presence in the core is negligible. There are speculations, however, that a local uranium concentration somewhere in the solid inner core might be functioning as a natural fission reactor.[5] The new data put an upper limit of 3 TW on the power of such a putative reactor. Whether the turbulent geodynamo action of the liquid outer core requires ongoing local radioactive heating remains an open question.

Figure 3 compares the total geoneutrino fluxes measured at KamLAND and Borexino with the fitted model's expectations, given separately for the crust and mantle at the two detectors and also at Hawaii, a possible mid-ocean setting for a future detector.

The KamLAND–Borexino fit yields a global ^{238}U plus ^{232}Th heat flux of 20.0 ± 8.7 TW. About 13 TW of that total is attributed to the mantle. "Radioactive heating of the mantle is of particular interest," says KamLAND spokesman Kunio Inoue (Tohoku University, Sendai, Japan), "because it's thought to contribute significantly to mantle convection, which drives plate tectonics and thus earthquakes."

Adding the roughly 4 TW of heating estimated for the ^{40}K decays neither detector can see, one gets a radiogenic contribution of about 24 TW to Earth's total 44 TW heat flux. The data exclude, with a confidence level of 97%, the notion that Earth's primordial heat is already exhausted.

In 1897, knowing that Earth's interior was still giving up heat but not yet aware of radioactivity, Lord Kelvin proclaimed that the planet couldn't be older than 40 million years, much to the annoyance of geologists and Darwinians. If Earth were any older, he argued from a naive conduction model, its heat of formation would already have radiated away.

Even before the geoneutrino results, the notion that the primordial heat of the 4.6-billion-year-old planet might already be exhausted had few adherents. But serious conjectures about the radiogenic fraction of Earth's heat flux range from 30% to 70%. So, more geoneutrino detectors at geologically varied sites are clearly important for probing Earth's interior with increasing precision. Directional sensitivity and lower detection thresholds would also help.

Bertram Schwarzschild

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Precision spectroscopy reveals a highly forbidden electronic transition in helium

Researchers combine optical trapping and frequency comb technology to control and measure the interaction of light with degenerate quantum gases.

Willis Lamb's 1947 measurement of the tiny energy splitting between the 2*S* and 2*P* states of atomic hydrogen largely spawned the development of quantum electrodynamics (QED). Ever since, precision spectroscopy of simple atomic systems has been used to test the theory and refine our understanding of it. In the latest contribution to that effort,[1] researchers led by Wim Vassen (Vrije University Amsterdam) have resolved—to a precision of 1.5 kHz, or 8 parts in 10^{12}—an exceedingly weak IR transition between the triplet and singlet metastable states of atomic helium, $2\,^3S_1$ and $2\,^1S_0$. So highly forbidden is the excitation, which violates both spin and parity selection rules, that it has never before been seen, much less measured to high precision.

Individually, the states are energy levels of different species of helium—orthohelium, in which electron spins are parallel, and parahelium, in which they're antiparallel. The distinct emission spectra of the two spin arrangements were noticed in the late 19th century but not understood until Werner Heisenberg explained them in 1926.

A photon's electric field does not interact directly with the electron spin. Nor can it connect two states of the same parity. Yet for the doubly forbidden excitation to occur, one of the orthohelium spins must flip to form parahelium. Were it not for the photon's magnetic field, which couples to an electron's magnetic moment, such flips would be impossible. In fact, the magnetic interactions and relativistic corrections to the Schrödinger equation show that the triplet-to-singlet excitation is allowed as a magnetic dipole transition, but with a probability 14 orders of magnitude weaker than that of the familiar electric dipole transition in He from $2\,^3S$ to $2\,^3P$.

Why go to the trouble of probing it? With the *S* states' large electron density at the He nucleus, their energy levels are more sensitive to two-electron QED and to nuclear-size effects. In addition, because the singlet state $2\,^1S_0$ is long-lived (20 ms), it has a natural linewidth of just 8 Hz, 200 000 times as narrow as $2\,^3P$.

To measure so weak a transition requires either high laser power or long interaction times. Whereas earlier spectroscopy of He exploited atomic beams or gas discharge cells, in which atoms and light intersect for mere nanoseconds, the Amsterdam experiment combines optical trapping and frequency comb technology.[2] The trap brings a few million He atoms to a near standstill, effectively eliminating Doppler broadening, and allows them to interact with excitation light for up to 6 s; the comb, in turn, is locked to a rubidium clock and provides a rock-solid laser-frequency calibration (see figure 1).

Load, cool, and drop

The Amsterdam team can load ^{3}He, ^{4}He, or both into the optical trap. To create a Bose–Einstein condensate of ^{4}He, the researchers evaporatively cool the gas, which draws off the highest-energy atoms and leaves the rest to reequilibrate through elastic collisions. Fermionic ^{3}He atoms are harder to tame: Because of Pauli exclusion, they stop colliding at millikelvin temperatures. Five years ago Vassen's group succeeded in creating the first ^{3}He degenerate Fermi gas by further cooling the ^{3}He atoms "sympathetically" through collisions with ^{4}He atoms to reach microkelvin temperatures. An appropriately tuned RF pulse can then spring the bosons, but not the fermions, from the trap. The following year the group used the experimental setup to study the pattern of bunching or antibunching that occurs when the bosons or fermions fall onto a surface (see PHYSICS TODAY, March 2007, page 18).

The advantage of using degenerate or near-degenerate gases in spectroscopy is the high density of atoms that can be packed into a tight laser focus. The disadvantage is the possible interactions between them. Surprisingly, though, Vassen and colleagues found that any frequency shifts associated with atomic collisions are so small as to fall within their error bars.

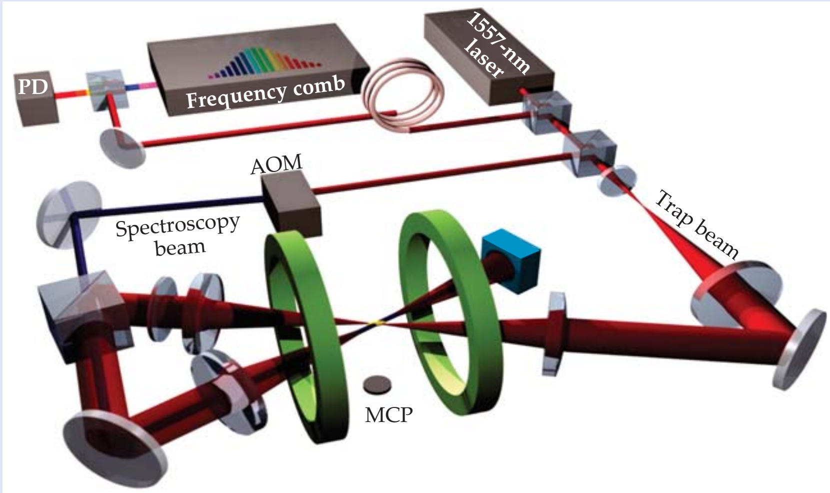

Figure 1. Experimental setup. A small fraction of 1557-nm laser light is coupled by an optical fiber to a photodiode (PD) and to a frequency comb that monitors the laser's absolute frequency by beating it against a tooth of the frequency comb. The rest of the light is divided between a trap beam and a spectroscopy beam, both overlapping and focused to a waist of about 85 µm, where the atoms are trapped. The spectroscopy beam is frequency shifted by a 40-MHz acousto-optical modulator (AOM). When the trapping light is turned off, helium atoms fall onto a microchannel plate detector (MCP) that counts them. (Adapted from ref. 1.)

Another advantageous feature of the experiment, using either isotope of He, is that the same IR (1557-nm) laser used to trap the triplet-state atoms can also be used to excite them. Fortuitously, whereas the triplet-state atoms feel an attractive trapping potential from the light, the singlet-state atoms feel a repulsive one. So when the spectroscopy beam is resonant with the atomic transition, any atoms excited to the singlet state are subsequently expelled from the trap.

After a few seconds, the trapping and spectroscopy beams are turned off and the remaining atoms fall onto a microchannel plate that counts them. The researchers ran hundreds of experiments to resolve the transition frequency for the different isotopes. One such experiment is depicted in figure 2, which shows a Gaussian fit to the dip observed in the percentage of triplet-state ^{4}He atoms as the applied laser frequency was stepped up or down through the resonance.

The group used an off-the-shelf IR laser. Its linewidth, combined with a contribution from the feedback loop between the laser and frequency comb, largely accounts for the broad 90-kHz width of the result. The linewidth for state-of-the-art lasers at national metrology labs is on the order of a hertz, so orders-of-magnitude improvement may be possible, at least in principle.

Nonetheless, the fitted plots, once corrected for systematic frequency shifts, such as the Zeeman effect caused

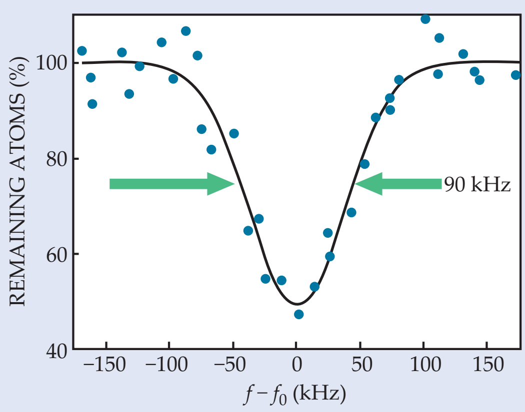

Figure 2. The percentage of Bose-condensed helium-4 atoms that remain in the $2\,^3S_1$ state as a function of applied laser frequency *f*, relative to the center frequency f_0 determined by a least-squares fit. Each data point represents a separate experimental trial. The line is a fit of a Gaussian to the data. Its 90-kHz width is limited by the trap depth and the laser. (Adapted from ref. 1.)

by Earth's magnetic field, revealed the transition frequency to a precision 1000 times better than that of current QED calculations. Reassuringly, experiment and theory agree, as nearly everyone expected. But the two approaches closely interact; improved experimental values may inspire better calculation methods to explain them.

Spectroscopy can even transcend atomic physics. So precise are the electronic measurements that even tiny variations in the size and shape of the nucleus influence them. Equally precise QED calculations for He are required to interpret that influence. Fortunately, the main problem of calculating the effect of emission and reabsorption of a virtual photon has recently been solved.[3] By measuring the isotope shift—the slightly different transition energies between triplet and singlet states in ^{3}He and ^{4}He—the Amsterdam group was able to deduce a competitive value for the charge radius of the ^{3}He nucleus (1.961 ± 0.004 fm).

And that, down the road, may come in handy for calculating an improved value for the Lamb shift in He.

Mark Wilson

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Minimalist model captures water-cycle complexities

Equations inspired by population-dynamics theory may help explain drizzles, downpours, and disappearing clouds.

Images taken 18 August 2009 from a European Space Agency satellite stationed in a geosynchronous orbit above the equator and prime meridian show a typical pattern of cloud cover off Africa's west coast. Sprawling marine stratocumulus clouds are visible in two familiar forms: a so-called closed-cellular field, a densely packed layer of clouds separated by thin rings of clear sky; and a more sparsely populated open-cellular field, a honeycomb-like lattice of rings of clouds encircling large pockets of clear sky.

When scientists led by Graham Feingold (National Oceanic and Atmospheric Administration, Boulder, Colorado) zoomed in on the satellite images, they saw intriguing behavior.[1] After accounting for wind advection, they noticed that now and then, a cloud in the open-cellular field would vanish, leaving clear sky. Kilometers away, a new cloud would form. Every hour or so, the disappearing act would repeat.

The oscillations Feingold and his colleagues observed are among several surprising dynamical phenomena seen in the water cycle. Meteorologists have also witnessed abrupt changes in cloud morphology and seemingly unprovoked transitions from drizzles to downpours. Although such complexities affect long-term climate trends—they play a part in determining Earth's albedo as well as the distribution and intensity of rainfall events—most climate models gloss over them in the name of computational efficiency.

More sophisticated models such as large-eddy simulation (LES) strive to incorporate as much physical detail as possible by coupling cloud microphysics with fluid dynamics. Aided by LES, Feingold and company were able to replicate the oscillations they had seen in the satellite images; their explanation—that rainfall reverses the convection patterns—is detailed in figure 1.

But the extensive detail of an LES can mask underlying patterns. It doesn't explain, for example, why some cloud-precipitation systems seem to oscillate and others remain steady. Now, inspired by a 100-year-old model of a predator–prey ecosystem, Feingold and coauthor Ilan Koren (Weizmann Institute of Science, Rehovot, Israel) have captured some of the water cycle's complexity—including behavior related to the oscillating clouds—in a model simple enough for pen-and-paper analysis.[2]

The water cycle

Koren and Feingold are mainly interested in liquid water clouds, formed when water vapor—supplied mostly by evaporation at Earth's surface and carried upward by thermal convection—creates supersaturated conditions in cooler regions of the atmosphere. There, the water vapor condenses into the liquid droplets that make up a cloud, with aerosol particles serving as the condensation nuclei. Once cloud