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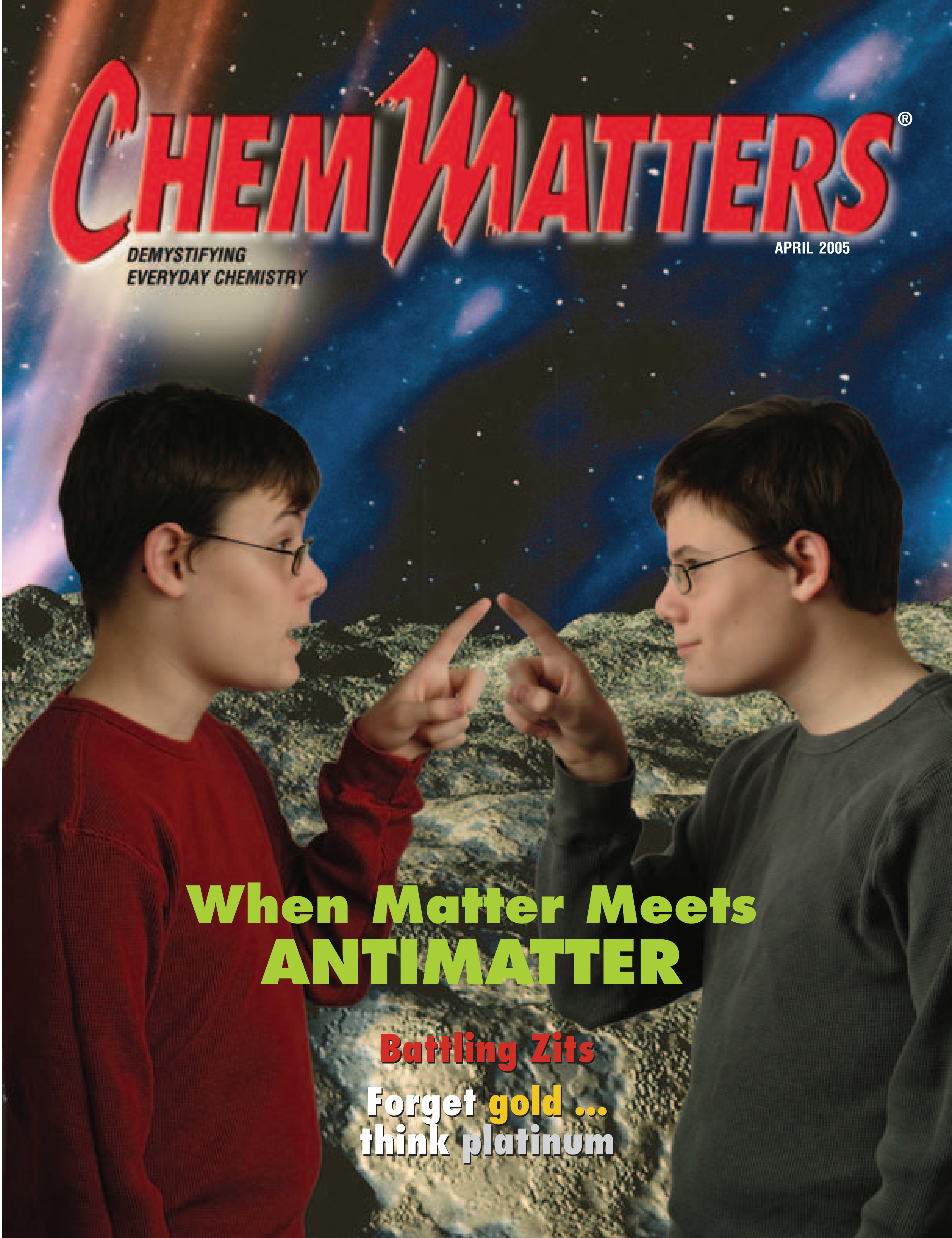
DEMYSTIFYING
EVERYDAY CHEMISTRY

APRIL 2005



When Matter Meets ANTIMATTER

Battling Zits

Forget gold ... think platinum

Question From the Classroom

By Bob Becker

Q: What is uranium enrichment?

A: Lately, uranium has been in the news, especially in connection with countries suspected of trying to acquire nuclear weapon capabilities.

Just like iron, aluminum, and other useful metals, uranium is mined from the earth as an ore—a mineral that contains the desired metal. Although uranium exists throughout the world, on average, its abundance in the earth's crust is a mere 0.0000018%. Compare this to 6.3% for iron and 8.2% for aluminum!

Once the uranium ore is mined, it is separated from impurities by a combination of physical and chemical processes that eventually produce water-soluble uranyl ions such as $UO_2(SO_4)_3^{4-}$. These ions are then reacted with an organic compound, usually an amine sulfate, $(R_3NH)_2SO_4$, dissolved in kerosene. Like oil, kerosene does not mix with water. Instead, it forms a separate layer on top. As the amine sulfate reacts with the uranyl ions, the uranium is converted from a water-soluble compound into one that is kerosene-soluble. As the uranium compound passes into the top (organic) layer, the impurities are left behind in the water layer below. Extraction is a very common chemical technique that is used in many industrial applications.

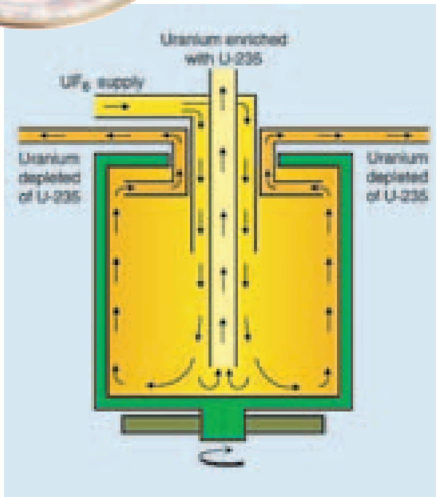
To separate the uranium from the organic layer, ammonia is added and $(NH_4)_2U_2O_7$ precipitates out. Upon heating, it converts to a powder, U_3O_8. Because of its bright golden color, this powder is commonly referred to as "yellow cake." This yellow cake is then transported to an enrichment plant, where the really challenging separation occurs.

Naturally occurring uranium is composed primarily of just two isotopes: U-235 (0.7%) and U-238 (99.3%). Although these two isotopes behave the same from a chemical point of view, from a nuclear point of view, they are very different: One is capable of undergoing fission (a very useful, energy-releasing process); the other is not. Unfortunately, in order to be of any use for a nuclear power plant, the uranium must contain around 3–5% U-235 by mass. The heat released by this fission process is used to boil water, which, in turn, spins turbines that generate the electricity for our factories, businesses, and homes.

No...Not this yellow cake!

PHOTODISC

Enriching the uranium, however, is a very difficult and costly process, much more so than the refining of the uranium ore. Because the uranium in the ore reacts differently than the impurities around it, it was quite easy to separate out using entirely chemical means. But because the two isotopes of uranium are essentially identical in terms of how they react with other compounds, separating one isotope from another requires a very different technique.



A gas centrifuge uses rapidly spinning cylinders to separate $^{238}UF_6$ from less dense $^{235}UF_6$.

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The characteristic used to separate the two isotopes is their very slight difference in masses. Both isotopes have 92 protons per atom, but U-235 has 143 neutrons, while U-238 has 146. This causes each U-235 atom to be about 1% lighter. Being lighter means U-235 particles move a tiny bit faster at the same temperature. In the gaseous state, this means they diffuse across a porous membrane more readily than do U-238 particles (Graham's law). Because both uranium and U_3O_8 are solids at standard temperature, it is common to ship the yellow cake to a conversion plant to change the yellow cake (U_3O_8) into gaseous UF_6.

At an enrichment facility, the gaseous UF_6 is passed through a series of porous membranes. Since the $^{235}UF_6$ molecules diffuse slightly faster than the $^{238}UF_6$ molecules, what passes through the membranes in a certain period of time is slightly richer than that which did not pass through. This process only enriches the uranium by about 0.002%; thus, it must be repeated in a succession of stages known as a "cascade." Typically, it requires somewhere around 1400 stages to obtain a product suitable for manufacture into nuclear fuel rods (3 to 5% U-235).

Diffusion is one means for enriching uranium. Another is the gas centrifuge process. Here, UF_6 is fed into a series of cylinders spun very rapidly—around 1000 revolutions per second! This creates an acceleration roughly 1 million times stronger than the Earth's gravity! The slightly denser $^{238}UF_6$ molecules concentrate at the outer edge of the cylinder, while the less dense $^{235}UF_6$ molecules accumulate near the center. Again, the enrichment is only slight, and the gas drawn from the center is passed into a second spinning cylinder, which enriches the U-235 further. But whereas diffusion requires 1400 stages, centrifugation requires only 10–20 stages to reach the same 3–5% enrichment level. Keep in mind that this 3–5% enrichment is only for the production of fuel rods for nuclear power plants. The far bigger political concern is over uranium enrichment for the production of nuclear weapons. Fortunately, this is a much more difficult and costly process, requiring enrichment to levels as high as 90%.

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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 antielectrons 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.

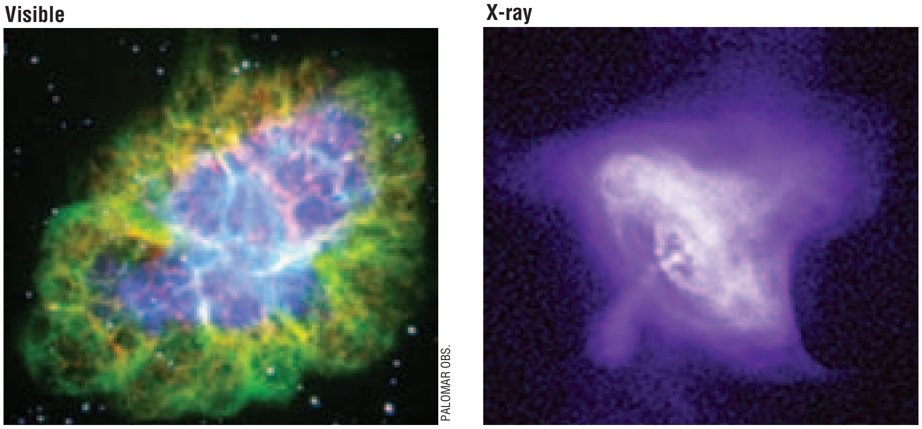
Scientists have speculated that the only way to accomplish long-distance space travel would be to use antimatter as a fuel. Any *Star Trek* fan can tell you that the starship *USS Enterprise* is powered by the energy released when matter and antimatter combine.

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.


Visible

X-ray

PALOMAR OBS.

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.

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 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!

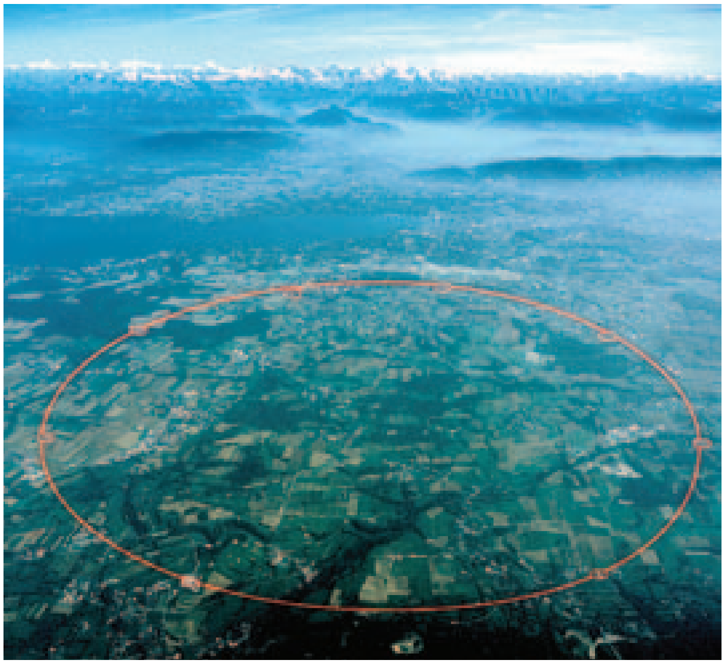
In particle accelerators, gamma rays are generated when particles are broken apart at high velocities. If these gamma rays are of sufficiently high energy, they can spontaneously transform into a particle-antiparticle pair. This is the reverse process of what happens when a particle and an antiparticle 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

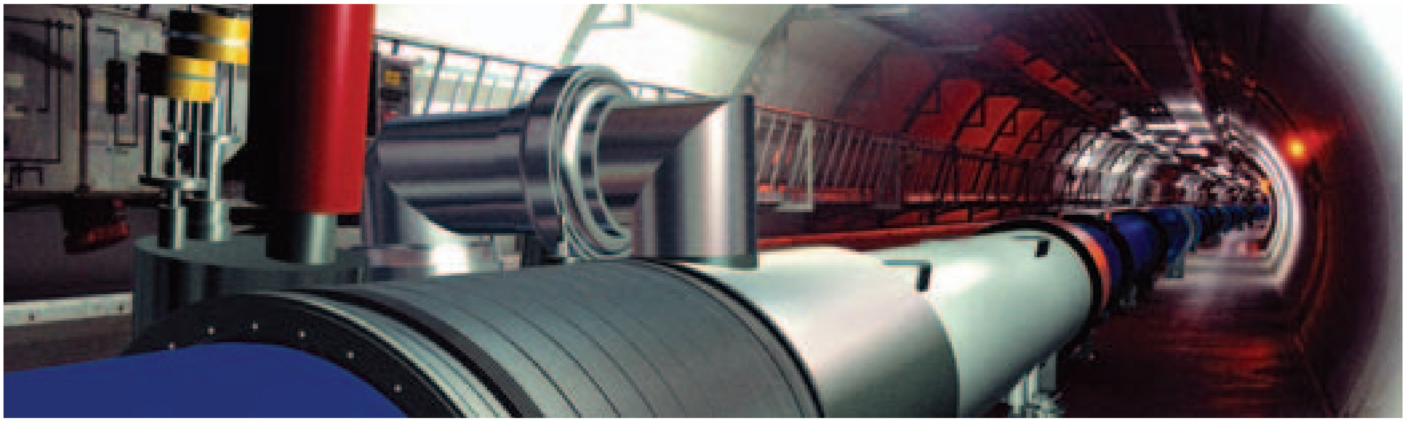
An artist's depiction of the solar antimatter factory. When accelerated particles hit the surface of the sun, antimatter is created and then contacts normal matter. The resulting matter/antimatter explosion heats the area to over 20 million degrees and releases X-rays and gamma rays.



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

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 (RHESSI) 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

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

Positron emission tomography scanner.

PHILIPS MEDICAL SYTEMS

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

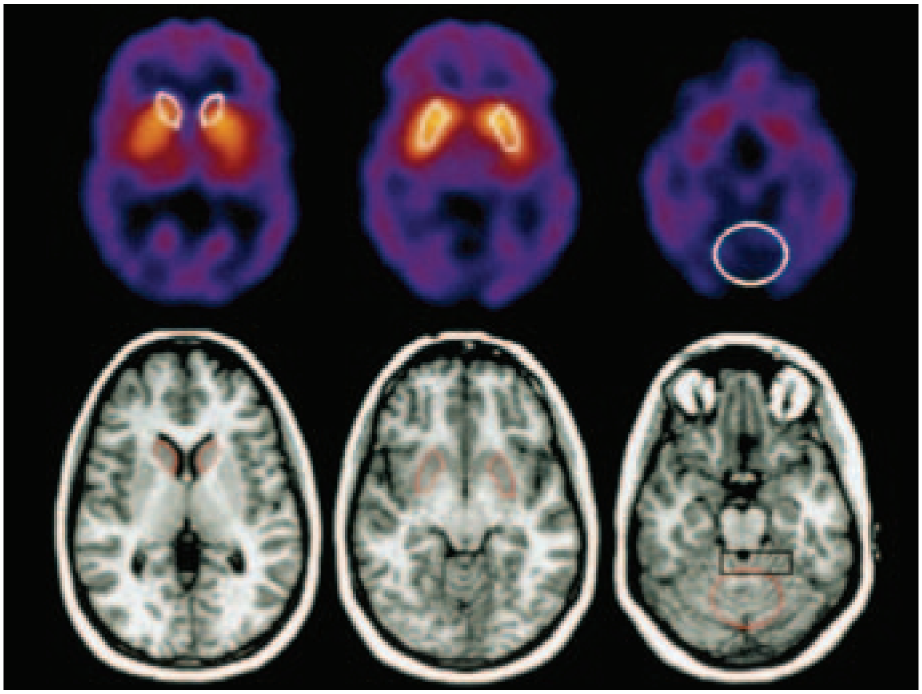
Everyday antimatter

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.

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!

PET scan of a brain.



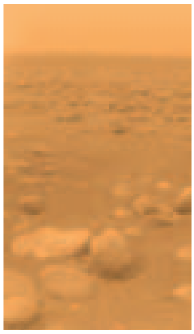
GETTY IMAGES

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*.

Chem.matters.links

A Titan success for Huygens!

On January 14, the European Space Agency's (ESA) Huygens probe made the first ever descent to the surface of Titan, a moon of Saturn. It's particularly exciting because, unlike most planets and moons in the solar system, Titan has a significant atmosphere (about 1.5 times Earth's). Huygens' data provide strong evidence for liquids flowing on Titan. However, the fluid involved is methane (CH_4), which can exist as a liquid at Titan's sub-170°C temperatures. The "rocks" shown in the picture are thought to be dirty ice. To see and hear (sort of) more pictures from the Huygens craft, visit **http://www.esa.int/SPECIALS/Cassini-Huygens/index.html** or the NASA site at **http://saturn.jpl.nasa.gov/home/index.cfm.**


ESA/NASA

First color image of Titan's surface.

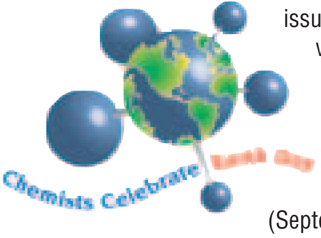
Antimatter spacecraft

Just like in *Star Trek*, antimatter fuel may someday propel us to distant planets and stars. Sure, there might not be a *warp field* involved, but it's estimated the explosive energy from just 10 grams of antimatter protons could propel a spacecraft to Mars in just a month. The details can be found at **http://science.howstuffworks.com/antimatter.htm**

Alternative fuels

The Department of Energy's Alternative Fuels Data Center is a vast collection of information on alternative fuels and the vehicles that use biodiesel, electricity, ethanol, hydrogen, natural gas, and propane. This site has more than 3,000 documents in its database, an interactive fuel station mapping system, current listings of available alternative fuel vehicles, and lots of alternative fuel information and related links at **http://www.eere.energy.gov/afdc/.**

Chemists celebrate Earth Day



That's right. The American Chemical Society will observe Earth Day on April 22. The theme for the 2005 celebration is "Air—Here, There, and Everywhere. To help celebrate the day, a series of hands-on activities are available for teachers and students at **http://chemistry.org/earthday.** The full text of our special NASA issue "Earth's Atmosphere" will be available through April at **http://chemistry.org/education/chemmatters.html.**

Renew or subscribe now

Renewal notices for 2005–06 will be mailed in early April. Renew or subscribe now before the hectic end of the school year. Next year, we have a special (extra) September issue planned.

You'll get five issues. If you wait until September to subscribe, the first two issues (September and October) won't go with our normal mailing and you might get them late.

Last year, we added multiyear subscriptions so that you can lock in current rates for two or three years. Look for the option on your renewal notice. Also, complete your classroom *ChemMatters* set with our new 20-year CD. You'll find every issue from 1983 through 2003 along with every *ChemMatters* Teacher's Guide ever published. We've made it easy to search for your favorite everyday chemistry topics featured in *ChemMatters* over the years. The price is only $25! Call 1-800-227-5558, or order online at **http://chemistry.org/education/chemmatters.html.**

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