

enabled precise measurements to be made of the antiproton-to-electron mass ratio⁷. 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 1s ground state to the excited 2s 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 report⁸ 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 later⁹.

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 1s–2s and other optical transitions will profit from the use of advanced spectroscopy techniques¹⁰ that have yielded fractional uncertainties of the order of just 10^{-15} in studies of hydrogen.

The ALPHA Collaboration previously reported¹¹ the first spectroscopic measurements of a phenomenon called 'ground-state hyperfine splitting' in antihydrogen,

and further such experiments are planned by CERN's ASACUSA collaboration¹². The resolution of these measurements will benefit greatly from the improved antihydrogen trapping rate reported by Ahmadi and co-workers. Unlike the 1s–2s 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 model¹³.

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 Collaboration¹⁴ 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 ions¹⁶, GBAR will provide colder, and thus more controllable, antihydrogen atoms than are currently available, making the future of high-precision antimatter physics even brighter. ■

Stefan Ulmer is at the *Ulmer Initiative Research Unit, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan.*
e-mail: ulmer@riken.jp

- Ahmadi, M. *et al.* *Nature* **541**, 506–510 (2017).
- Patrignani, C. *et al.* (Particle Data Group) *Chin. Phys. C* **40**, 100001 (2016).
- Van Dyck, R. S., Schwinnberg, P. B. & Dehmelt, H. G. *Phys. Rev. Lett.* **59**, 26 (1987).
- Gabrielse, G. *et al.* *Phys. Rev. Lett.* **82**, 3198 (1999).
- Ulmer, S. *et al.* *Nature* **524**, 196–199 (2015).
- Schwingerheuer, B. *et al.* *Phys. Rev. Lett.* **74**, 4376 (1995).
- Hori, M. *et al.* *Science* **354**, 610–614 (2016).
- Andresen, G. B. *et al.* *Nature* **468**, 673–676 (2010).
- Gabrielse, G. *et al.* *Phys. Rev. Lett.* **108**, 113002 (2012).
- Parthey, C. G. *et al.* *Phys. Rev. Lett.* **107**, 203001 (2011).
- Amole, C. *et al.* *Nature* **483**, 439–443 (2012).
- Kuroda, N. *et al.* *Nature Commun.* **5**, 3089 (2014).
- Ding, Y. & Kostelecký, V. A. *Phys. Rev. D* **94**, 056008 (2016).
- Doser, M. *et al.* *Class. Quantum Grav.* **29**, 184009 (2012).
- Walz, J. & Hänsch, T. W. *Gen. Rel. Grav.* **36**, 561 (2004).
- Brown, K. R. *et al.* *Nature* **471**, 196–199 (2011).

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, Dauphas¹ 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 Kleine² 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 meteorites³. 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

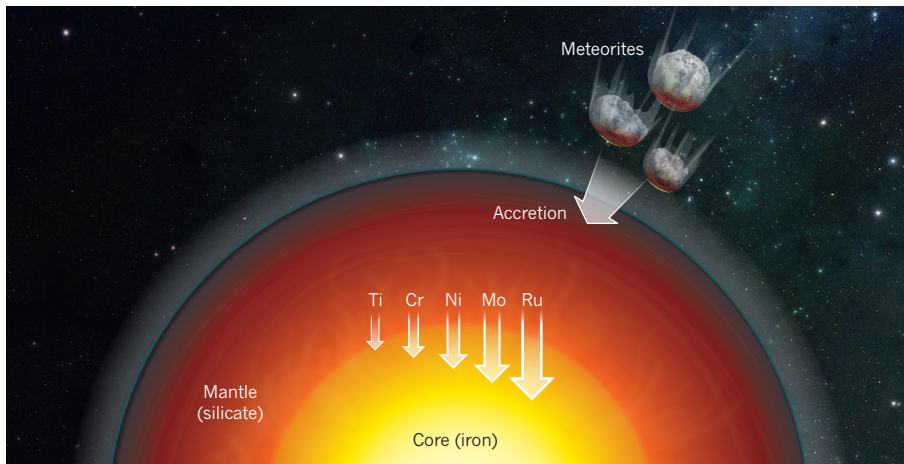


Figure 1 | Probing Earth's formation. When Earth's iron-metal core separated from its silicate mantle, elements more soluble in metal than in silicate were transferred to the core. After core formation was complete, these elements were added back to the mantle by accretion of meteoritic material. Dauphas¹ considers the elements titanium, chromium, nickel, molybdenum and ruthenium (listed in order of their increasing preference for the core). Using the isotopic differences in these elements between Earth and meteorites, the author shows that our planet formed from a mixture of meteorite types during the first 60% of its growth and subsequently almost entirely from oxygen-poor meteorites called enstatite chondrites. Fischer-Gödde and Kleine² use high-precision ruthenium isotopic measurements to confirm that the last 0.5% of the accreted material was most like enstatite chondrites.

form of metal or sulfide, rather than oxide). This similarity drove several models that based Earth's composition on enstatite chondrites^{4,5}. However, the mismatch in the elemental composition between such meteorites and Earth's rocks led most researchers to continue using models based on more-oxidized and volatile-rich meteorites known as carbonaceous chondrites^{6,7}.

Improvements in the ability to determine precise isotopic abundances led to the discovery that many elements can be used to distinguish between Earth and meteorites⁸. In 2011, a study of these isotopic differences suggested that Earth was made from a mixture of meteorite types⁹, not just the carbonaceous chondrites that had been the main component of most models. Dauphas takes this approach further by developing a methodology in which the isotopic disparity between different groups of meteorites and Earth can be used to track the composition of the materials that accreted to our planet throughout its formation.

The most important chemical differentiation event in Earth's history was the separation of its iron-metal core from its silicate mantle (Fig. 1). When the core formed, elements that are more soluble in metal than in silicate were selectively removed from the mantle. Some elements (such as iridium, platinum, palladium and ruthenium) are so soluble in metal that the mantle should have been effectively stripped of them during core formation. However, the observed abundances of these elements in the mantle are in the same relative proportion as those seen in primitive meteorites. Furthermore, they are depleted by a factor of only about 350 with respect to their abundance in meteorites¹⁰, compared with the million-fold

depletion¹¹ that would be expected were the mantle in chemical equilibrium with the core.

One explanation is that these elements were added back to the mantle by subsequent accretion of meteoritic material (with a mass of about 0.5% that of Earth) after core formation was complete¹². Dauphas notes that, if this is so, the isotopic composition of ruthenium in the mantle tracks only the last 0.5% of the material from which our planet formed. By contrast, the mantle isotopic composition of elements that are completely insoluble in metal reflects the average composition of all the material from which Earth grew.

Using this approach, for the series of elements titanium, chromium, nickel and molybdenum (listed in order of their increasing preference for the core), Dauphas estimates that their isotopic composition in the mantle reflects the last 95%, 85%, 39% and 12% of material accreted by Earth, respectively. Then, using the isotopic differences in these elements between Earth and meteorites, the author finds that our planet formed from a mixture of meteorite types for about the first 60% of its growth and almost entirely from enstatite chondrites for the remainder. The high-precision ruthenium isotopic measurements presented by Fischer-Gödde and Kleine reinforce the conclusion that the last 0.5% of the accreted material was isotopically most like enstatite chondrites.

The disturbing aspect of this conclusion is that the chemical composition of enstatite chondrites is very different from that of rocks on Earth's surface. Consequently, if Earth is mostly made from enstatite chondrites, its deep interior must have a substantially different composition from its outer layers³.



50 Years Ago

Some of the problems of the links between psychiatry and genetics are discussed in *Research on Genetics in Psychiatry*, the report of a scientific group of WHO. There is clear evidence that genetic factors are involved in the aetiology of a number of mental diseases, although the genetic factors are more obvious in some than in others. Huntington's chorea is the best example of a hereditary mental disease — family trees showing very clearly the inheritance of a single dominant gene have been compiled for a number of families in which the disease is current. In most of the more common mental diseases, schizophrenia, epilepsy and manic-depression, for example, the genetic component is far less clear cut ... The WHO group puts forward a number of proposals for topics on which work should be concentrated. It calls for research into the frequency of chromosome abnormalities and the relationship of these abnormalities with mental disorder, particularly from the biochemical point of view. It would like to see more work on twins, preferably on an international scale, including studies of twins separated in early life.

From *Nature* 28 January 1967

100 Years Ago

Stars at a Glance — This simple guide to the stars will admirably meet the requirements of those who are commencing the study of astronomy or who have become interested in the heavens since the lighting restrictions came into operation. It provides an "aspect chart" for each month, which will enable the observer to make a general acquaintance with the stars visible at a specified time and date, and four additional charts showing the constellations in greater detail.

From *Nature* 25 January 1917

Although possible, this explanation is not easily reconciled with many lines of evidence. An alternative offered by Dauphas is that the enstatite chondrites might be leftovers of the processes that formed Earth, but whose compositions were modified by the planet-forming process. This is an intriguing suggestion, but one whose consequences will need much more investigation.

If the last 0.5% of material accreted by Earth had been composed of a particular type of volatile-rich carbonaceous chondrite, known as a CI chondrite, an amount of water equivalent in mass to Earth's oceans would have been added to the planet¹⁰. Fischer-Gödde and Kleine's measurements instead show that this late-accreted material consisted of relatively 'dry' enstatite chondrites. Water was therefore

supplied to Earth throughout its growth, rather than being added late in its history through the accumulation of volatile-rich materials such as carbonaceous chondrites or comets.

The results presented in these papers lead to the troubling conclusion that the meteorites in our collection are not particularly good examples of Earth's building blocks. Although this makes estimation of the planet's bulk composition more difficult, new isotopic data and approaches to interpreting those data provide the next step towards a better understanding of how Earth formed. ■

Richard W. Carlson is in the Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington DC 20015, USA. e-mail: rcarlson@carnegiescience.edu

1. Dauphas, N. *Nature* **541**, 521–524 (2017).
2. Fischer-Gödde, M. & Kleine, T. *Nature* **541**, 525–527 (2017).
3. Clayton, R. N., Onuma, N. & Mayeda, T. K. *Earth Planet. Sci. Lett.* **30**, 10–18 (1976).
4. Herndon, J. M. *Proc. R. Soc. A* **368**, 495–500 (1979).
5. Javoy, M. *et al.* *Earth Planet. Sci. Lett.* **293**, 259–268 (2010).
6. McDonough, W. F. & Sun, S. *Chem. Geol.* **120**, 223–253 (1995).
7. Palme, H. & O'Neill, H. St C. in *The Mantle and the Core* (ed. Carlson, R. W.) 1–39 (Elsevier, 2014).
8. Qin, L. & Carlson, R. W. *Geochem. J.* **50**, 43–65 (2016).
9. Warren, P. H. *Earth Planet. Sci. Lett.* **311**, 93–100 (2011).
10. Wänke, H., Driebus, G. & Jagoutz, E. in *Archaeo Geochemistry* (eds Kröner, A., Hanson, G. N. & Goodwin, A. M.) 1–24 (Springer, 1984).
11. Borisov, A. & Palme, H. *Geochim. Cosmochim. Acta* **61**, 4349–4357 (1997).
12. Walker, R. J. *Chem. Erde* **69**, 101–125 (2009).

MATERIALS SCIENCE

Versatile gel assembly on a chip

Materials called hydrogels have potential applications as scaffolds for tissue engineering, but methods are needed to assemble them into complex structures that mimic those found in nature. Just such a method has now been reported.

SHOJI TAKEUCHI

Hydrogels are jelly-like materials that are made up of water-absorbing, 3D polymer networks. Their excellent properties, such as deformability, biocompatibility and diverse chemical functionalities, have led to them being widely studied as materials for use in foods and medical implants, as scaffolds for cell culture and as drug-delivery vehicles. However, it is still challenging to construct complex, hierarchical architectures from them. Writing in *Science Advances*, Chiang *et al.*¹ report a sophisticated method for the programmable assembly of high-order hydrogel architectures.

One reason for the interest in hydrogel assembly is that the resulting structures could be used to mimic the morphology of living tissues. Such tissues often contain many cell types that form hierarchical structures from various microscopic modular units, such as kidney nephrons, liver lobules and pancreatic islets. In the past few years, 'bottom-up' strategies — in which microscopic cellular building blocks are assembled into dense hierarchical 3D constructs — have attracted attention for tissue construction^{2,3}. The building blocks can be categorized into three standard shapes: points, lines and planes⁴. Chiang and colleagues use their method to make a cell-laden hydrogel architecture that belongs to the plane category,

which can stack or roll up into higher-order structures.

The authors developed an electromicrofluidic device that effectively allowed them to assemble hydrogels on a chip. More specifically, they used a fluid-handling technique called electrowetting to dispense, mix, transport and position single droplets (0.1 microlitres in volume) of a polymer solution into designated spots. They then used a technique called dielectrophoresis to manipulate dielectric (insulator) particles suspended within the droplets into a controlled pattern. They used positive dielectrophoresis to gather the particles in the high region of an electric field; and negative dielectrophoresis to gather those in the low electric-field region. In the final step of the process, the authors converted the droplets into hydrogels by crosslinking the dissolved polymer molecules using one of three methods (light- or heat-induced crosslinking, or chemical crosslinking).

In one example, they manipulated nine droplets, each containing a different fluorescent dye, into a 3 × 3 tiled pattern. They then crosslinked the polymers in the droplets using ultraviolet light to obtain a seamless heterogeneous hydrogel architecture (Fig. 1a) that could be handled with tweezers. Chiang *et al.* also used their platform to arrange hydrogels into controlled patterns after crosslinking.

The researchers used their system to arrange

and culture cells (fibroblasts and cardiomyocytes) on biocompatible hydrogels such as poly(ethylene glycol) diacrylate (PEGDA) and gelatin methacryloyl (GelMA). They used electrowetting to move droplets containing both pre-crosslinked GelMA and cells into a hexagonal pattern, used dielectrophoresis to arrange the cells, and then immobilized the cells by crosslinking the polymers to form hydrogels (Fig. 1b). The cells survived the process well, suggesting that the procedure is able to manipulate and assemble cells without severely damaging them.

One advantage of Chiang and colleagues' method is that the technology provides a highly programmable 3D microenvironment for studying cell behaviour. For example, the authors constructed assemblies that contain hydrogels of different stiffnesses to observe the effect on cultured cells. They found that, when cardiomyocytes from newborn mice were seeded onto an assembly containing both GelMA and PEGDA hydrogels, the cells adhered mainly to the stiffer GelMA, where they exhibited their characteristic beating behaviour (contracting and lengthening). And when fibroblasts were cultured in GelMA hydrogels of different stiffnesses, the cells on the stiffer gels tended to exhibit increased polarization (that is, an asymmetrical shape or asymmetrical organization of cellular components) and aspect ratios (the ratio of length to width).

Many other systems have been reported for handling droplets or particles using electrowetting⁵ and dielectrophoresis⁶ — such technology is known as digital microfluidics⁷. But Chiang *et al.* have combined the two methods into a single platform. Their work also offers an advance for tissue engineering. In general, previously reported methods for tissue engineering precisely controlled the size of the cellular building blocks to be assembled, but the internal morphology of the blocks depended on self-assembly processes. By contrast, Chiang and colleagues' approach actively controls internal