gene expression[6]. Erez *et al*. sequenced the phi3T genome and identified a gene encoding a protein 43 amino-acid residues long that they named AimP. This protein shows strikingly similar features to those of proteins involved in quorum sensing and other peptide-mediated signalling pathways in *B. subtilis*.

Erez *et al*. found that, during bacterial infection by phage phi3T, enzyme-mediated cleavage of AimP produced a six-residue peptide, called arbitrium by the authors, which was secreted from the bacteria. Uptake of arbitrium by other bacterial cells through the bacterial oligopeptide permease (OPP) transporter protein increased the probability that phi3T infection of the bacteria would result in lysogeny. At the high concentrations of arbitrium reached during the late stages of a phage-infection process, bacterial-cell lysis was strongly suppressed because of the high frequency of phage lysogeny (Fig. 1).

The authors found that arbitrium acts by binding to an intracellular phage protein, AimR, and inhibiting its activity. AimR can bind to a specific site on the phage genome and activate transcription of the *aimX* gene, which promotes the lytic pathway through an unknown mechanism. Erez and colleagues observed that arbitrium in bacterial cells reduces the expression of *aimX*, and thus increases the probability of lysogeny.

Notwithstanding the complexity of the arbitrium system, the logic is simple. During the initial period of phage infection, when the concentration of phage particles is low and that of bacteria high, the production of phage particles through the lytic pathway could provide a successful bacterial-infection strategy. However, as the number of phage particles increases, the concentration of host cells might decrease to a level at which phage particles could no longer find a host cell to infect. In this context, an approach to preserve host cells and phage genomes by promoting the phage's lysogenic life cycle would be preferable. Interestingly, the probability of phage lambda lysogeny increases when multiple phages simultaneously infect the same cell[7]. However, the phi3T system provides the first example that I know of in which phages infecting different cells have been shown to communicate with one another through a small molecule, and this communication aspect is what makes the work by Erez and colleagues so exciting.

The authors found that communication systems similar to that involving arbitrium exist in more than 100 phages, indicating their general utility for phage survival. Furthermore, Erez *et al.* demonstrated that the arbitrium system of another phage operates in a similar manner, although it uses a different peptide sequence. These arbitrium peptides affect only the phage that produces them. The authors observed a wide diversity of peptide sequences among phages that had arbitrium-like systems, implying an evolutionary drive for phage specificity. These phages are 'speaking' different molecular languages and so convey messages only to their own kind.

Small-molecule communication between phages enables the viruses to strongly influence the decisions of their descendants. Such communication provides a stunning example of the complexity and nuance of function that can be achieved by 'simple' entities. Despite extensive investigation of phage genomes, most have many genes of as yet unknown function. Erez and colleagues' discoveries provide a hint that some uncharacterized phage genes might be involved in mechanisms that increase the viruses' evolutionary fitness. Perhaps we will find that phages can communicate with each other on many other topics, too. ■

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PHYSICS

Optical transition seen in antihydrogen

Precise measurements of antimatter systems might cast light on why the Universe is dominated by matter. The observation of a transition in an antihydrogen atom heralds the next wave of high-precision antimatter studies. **See Letter p.506**

STEFAN ULMER

On page 506, Ahmadi *et al.*[1] report a milestone in antimatter research — the first measurement of a light-induced transition in a pure antimatter atom, antihydrogen. This experimental masterpiece paves the way for investigations of unexplored regions of the antimatter world with unprecedented sensitivity.

In the standard model of particle physics, every particle has its own antimatter counterpart — particles of quasi-identical fundamental properties, the most well-known of which have opposite magnetic moments and electric charge from the matter particle. However, these anti-particles are not just 'model' particles. They can be observed in radioactive decay processes, cosmic rays and high-energy reactions such as particle collisions.

Anti-particles can even be produced using a process called pair production, an application of Einstein's famous equation of mass–energy equivalence, $E = mc^2$. When the kinetic energy (E) of a collision reaction exceeds a certain threshold, collisions naturally produce particles of mass m. The particles are produced in matter–antimatter pairs as a consequence of several conservation laws. Electrons and positrons are examples of matter–antimatter counterparts from the lepton family of particles, whereas protons and antiprotons are from the baryon family.

These reactions can be reversed in processes called annihilations. Some annihilations produce tiny excesses of matter[2], but these are almost ten orders of magnitude too small to explain why, on cosmological scales, the Universe is composed almost entirely of matter. This imbalance is one of the most intriguing puzzles and hottest topics in modern physics.

Experimentalists compare the fundamental properties of matter particles with those of their antimatter counterparts with high precision, hoping to find tiny dissimilarities that might contribute to a consistent explanation for the Universal imbalance. In the 1980s, the fundamental properties of charged leptons were compared[3] with some precision, down to parts per billion. Then, in the 1990s, techniques were developed to catch and cool antiprotons in electromagnetic containers known as Penning traps. This led to a comparison[4] of the charge-to-mass ratio of protons with that of antiprotons with a precision of 90 parts per trillion (p.p.t.). A later study improved the precision to 69 p.p.t. (ref. 5).

Electrically neutral matter–antimatter counterparts have also been investigated. For example, neutral K-meson masses were compared[6] with fractional precisions of the order of parts per quintillion (1 quintillon is 10^{18}). The study of another neutral system, antiprotonic helium (which consists of an antiproton and an electron orbiting a helium nucleus), has also enabled precise measurements to be made of the antiproton-to-electron mass ratio[7]. So far, the examined matter–antimatter counterparts seem to be exact analogues of each other at the achieved levels of experimental uncertainty.

However, the optical spectra of neutral anti-atoms made entirely from antimatter had never been compared to those of their matter counterparts. This experiment is now reported by Ahmadi and colleagues (members of the ALPHA Collaboration at CERN, Europe's particle physics laboratory near Geneva in Switzerland). They have observed the response of trapped antihydrogen atoms to optical light: the transition of the antihydrogen's positron from the 1*s* ground state to the excited 2*s* state. The wavelength of the light needed to generate the transition has been determined with a precision greater than nine significant figures, and seems to be identical to that needed to excite the equivalent transition in hydrogen. This achievement is based on the use of a sophisticated experimental machine that took almost 20 years to develop. The measurement required great experimental skill and combined key techniques of particle physics, non-neutral plasma physics, trap physics and high-resolution laser spectroscopy.

Experiments with charged anti-particles use well-established electromagnetic trapping techniques[3–5], but investigations of antihydrogen require very different approaches. First, the electrically neutral antimatter atoms must be synthesized and trapped. This is immensely difficult, because neutral-atom traps are orders of magnitude more shallow than their ion-trap partners, and require strong magnetic gradients that are technically complicated to produce. The first report[8] of antihydrogen trapping was published in 2010 after a series of innovative experimental developments, and achieved a trapping rate of only about 0.11 atoms per trial. Higher trapping rates of about 5 per trial were reported 2 years later[9].

The challenge of having such a small number of trapped neutral particles to work with had to be overcome by Ahmadi and colleagues. A key ingredient in their success was their improvement of methods for synthesizing antihydrogen, which increased the trapping rate they could achieve to approximately 14 atoms per trial. This advance greatly increases the strength of the signals that can be obtained from their antihydrogen experiments.

The current result is just the starting point for a multitude of measurements in which antihydrogen is used to test matter–antimatter symmetry. Planned full scans of the 1*s*–2*s* and other optical transitions will profit from the use of advanced spectroscopy techniques[10] that have yielded fractional uncertainties of the order of just 10^{-15} in studies of hydrogen.

The ALPHA Collaboration previously reported[11] the first spectroscopic measurements of a phenomenon called 'ground-state hyperfine splitting' in antihydrogen, and further such experiments are planned by CERN's ASACUSA collaboration[12]. The resolution of these measurements will benefit greatly from the improved antihydrogen trapping rate reported by Ahmadi and co-workers. Unlike the 1*s*–2*s* transition, hyperfine splitting is a purely magnetic phenomenon, and its spectroscopy will thus probe very different physics from the current experiment.

How precise will future experiments need to be to persuade physicists that matter and antimatter are equivalent? In truth, no result will be precise enough — as long as ideas are available for ways to further reduce experimental uncertainties, the arguments to continue investigating are too strong. Moreover, the reason for studying matter–antimatter counterparts so precisely is to search for as yet unknown, presumably rather weak, interactions, that could manifest themselves at any level of precision. Some of these interactions might exclusively involve antimatter, which thus constitutes a crucial probe to test related aspects of physics beyond the standard model[13].

One very weak interaction is gravity. Even the gravitational field of a body as large as Earth causes only fractional redshift effects (a modification in the frequency of electromagnetic radiation) of about 10^{-16} per metre. Several experiments that will profit from Ahmadi and colleagues' findings — especially the improved trapping rate — are planned to study the gravitational behaviour of antihydrogen. Some model-dependent limits on the gravitational behaviour of antimatter have already been derived from measurements of antiprotons[4,5]. Studies of falling antihydrogen are planned by the AEGIS Collaboration[14] at CERN, and by ALPHA's side-project, ALPHA-g; these will provide model-independent results.

CERN will continue to strongly support antimatter physics research by setting up the Extra Low Energy Antiproton (ELENA) synchrotron, a facility that will enable much more efficient use of antiprotons. CERN's upgrade package also includes a new antihydrogen gravity experiment, GBAR (ref. 15). A key component of this experiment is the production of positively charged antihydrogen ions. If used with methods reported in 2011 for cooling ions[16], GBAR will provide colder, and thus more controllable, antihydrogen atoms than are currently available, making the future of high-precision antimatter physics even brighter. ■

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PLANETARY SCIENCE

Earth's building blocks

Earth grew by the accretion of meteoritic material. High-precision isotopic data reveal how the composition of this material changed over time, forcing revision of models of our planet's formation. **See Letters p.521 & p.525**

RICHARD W. CARLSON

For more than half a century, scientists have estimated the bulk chemical composition of Earth by comparison with its potential cosmic building blocks, as sampled by meteorites. In a conceptual breakthrough, on page 521, Dauphas[1] uses the unique isotopic content of different types of meteorite to identify those that best represent these building blocks. The author also evaluates whether the material added to Earth during its formation changed over time. On page 525, Fischer-Gödde and Kleine[2] show that not even the most recently accreted 0.5% of such material consisted of the type of meteorite long thought to be a major contributor to our planet's composition. This realization challenges our understanding of how Earth obtained its inventory of volatile elements and water.

In the 1970s, Earth was shown to have a different oxygen-isotope composition from most meteorites[3]. The only meteorites that have a similar oxygen isotopic abundance are called enstatite chondrites, which are silicon-rich and highly reduced (most iron is in the