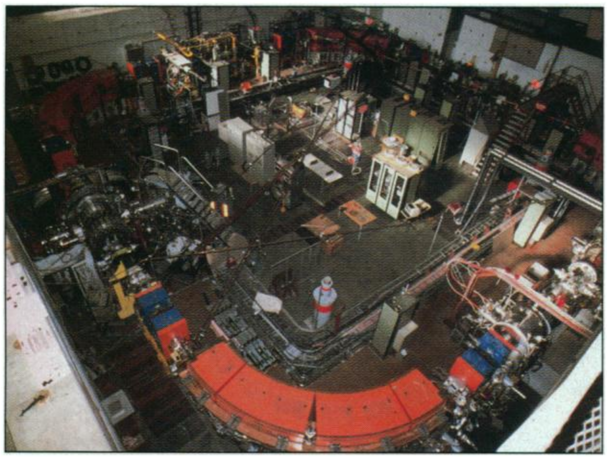
Physicists Take Aim at Antihydrogen

The tools and ingredients for making this first atom of antimatter are in hand; now researchers need to choose the right recipe



CERN

King LEAR. CERN's Low Energy Antiproton Ring.

Dreams of antimatter have been troubling physicists' sleep practically since it was discovered. The first crumb of antimatter, the positron, was detected in 1932, and just a year later Paul Dirac shared the Nobel Prize in physics with Erwin Schrödinger, in large part for having predicted the existence of this antimatter counterpart to the electron. But the novelty of the subject didn't keep Dirac from speculating in his Nobel lecture about the existence of entire antimatter worlds. Indeed, he wondered whether many of the stars we see at night might actually be made of antimatter.

Nearly 60 years later, antimatter still fascinates physicists and the public alike. *Star Trek* aficionados can buy detailed schematics of the antimatter reactor that powers the starship Enterprise. And in the real world, particle accelerators have created, for almost every fundamental particle, a shortlived antiparticle that "annihilates" in a burst of energy when it encounters its matter counterpart. Now, researchers around the world are poised to take the next step into Dirac's universe. Their goal: to construct the first antimatter atom, namely antihydrogen.

Although antihydrogen is the simplest possible antiatom, a supply of the material would enable physicists to find out whether antimatter is an exact mirror of normal matter, as their theories predict. "One isn't expecting a surprise. It's a question of doing experiments to test fundamental principles," says Richard Hughes, a theoretical physicist at Los Alamos National Laboratory. The experiments could, for example, yield a better comparison of the charges of antiprotons and protons than tests of the isolated antiparticle can. They could also reveal whether antimatter falls differently under gravity than matter does—a test difficult to perform with single antiparticles.

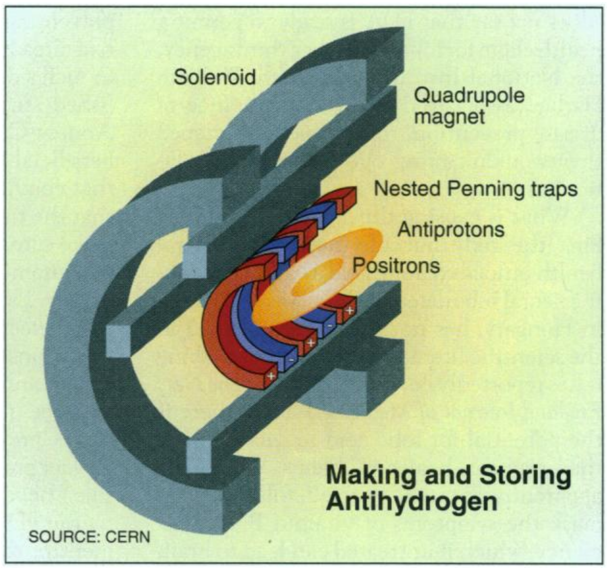
Until recently the difficulty of pinning down antihydrogen's constituents—antiprotons and positrons—and encouraging them to unite made studying antihydrogen appear little more than a pipe dream. But progress on both fronts has encouraged researchers to reevaluate the notion's feasibility. "Five or 6 years ago, the subject was totally visionary; now it's just extremely difficult," says physicist Daniel Kleppner of the Massachusetts Institute of Technology, who attended an antihydrogen workshop on 30 to 31 July in Munich that drew more than 100 scientists.

One of the main obstacles to antihydrogen production is the high energy of antiprotons, which are produced by colliding protons with matter in particle accelerators. When they're first made, the antiprotons are moving at close to the speed of light. By confining those particles in specially designed storage rings like CERN's Low Energy Antiproton Ring (LEAR), physicists can shear away much of that energy, slowing the antiprotons to about 6 MeV (million electron volts). But even that is too energetic for most of the planned methods of making antihydrogen: Such antiprotons would rarely "stick" to positrons. "If you want to do antihydrogen experiments, you have to get down to milli-electron volts [thousandths of an electron volt]," says John Eades, a CERN physicist.

Cold comfort. A collaboration led by Gerald Gabrielse of Harvard University has recently done just that. The effort reached its first milestone in the early 1980s, when Gabrielse (then at the University of Washington in Seattle) began trapping antiprotons from LEAR in an electromagnetic snare called a Penning trap. To slow LEAR's "lukewarm" antiprotons enough to stay in the trap, the team sends them through a metal foil, typically aluminum or beryllium, and closes off the far end of the trap with a 3000-volt potential barrier. Most of the particles still speed through the barrier and out of the trap, but a few bounce back towards the entrance. In the nanoseconds before the recoiling antiprotons escape, the trap snaps shut, erecting a second potential barrier across the entrance. By 1989, Gabrielse and his colleagues had refined the technique enough to capture thousands of antiprotons for nearly ten minutes at a time.

The trapped antiprotons, however, still had energies of up to 3000 eV—too high for antihydrogen assembly. To slow the particles to a crawl, Gabrielse's team incorporates a second trap into the middle of the Penning trap to hold a dense cloud of "cold," slow-moving electrons. As the trapped antiprotons oscillate back and forth through the cloud, the electrons absorb energy from the antimatter and emit it as synchrotron radiation. "It's like mixing hot and cold liquids," explains Eades. In a matter of seconds, the electron cooling reduces the energy of the antiprotons to 0.3 milli-electron volts—the equivalent of 4 degrees Kelvin.

With cold antiprotons safely in the fold, physicists are already forming collaborations to synthesize antihydrogen at LEAR—even though, says Kleppner, "right now no one knows exactly how to make the stuff." The basic idea,



Brewing antimatter. Nested electromagnetic traps contain overlapping plasmas of antiprotons and positrons.

A Fast Track to Antihydrogen?

Charles Munger has a unique strategy to win the race to antihydrogen. Even as other researchers work diligently to make the first atoms of this antimatter by the end of the century (see main story), the Stanford Linear Accelerator Center (SLAC) physicist is counting on a shortcut to give him the first look at antihydrogen. Munger thinks that physicists have already synthesized antihydrogen—albeit unwittingly—in an existing experiment at Fermilab. By piggybacking an antihydrogen detector on the experiment, he and colleagues from the University of California, Irvine, and Pennsylvania State University hope to observe this long-sought piece of antimatter as early as 1994.

Munger says the idea that a windfall of antihydrogen might be waiting to be harvested emerged recently when he and two theoretical physicists, Stanley Brodsky of SLAC and Ivan Schmidt of the Universidad Federico Santa Maria in Chile, were discussing a Fermilab experiment called E760. In that project, researchers direct a fast beam of antiprotons at a hydrogen gas target to study the annihilation of antimatter when it meets matter. The encounters don't always end in antiproton annihilation, however; sometimes the antiprotons narrowly miss the hydrogen nuclei, disturbing their electric field and, in the process, creating electron-positron pairs. In even rarer instances, the trio concluded, an antiproton should be able to snatch a positron and form an antihydrogen atom.

Munger set up a collaboration to detect and study those atoms, even though he calculates that each run of the experiment creates just a handful of them—up to 1000 over several months. "You don't get much of it this way," he admits. The scattered atoms of antihydrogen, however, should be easy to separate from the antiproton beam, since they are neutral and the beam is charged. To confirm their presence, Munger and his colleagues plan to allow the atoms to strike a thin membrane—say, aluminum foil. The collision should break the antihydrogen into its component parts, positrons and antiprotons, whose energy and momentum would reveal that they had been paired as atoms.

The strategy has the virtue of low cost—an estimated $300,000—and even antihydrogen researchers who could be scooped by it like its audacity. "It sounds like fun," says Harvard physicist Gerald Gabrielse, the leader of one of the teams trying to make antihydrogen. But this makeshift test doesn't seriously threaten to put Gabrielse and other antihydrogen researchers out of business. Not only will very few antiatoms be created, but they will emerge at relativistic speeds, allowing only the quickest and crudest of measurements. Munger and his colleagues hope to measure a certain energy transition known as the Lamb shift, for example, to see if it's the same for both versions of hydrogen. That would be one test of CPT invariance, a theorem describing the symmetries between matter and antimatter.

But even if his group can achieve that feat, Munger admits, it will be merely a "curiosity" once slow-moving, or "cold," antihydrogen, with its potential for much more detailed analysis, is synthesized. But being first has its rewards; he may be able to tell his grandchildren that he helped "discover" antihydrogen.

–J.T.

of course, is to combine the antiprotons with positrons. The problem, says Eades, is that in order to get the particles to join up in stable antihydrogen atoms, you need an additional body—a photon, say, or an electron—to carry away energy and momentum from the union. And just how to arrange that is the question dominating the field today.

One antihydrogen recipe discussed at the Munich workshop is based on the recent discovery by Japanese researchers that antiprotons fired into liquid helium don't always spiral immediately into the helium atom nucleus, where they encounter protons and annihilate. Once in a while, the collisions yield metastable pairings called "antiprotonic helium atoms" that last several microseconds. A team led by Toshimitsu Yamazaki at the University of Tokyo's Institute of Nuclear Study now proposes to breed antihydrogen from these exotic helium atoms by colliding them with positrons or positronium "atoms" (short-lived unions of a positron and an electron). In theory, the antiprotons could then change partners, switching from the helium atoms to the positrons to form antihydrogen; the electrons or other positrons would carry off energy to stabilize the newborn antiatom. There's one major hitch, however, believes Gabrielse: Any antihydrogen formed this way should immediately annihilate itself within the liquid helium.

Much more promising are strategies that would generate antihydrogen in a vacuum chamber, safe from instant annihilation. In the simplest scheme discussed at Munich, beams of antiprotons and positrons would simply collide and shed their excess energy as photons of radiation—a process called radiative recombination. The problem, explains Gabrielse, is that "it takes a long time to radiate a photon compared to the collision time." As a consequence, chances are high that an antiproton and a positron will bounce apart before the marriage is consummated. And although two groups showed last year that a laser tuned to the right frequency can speed up the emission of photons when protons and electrons combine to form normal hydrogen, the rate is still low enough that researchers are looking for a better way to make antihydrogen.

To speed up the recombination process further, investigators are turning their attention to three-way collisions, in which the odd particle out would carry off the excess energy. One proposal on the table at Munich was to aim a high-energy beam of positronium at antiprotons trapped in Gabrielse's snare. When an electron-positron pair collided with an antiproton, says Gabrielse, "the electron would just squirt off [from the positronium] and take off the excess energy," leaving behind an atom of antihydrogen.

Another three-body mechanism, championed by Gabrielse's own collaboration, might be even more efficient—perhaps a million times more productive than radiative recombination. He and his colleagues have suggested that two Penning traps, one designed to hold cold antiprotons and the other cold positrons, could be "nested" so that the two oppositely charged plasmas overlapped. The slow-moving particles would have a good chance of drifting into three-way encounters. And when two positrons and an antiproton all wandered into proximity, the group has calculated, the antiproton and one positron could form antihydrogen and the second positron would recoil, sponging up energy and momentum. A successful trial run of this system with electrons and protons showed that the two plasmas could be brought together, although the group has not yet detected the ordinary hydrogen atoms that should be spawned.

"The details of what will work out best are far from established," admits Gabrielse. And it may be a few years before all the needed instruments are completed and actual tests with antiprotons are scheduled at LEAR. But the investigators think the effort will be worthwhile, because once they have made antihydrogen, they can look forward to a wealth of matter-antimatter comparisons.

How true a mirror? One key principle to be examined is CPT invariance, a theorem derived from quantum mechanics and special relativity. CPT invariance holds that a particle and its antimatter twin have, among other symmetries, equal but opposite charges and an equal mass. Physicists have already made some inroads into confirming CPT invariance. But once investigators have their hands on a complete atom of antimatter, they should be able to make even more precise comparisons. Like normal atoms, an atom of antihydrogen should absorb and emit light at characteristic wavelengths, allowing investigators to exploit the advances in the high-resolution spectroscopy of hydrogen that have come from investigators such as Ted Hansch of the Ludwig Maximilian University in Munich. And because an atom's spectrum is a kind of blueprint of its electronic structure, Los Alamos' Hughes and Bernard Deutch of the University of Aarhus recently suggested that antihydrogen spectroscopy should make it possible to compare the charges of the proton and antiproton with a precision of 1 part in 100 billion.

Another fundamental test on the agenda for future batches of antihydrogen will be a study of how it falls under gravity. Specifically, researchers would like to test the weak equivalence principle, a cornerstone of general relativity that says that all particles accelerate at the same rate under gravity. "It's never been tested for antiprotons or positrons," says Hughes, primarily because their electric charges complicate the measurements. As a result, scientists have not been able completely to rule out fanciful theories that suggest antimatter "falls up" in a gravitational field. Given a neutral atom of antihydrogen, however, investigators could clock its fall directly or—and this appears more practical—search for "gravitational redshifts" in its spectrum.

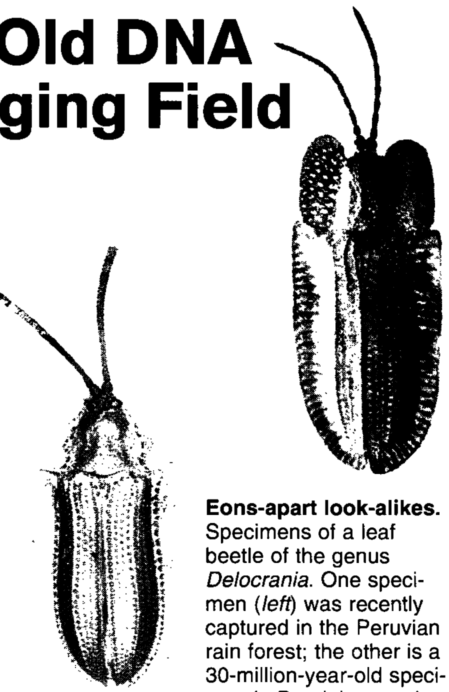
Before the antimatter researchers can perform their 21st-century equivalent of Galileo's experiment at the Leaning Tower of Pisa, though, they'll have to surmount some bureaucratic hurdles as well as the technical ones. For one thing, the future of LEAR itself is far from assured. "Something small like LEAR might get lost in the drive for the bigger machine [the proposed Large Hadron Collider]," worries Hughes. And some researchers see that as a potential calamity. "If you don't have LEAR, you would have to fold up your tents," says Kleppner. Over the next few months, an advisory committee at CERN will begin deciding LEAR's future.

As part of their plea to the committee, antihydrogen researchers have made certain its members know just how far the research has come in the past 7 years. Before Gabrielse's collaboration captured antiprotons and cooled them to 4 degrees Kelvin, the possibility of studying full-fledged atoms of antimatter would have been labeled science fiction. Laughs Hughes, "If you had talked about making antihydrogen, people would have said your ideas were weird." But no longer. In spite of the remaining hurdles, Dirac would be proud to see where his musings have led.

–**John Travis**

EVOLUTIONARY BIOLOGY

30-Million-Year-Old DNA Boosts an Emerging Field



B. FARRELL

Eons-apart look-alikes. Specimens of a leaf beetle of the genus *Delocrania*. One specimen (*left*) was recently captured in the Peruvian rain forest; the other is a 30-million-year-old specimen in Dominican amber.

When does a novel scientific technique cease to be a virtuoso trick and become central to a discipline's technical repertoire, helping solve some outstanding fundamental problems? One indication may be that lab jokes stop. Take the case of entomologist Dave Grimaldi and his colleagues at the American Museum of Natural History in their effort to get DNA from ancient termites trapped in amber. "We used to joke about it in the lab: 'Yeah, it's probably just another one of those stupid PCR tricks,'" says Grimaldi. The reason for the jokes was that the polymerase chain reaction, or PCR, had been used to amplify minute DNA samples from all kinds of unlikely specimens, but those feats were nothing more than technical star turns: The information from the DNA hadn't been correlated with anatomical changes—and hence hadn't advanced evolutionary knowledge all that much.

Grimaldi and his colleagues Rob DeSalle, John Gatesy, and Ward Wheeler are no longer joking—at least not about PCR. Using that method, they have now succeeded in extracting and amplifying tiny remnants of DNA from a 30-million-year-old termite fossilized in amber from the Dominican Republic—and published their results in this issue of *Science* (p. 1933). The feat of obtaining ancient DNA from specimens in amber, which many in the field thought was impossible, makes it feasible to correlate specific aspects of body size and shape with DNA sequences. As paleoentomologist Conrad Labandeira at the Smithsonian Institution says, specimens preserved in amber "were always special, because the specimens are three-dimensional, enabling you to see things such as the mouth parts and genitalia in detail. But [having the DNA] will allow us to get a molecular handle" on the evolutionary history of those specimens.

In their effort to be the first to extract and amplify DNA from amber specimens, Grimaldi and his colleagues have arrived at the finish line in a virtual dead heat with George Poinar, an entomologist at the University of California, Berkeley, who published a report in the latest issue of *Medical Science Research*, a British journal, announcing his team's success in extracting and sequencing DNA from a 30-million-year-old amber-preserved stingless bee. And in extracting this prehistoric DNA, the two groups haven't just smashed the world's record for the oldest genetic sequences (the former record-holder being a 17-million-year old-magnolia leaf), they've begun to throw light on the perplexing, but fundamental, question of why insects are so conservative in evolutionary terms.

Naturally, this potential of PCR coupled with well-preserved ancient specimens hasn't been lost on other investigators, who are at this moment speeding to extract older and older examples of genetic information. Among them: DNA from 200-million-year-old fishes, perhaps even a dinosaur or two. And the researchers crowding into this area could even be in the process of defining a new discipline. Says Michael Clegg, a plant

AMERICAN MUSEUM OF NATURAL HISTORY

Genetic screening. Rob DeSalle, Ward Wheeler, Dave Grimaldi, and John Gatesy examine DNA sequences from insects trapped in amber.