Bound Antimatter. Strong Interaction of Antibaryons in ALICE and AEgIS experiments at CERN

Ordinary matter is composed of atoms, which consist of a nucleus surrounded by an electron cloud. The nuclei are made up of protons and neutrons, which in turn are made up of quarks, which appear to be the elementary constituents of matter. No quark has been observed in isolation; Quarks, like gluons, are permanently bound to each other and trapped inside composite particles such as protons and neutrons.

In head-on collisions of heavy nuclei (such as the nuclei of lead atoms) accelerated in the Large Hadron Collider (LHC) to a speed close to the speed of light, we obtain, although in a very small volume, close to the size of the nucleus, and for a short time, a droplet of primary matter composed of quarks and gluons, in the state of the so-called Quark-Gluon Plasma (QGP). We can watch it being transformed back to ordinary matter through expansion and cooling. This happens when the plasma expands and cools down to a temperature of 10 million million Kelvin, just 10^{-23} seconds after the collision. This matter is created directly from the kinetic energy of accelerated nuclei, according to the famous formula $E = mc^2$. However, in nature, balance must be kept - matter can be created "out of nothing" (i.e. from energy) only on the condition that the same amount of antimatter is created at the same time. As a result, collisions produce practically as many protons as antiprotons, as many neutrons as antineutrons, and so on. There are also particles composed of heavier quarks (called "strange") - and also an equal number of corresponding antiparticles of "opposite" "strangeness". All these particles fly at almost the speed of light towards our detectors.

The ALICE experiment, used in this project, is able to register all these particles and measure their properties. This is used to study the Quark Gluon Plasma. Weighing 10,000 tons, 16 meters high and 26 meters long, the ALICE detector is a complex device consisting of 18 sub-detectors. Sometimes it happens that particles of matter and antimatter (in our project we focus on "baryons" of three quarks and "anti-barions" of three "anti-quarks") fly close together in the same direction. They have time to interact with each other. How they do it is extremely interesting to us - that's what we want to measure. Previous pioneering measurements in the ALICE experiment have shown that we should additionally check whether such a particle-antiparticle pair can generate a bound state under favorable conditions. In short: we want to see if we can bind antimatter. We take advantage of the fact that the ALICE experiment, after a 2-year hiatus and extensive upgrades, resumes operations with data collection capabilities increased by up to a hundred times. Thanks to this, we will know very precisely how antimatter interacts, and we will also be able to observe antimatter bound states, if they exist.

Antimatter is produced not only at the LHC, but also in the Antiproton Decelerator (AD), also located at CERN. There, the antiprotons are slowed down until they can be trapped in a strong electromagnetic field and stored for further study. In the AEgIS experiment, anti-hydrogen atoms are created in ultra-high vacuum conditions and at cryogenic temperatures around -270 C. Such conditions allow for keeping antimatter in a trap for a very long time and conducting research on its properties. AEgIS wants to find out what the gravitational constant for antimatter is by measuring the parabolic drop of the cold anti-hydrogen beam.

These conditions are also suitable for the formation of other artificial exotic atoms consisting of matter and antimatter bound by electromagnetic forces. The lightest of these atoms is protonium, that is, the bound state of a proton and an antiproton. It is very similar to regular hydrogen in which the electron has been replaced by an antiproton with the same charge. However, due to the large mass difference between them of around 2000, the average distance between the two particles is much smaller. When an atom is in the lowest energy state, its size is about several dozen fm, which is 10,000 times smaller than normal hydrogen, and the strong interaction also plays an important role in determining the properties of this exotic atom. We want to study the strong interaction between matter and antimatter in the proton-antiproton bound state and observe how they behave before annihilation.

The obtained results are disseminated in the form of publications in scientific journals, presentations at international scientific conferences and at national and international seminars. They enrich the existing knowledge of the fundamental properties of the state of matter produced in these collisions.