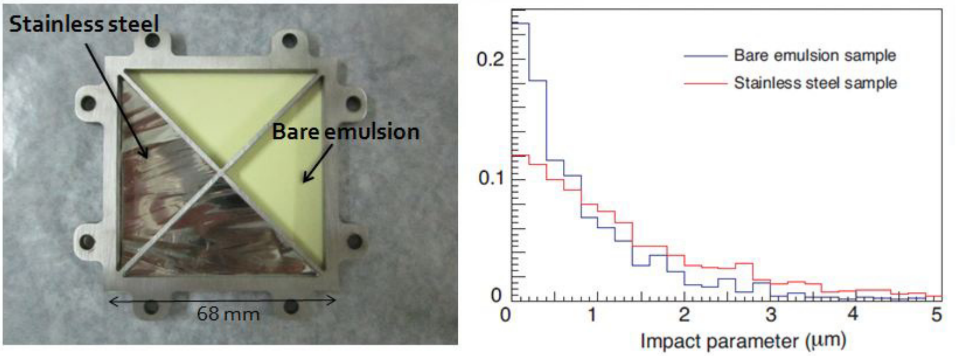

Fig. 7. (Color online) Impact parameter distribution for annihilations on the bare emulsion surface and in the stainless steel foil.

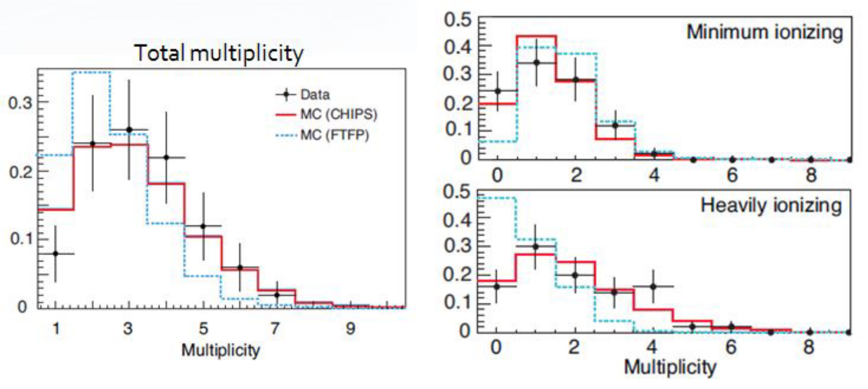

Fig. 8. (Color online) Multiplicity distribution in antiproton annihilations in emulsion layers for data and for Monte Carlo predictions based on the CHIPS package embedded in GEANT4 (red continuous histogram) and FTFP (blue dashed histogram). Particles with dE/dx below $3MeV \cdot g \cdot cm^{-}2$ were defined as being minimum ionizing.

12, 13) and FTFP (Refs. 15, 16). The data is in better agreement with the CHIPS model.

5. Prospects

The performance of emulsion detectors in the real experimental set up is currently under study. A resolution of 1-2 μm and efficiency of 40–50% can be obtained if there is no distance between the thin silicon strip detector target and the emulsion detector. Further R&D to improve the performance of emulsion detectors is ongoing. Also upgrades to the scanning system are foreseen, in particular by implementing new objective lens and camera.

The construction of the hybrid detector, consisting of a thin silicon strip detector, emulsion detector and scintillating fiber tracker for time of flight measurement is planned for 2014-15.

6. Conclusions

The AEgIS experiment aims at a measurement of the gravitational acceleration for antihydrogen with 1% accuracy. High vertex position resolution is required for a position detector and an emulsion based detector has been chosen. Its resolution 1-2 μm is 5-10 times better than the original proposal. Intensive R&D is ongoing at LHEP to use the emulsions in the challenging environment (in vacuum, at 77 K) and successful commissioning was done in the 2012 run. Fast 4π track reconstruction based on GPU technology has been implemented and further upgrades are foreseen. Based on these developments and achievements, an emulsion detector as a high resolution tracking part of a hybrid detector will enable to reach 1% on gbar measurement with less than 1000 $\bar{H}$ atoms.

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