

The [Atomic Spectroscopy And Collisions Using Slow Antiprotons](#) (ASACUSA) experiment studies the fundamental symmetries between matter and antimatter by precision spectroscopy of atoms containing an antiproton (the antimatter equivalent of the proton). The experiments focused in particular on hybrid atoms (antiprotonic helium), as well as pure antiatoms (antihydrogen). It also studies the interactions that occur during collisions between matter and antimatter.

ASACUSA aims to precisely measure a property of antihydrogen called the “hyperfine structure” and compare it to the well-known value for hydrogen. Since this quantity is very sensitive to magnetic fields, ASACUSA does not aim to trap antiatoms but rather to create a beam of antihydrogen atoms that can be transported to a region where no disturbing fields are present. To do this, a unique magnetic field configuration called “CUSP” is used to create a polarized beam of antihydrogen, which is then studied in flight using microwave radiation.

Helium has the second simplest atomic structure after hydrogen. It contains two electrons orbiting a central nucleus. The ASACUSA team makes antiprotonic helium by replacing one of these electrons with an antiproton. This is possible because, like the electron, the antiproton has negative charge. These hybrid atoms are formed by injecting antiprotons into a helium gas cell. Most of the antiprotons quickly [annihilate with ordinary matter](#) in the surroundings, but a tiny proportion combines with the helium to form hybrid atoms that contain both matter and antimatter. Using laser beams to excite the atoms, ASACUSA can determine the mass of the antiproton to an unprecedented level of accuracy for comparison with the proton.

ASACUSA also studies the interactions that occur between matter and antimatter, by colliding beams of antiprotons on various kinds of normal atoms and molecules. These phenomena include the so-called “ionization” process where the fast antiproton rips away the electrons that circle the atoms. Another interesting process occurs when the antiprotons strike and annihilate with the atomic nuclei.

The ASACUSA team uses the Radio Frequency Decelerator downstream of [Antiproton Decelerator](#) at CERN to decelerate a 5.3 MeV antiprotons down to 100 keV. In this way, the ASACUSA team uses antiprotons 10-100 times more efficiently than other collaborations.

The Antihydrogen trap (ATRAP) is an experiment to compare hydrogen atoms with their antimatter equivalents – antihydrogen atoms. In 2002, ATRAP [provided the first glimpse inside antihydrogen atoms](#) after researchers successfully created and measured a large number of them.

An atom of antihydrogen consists of an antiproton and a positron (an antielectron). One of the difficulties in making antimatter is the energy the antiprotons possess when they are first made, shooting out of the apparatus at close to the speed of light. The researchers use a process called "cooling" to slow the antiprotons down so that they can be studied.

ATRAP was the first experiment to use cold positrons to cool antiprotons. The two ingredients were confined in the same trap and when they had both reached a similar temperature, some combined to form atoms of antihydrogen (a positron orbiting an antiproton). This technique was developed from another experiment at CERN called TRAP, the predecessor of ATRAP.

The current experiment was set up in the late 1990s at the same time as the ATHENA experiment. Both experiments had the same goals and used similar methods to produce antihydrogen atoms, but had different detectors.

While the ATHENA experiment came to an end in 2004, ATRAP is still in operation. It [continues to create antihydrogen](#) cold enough and trapped for long enough to enable precise measurements and comparisons with ordinary hydrogen.

The [Gravitational Behaviour of Antimatter at Rest](#) experiment's acronym refers to the fact that it measures the freefall acceleration under gravity of antimatter, which is denoted by g (pronounced g-bar). It operates in the [Antiproton Decelerator \(AD\)](#) Hall, using antiprotons slowed down by the ELENA facility.

GBAR first combines the antiprotons with two antielectrons to form antihydrogen ions with a positive charge. Although more difficult to produce than the simpler antiatoms, the antimatter ions can be more easily manipulated. Using laser-cooling techniques, these ions are brought to microkelvin temperatures before they are stripped of the additional antielectron, transforming them into antihydrogen atoms. These antihydrogen atoms are then allowed to fall from a height of 20 centimetres, and their annihilation at the end of the fall is recorded.

By measuring the acceleration of antihydrogen under gravity and comparing it with the acceleration of regular hydrogen, GBAR scientists can look for differences in the behaviour of matter and antimatter. In particular, the scientists are testing the Equivalence Principle put forth by Albert Einstein, which states that the trajectory of a particle is independent of its composition and internal structure when it is only submitted to gravitational forces. Observing a difference in the way hydrogen and antihydrogen fall under gravity would demonstrate that this principle is in fact wrong.

GBAR was approved by the CERN Research Board in May 2012 and [received its first beam of antiprotons from ELENA in October 2018](#).

The [Standard Model](#) of particle physics describes all the known fundamental particles and the forces between them. A part of this Model – called CPT symmetry – implies that the fundamental properties of particles should be equal and partly opposite to those of their corresponding antiparticles. Any measured difference between the masses, charges, lifetimes or magnetic moments of matter and [antimatter](#) could contribute to understanding [why there is more matter than antimatter](#) in the universe.

The [Baryon Antibaryon Symmetry Experiment](#) (BASE) at CERN will compare the magnetic moments of protons and antiprotons to look for differences between matter and antimatter.

Using an experimental set-up with two Penning traps – devices that hold particles in place with electromagnetic fields – the team aims to measure the antiproton magnetic moment to a hitherto unreachable part-per-billion precision.

A direct measurement of the magnetic moment requires the measurements of two frequencies: the Larmor frequency, which characterizes the precession of the spin of a particle, and the cyclotron frequency, which describes a charged particle's oscillation in a magnetic field.

BASE's double Penning trap separates the measurements of the Larmor as well as the cyclotron frequency from the spin-state analysis. Two traps are used for the measurements: the analysis trap, which will identify the spin state of the particle, and the precision trap, which will flip the spin of the particle while measuring the cyclotron frequency.

Two further traps are used. The monitor trap will check for any variance in the magnetic field caused by external sources, allowing the BASE team to make instant adjustments to the core traps while measurements are under way. The reservoir trap will store antiprotons for months on end, allowing the BASE collaboration to continue operating even without beam.

In June 2014 the BASE collaboration reported the first direct high-precision measurement of the proton magnetic moment with a fractional precision of 3.3 parts per billion. The team took new measurements of the antiproton magnetic moment at CERN's [Antiproton Decelerator](#) during beam time in 2014.

The primary scientific goal of the Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy ([AEgIS](#)) is the direct measurement of the Earth's gravitational acceleration, g , on antihydrogen.

AEgIS is a collaboration of physicists from a number of countries in Europe and from India. In the current phase of the experiment, the collaboration is using antiprotons from the [Antiproton Decelerator](#) to make a pulsed beam of antihydrogen atoms. They will then pass the antihydrogen beam through an instrument called a Moire deflectometer coupled to a position-sensitive detector to aim to measure the strength of the gravitational interaction between matter and antimatter to a precision of 1%.

A system of gratings in the deflectometer splits the antihydrogen beam into parallel rays, forming a periodic pattern. From this pattern, the physicists can measure how much the antihydrogen beam drops during its horizontal flight. Combining this shift with the time each atom takes to fly and fall, the AEgIS team can then determine the strength of the gravitational force between Earth and the antihydrogen atoms.

In 2018, AEgIS demonstrated the [first pulsed production of antihydrogen atoms](#), by interacting pulse-produced positronium (an atom consisting of only an electron and a positron) with cold, trapped antiprotons. This was a necessary step towards the required pulsed beam of antihydrogen and also opens the door to other physics topics, which build on forming beams of pulse-produced positronium and also pulse-produced antiprotonic atoms, where the orbiting electron of an atom is replaced by an antiproton.