which take a long time to cascade down to the ground state. Atoms produced by radiative recombination are formed in lower-lying states.

No one knew exactly which one of those two antihydrogen production processes would dominate in the ATHENA and ATRAP experiments and hence what quantum states would be formed. To get an idea of the quantum state of the $\bar{H}$ atoms, ATRAP researchers added another feature to their experimental setup: a state-analysis region, through which an $\bar{H}$ atom must pass on its way to the ionization region, as seen in the figure.

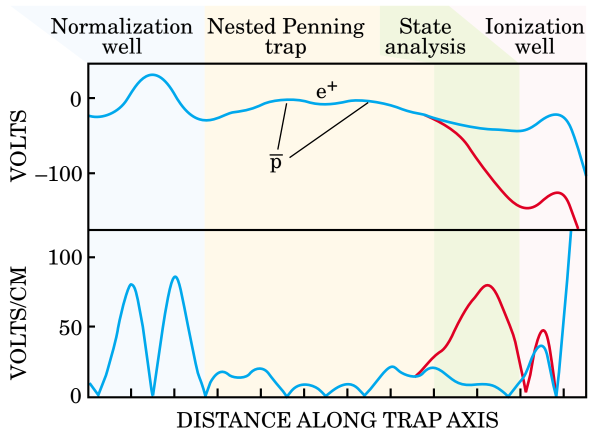
In the state-analysis region, the researchers apply an electric field, shown by the red curve, to ionize the $\bar{H}$ atoms. When ionization occurs, the resulting antiprotons will escape and the number of antiprotons snared in the ionization trap will decrease.

Gabrielse and company varied the electric field in the state-analysis region and recorded the drop in the numbers of antiprotons accumulated. They found the drop by comparing the numbers of antiprotons in the ionization trap with those in a normalization trap on the other side of the Penning trap, where there is no state-analysis region.

The strength of the field that ionizes an atom is a measure of the energy level occupied by the positron: The more tightly bound a positron, the higher the ionization field must be. Thus the observed decrease in the numbers of accumulated antiprotons is a measure of the number of $\bar{H}$ atoms with a given quantum number. It's hard to translate the measured ionization potential exactly into the principal quantum number n. Still, the experimenters estimate that all the atoms they formed were Rydberg atoms, with values of n greater than about 50.

The ATRAP collaborators saw no evidence for lower-lying states. They found that the numbers of ionized $\bar{H}$ atoms declined as they raised the field to higher values. Beyond an electric field of 62 V/cm, they saw no further decreases. The experimenters took that as evidence that they were not seeing any tightly bound states. In future experiments, researchers might look for lower-lying antihydrogen states more directly by exciting them with a laser to states that can be ionized.

Whereas the ATRAP researchers have determined that their experiment forms Rydberg atoms, the same conclusion does not necessarily hold for the ATHENA setup, in part because ATHENA produces $\bar{H}$ atoms at higher temperatures. Rolf Landua, ATHENA's spokesman, said that his team now has evidence that three-body recombination is not the dominant process in their experiment.



Antihydrogen detection scheme. Blue curves indicate the electric potential (top) and field magnitude (bottom) as a function of distance along the axis of a nested Penning trap. Positrons are held by a small dip in the potential at the trap's center. The small peaks on either side of this potential dip confine antiprotons, which bounce back and forth through the positrons. If $\bar{H}$ atoms are formed, some of those that escape are stripped of their positrons by an electric field in the ionization well. These antiprotons serve as a measure of the number of $\bar{H}$ atoms formed. When an electric field applied in the state analysis region (red curves) ionizes some $\bar{H}$ atoms, fewer antiprotons are caught in the ionization well, and the drop in numbers reflects how many $\bar{H}$ bar atoms were formed in a given quantum state. The drop is found by comparison with the normalization well on the other side of the Penning trap. (Adapted from ref. 5.)

Rydberg atoms

No one has yet calculated the properties of Rydberg atoms moving randomly in magnetic fields as high as those found in a Penning trap. However, the ATRAP team's measurements may well motivate some new calculations. One complication, says Hossein Sadeghpour of the Harvard–Smithsonian Center for Astrophysics, is that one can't separate the center-of-mass motion from the internal coordinates, as can be done with many other systems. Thomas Gallagher of the University of Virginia notes that "using field ionization as a detection technique has subtleties even without a magnetic field. Understanding it with one presents quite a challenge."

One goal of such Rydberg calculations will be to guide the experimenters as they devise techniques to bring the highly excited atoms quickly down to their ground states, where the precision experiments must be performed. Left to their own devices, Rydberg atoms tend to take a long time to decay, during which time they might be lost from their trap. Daniel Kleppner of MIT notes that, to date, those studying Rydberg atoms have been concerned with how to put them in the higher states; they now face the reverse problem.

Gabrielse said that in ATRAP's next run, which begins in June 2003, his group will try to bring the Rydberg $\bar{H}$ atoms to lower energy levels with laser deexcitation methods. He and his collaborators also hope to test ways to select specific Rydberg states. Furthermore, they also need to figure out a way to store the neutral particles.

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Isotope Ratio Measurements Firm Up Knowledge of Earth's Formation

New measurements on primitive meteorites suggest that Earth's core formed earlier than was previously thought.

A complicated interplay of processes occurred 4.6 billion years ago in the early stages of the Solar System as material from the initial solar nebula condensed and collided to form aggregates, planetesimals, and eventually planets. And on Earth as well as the other terrestrial planets and the larger asteroids, heat from accretion and from the decay of short-lived isotopes such as aluminum-26 was sufficient to melt—at least partially—the assembled material, which led to the segregation of the iron-rich core and the silicate mantle.

Determining when Earth's core formed can provide constraints on models of the planet's formation. Studying Earth's isotopic composition can provide such constraints, but this approach has led to conflicting answers.

Recently, three reports—by Ronny Schoenberg, Ken Collerson, and coworkers at the University of Queensland and the University of Bern;[1] by Qingzhu Yin, Stein Jacobsen, and colleagues at Harvard University and the Ecole Normale Supérieure in Lyon, France;[2] and by Thorsten Kleine, Klaus Mezger, and coworkers at the University of Münster and the University of Cologne[3]—have independently established a chronometry, based on careful measurements of tungsten isotopic compositions, that appears to have settled the timescales.

The core of the matter

As the Solar System formed, according to prevalent models, Earth accreted rapidly—over a period of a few million to a few tens of millions of years.[4] But confirming such models requires resolving what happened in the first few tens of millions of years in the 4.6-billion-year-old Solar System.

The hafnium–tungsten (Hf–W) system is well suited for dating the formation of Earth's core. One Hf isotope, ^{182}Hf, decays to stable ^{182}W with a halflife of 9 million years. Produced like other heavy elements (including ^{182}W) in supernova explosions, ^{182}Hf was present in the original solar nebula, but the initial supply of ^{182}Hf has long since decayed. Thus, its concentration can't be extrapolated back, unlike the concentrations of uranium-235 and uranium-238—whose decays to lead-207 and lead-206 form another chronometer of the early Solar System. The erstwhile presence of ^{182}Hf is revealed, however, in the isotopic composition of W. Today's deviations from the average Solar System ratio of ^{182}W to other stable, nonradiogenic W isotopes reflect variations in the Hf/W ratio in the earliest period of the Solar System.

The chemistry of the Hf–W system also is vital to dating core formation. Lithophile ("stone loving") Hf stayed in the silicate mantle when the metallic core formed. Tungsten, in contrast, is moderately siderophile ("iron loving"), preferentially dissolving in the metallic core. Thus, following the core formation, the mantle had a higher Hf/W ratio than the core. And so, if Earth's mantle and core have different ^{182}W abundances, mantle–core separation must have occurred before the ^{182}Hf vanished.

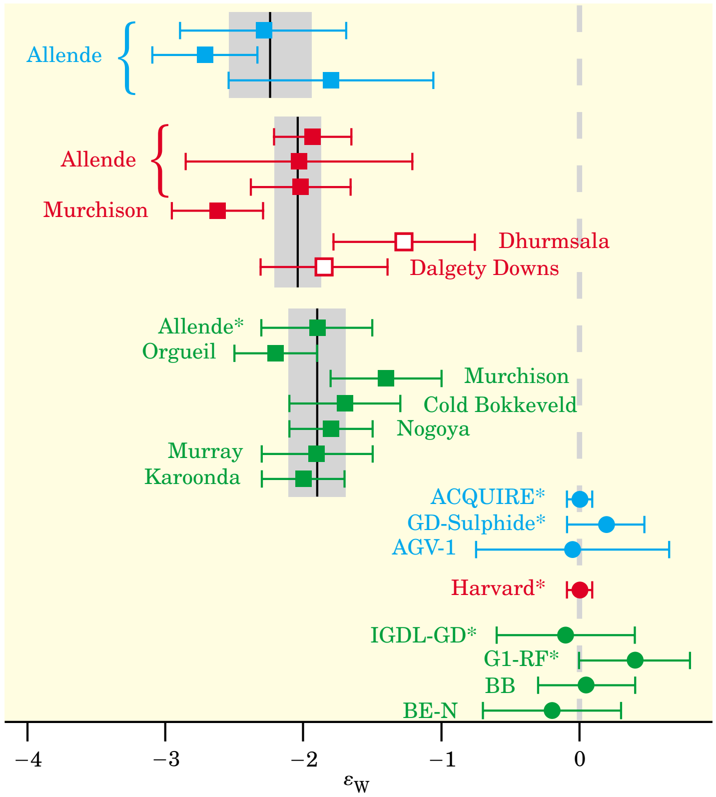
Tungsten samples are easily obtained from the silicate Earth—just break open an incandescent light bulb—but not from the ferrous core. Fortunately, there is another source of W samples that can be tapped: meteorites. Carbonaceous chondrites are a class of primitive meteorites that are widely thought to have the same chemical composition (except for volatile elements such as hydrogen, helium, and the alkalis) as the solar nebula from which Earth and the other planets formed. Such meteorites can thus serve as proxies for establishing a baseline from which to look for deviations in W isotope ratios. (For more on what can be learned from meteorites, see the article by Thomas Bernatowicz and Robert Walker in PHYSICS TODAY, December 1997, page 26.)

Measuring W isotope ratios in chondrites is challenging, however. The assays require a sensitive mass spectrometer to detect differences of less than one part in 10^4 in W isotope abudances, and the chondrites themselves contain W only at the parts-per-billion level. Furthermore, corrections must be made for instrument effects and for background signals from other elements.

Following reports[5] in the mid-1990s by Jacobsen and Charles Harper (Harvard) that iron meteorites—thought to be the cores of early planetesimals—showed a deficiency in ^{182}W, Der-Chuen Lee and Alex Halliday (then at the University of Michigan) reported the first measurements of the ^{182}W abundance in carbonaceous chondrites; they found essentially no difference from the composition of the silicate Earth.[6] The apparent absence of any significant deviation indicated that the fractionation of Hf and W due to core formation must have occurred after the ^{182}Hf was extinct. Lee and Halliday thus concluded that, unless planetary accretion was a slow process occurring over tens of millions of years, Earth's core must have formed at least 50 million years after the birth of the Solar System.

The three recent experimental efforts, which reexamine the Hf–W chronometry based on new measurements of chondrites, have challenged the late formation time. The figure shows the new results for the abundance of ^{182}W in various chondrite and terrestrial samples. These results each reveal a clear difference in the ^{182}W content, with the chondrites having about 2 parts in 10^4 less than Earth's mantle and crust.

At the 2002 Goldschmidt Conference, held last August in Davos, Switzerland, Halliday, now at ETH Zürich, reported finding chondritic W concentrations that agree with the new sets of results, rather than with his earlier measurements, and said he has reproduced the Münster results. Thus the question of the ^{182}W abundance in chondrites appears to be settled.



Differences in the isotopic abundance of tungsten-182. The horizontal axis plots ε_W, the deviation in parts per 10^4 of the fractional amount of ^{182}W in a sample compared to a terrestrial standard. Squares indicate samples from chondritic meteorites, thought to represent the original chemistry of the Solar System (filled squares are carbonaceous chondrites; open squares are whole-rock averages of ordinary chondrites). Circles are terrestrial samples. The average chondritic value of $\varepsilon_W \approx -2$ (shaded areas) indicates that Earth's core formed before the supply of radioactive hafnium-182 had fully decayed, and thus implies an early formation of the core. (Blue data from ref. 1; red data from ref. 2; green data from ref. 3. Asterisks indicate mean values of multiple measurements.)

A new consistency

The new findings point to an earlier formation of Earth's core, when there was still ^{182}Hf left in the hafnium-enriched mantle to decay and thereby increase the ^{182}W fraction. Determining how much earlier requires additional information: the relative abundances of Hf and W, and the initial ratio of ^{182}Hf to other Hf isotopes at the birth of the Solar System.

Each team drew on existing estimates of 12–18 for the Hf/W ratio in bulk silicate Earth. The Münster group inferred an initial $^{182}Hf/^{180}Hf$ ratio of about 1.0×10^{-4} from W isotope measurements of various phases in a well-dated chondrite that formed very soon after the beginning of the Solar System. The Harvard group found the same ratio from its study of chondritic meteorites. The Queensland researchers obtained a value 50% higher based on other reported measurements on iron meteorites, but found a value comparable to that of the other groups when considering their own measurements on iron meteorites.

Conclusions about the core formation date also rest on assumptions regarding how the core formed. Models commonly assume that small planetesimals formed early and had differentiated cores. As those objects collided to form bigger ones, the accreting material was at least partly molten, allowing some degree of equilibration between the silicate and metal melts before the metal sank to Earth's core. This equilibration is what the Hf–W studies date, but the extent of equilibrium varies from model to model.

Putting all the isotope ratios together, and assuming fully equilibrated element distribution between the mantle and core, the three teams reported a consistent value of about 30 million years as the latest time after the birth of the Solar System for Earth's core to have formed in a single event. Such an earlier formation time is in better agreement with other chronometries[7] and with models. Arguing that Earth's core is more likely to have segregated continuously as the planet grew, the Harvard group calculated 11 million years as the mean core formation time.

The new chronometry also has implications for other parts of the Solar System. For example, the Moon, which has a chemical composition similar to that of Earth's mantle, is commonly thought to have been formed by a giant impact with Earth. Based on their data, the Harvard and Münster groups estimate that the Moon formed 25–33 million years after the beginning of the Solar System, comparable—and perhaps related—to the date they obtained for Earth's core formation.

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