Enhanced antihydrogen accumulation with laser-cooled Be^+

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The study of cold antihydrogen for CPT symmetry tests began in 2010 with the first successful demonstration of trapping individual antihydrogen atoms [1]. In the ALPHA experiment, antihydrogen is produced via a three-body recombination process involving one antiproton and two positrons [2]. Antihydrogen is formed by combining cold plasmas of positrons and antiprotons in a specialized Penning-Malmberg trap, which spatially overlaps with a magnetic minimum trap designed to confine antihydrogen atoms [3]. Due to the shallow depth of the magnetic potential - capable of trapping only atoms with kinetic energies corresponding to temperatures below 0.5 K - early experiments typically confined ~20 antihydrogen atoms per production cycle. In 2017 the technique was advanced to allow continuous synthesis and accumulation of antihydrogen [4, 5], enabling key milestones such as the first high-precision measurement of the 1S–2S transition [6] and the first observation of gravity's influence on antimatter [7].

Antihydrogen production through the three-body recombination process depends on the thermal energy of the positrons; both the production and trapping rates increase as the positron temperature decreases. So far the temperature of positron plasma in ALPHA-2 trap was limited to around 20K, which was achieved via the cyclotron cooling mechanism in the high magnetic field. To reduce the temperature of the positron plasma even further, an active cooling mechanism is required.

Inspired by pioneering work at NIST [8], a sympathetic cooling of positrons with laser-cooled beryllium ions (Be^+) was proposed [9]. The Be^+ ions are generated via laser ablation of a solid beryllium target [10], then confined within a Penning-Malmberg trap and Doppler cooled using a 313 nm laser. Upon merging with the positron plasma, the laser-cooled Be^+ ions carry away thermal energy from the positrons through Coulomb interactions. Sympathetic cooling technique allowed to achieve ~2.5 times lower temperatures of positron plasma than before [11].

Early development of Be^+ laser-cooling technique suffered from irreproducibility of the number of ablated beryllium ions and inefficient laser-cooling scheme. Several laser system upgrades were performed, most importantly to allow for simultaneous laser-cooling and Be^+ cloud compression using Rotating Wall technique [12]. This improved laser-cooling technique was successfully integrated into the standard antihydrogen synthesis cycle. An eight-fold enhancement in antihydrogen trapping efficiency per synthesis cycle has been demonstrated, enabling the accumulation of over 15,000 antihydrogen atoms in less than seven hours.

The implementation of sympathetic cooling of positrons method into antihydrogen production cycle has not only accelerated the experimental timeline but also opened new opportunities for detailed investigations of fundamental symmetries. These include potential searches for sidereal variations and other precision tests of antimatter and its interactions, which were previously inaccessible due to limited sample sizes and extended accumulation times.

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