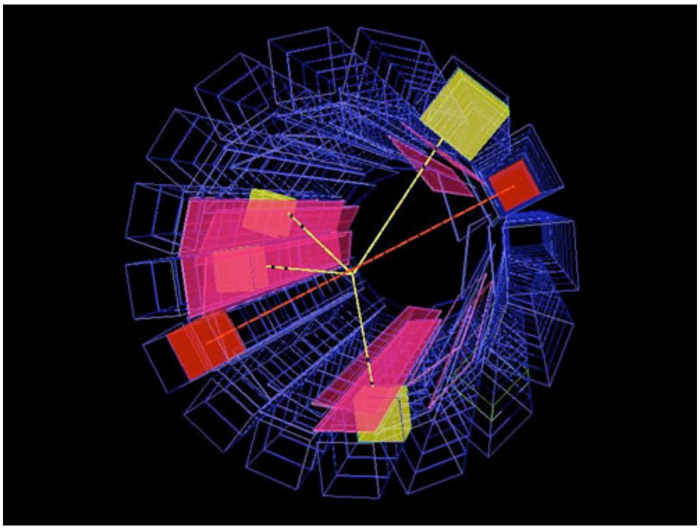
The five greatest mysteries of antimatter



ANTIMATTER: NOT AS SCARY AS WE THINK

"No!" Vittoria said from above, breathless. "We must evacuate right now! You cannot take the antimatter out of here! If you bring it up, everyone outside will die!"

Angels and Demons,**Dan Brown**, Pocket Books

IT WAS not so long ago that we were hearing how CERN's Large Hadron Collider would produce planet-destroying black holes. Now a movie based on Dan Brown's blockbuster, due to hit the big screen next month, provides us with another supposed danger emanating from the particle physics laboratory near Geneva, Switzerland: antimatter, the seed of a weapon of unsurpassed destructive power.

While Brown's take on antimatter is fictional, the stuff itself certainly isn't. We see its signature in cosmic rays, and it is routinely made in high-energy collisions inside particle smashers the world over. In hospitals, radioactive molecules that emit antimatter particles are used for imaging in the technique known as positron emission tomography.

Brown was right about one thing, though: if you want to find out more about antimatter, CERN is the place to go. In this special feature, we explain how experiments at the laboratory are helping to answer some of our more pressing questions about this most elusive of substances.

1.

Where is all the antimatter?

Standard theory predicts that the big bang should have created as much antimatter as matter – so why does the universe seem to be made entirely of matter?

If you were to list the imperfections of the standard model - physicists' remarkably successful description of matter and its interactions - pretty high up would have to be its prediction that we don't exist.

According to the theory, matter and antimatter were created in equal amounts at the big bang. By rights, they should have annihilated each other totally in the first second or so of the universe's existence. The cosmos should be full of light and little else.

And yet here we are. So too are planets, stars and galaxies; all, as far as we can see, made exclusively out of matter. Reality 1, theory 0.

There are two plausible solutions to this existential mystery. First, there might be some subtle difference in the physics of matter and antimatter that left the early universe with a surplus of matter. While theory predicts that the antimatter world is a perfect reflection of our own, experiments have already found suspicious scratches in the mirror. In 1998, CERN experiments showed that one particular exotic particle, the kaon, turned into its antiparticle slightly more often than the reverse happened, creating a tiny imbalance between the two.

That lead was followed up by experiments at accelerators in California and Japan, which in 2001 uncovered a similar, more pronounced asymmetry among heavier cousins of the kaons known as B mesons. Once the LHC at CERN is back up and running later this year, its LHCb experiment will use a 4500-tonne detector to spy out billions of B mesons and pin down their secrets more exactly.

But LHCb won't necessarily provide the final word on where all that antimatter went. "The effects seem too small to explain the large-scale asymmetry," says Frank Close, a particle physicist at the University of Oxford.

The second plausible answer to the matter mystery is that annihilation was not total in those first few seconds: somehow, matter and antimatter managed to escape each other's fatal grasp. Somewhere out there, in some mirror region of the cosmos, antimatter is lurking and has coalesced into anti-stars, anti-galaxies and maybe even anti-life.

"It's not such a daft idea," says Close. When a hot magnet cools, he points out, individual atoms can force their neighbours to align with magnetic fields, creating domains of magnetism pointing in different directions. A similar thing could have happened as the universe cooled after the big bang. "You might initially have a little extra matter over here and a little extra antimatter somewhere else," he says. Those small differences could expand into large separate regions over time.

These antimatter domains, if they exist, are certainly not nearby. Annihilation at the borders between areas of stars and anti-stars would produce an unmistakable signature of high-energy gamma rays. If a whole anti-galaxy were to collide with a regular galaxy, the resulting annihilation would be of unimaginably colossal proportions. We haven't seen any such sign, but then again there's a lot of universe that we haven't looked at yet - and whole regions of it that are too far away ever to see.

Finding anti-helium or other anti-atoms heavier than hydrogen would be concrete evidence for an anti-cosmos. It would imply that anti-stars are cooking up anti-atoms through nuclear fusion, just as regular stars fuse normal atoms. The Alpha Magnetic Spectrometer is a $1.5 billion piece of kit built to scour cosmic rays for just such signs. It is grounded at the moment, waiting for a lift up to the International Space Station, but will hopefully hitch a ride on one of NASA's final space shuttle launches in 2010 or 2011.

2.

How do you make antimatter?

Researchers at CERN are trying to make antimatter in useful quantities. But it's hard to pin down a substance that vanishes as soon as it touches anything

If we really wish to fathom the mysteries of antimatter, we must first get to grips with the stuff itself. Easier said than done. How on earth do you pin down a substance that vanishes the moment it touches anything?

Two CERN experiments, ATRAP and ALPHA, are grappling with that question. Their aim is to make antihydrogen - the simplest anti-atom possible, just an antiproton and a positron bound together - in sufficient quantity and for long enough to compare the spectrum of light it emits with that of regular hydrogen. Even the slightest difference between the two would shake up the standard model.

The experiments require a near-perfect vacuum, as encountering a mere atom of air would spell the end for any antiparticle, and there must be some way of trapping the antiparticles: not in a conventional container, but using electric and magnetic fields.

ATRAP and ATHENA, ALPHA's forerunner, did successfully isolate antihydrogen in 2002, bringing together antiprotons from a particle accelerator and positrons from a sodium radioactive source in a magnetic trap. Unfortunately, such success is fleeting: magnetic traps work just fine for charged particles such as antiprotons and positrons, but antihydrogen is neutral, so it can slip right through the containing field lines.

It's a problem ATRAP and ALPHA are still working on. "Capturing antihydrogen atoms is the current frontier, and it's a challenge," says Rolf Landua, a physicist at CERN who advised on the Angels and Demons movie and is rumoured to be the inspiration for Leonardo Vetra, an antimatter scientist in the original story. "So far nobody has managed to do it, but I'm pretty sure we will." Still, encasing a smouldering chunk of antimatter in a portable antihydrogen trap as happens in the book is a quite a way off, he says.

3.

Does antimatter fall up?

Gravity works the same way on all matter – but what about antimatter? If it behaves differently, it could overturn our understanding of physics

AEGIS, a CERN experiment that has just been given the go-ahead, is designed to find out. Gravity is a relatively weak force, so the experiment will use uncharged particles to prevent electromagnetic forces drowning out gravitational effects. It will first build highly unstable pairings of electrons and positrons, known as positronium, then excite them with lasers to prevent them annihilating too quickly. Clouds of antiprotons will rip these pairs apart, stealing their positrons to create neutral antihydrogen atoms.

Pulses of these anti-atoms shot horizontally through two grids of slits will create a fine pattern of impact and shadow on a detector screen. By measuring how the position of this pattern is displaced, the strength - and direction - of the gravitational force on antimatter can be measured.

It's a clever idea, but the devil is in the detail, says AEGIS spokesman Michael Doser. "No one has ever made controlled positronium like this, nobody has ever made a positronium excited state with lasers in an environment like this and nobody has ever made an antihydrogen pulse like this."

If the researchers succeed, it will be well worth the effort. If gravity does affect antimatter differently, it will tell us something not just about antimatter but also about the fundamental theories that underpin modern physics. Einstein's general relativity, the currently favoured theory of gravity, tells us that the force should work identically on any type of matter. Equally, the standard model predicts that matter and antimatter are identical to all intents and purposes. "If we find that either of these things differ," says Landua, "then we have found something extremely important."

Doser is hedging his bets. "I'll wager a crate of champagne that we won't see a difference," he says. "But I'd gladly lose that crate."

4.

Can we make an anti-world?

Physicists are finding it difficult to tame antihydrogen, the simplest possible anti-atom. Is there any hope of making more complex anti-atoms?

At the moment physicists are having enough difficulty just taming antihydrogen, the simplest possible anti-atom. Can we ever expect them to make antihelium, and then organic antimolecules made from anticarbon and a whole anti-periodic table, too?

The problem here is that every anti-atom has to be built one subatomic antiparticle at a time. For example, if you want to make antideuterium - like antihydrogen, but with an added antineutron - you first have to make the antineutron. Antineutrons are neutral, making them impossible to steer in the conventional way with electromagnetic fields, so you just have to make great numbers of them and hope that for every million or so antineutrons you make, one ends up in the right place to make an antideuterium atom. "And for every further antineutron or antiproton you add, you lose another factor of a million," says Michael Doser, spokesman for CERN's AEGIS experiment studying the properties of antimatter.

While no one's cracked that problem yet, one experiment at CERN is making use of a neat short cut to at least make something other than antihydrogen. ASACUSA has created atoms of "antiprotonic helium", in which one of the electrons orbiting a helium nucleus is replaced by an antiproton. By studying the light spectra emitted by this composite matter-antimatter atom, the electrical and magnetic properties of the antiproton can be measured with great precision - and compared with those of a regular proton.

As for our chances of making anything more complex, Frank Close, a particle physicist at the University of Oxford, is pessimistic, saying it will take a billion years, give or take. "It depends on how long the human race lasts," he says. It seems that our best bet for spying more exotic elements of the anti-periodic table is to look up at the sky - and hope that somewhere antistars are busy churning them out for us.

5.

Could antimatter be used to make the ultimate bomb?

The idea that humanity might one day harness antimatter for destructive purposes has a ghastly fascination

Antimatter was a lethal weapon. Potent, and unstoppable. Once removed from its recharging platform at CERN... A blinding light. The roar of thunder. Spontaneous incineration.

The idea that humanity might one day harness the annihilative power of antimatter for destructive purposes has a ghastly fascination - and it's a central part of the Angels and Demons plot, in which a bomb containing just a quarter of a gram of antimatter threatens to obliterate the Vatican.

Relax, says Rolf Landua, a physicist at CERN. There's a very good reason why nothing like that is going to happen any time soon. "If you add up all the antimatter we have made in more than 30 years of antimatter physics here at CERN, and if you were very generous, you might get 10 billionths of a gram," he says. "Even if that exploded on your fingertip it would be no more dangerous than lighting a match." Patients undergoing PET scans have natural radioactive atoms in their bloodstreams emitting tens of millions, if not more, positrons to no ill effect.

Even if physicists could make enough antimatter to build a viable bomb, the cost would be astronomical. "A gram might cost a million billion dollars," says Landua. "That's probably more than Barack Obama wants to invest right now." Frank Close, a particle physicist at the University of Oxford, points out the time problem, too. "It would take us 10 billion years to assemble enough anti-stuff to make the bomb Dan Brown talks about," he says.

If that seems reassuring, unfortunately the same kind of reasoning does for antimatter as a clean, green energy source. "Maybe it would work if there were lumps of antimatter that nature had spent 15 billion years making for us," says Close. As it is, we would have to make them one anti-atom at a time, which costs far more energy to make it than we would get out of it - about a billion times more, says Landua.

That's not to say we can't harness antimatter in new ways. In 2007, physicists David Cassidy and Allen Mills of the University of California, Riverside, made the first molecules comprised of more than one positronium atom. Positronium atoms quickly annihilate into high-energy gamma rays, so pack lots of them together, and it should be possibly to get them annihilating and emitting light in synchrony - creating an enormously high-powered "gamma-ray annihilation laser" that could be used to image objects as small as atomic nuclei, or to set off nuclear fusion in reactors.