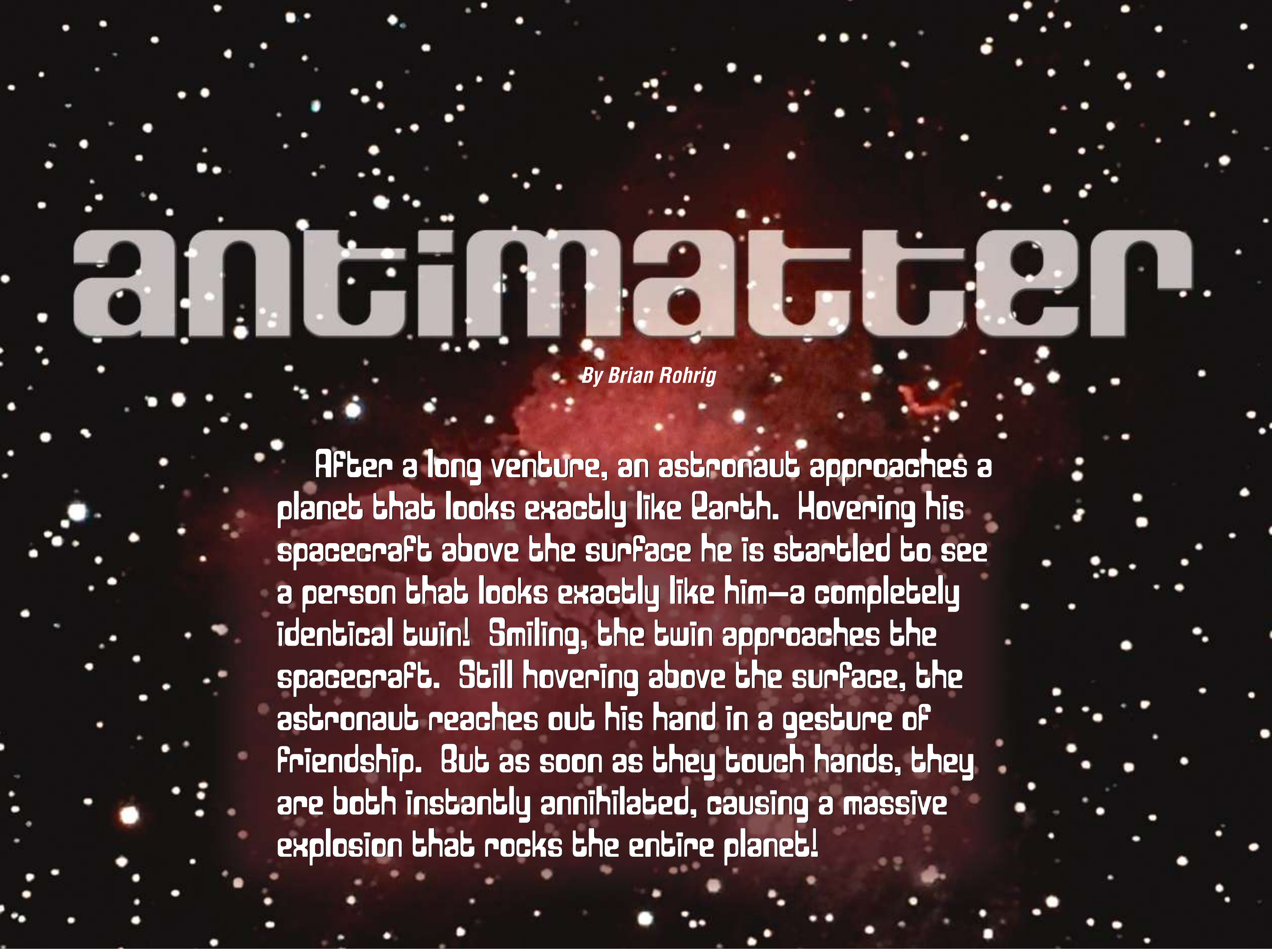


antimatter

By Brian Rohrig

After a long venture, an astronaut approaches a planet that looks exactly like Earth. Hovering his spacecraft above the surface he is startled to see a person that looks exactly like him—a completely identical twin! Smiling, the twin approaches the spacecraft. Still hovering above the surface, the astronaut reaches out his hand in a gesture of friendship. But as soon as they touch hands, they are both instantly annihilated, causing a massive explosion that rocks the entire planet!

Science fiction? Absolutely. However, there is a kernel of scientific truth behind this oft-repeated fictional scenario. Although the concept of a parallel universe only exists in the minds of science fiction writers (at least as far as we know), antimatter itself is a very real, and very strange phenomenon.

Antimatter is identical to ordinary matter in nearly every way. Antiparticles have the same mass as their corresponding particles. If an antiparticle has a spin, like an electron, the spin is the same as that of the corresponding particle. What differs is the sign of the electrical charge. Antiparticles always have a charge that is opposite in sign of the charge on the corresponding particle.

The existence of antiparticles was predicted from theory before they were actually discovered. In 1928, Paul A. M. Dirac, a British physicist, formulated a theory about the motion of electrons in electric and magnetic fields that included the effects expected according to Einstein's Special Theory of Relativity. This more complete theory was able to describe many characteristics of electron motion that earlier theories could not. It appeared to be an excellent theory, but it also made a very surprising prediction—for every particle in the universe there would have to exist an antiparticle—a notion never before proposed. Only four years later, the first antiparticle was discovered by Carl Anderson, a physicist from Caltech. He discovered anti-electrons while studying the effect of cosmic rays in the atmosphere on the nuclei of atoms with which they collided. He noticed that some particles were identical in every way to an electron except they had an opposite charge. He dubbed these positive electrons positrons.

Since the monumental discovery of this first antiparticle, scientists have since discovered that for every type of particle, there always exists its corresponding antiparticle. This is not to suggest that every single particle itself has an antiparticle, but rather that every single type of particle has its counterpart. Antimatter itself is quite rare in our universe. It has been estimated that only about one particle in 10–100 million in our universe is composed of antimatter.

In 1995, the first antiatoms were created at the European Center for Nuclear Research (CERN) in Geneva, Switzerland. Antihydrogen was created by forcing an antielectron around a nucleus composed of an antiproton. In all, nine antihydrogen atoms were created in 1995. Seven years later, experiments at CERN began to make antihydrogen atoms by the thousand. To date, no other antiatoms besides hydrogen have been created. But some have dared to speculate that if one type of antiatom has been created, why not others? And because atoms are the building blocks of all matter, perhaps entire planets or galaxies could be composed of antimatter. But so far, no evidence exists to support these speculations.

Tremendous energy

As if antimatter is not strange enough by itself, it displays even stranger behavior if it encounters ordinary matter. Every time an antiparticle meets its corresponding particle, they are both instantly annihilated with the release of pure energy in the form of gamma rays! Antimatter is considered to be the most powerful fuel in the universe. The energy generated by matter-antimatter collisions is even stronger than that of more conventional forms of nuclear energy such as fission or fusion. Fission is used in most nuclear warheads and nuclear power plants, and the energy of the Sun is a result of fusion.

The energy generated by matter-antimatter collisions is enormous. A milligram of antimatter could produce more energy than 2 tons of rocket fuel. If a human were to meet his antihuman and they were both annihilated, the energy generated would be equivalent to 1,000 one-megaton nuclear bombs. Each of these bombs could easily destroy an entire city. Yet antimatter's usefulness as a fuel is limited at the present time, partly because of its prohibitive cost. Because of its extreme rarity, the going rate for antimatter is around $60 billion per gram.

Scientists have speculated that the only way to accomplish long-distance space travel would be to use antimatter as a fuel. Any *Star Trek* fan can tell you that the starship *USS Enterprise* is powered by the energy released when matter and antimatter combine.

Albert Einstein's most famous equation—$E = mc^2$—beautifully describes where this energy comes from. According to this equation, E represents energy, m represents mass, and c represents the speed of light. Because the speed of light is a very large number (3×10^8 m/s), this equation shows that just a tiny bit of mass can be converted into a tremendous amount of energy, and vice versa. Experiments where matter and antimatter meet verify Einstein's equation.

Antimatter has a very short life span here on the Earth, severely limiting its usefulness. Most antiparticles created last only a few nanoseconds before combining with ordinary matter and being annihilated. And if antiparticles could be isolated, where would they be stored? Any container, if made of matter, would instantly react with the antiparticles. The only solution is to store them in an invisible container comprised solely of magnetic fields, which creates its own set of problems. However, antiatoms, which are neutral, are not restrained by a magnetic field. They will drift aimlessly, meeting sudden annihilation whenever they encounter normal matter. Probably the only solution to the problem of antimatter storage is to make antimatter as you need it. But this is easier said than done.

FACT

The catastrophic result of touching an antimatter version of you is an intriguing idea. But realistically, considering the energies involved, you probably wouldn't last that long—touching even a grain of antimatter sand or breathing antimatter atmosphere would, shall we say, ruin your day.

Making antimatter

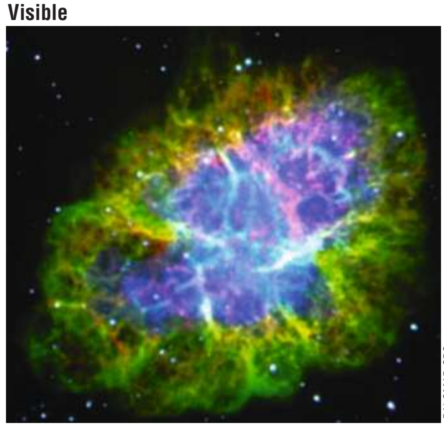
In laboratories, antimatter is created in enormous particle accelerators. Particle accelerators can be either linear or circular and involve accelerating particles to nearly the speed of light using powerful electric fields. One of the largest linear accelerators in the world is the Stanford Linear Accelerator in California. It is about 3 km (2 miles) long! This distance is necessary to accelerate particles to speeds approaching the speed of light. A circular accelerator outside of Chicago known as the Fermi National Accelerator Laboratory (Fermilab) is composed of a ring that is 6.3 km (3.8 miles) in circumference. Fermilab is the world's largest producer of antimatter. At full capacity, it can produce 60 billion antiprotons per hour. Despite this impressive-sounding statistic, this amounts to less than a nanogram of antimatter per year.

A particle accelerator can only accelerate charged particles, because only charged particles interact with and be accelerated by an electric field. Neutral particles like neutrons are not affected by magnetic fields. In a particle accelerator, a beam of electrons or protons will generally be accelerated to near the speed of light, and then smashed into a block of solid metal, such as copper or tungsten. Sometimes, two beams of particles will undergo a head-on collision. These intense collisions cause the particles to break apart, releasing a shower of secondary particles.

Particle accelerators are sometimes known as atom smashers. To put it crudely, scientists discover what is inside of a particle by smashing it apart. An analogy would be to discover what is inside of a television set by firing it from a cannon into a concrete wall, and then observing the parts that fly outward after the collision. A big difference is that in the subatomic realm some of this debris will recombine to form new stuff.

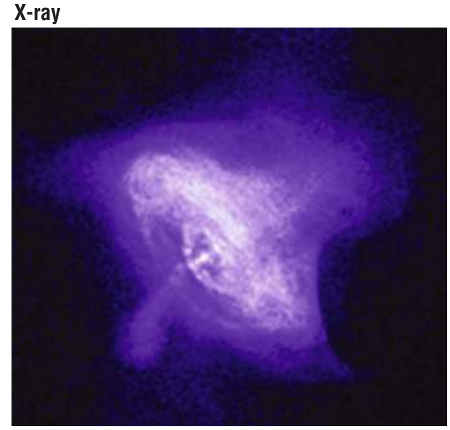
However, subatomic particles are much too small to be seen with the naked eye, or

Visible



PALOMAR OBS.

X-ray



NASA/CXC/SAO

The Crab Nebula is a remnant of a supernova. At the center is a spinning neutron star. It produces a high-speed wind of matter and antimatter that explodes when it hits the surrounding nebula. Energetic particles produce the extended glow in the X-ray image.

even with the most powerful microscope. Instead, scientists must rely on an image that the smashed particle makes on a special type of film. A chemical reaction occurs on normal photographic film when it is exposed to light, a type of electromagnetic energy. When a particle breaks apart, numerous secondary particles and waves of energy are released. A special type of film can record the paths or tracks left by these particles, and when analyzed, the identities of these particles and the energies they possess can be revealed.

According to Einstein's equation ($E = mc^2$), if mass can be converted into energy, then energy can also be converted into mass. Experiments have shown that pure energy in the form of gamma rays can produce matter, if the gamma rays have sufficient energy. And every time this happens, every matter particle is always accompanied by its antiparticle!

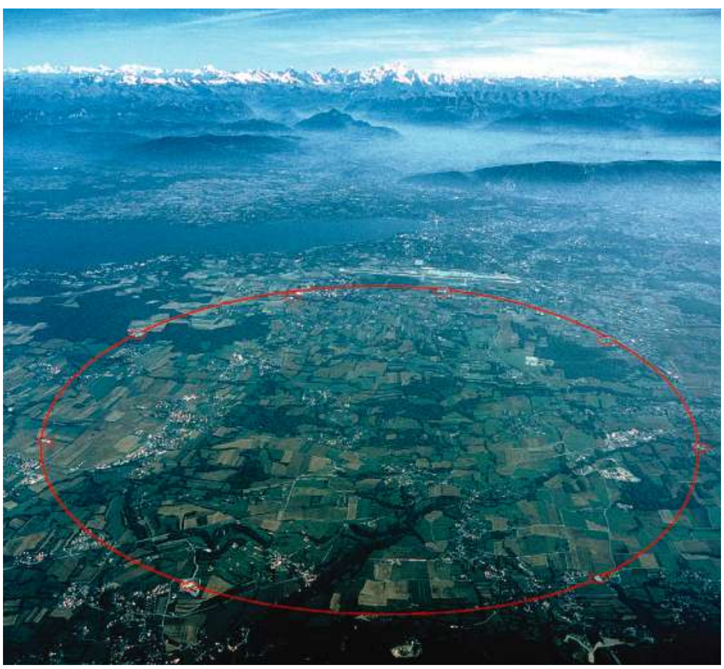
In particle accelerators, gamma rays are generated when particles are broken apart at high velocities. If these gamma rays are of sufficiently high energy, they can spontaneously transform into a particle-antiparticle pair. This is the reverse process of what happens when a particle and an antiparticle meet. It may seem like antiparticles are being created out of nothing, but in actuality they are being created from energy. Energy changes forms all the time. When a log burns in a fireplace, potential energy is changed into kinetic energy. The transformation of energy into matter is no less mysterious in the quantum world inhabited by subatomic particles.

Supernovas and Sun flares

Antimatter can be found naturally, but it is still quite rare. Supernovas—the result of exploding stars—shoot out massive quantities of particles at very high speeds. These particles are known as cosmic rays, and they possess enormous energies. If one of these particles collides with another high-energy particle, a fraction of this energy can be converted into a particle-antiparticle pair.

NASA

An artist's depiction of the solar antimatter factory. When accelerated particles hit the surface of the Sun, antimatter is created and then contacts normal matter. The resulting matter/antimatter explosion heats the area to over 20 million degrees and releases X-rays and gamma rays.

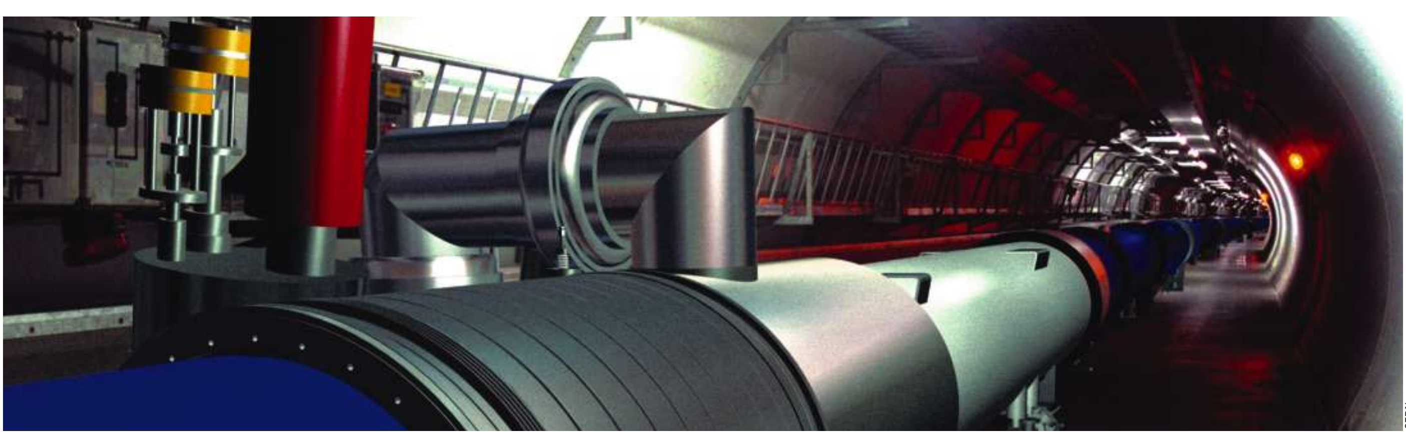


Left, Accelerators can be huge! The CERN accelerator in Geneva, Switzerland has a tunnel 27 kilometers long (red circle).

Below, Computer-generated image of the future Large Hadron Collider at CERN.

Solar flares are extremely powerful explosions on the Sun that create and destroy antimatter. During a flare, it's believed that antimatter is created when ordinary particles (electrons and various ions) are accelerated to extremely high speeds and then collide with slower particles in the Sun's atmosphere. On July 23, 2002, NASA's Reuven Ramaty High-Energy Solar Spectroscopic Imager spacecraft took gamma and X-ray pictures of one such event. That particular solar flare created half a kilogram of antimatter—enough to power the entire United States for two days!

Some scientists believe that regions of antimatter may exist somewhere in our universe. Evidence for this idea was observed in 1996 in the center of our own Milky Way galaxy, where a huge fountain of positrons (antielectrons) was annihilating furiously with electrons, spewing out large quantities of gamma rays. However, very little heavier anti-



CERN

Positron emission tomography scanner.

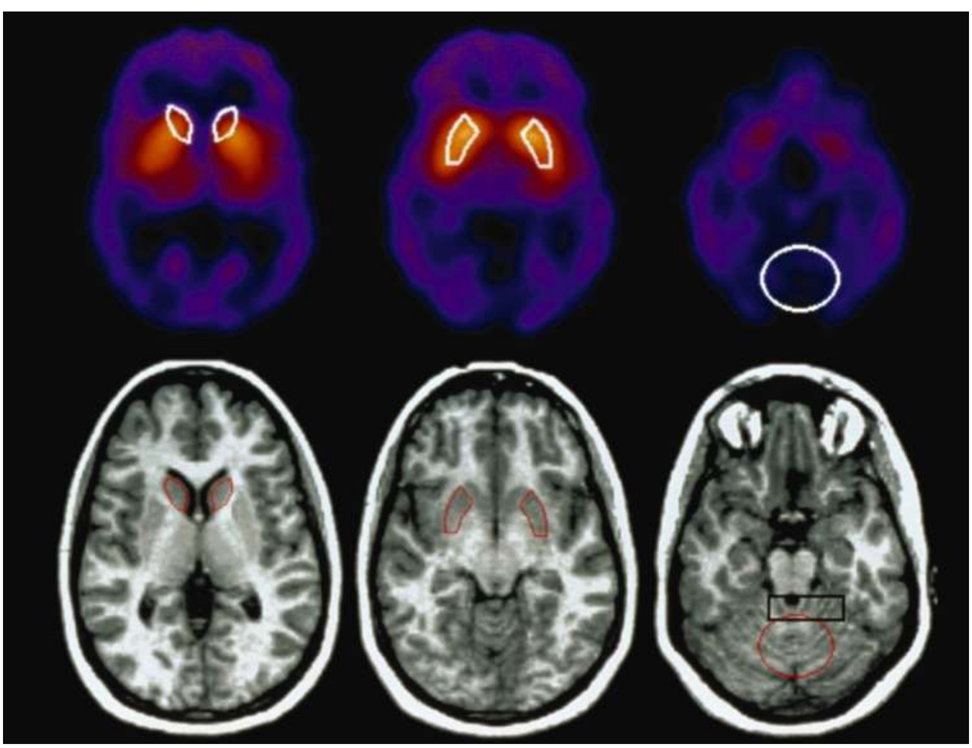
matter, such as antiprotons, has been found. This would indicate that there are no antiplanets or antigalaxies out there.

Everyday antimatter

Perhaps the most practical use of antimatter is in positron emission tomography (PET) scans. A patient is injected with a compound containing a particular isotope such as C-11, F-18, O-15, or N-13 dissolved in a liquid such as a glucose solution or water. These isotopes have very short half-lives, but they are strong positron emitters. When these positrons encounter electrons in the tissue, they are annihilated, producing gamma rays. Donut-shaped gamma ray detectors placed around the patient's body pick up these gamma rays. This information is then fed into a computer, which makes a three-dimensional image of the patient's body.

PET scans can be used to monitor blood flow, glucose metabolism, and to detect cancerous tumors. A cancerous cell, for example, will absorb more glucose than a noncancerous cell. The gamma ray detectors will reveal this. PET scans are especially useful in the diagnosis of brain disorders. PET scans can be used to find tiny blockages in blood vessels that may be a precursor to a stroke. They can also be used to find tumors, as well as the early chemical warning signs of schizophrenia, manic depression, Alzheimer's disease, and epilepsy. PET scanners must be located near particle accelerators, which are needed to produce the positron-emitting radioactive isotopes.

PET scan of a brain.



The rarity of antimatter in our universe is a good thing. If the amounts of matter and antimatter in our universe were exactly equal, the universe as we know it would cease to exist as soon as this matter met its antimatter component. The fact that you are reading this magazine demonstrates that it has not yet encountered its antimagazine. At least in our remote corner of the universe, matter is the norm. It is fun to speculate that perhaps the tiny bits of antimatter that have made it here from the other side are a hint of a parallel antiuniverse. But so far the scientific evidence says otherwise. But still, keep your eye out for that antiperson who looks exactly like you. And should you ever find him, do not shake his hand, but instead run as fast as you can in the opposite direction!

Brian Rohrig is a chemistry teacher at Jonathan Alder High School in Plain City, OH. His most recent article "The Science of Slime" appeared in the December 2004 issue of *ChemMatters*.