# ANTIMATTER

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Studying antimatter could help us decipher some of the Universe's deepest mysteries, but, of course, the Universe doesn't give answers that easily. That's why scientists at CERN and other organizations have made and are still making experiments to this day to study antimatter and its properties.

## The discovery of antimatter

Antimatter is matter consisting of elementary particles which are the antiparticles of those making up normal matter. The existence of antimatter was originally predicted by the British physicist Paul Dirac, who won the Nobel Prize in 1933 for his quantum mechanical theory.
Dirac was able to sense the existence of antimatter thanks to an equation which described the behaviour of an electron moving at a relativistic speed. This equation could have two possible solutions:

- one electron with positive energy
- one electron with negative energy

*Figure 1.* Picture of Paul Dirac. Credits: Wikipedia

However, according to classical physics, a particle's energy cannot be described by a negative number. Nevertheless, Dirac believed that for every existing particle, there must be a corresponding antiparticle, which has the exact same characteristics of the first one, but opposite charge. For example the counterpart of the electron is called positron or anti-electron.

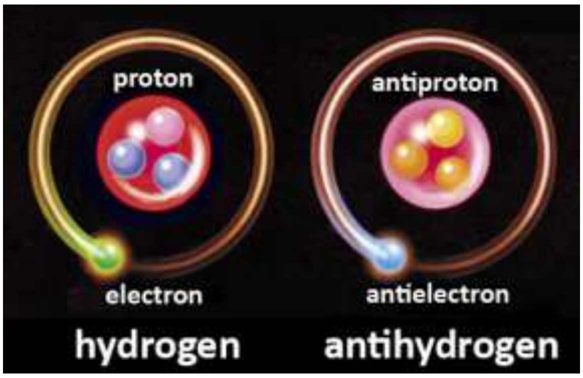


*Figure 2.* This figure is a Schematic diagram of a hydrogen atom and an antihydrogen atom. Credits: INFN

The first scientist to actually discover antimatter was the American physicist Carl David Anderson. In 1932, he came across the first positron, the first antiparticle proven experimentally, during his cosmic-ray studies. He demonstrated that cosmic rays produce positrons when passing through material substances. He received the Nobel Prize in Physics in 1936 for this discovery.

## Matter and antimatter

Matter and antimatter differ for two main aspects: their properties (which of some are opposite) and their amount in the universe. Technically, the Big Bang should have created the same quantity of matter and antimatter, because the corresponding particles are always created two by two, but there is way more matter than antimatter in the universe. One of the major challenges of modern physics is to find out the reason for this asymmetry. Discovering any slight difference between the behaviour of matter and antimatter would be crucial to answer this question.

Matter and antimatter cannot coexist at a close distance, because in a fraction of a second they collide and annihilate one another. As a consequence, all of their mass is converted to energy (in line with Einstein's theory of relativity $E=mc^2$) in the form of gamma rays or elementary particles. This happens because the particle and its antiparticle have the same mass, but opposite properties.

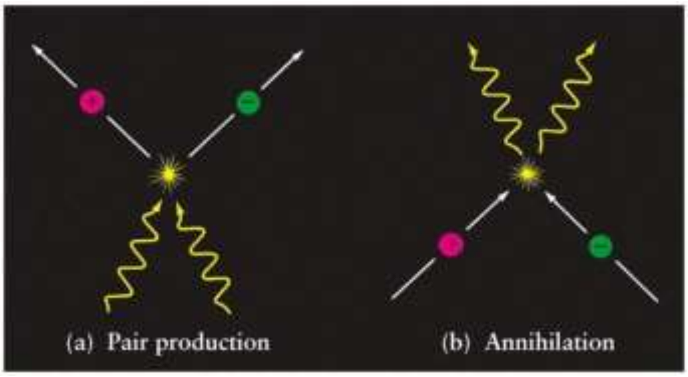


*Figure 3.* This annihilation is a reversible reaction: matter/antimatter pairs can be produced from pure energy.
Credits: University of Alberta

## Gravitational interaction of antimatter

When antimatter was first discovered in 1932, physicists wondered about how it would react to gravity. Several theoretical arguments arose which convinced physicists that antimatter would react exactly the same as normal matter. They inferred that a gravitational repulsion between matter and antimatter was implausible. However, since the gravitational interaction has not been proven experimentally, the option that antimatter would react oppositely to matter, is still open.

The most common theory of gravitational attraction is the equivalence principle, which predicts that the gravitational acceleration of antimatter is the same as that of ordinary matter, assuming that the gravitational and the inertial mass are identical. The inertial mass is the mass of an object measured by its resistance to acceleration.

The Elementary Process Theory of Marcoen Cabbolet argues the gravitational repulsion. The core idea is that non zero rest mass particles such as electrons, protons, neutrons and their antimatter counterparts exhibit stepwise motion as they alternate between a particlelike state of rest and a wavelike state of motion. Gravitation then takes place in a wavelike state, and the theory allows, for example, that the wavelike states of protons and antiprotons interact differently with the earth's gravitational field.

A more classical theory has been published by Ruggero Santilli and Massimo Villata. Their theories are extensions of general relativity and are experimentally indistinguishable. There have been a lot of comments on this theory.

Another theory of repulsive gravity was a quantum theory published by Mark Kowitt. The idea is that the wave function of a positron moving in the gravitational field of a matter particle evolves such that in time it becomes more probable to find the positron further away from the matter particle.

## Antimatter created in laboratories

The first atoms of antimatter appeared in Geneva in 1995. Prof. Walter Oelert and an international team from Jülich IKP-KFA, Erlangen-Nuernberg University, GSI Darmstadt and Genoa University managed to create anti-atoms. These atoms only existed for forty billionths of a second, before colliding with ordinary matter and disappearing. In this minuscule time interval, they travelled 10 meters at the speed of light. Scientists realised that they had synthesised those atoms of antimatter thanks to the destruction of the ordinary ones. This first creation opened the way to further explorations of the anti-world. Scientists managed to keep the anti-atoms in existence for increasing amounts of time.

In June 2011, ALPHA succeeded in trapping antimatter atoms for a very long time (over 16 minutes). Longer times allow researchers to observe those atoms and study their properties in depth.

In one of the latest studies at CERN, scientists worked with antihydrogen atoms to learn more about matter and antimatter. An antihydrogen atom consists of an antiproton and a positron. It is the antimatter version of a hydrogen atom. Researchers used the Antiproton Decelerator at CERN's ALPHA instrument (ALPHA stands for Antihydrogen Laser Physics Apparatus) and combined antiprotons with positrons to form antihydrogen atoms.
Then, they trapped antihydrogen atoms in a vacuum and used lasers to make the atoms jump into a higher energy state. When the atoms drop back to a lower energy state, they release photons. The scientists analysed these photons, which revealed that the antihydrogen emissions were the same as a normal hydrogen atom.
"The Lyman-alpha transition is the most basic, important transition in regular hydrogen atoms, and to capture the same phenomenon in antihydrogen opens up a new era in antimatter science", said Takamasa Momose, lead researcher of the experiment and a physicist at the University of British Columbia in Canada.
This experiment is an example of the work that the ALPHA collaboration does at CERN and the results of this experiment were published on 22 August 2018 in *Nature*.


*Figure 4.* The ALPHA experiment at CERN. Image credit: CERN

In March 2019, the AEgIS group at CERN published a paper describing a new method of making more long-lasting positronium atoms, which consist of an electron and a positron. Analysing the behaviour of these atoms is helpful to understand whether antimatter falls at the same rate as matter in Earth's gravitational field. AEgIS's positronium source produces a large number of long-lived atoms, which travel at known velocities and remain uninfluenced by external interferences, such as electric or magnetic fields.

## Antimatter as an energy source

Given that the annihilation of matter-antimatter creates a great quantity of energy, the question arises: could matter-antimatter reactors be used as energy sources? Interstellar travel in science fiction is often powered by antimatter. Could antimatter be an efficient fuel for the starships of the future or terrestrial uses?

Actually, producing antimatter requires a huge amount of energy, way more than annihilation could liberate. Also, storing antimatter implies lots of energy as well, since it has to be preserved from getting in contact with ordinary matter.

One of the most ambitious ideas to collect antimatter is exploiting the sun: studies show that cosmic rays from the sun produce positrons. The sun could be stimulated through specific devices  to generate more of those positrons, yet these proposals are still utopian.

### The creation of a container for antimatter

CERN's antiProton Unstable Matter Annihilation (PUMA) project is trying to store antimatter to be able to transfer it to another facility.

The team is designing a technology that locks antiprotons in a "bottle", keeping the atoms stuck in the centre with powerful magnetic and electric fields. The atoms will be stored in a vacuum and at a temperature slightly above zero. Sadly, development and testing will take about four years before antimatter could be transported. If this technology is successful, it will give other scientists around the world a chance to work with and study antimatter.

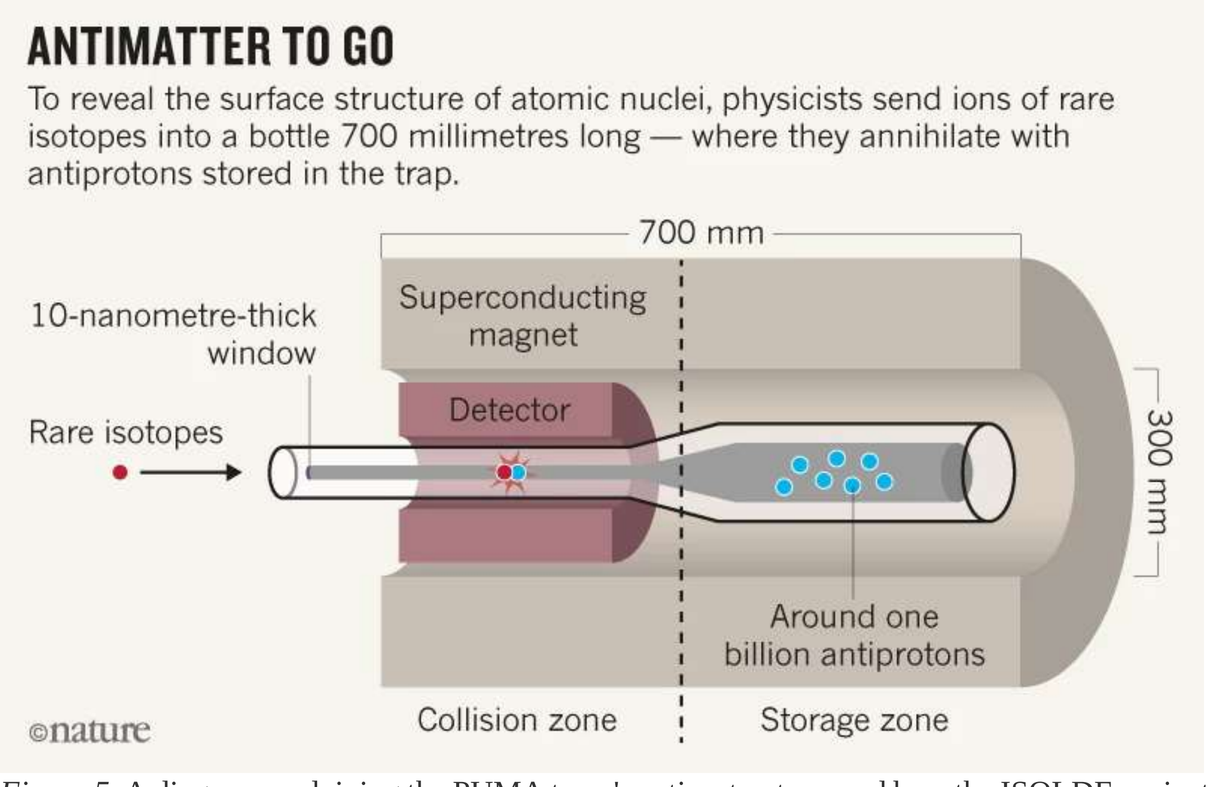


*Figure 5.* A diagram explaining the PUMA team's antiproton trap, and how the ISOLDE project will study them. Credits: Nature

### Are the films right?

The physics behind antimatter intrigued plenty of science fiction writers. They dream of antimatter engines powering future civilizations or star ships. Including the film Angels and Demons, in which they create some antimatter in an experiment, which is then used to annihilate matter. According to the film, less than a gram of this would form a sort of bomb with a power of 5,000 tons of TNT. Unfortunately, this is impossible. "If you take all the antimatter produced in the history of the world and annihilated it all at once, you wouldn't have enough energy to boil a cup of tea", said Gerald Gabrielse, a Harvard physicist who currently leads an international research team at CERN.

Where the film has succeeded, is the way they trapped the antimatter. You need a trap with magnetic fields, keeping the antimatter particles in a vacuum away from any matter. Put in another way: you need a container with no walls. However, you can't transport that, like they do in the movie.

The main problem and unrealistic part with this film is in how they create the antimatter. With the existing techniques, by accelerating particles and smashing them into each other, it would take 100 million years to make 1/4 gram. In addition, this process requires a very large amount of energy. (This also debunks the destruction theory used in the film.)

In the pictures below, you can see the constructions used to trap antimatter in real life versus how they did it (very unrealistically) in the film.

*Figure 6.* Installation in the CERN lab. Credits: CERN

*Figure 7.* Container used in the film *Angels and Demons*. Credits: Angels and Demons

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