ANTIMATTER MATTERS

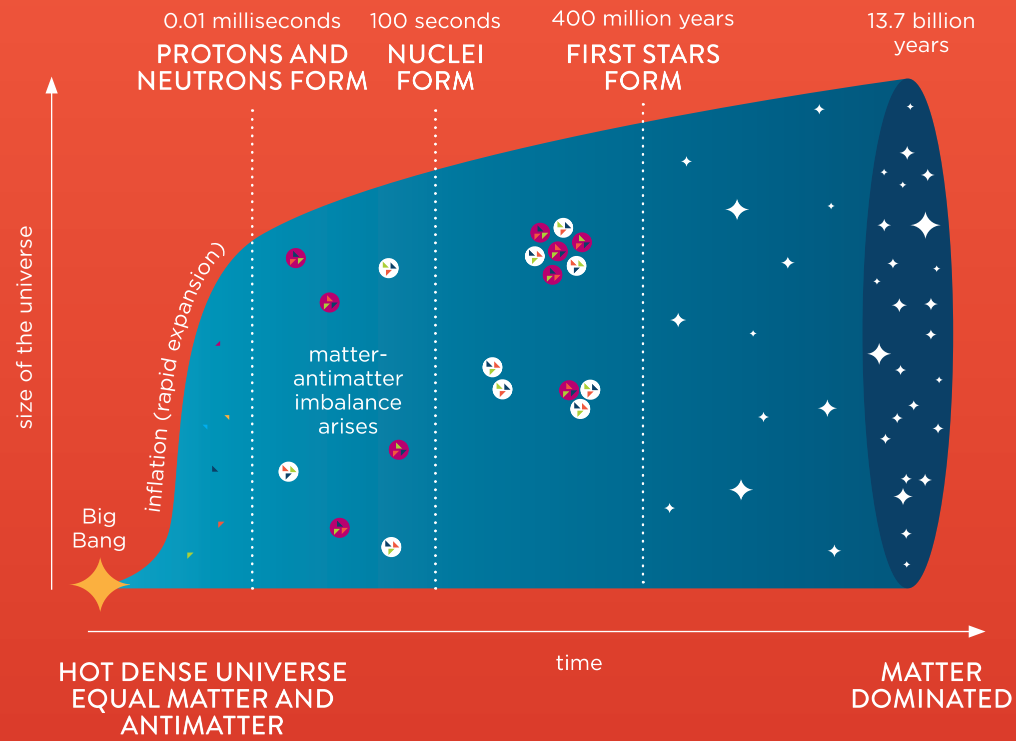
SELECTED FOR
THE ROYAL SOCIETY SUMMER SCIENCE EXHIBITION 2016

WHY ANTIMATTER MATTERS!

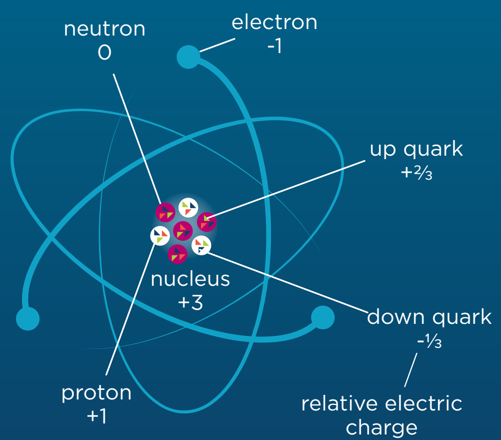
One of the most striking facts about the Universe is that it is composed almost entirely of matter. At the Big Bang equal amounts of matter and antimatter would have been created. This immediately raises the question, what happened to the antimatter? At first sight, the answer seems clear. In the early Universe, just after the Big Bang, antimatter and matter collided and annihilated into photons (particles of light). Today, the ratio of the number of left-over matter particles to photons is tiny, just one proton or neutron for every 10 billion photons, yet this is enough to make all the galaxies, stars and planets in the present-day Universe. If the fundamental laws of nature were entirely symmetric between particles and antiparticles all the matter (and antimatter) would have completely annhilated. So the real question is how does the difference between matter and antimatter arise?

Experiments being carried out at CERN (the European Laboratory for Particle Physics) are making precision measurements of the small differences between fundamental particles and their antiparticles as well as producing and studying entire atoms made from antimatter. However, antimatter isn't only confined to the laboratory and is found in naturally occurring sources as well as being used for medical diagnosis and in industrial applications.

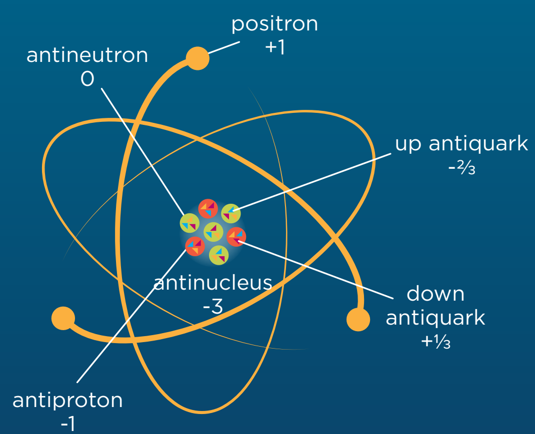
Antimatter Matters is an opportunity to learn about the properties of antimatter, the experiments being performed to study it and how it appears in everyday life.



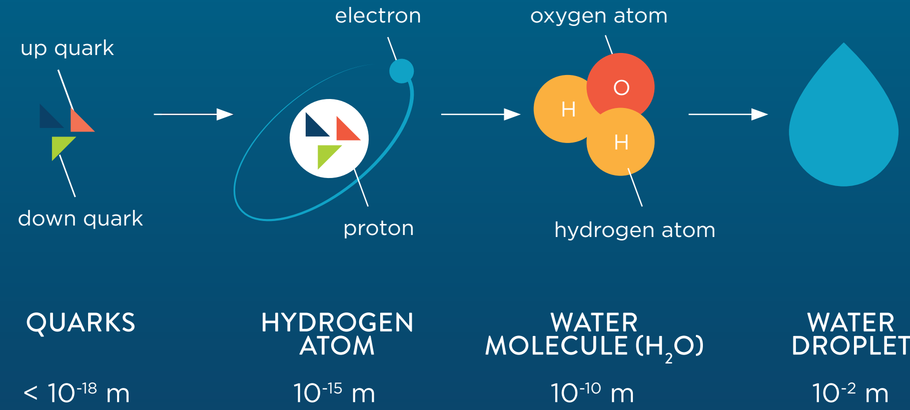
MATTER



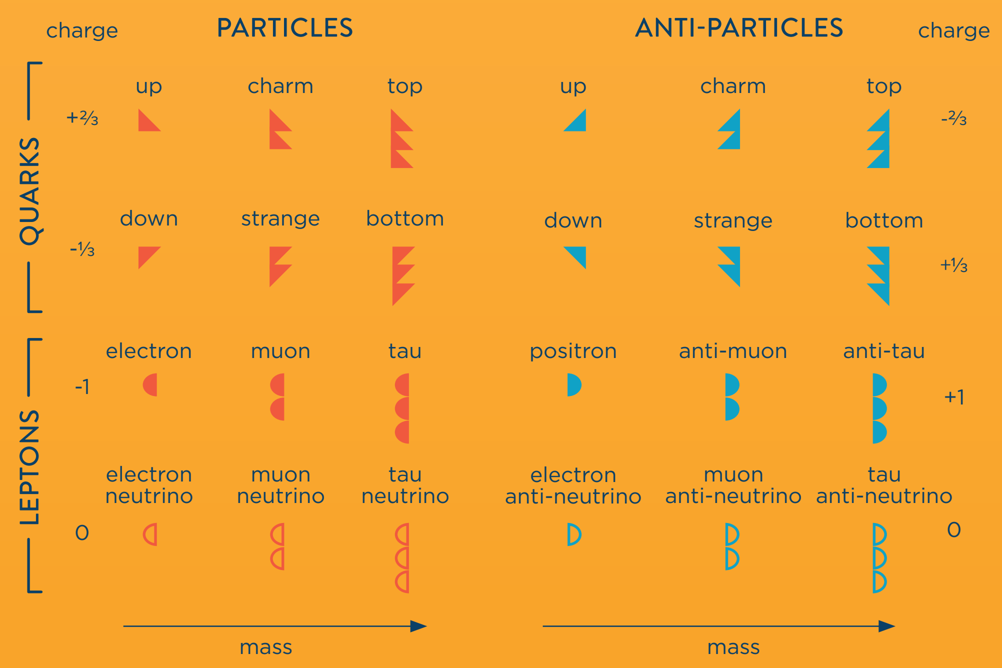
ANTIMATTER

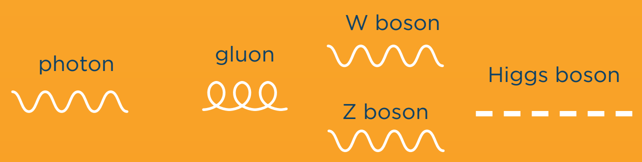


THE SCALE OF THINGS



STANDARD MODEL PARTICLES





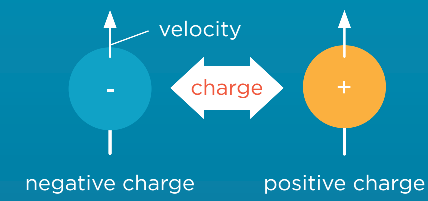
The Standard Model of particle physics describes the interactions of all known particles and forces (except gravity). There are twelve fundamental particles and their antiparticles: the six quarks, the electron and its heavier cousins the muon and tau as well as their three associated neutrinos. These particles interact with each other via the exchange of the force-carrying bosons: the photon of the electromagnetic force; the W and Z particles of the weak force that are responsible for radioactive decay; and the gluons of the strong force that bind combinations of three quarks into baryons and quark-antiquark pairs into mesons. Well-known baryons are the protons and neutrons that form atomic nuclei. The Higgs boson, which gives all particles their bare mass, was discovered in 2012 at the Large Hadron Collider at CERN.

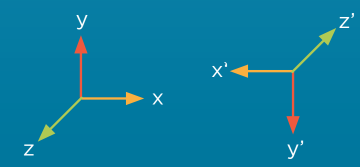
C,P,T (CHARGE, PARITY, TIME) SYMMETRIES

Symmetries are key to understanding the Universe and the relationship between matter and antimatter.

C
CHARGE

Charge conjugation swaps positive and negative charges



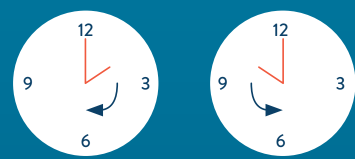


P
PARITY

Parity reversal swaps up and down, left and right, forwards and backwards

T
TIME

Time reversal swaps past and future

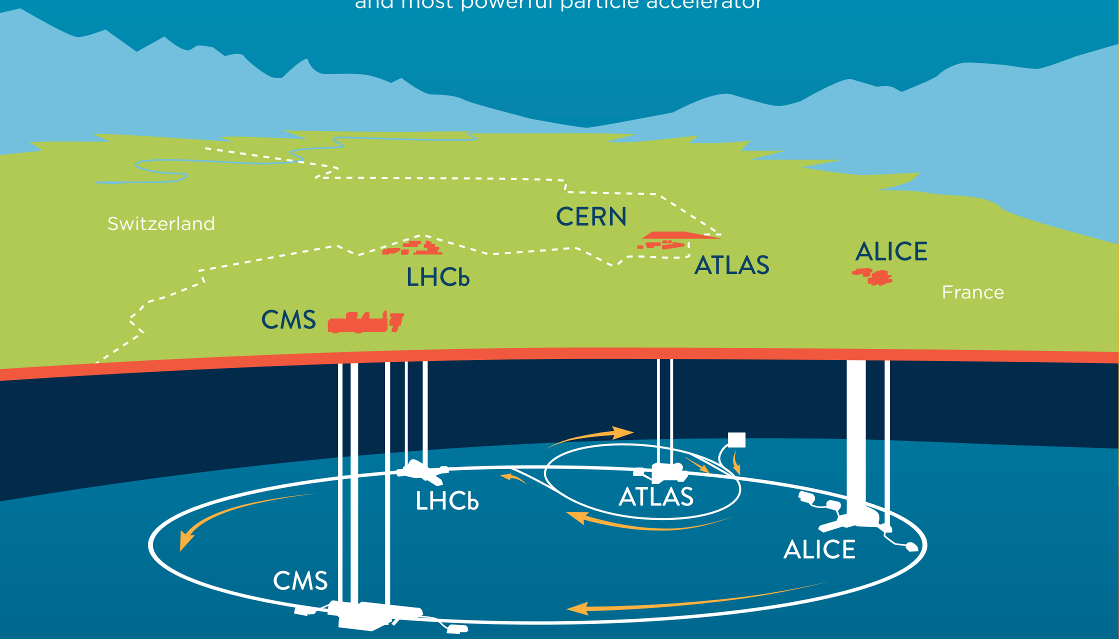


CP SYMMETRY

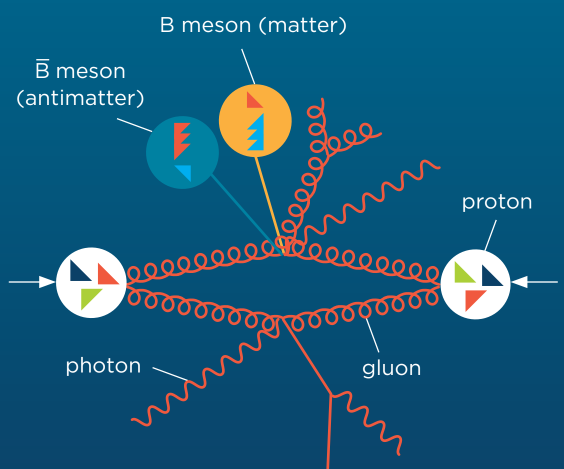
Almost all physics processes remain the same (are symmetric) under any combination of C, P and T. The only known exception are processes involving the weak force. In this case, the physical laws are very different after applying either C or P. There is also a tiny difference when C and P are applied in combination. This is referred to as a violation of CP symmetry and results in particles and antiparticles not behaving identically. The difference in behaviour is essential to explain why the Universe contains so much more matter than antimatter. The LHCb experiment at CERN is making precise measurements of this CP symmetry violation, while the ALPHA experiment is searching for matter-antimatter differences by studying antihydrogen atoms.

THE LARGE HADRON COLLIDER

The Large Hadron Collider (LHC), at CERN, Geneva, is the World's largest and most powerful particle accelerator



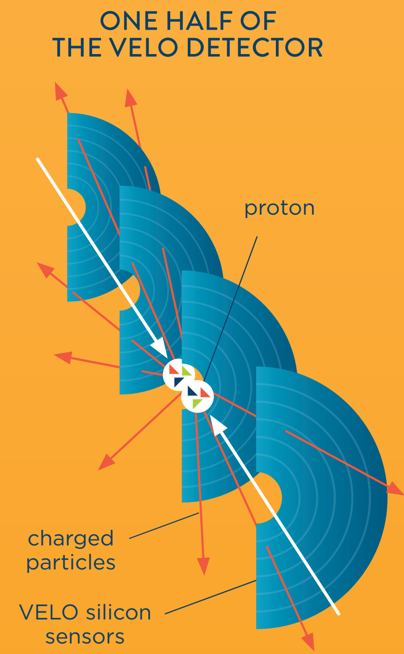
Proton beams are circulated in both directions around the LHC's 27km circumference ring and are brought into collision at four points, approximately 100m below ground. The LHCb experiment is located at one of these points and is the LHC experiment dedicated primarily to looking for differences between matter and antimatter in particles containing beauty and charm quarks. The UK is the lead contributing nation to the LHCb experiment.



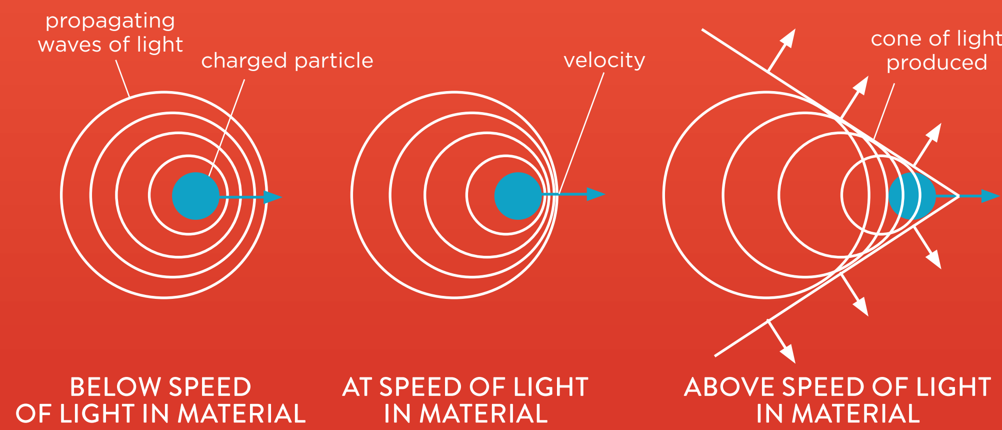
LHCb

The particles produced from each proton-proton collision travel through the LHCb detector. Each of LHCb's sub-detectors specialises in measuring a different characteristic of the particles such as its identity, trajectory, momentum and energy. The UK has responsibilities in two key sub-detectors: the vertex locator and the ring-imaging Cherenkov system.

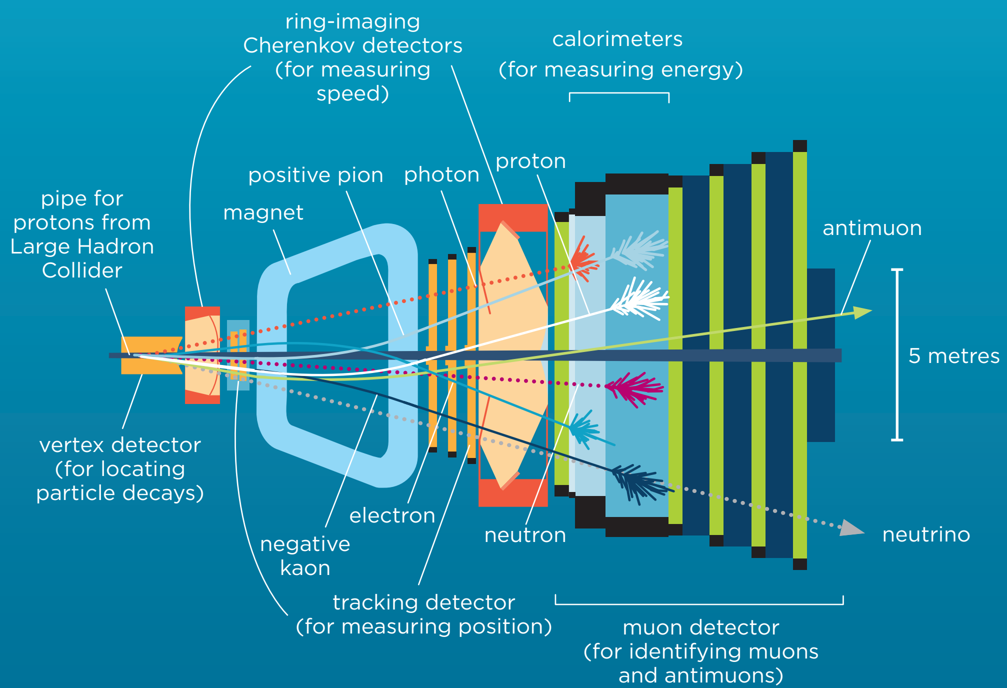
The Vertex Locator (VELO) identifies the production and decay points of the particles containing beauty and charm quarks. It is based on silicon sensors, similar to those in a digital camera, but takes "pictures" forty million times per second.



The ring-imaging Cherenkov detectors distinguish between different types of charged particles such as muons, protons, pions and kaons. As the particles travel through the gas volume of the detector at faster than the speed of light in the gas they emit a coherent shockwave of light, much like a sonic boom of an aeroplane travelling faster than the speed of sound in air. The system is composed of sensors that are sensitive to individual photons of this light.

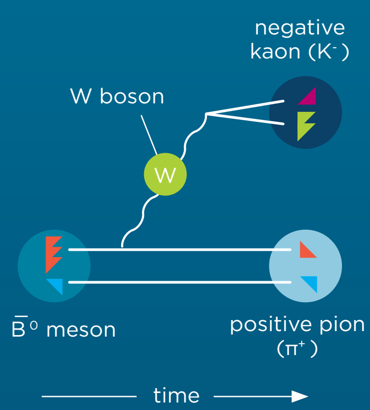


THE LHCb DETECTOR FROM ABOVE



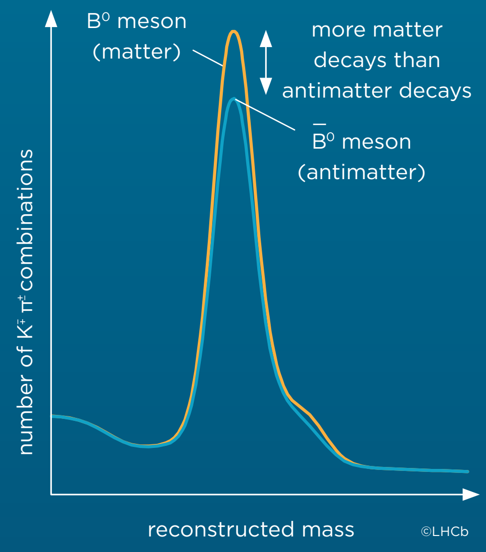
A next generation upgrade to the experiment has recently been approved to start in 2021 and will give another leap in the precision at which CP violation can be measured. Many parts of the experiment are being designed and constructed at ten universities across the UK, working closely with industry.

DECAY OF $\bar{B}^0$ TO $K^- \pi^+$



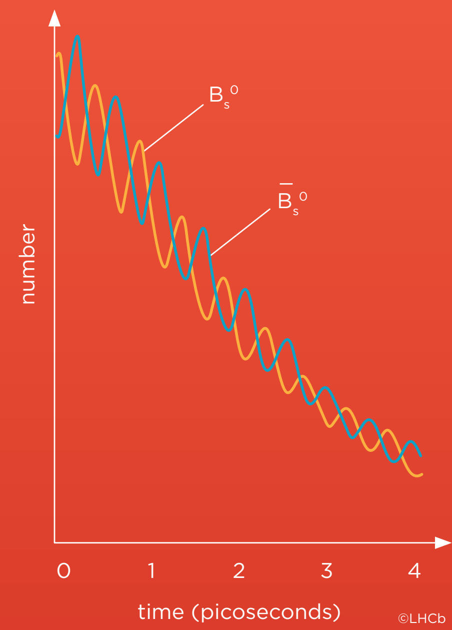
Mesons and baryons containing beauty and charm quarks will decay after a short time (roughly 1 picosecond or 0.000000000001 seconds) into other mesons and baryons that are more long-lived and can be detected as they pass through a particle detector. In the decay of a $\bar{B}^0$ meson to a kaon and a pion, the beauty quark changes into an up quark via the emission of a W boson. The up quark and remaining down antiquark combine to form a negatively charged pion while the W boson decays into a strange quark and up antiquark, which combine to form a positively charged kaon. The antiparticle of a $\bar{B}^0$ meson is the B^0 meson, which can decay into a positively charged pion and negatively charged kaon.

CP VIOLATION



By combining information from sets of detected particles, it is possible to calculate the mass that would have been possessed by the parent particle that decayed to produced them. The so-called reconstructed mass has a well-defined value if the sets of detected particles really come from a particle decay, or has a random value otherwise. Repeating this process for many different combinations and adding the numbers to a graph will give rise to a peak indicating the number of times that the decay actually occurs. In the LHCb experiment, for example, peaks have been obtained for $\bar{B}^0$ and B^0 mesons decaying to a kaon and a pion. Differences in the peak heights signal a difference between matter and antimatter.

MATTER-ANTIMATTER OSCILLATIONS



The phenomenon of matter-antimatter oscillation is an intriguing quantum mechanical effect where a neutral matter particle and neutral antimatter particle change back and forth between each other. The LHCb experiment has measured the frequency of these oscillations between B_s^0 and $\bar{B}_s^0$ mesons very precisely and uses them as a tool to study CP violation. LHCb counts the number of B_s^0 and $\bar{B}_s^0$ mesons as a function of the time between their production and decay. This number decreases as the time increases, modulated by a clearly visible oscillation.

B_s^0 MESON

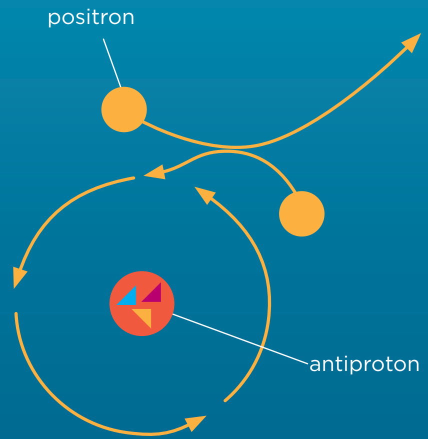
ALPHA

In addition to studying the fundamental particles and antiparticles, experiments at CERN are also investigating antimatter through the simplest atom of antimatter: antihydrogen. Just as hydrogen is formed from the combination of a proton and electron, antihydrogen is formed from an antiproton and an antielectron (positron). The ALPHA experiment has successfully made and trapped hundreds of antihydrogen atoms.

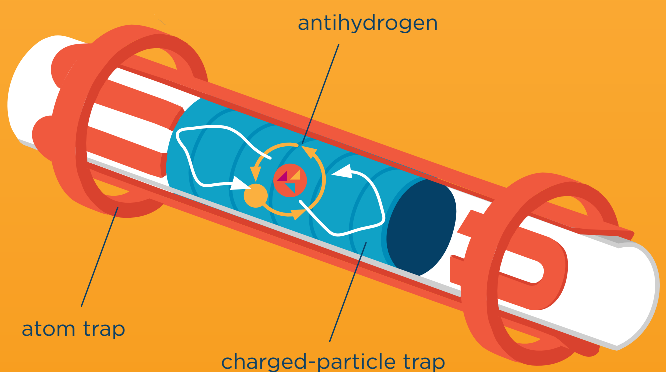
Charged particles can be easily manipulated, as they respond in well-known ways to electric and magnetic fields. Such fields can be used to confine the particles in so-called electromagnetic bottles, away from the material walls of the surrounding container. This is particularly important for antiparticles, which would annihilate with the atoms in the walls of the chamber were they to come into contact.

One example of a confining device is the Penning trap. It uses a stack of electrodes to provide an electrical well, together with a strong magnetic field pointing along the axis of the chamber to pin the antiparticles radially and stop them drifting towards the walls. These traps allow positrons and antiprotons to be stored for long periods until they are mixed to form antihydrogen.

FORMATION



ANTIHYDROGEN FORMATION & TRAPPING



THE CERN ANTIPROTON DECELERATOR

To form antihydrogen the positrons and antiprotons are combined one at a time. The positrons are easily obtained from radioactive sources, but the antiprotons are only available at CERN's unique Antiproton Decelerator facility.

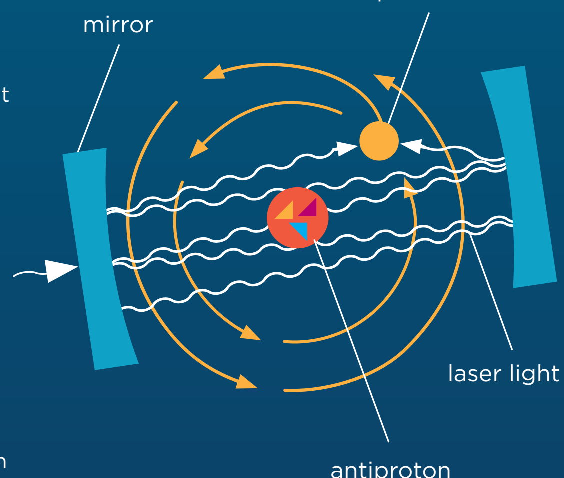
The Antiproton Decelerator provides ALPHA with about 30 million antiprotons every two minutes. Some of these are captured in the Penning trap where they are slowed down and carefully mixed with the waiting positrons. Many thousands of antihydrogen atoms are produced in each mixing cycle.

TRAPPING ANTIHYDROGEN AT CERN

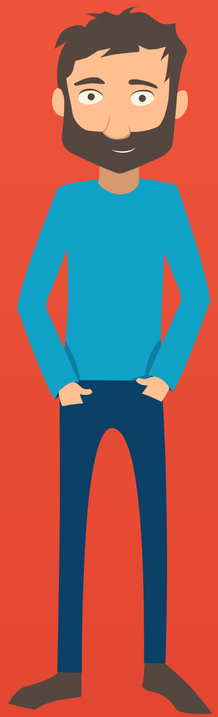
Once the electrically neutral antihydrogen atom is formed, it is no longer held in place by the Penning trap. To prevent the antihydrogen reaching a wall and annihilating, another trap is used. This is made from a special combination of magnets that creates a magnetic bowl, which has a minimum in the centre of the device. For the trap to work, and keep antihydrogen atoms away from the walls, the atoms must have kinetic energies corresponding to a temperature of less than half a degree kelvin above absolute zero. Only about one antihydrogen atom is trapped in each time the experiment is performed, but since it can be held for up to 16 minutes, detailed studies can be made.

SPECTROSCOPY

Once the very cold antihydrogen has been trapped, the ALPHA experiment shines a laser on it to make very precise measurements of the antihydrogen spectrum.
he experiment has recently used a similar technique with microwaves to make the first observation of quantum jumps in an antiatom. ALPHA is now poised to make the most precise comparison of the properties of matter and antimatter. In doing so it may shed some light on the mystery of the fate of antimatter.



DECAY OF POTASSIUM-40



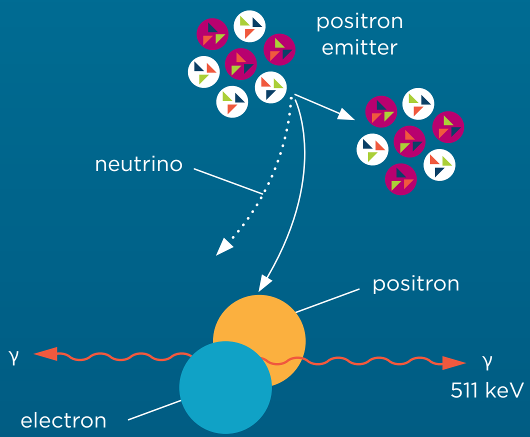
A person weighing 80kg emits 180 positrons per hour

A banana emits 2 positrons per hour

NATURALLY OCCURRING ANTIMATTER

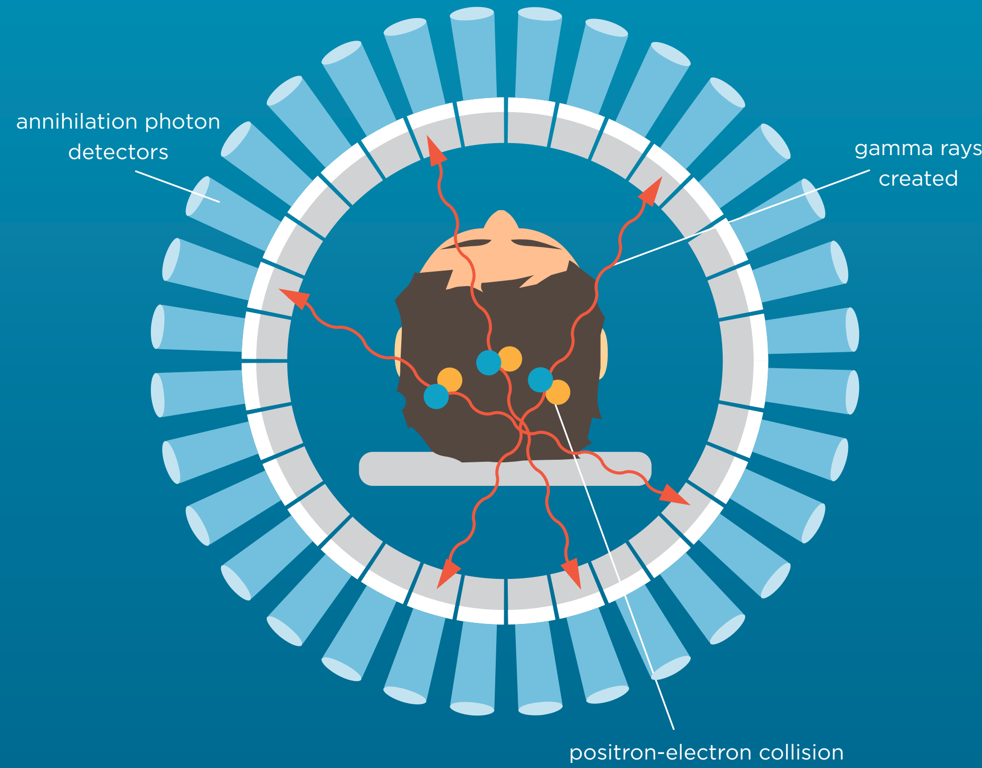
Although the Universe is dominated by matter, antimatter still occurs naturally in cosmic rays from space and in the radioactive decay of certain isotopes, for example fluorine-18 and potassium-40. Isotopes are variants of a particular element that differ in the number of neutrons in their nucleus (the number of protons is the same). Isotopes can be produced in a variety of ways, including within nuclear reactors and using particle accelerators. In some cases the isotopes will decay by a process known as positive beta decay where one of the protons in the nucleus is converted to a neutron, and the positive charge is emitted in the form of an antielectron (positron). This positron then annihilates with an electron, creating a pair of photons (gamma rays) travelling in opposite directions. This behaviour is useful when designing medical or engineering applications that use antimatter.

POSITIVE BETA DECAY AND POSITRON ANNIHILATION



POSITRON EMISSION TOMOGRAPHY

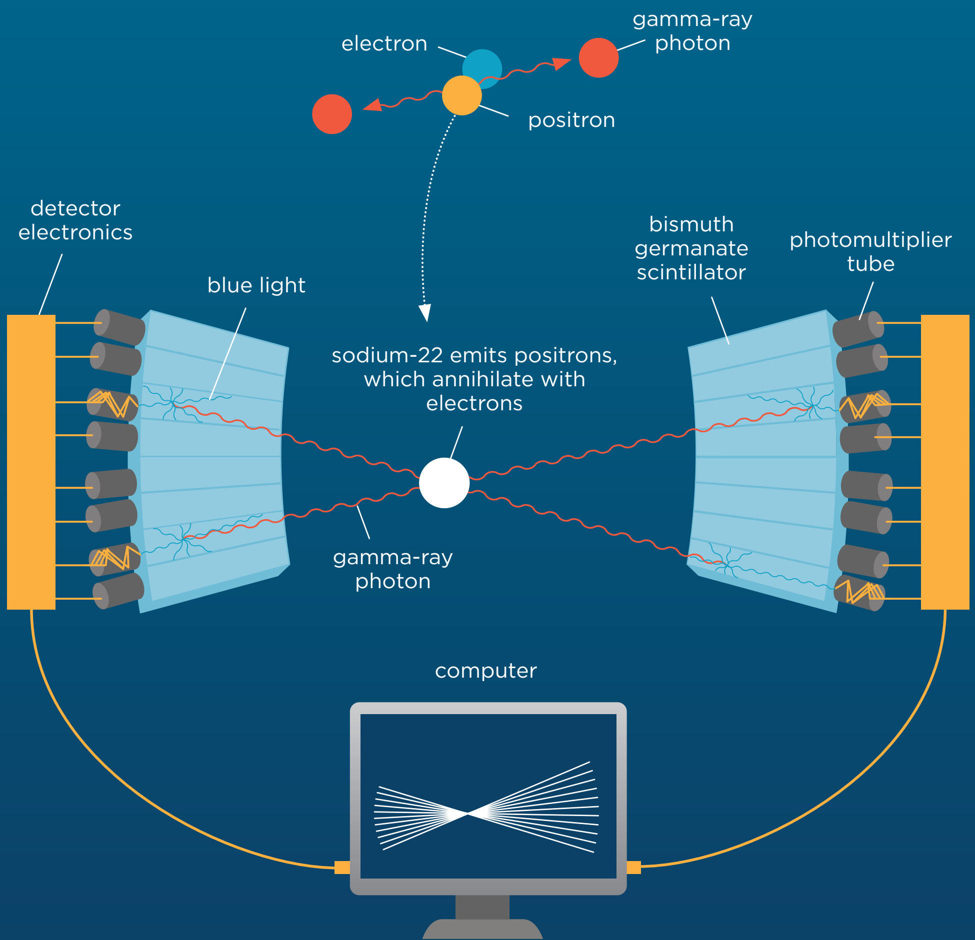
PET SCANNER



The medical technique of positron emission tomography (PET) is used to diagnose the presence of small cancer tumours or of abnormal brain function. It does this by tagging certain biologically interesting molecules using radioactive isotopes whose nuclei have too few neutrons. For example, a form of glucose is tagged with fluorine-18 atoms and used to map energy metabolism within the body. A PET scanner consists of many small detectors arranged in a ring. If two detectors simultaneously identify the two gamma rays from positron-electron annihilation then the isotope must have decayed along the line joining these two detectors. Combining millions of such lines builds up a map of glucose concentration in the body, reflecting the energy uptake of different tissues.

POSITRON EMISSION PARTICLE TRACKING

Positron emission particle tracking (PEPT) is another technique based on detecting pairs of photons from positron-electron annihilation, following positron emission in a radioactive decay. However instead of mapping the concentration of a radioactive fluid a single radioactively-labelled object is tracked to allow the motion of granular solids and fluids to be studied. The technique has been used to understand and improve devices such as dishwashers and aeroplane engines.



ANTIMATTER MATTERS

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