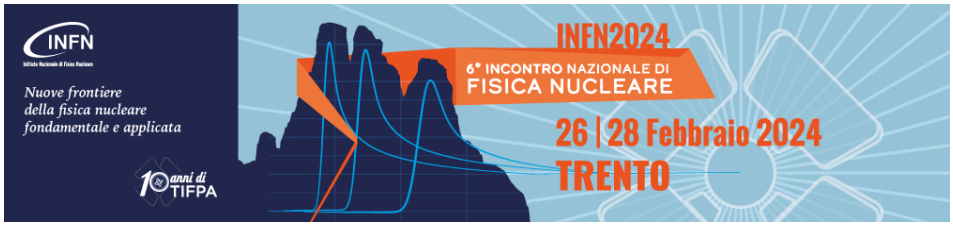


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# The CERN Antimatter Factory: testing the Equivalence Principle, the CPT symmetry, and beyond (Invited)

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The Antimatter Factory at CERN, comprising the AD and ELENA particle decelerators, is a unique facility for experimental research with low-energy antiprotons. During its 20 years of activity, its main goal has been to allow forming (in combination with cold positrons plasma techniques) and studying cold antihydrogen atoms, as well as to deepen the investigations started at LEAR of the antiproton properties (mass, magnetic momentum) and its exotic compounds with matter (e.g. antiprotonic helium). The main physics drives of the facility were to test the Charge, Parity, and Time (CPT) symmetry and, more recently, the Equivalence Principle with antimatter, both pillars of relativistic quantum field theories and metric theories of gravity, respectively.

An overview of the accurate tests of the CPT symmetry performed by the experiments in the Antimatter Factory over the years is presented. Among the several, the accurate determinations of the proton/antiproton charge-to-mass ratio with single particle techniques (ATRAP [1] and BASE [2] collaborations), the spectroscopic surveys of antihydrogen (ALPHA collaboration[3]), and antiprotonic helium (ASACUSA collaboration [4]), are the most sensitive to date.
The possibility to measure the gravitational coupling between matter and antimatter is, on the other hand, a novelty of the most recent years. Very recently, a first direct measurement of the sign of this coupling was obtained by releasing trapped antihydrogen atoms from a vertical magnetic trap and measuring the vertical anisotropy in their annihilation spatial (ALPHA-g collaboration [5]). This result came only a year later than the first model-independent (yet assuming perfect CPT invariance) test of the Equivalence Principle with antiprotons, obtained by searching for a yearly modulation in the cyclotron frequency of single trapped antiprotons as the Earth orbits elliptically in the Sun's gravitational potential (BASE collaboration [2]).
Other techniques are also being investigated at the same time by other collaborations, from measuring the horizontal deflection of a pulsed free-falling antihydrogen beam in the absence of external fields (AEgIS collaboration [6]) to forming, sympathetically cooling and photo-ionizing positive antihydrogen ions to get an ultracold sample of free-falling antihydrogen atoms (GBAR collaboration [7]).
Beyond testing CPT and the EP with antimatter, several other activities are ongoing at the Antimatter Factory. These range from developing portable antimatter traps, such as those in the BASE-STEP and PUMA collaborations, to studying nuclear physics with antiprotonic atoms. Additionally, some collaborations are actively searching for dark matter candidates and developing the research field of positronium (Ps), a short-lived atomic bound state of an electron and a positron, originally introduced as an intermediate step to form antihydrogen. Ps is an alternative testing ground for CPT and the EP, complementary to antihydrogen being purely leptonic and constituted by 50% antimatter mass on-shell. Active research is being conducted to first laser cool it (AEgIS collaboration), as well as produce unprecedented densities to form the positive antihydrogen ions (GBAR collaboration). These two techniques may lead, in the mid-term future, to the first Bose-Einstein condensation of antimatter.

[1] J. DiSciacca et al. (The ATRAP collaboration), One-Particle Measurement of the Antiproton Magnetic Moment, Phys. Rev. Lett. 110, 130801 (2013)
[2] M. J. Borchert et al. (The BASE collaboration), A 16-parts-per-trillion measurement of the antiproton-to-proton charge-mass ratio, Nature 601, 53-57 (2022)
[3] M. Ahmadi et al. (The ALPHA collaboration), Observation of the 1s-2s transition in trapped antihydrogen, Nature 541 (2017)
[4] M. Hori et al. (The ASACUSA collaboration), Two-photon laser spectroscopy of

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[5] E. K. Anderson et al. (The ALPHA-g collaboration), Observation of the effect of gravity on the motion of antimatter, Nature 621 (2023)
[6] C. Amsler et al. (The AEgIS collaboration), Pulsed production of antihydrogen, Commun. Phys. 4 19 (2021)
[7] P. Adrich et al. (The GBAR collaboration), Production of antihydrogen atoms by 6 keV antiprotons through a positronium cloud, Eur. Phys. J. C. 83, 1004 (2023)

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