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INSIDE
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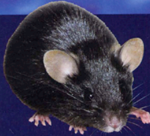
ANTIMATTER'S NEMESIS

The power to generate new atomic worlds



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When antimatter attacks...

...annihilation is the inevitable result. But something strange happens in the moments before particle and antiparticle vanish. **Eugenie Samuel Reich** investigates

THE intrigue of antimatter lies in its untouchability – its utter incompatibility with the stuff of our familiar world. Antimatter particles obey all the same physical laws as matter particles, but bring the two together and they annihilate one another in an explosive flash of energy.

Except that physicists are starting to discover it is not quite that simple. Annihilation is not all that matter and antimatter do together. Theory and experiments at the cutting edge of research are surprising us with the news that they can co-exist in a way that promises to open up some undreamed-of areas of science – a whole new kind of chemistry, in fact.

The existence of antimatter was predicted by Paul Dirac in 1928 and it was first seen four years later. But it is only now that we are discovering that, in the union of matter and antimatter, annihilation is not the only fruit.

This breakthrough has come from physicists' quest for an answer to one of the longest-standing puzzles about antimatter: how come annihilation sometimes happens so fast? The process is described by the "electroweak" theory, which unifies the electromagnetic and weak forces, two of the fundamental forces of the universe. Using this theory, antimatter researchers can work out how quickly an electron, for example, annihilates in the presence of its antimatter nemesis, a positron. Yet as long ago as 1963, experimenters began to notice that their results didn't tally with what the theory predicted. Annihilation can sometimes happen millions of times faster than it should.

Take Cliff Surko's experience. Surko, a physicist at the University of California, San Diego, is a master of antimatter. In 1987, he was using an ion trap, kept at extremely high vacuum, to test how long positrons could survive before annihilation. He used electric and magnetic fields to hold the positrons in space for as long as possible until they escaped and hit some matter, or – because the vacuum wasn't absolutely perfect – until they bumped into stray matter. Surko wasn't under any illusions that he could keep antimatter captive for long, but he was hoping for something better than what he got. "I expected the lifetime of positrons to be little more than a minute. It was three-tenths of a second," he says.

This posed a serious problem. Physicists had thought the electroweak theory nailed down all aspects of the interactions between matter and antimatter. "It was a crying question, a really crying, crying question," says theorist Gleb Gribakin of Queen's University Belfast in the UK.

Surko has been at the forefront of the attempt to deal with this problem. He has been creating beams of positrons, and firing them at various target molecules. The equipment he uses catches the positrons that are spat out in radioactive decay, and then accelerates them using an electric field to form a beam that he can tune to the energy he wants. Exotic though this sounds, such positron beams are now standard in medical imaging and for probing inside materials. Surko's results, however, are far from standard.

Antimatter researchers have coined a term, the Zeff, as a measure of how quickly a matter-based target annihilates when it is hit by a positron. A single electron, by definition, has a

Zeff of 1, so you might expect that the Zeff of an atom or molecule would be closely related to the number of electrons it contains. But in his experiments, Surko has shown that this isn't the case. On the contrary, he has found a huge variation in Zeffs for different molecules. Anthracene and sebacic acid dimethyl ester had Zeffs as high as 10,000,000, for example. These are stable organic molecules, with just a few hundred electrons, yet they were like dynamite when they encountered antimatter. It was a clear sign that something was wrong with the basics of the theory. "You think, why does the number become so very large?" says Gribakin, "What can I multiply in, or exponentiate, to get such a large number?"

Surko began to see these results around 1992. Around the same time, Gribakin was studying the interaction of antimatter with matter at the University of New South Wales in Sydney, Australia. He quickly found a possible problem with the standard approach. According to simple applications of electroweak theory, for an electron and a positron to annihilate, they need to hit virtually head-on. But what if the beam doesn't need to fire a positron exactly at the electron, Gribakin wondered. What if the positive charge of a positron made it able to bind to electrons in the molecule it was flying through? Would this make a near miss good enough?

There was a precedent for this idea. In 1951, while working at the Massachusetts Institute of Technology, in Cambridge, Massachusetts, physicist Martin Deutsch discovered that positrons could bind to electrons, creating a neutral, atom-like system called positronium that was stable for 100 nanoseconds. At the time, it was widely considered that it was the electric attraction of the negatively charged electron and the positively charged positron that held positronium together. While that seemed to make sense, Gribakin thought that it might also be possible for a positron to bind to a particle even if it had no net negative charge. If the positrons were able to deform the electron cloud surrounding the nucleus of a neutral atom, for example, that might allow positrons to form a bound state with that atom. ▶

"Stable organic molecules with just a few hundred electrons acted like dynamite when they encountered antimatter. It was a clear sign something was wrong"


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In this scenario, a positron would not have to hit an electron head-on to annihilate: it just had to come near enough to be drawn into a matter-antimatter hybrid. Eventually, the attraction between the particles would cause a collision, and thus an annihilation, and the hybrid would then decay. In 1997, Gribakin sent a model describing these ideas to *Physical Review Letters*, but he had no luck getting it published. He now thinks the way he set out his theory was too vague. "One of the reviewers said something to the effect that the positron physics community simply cannot believe in bound states in neutral atoms," he says.

But others had been working independently on antimatter annihilation, and in the same year Jim Mitroy and Gregory Ryzhikh of what is now Charles Darwin University in Darwin, Northern Territory, Australia, published calculations in *Physical Review Letters* (vol 79, p 4124) showing that the interactions between a positron and a lithium atom should allow a stable hybrid to form. Similar calculations were done by Krzysztof Strasburger and Henryk Chojnacki of the Technical University of Wroclaw in Poland.

Mitroy and Ryzhikh also predicted the lifetime of the atom-positron hybrid: the positron would hit one of the three electrons in the lithium atom after about a nanosecond, but until that happened the hybrid would act as a new kind of chemical entity. On the atomic timescale, that nanosecond is enough time for the positron to make plenty of orbits in the hybrid, and – crucially for the emerging science of antimatter chemistry – enough for all kinds of interaction with other atoms.

Atomic hybrids

Those calculations have led to a complete change in the way physicists view antimatter. Mitroy went on to predict that 10 different atoms could bind with a positron. None of the matter-antimatter compounds Mitroy predicted have been found experimentally – no one has worked out a way to test for their presence – but the calculations alone were enough to convince physicists that matter-antimatter hybrids exist.

It was a significant advance, but not as yet enough to dispel the mystery of Surko's results. Mitroy's calculations were only good for atoms, so they still did not explain why positrons annihilated so easily with large molecules. That next step came from Gribakin, when in 2000 he showed that positrons might be even more likely to bind with some molecules than with atoms.

For a positron to annihilate with an electron, it has to be able to get close enough to lose some of the kinetic energy of their relative motion. At an atomic level, energy cannot just be thrown away, it has to go somewhere. Molecules have exactly what is needed, which is a place to dump the extra energy. When a positron hits a molecule, its energy can be transferred into a vibration of the molecule – a kind of flexing of the bond between atoms. A large molecule can vibrate in many different ways, so there should be a wide range of energies of incoming positrons that it can accommodate.

Gribakin turned this idea into a model that predicts how different molecules should give quite different annihilation rates at different

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incoming energies of the positron. In 2001, when he gave a talk in Cambridge, Massachusetts, on his ideas for how antimatter compounds could form, Deutsch was in the audience. "He stood up and said 'Now I've seen what we're doing here, I feel much better'," Gribakin recalls. "I think he felt that puzzle of annihilation rates on molecules had nagged him for 40 years."

Sadly, Deutsch died before the puzzle was finally solved. But now Gribakin's model has produced predictions that Surko has been able to bear out in his experiments. For example, Surko has found that annihilation is particularly rapid if positrons with energies of about 0.3 electronvolts are fired into molecules of butane. That 0.3 electronvolts is very close to the energy of a known vibrational energy state of butane. Surko also found that substituting fluorine atoms for hydrogen in the butane leads to a huge drop in annihilation rates of positrons – which is just what Gribakin's model suggests should happen. Bonds involving hydrogen are quite loose, with plenty of scope for attaching to positrons, while fluorine atoms hold onto electrons much more tightly, not allowing them the freedom to snatch a positron and form a bound state.

Surko is now tuning the energy of his positron beam to create and probe many different kinds of matter-antimatter compounds. The positrons in these compounds sidestep the Pauli exclusion principle, which flows from the laws of quantum mechanics and says that two particles can never share the same quantum state. The result is an atom with chemical properties never found in normal atoms. The Pauli principle restricts the number of electrons that occupy each energy level in ordinary atoms. But there is nothing to stop a positron occupying a quantum state already occupied by an electron. Because the arrangement of electrons determines an atom's chemical properties, this opens up a whole new set of possibilities.

The opposite of chemistry

Dave Schrader, a chemist at Marquette University in Milwaukee, Wisconsin, is working on ways of putting this to work. "If you get a positron bound into an ordinary molecule and it annihilates there, it will perturb the molecule in a way that can be calculated," he says. "It could give us a pathway to products that could not be made by other means." Such products might already exist in space: our galaxy, for example, is known to contain sources of antimatter and could be hosting chemical reactions we have never observed on Earth (see "Antimatter in the Milky Way"). There is certainly more chemistry in the universe than we have yet managed to perform, says Nella Laricchia, a physicist at University College London. She points out that a positron can be used to break up a molecule into ion fragments that do not form when it is hit by an electron. This could be a useful tool in chemical manufacturing. "We all kind of have an eye on that," Laricchia says. "People talk about it as molecular scissors using positrons."

And the new chemistry does not stop with positrons. At the CERN particle physics centre in Geneva, Switzerland, physicists have created thousands of antihydrogen atoms, consisting of a positron orbiting an antiproton. Alexander Dalgarno of Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, and Bernard Zygelman of the University of Nevada at Las Vegas recently calculated how a molecule made of one hydrogen atom and one antihydrogen atom might form. In principle, such a mixed molecule should form more easily than an ordinary molecule made of a pair of hydrogen atoms. The approach of two identical atoms before they bind is prevented by the need to avoid configurations in which the two atoms would enter the same state – the Pauli exclusion principle at work again. But those configurations are allowed when a hydrogen and an antihydrogen atom bind. CERN researchers hope to eventually try making such a molecule.

While the experimenters grapple with such problems, theoreticians are relishing the matter-antimatter interactions for which they can now try to make predictions. The mix of positrons and electrons could interact with the electrons of other atoms in completely new ways – opening up a whole new set of chemical possibilities. They could even lead to a versatile tool kit for tinkering with molecules. It's chemistry, but not as we know it. ●

"The mix of positrons and electrons could interact with other atoms in completely new ways. A whole new set of chemical possibilities opens up"

ANTIMATTER IN THE MILKY WAY

The antimatter chemistry we are beginning to explore on Earth may be just a shadow of what is going on in our galaxy.

In 1997, NASA's Compton Gamma Ray Observatory detected hints that a stream of positrons, or an "antimatter fountain", was rising from a region near the centre of the Milky Way. The observatory's instruments also observed similar signals from within the galactic disc.

Possible origins of the signal include the radioactive decay of supernova fragments, or particle jets coming out of black holes in the galactic disc, or possibly even more exotic ideas like dark matter. But it is also possible that some of these annihilation signals could be coming from cold molecular clouds in the galactic disc, which are made up mainly of hydrogen but contain larger molecules, including aromatic hydrocarbons such as benzene. Richard Lingenfelter of the University of California, San Diego, says part of the signal may actually be coming from antimatter chemistry taking place in the cloud. "Though the large molecules are relatively rare, they could have big effects because of the high rate of annihilation," he says. Cliff Surko, also at UCSD, is working on measuring annihilation rates for positrons on aromatic compounds to see exactly what these effects might be.

The INTEGRAL gamma-ray imaging satellite may also shed light on the mystery, if it can pick up signatures of antimatter chemistry taking place within molecular clouds, says Mark Leising of Clemson University in South Carolina, who is studying data from the satellite. So far, INTEGRAL has not seen signals of annihilation in the molecular clouds, but magnetic fields in the clouds may prevent the positrons getting inside the clouds in large numbers, says François Lebrun of the CEA research centre at Saclay in France, a scientist for INTEGRAL. As INTEGRAL continues observing, he says, better pictures could pick it up.

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