tial agreement. The single best fit to the MiniBoone data has A nearly maximal. But the likelihood distribution is fairly flat over a large parameter range, and A bigger than 10% seems to be excluded by limits from experiments at reactors.

Violating *CP* symmetry

Taken seriously and together, the MiniBoone antineutrino result and its LANL antecedent appear to reveal a new Δm^2 much larger than the sum of those that fit the solar and atmospheric oscillation data. That inequality would require a fourth neutrino mass eigenstate, predominantly sterile in flavor, and presumably much heavier than the other three.

But given the absence of any oscillation signal in the earlier neutrino-mode MiniBoone data, a single sterile neutrino state probably won't do. Incorporating that kind of *CP* violation into the standard model of particle theory requires interference between the couplings of *two* different sterile mass eigenstates to the known neutrinos.

Therefore MiniBoone team member Georgia Karagiorgi (MIT) and coworkers have tried to fit all three accelerator results plus limits from other relevant experiments with a very general model with two sterile mass states.[2] "We did succeed in fitting the neutrino and antineutrino data separately," says Karagiorgi. "But the two fits weren't mutually compatible."

"The failure to get a global fit with so general a model is instructive," says Fermilab theorist Boris Kayser. "It suggests that if the data faithfully reflect nature, they may be hinting at new interactions beyond the standard model." And indeed, theorists Evgeny Akhmedov and Thomas Schwetz at the Max Planck Institute for Nuclear Physics in Heidelberg have now reported a global fit with just one sterile neutrino state plus non-standard-model interactions.[3]

The MiniBoone team is continuing to run in antineutrino mode, hoping at least to double its event tally before Fermilab's accelerator complex is scheduled to shut down in March 2012 for major reconfiguration.

Bertram Schwarzschild

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Isotope ratios hint at a piece of pristine Earth

Could any material on Earth have remained isolated and undisturbed for 4.5 billion years? And if it did, how could we tell?

A few humans have been from the Earth to the Moon, and many more have been around the world in 80 days or fewer. But no one has yet made a journey to the center of the Earth. Our experience with the planet on which we live is almost entirely confined to the material and information that makes its way to the surface.

For that reason and others, precise measurements of Earth's overall composition are difficult or impossible. The continental crust, the most familiar part of Earth for most of us, is not a representative sample: Its composition is not even the same as that of the crust beneath the oceans. The difference is attributed to the effects of partial melting of the silicate mantle that lies beneath the crust. Certain incompatible elements—so called because they strain the crystal lattices of the solid mantle—were preferentially pushed out of the solid and into the melt. The continents formed from the melt; the oceanic crust formed, and is constantly regenerated, from the material left behind in the upper mantle, depleted in the incompatible elements. Since then, volcanism, tectonic-plate movements, and thermal convection have all served to transport material within and across the crust and mantle, slowly stirring the silicate portion of Earth like a batch of cookie dough.

Geochemists have long assumed, quite reasonably, that Earth as a whole has the same composition as the rest of the solar system, best represented by certain meteorites called chondrites. The chondrites never underwent the large-scale differentiation that Earth did, so it's easy to measure their compositions. Their isotopic compositions, in particular, yield important clues about long-gone radioactive elements and their abundances on Earth.

In 2005, however, Richard Carlson and his postdoc Maud Boyet made a surprising discovery[1] (see also PHYSICS TODAY, September 2005, page 19). Compared to the chondrites, every terrestrial sample they looked at was anomalously rich in neodymium-142, the decay product of relatively short-lived samarium-146. It follows that either Earth formed with significantly more Sm and less Nd than the rest of the solar system or it contains a hidden Sm-poor, Nd-rich reservoir that's never been observed.

Now, partially based on that discovery, Matthew Jackson—another of Carlson's postdocs, now at Boston Univer-

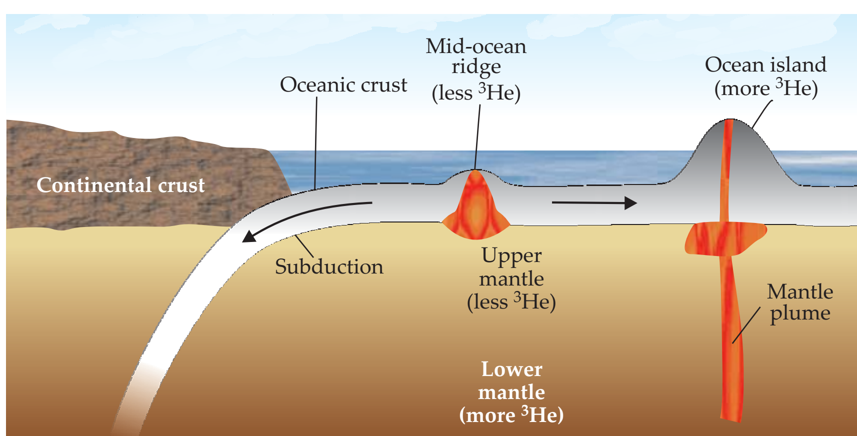


Figure 1. As oceanic crustal plates pull apart at the mid-ocean ridges, upper-mantle material melts and wells up to create new crust. The old crust subducts, or sinks beneath a neighboring plate back into the mantle. Ocean islands, in contrast to the ridges, form from molten plumes originating deep within the mantle. In each process, the molten mantle gives up some of its helium, including primordial ^{3}He that is never replaced. The upper mantle is thought to be more processed and more degassed than the lower mantle, so the mid-ocean ridges contain less ^{3}He than the ocean islands.

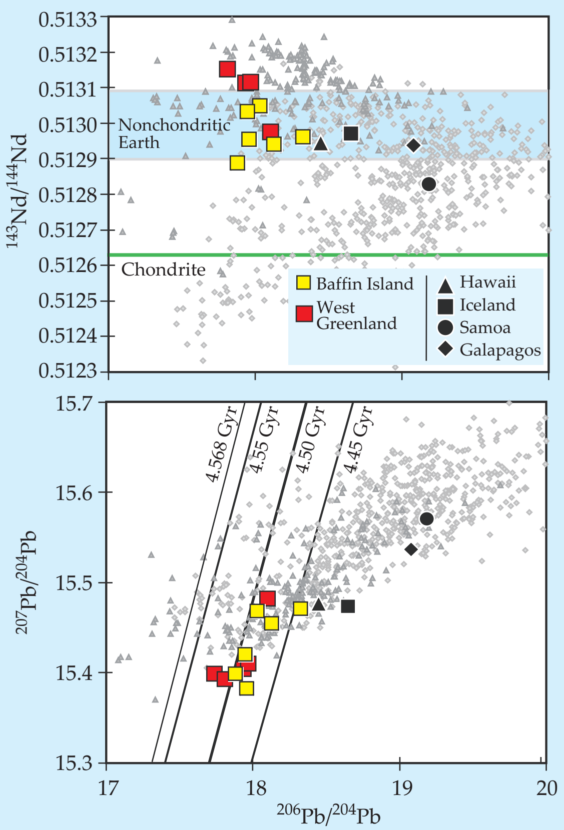


Figure 2. Isotopic measurements of Baffin Island (yellow), neighboring West Greenland (red), other especially helium-3-rich ocean islands (black), and other terrestrial samples (gray). As the top panel shows, the neodymium compositions of the Baffin samples fall within the range (blue stripe) expected of primitive material in a nonchondritic Earth. As the bottom panel shows, their lead isotopic compositions cluster around the 4.50-billion-year isochron, as expected of a mantle reservoir that's been isolated since early in Earth's history. (Adapted from ref. 2.)

sity—and collaborators have found that rocks from Baffin Island in northeastern Canada, the products of a massive volcanic eruption 60 million years ago, show all the signs of having come from an ancient mantle reservoir, undifferentiated and unmixed since not long after Earth's formation 4.5 billion years ago.[2] Whether Earth as a whole is Sm rich or not, the Baffin samples appear to be made of the original Sm-rich material from which all the continental and oceanic crust is derived. The researchers base their conclusion on isotopic measurements of several elements, including Nd, helium, and lead.

Helium

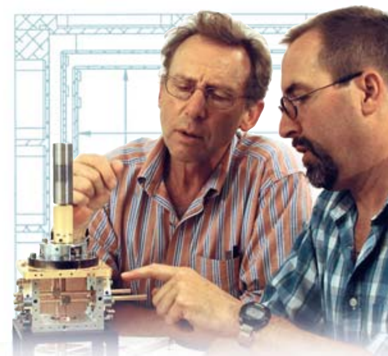
Earth's primordial helium (primordial with respect to the formation of the solar system, not the universe) contained considerably more ^{3}He than is present in the air today. Helium in the air is eventually lost into space. It's replaced by radiogenic He, which is almost exclusively ^{4}He produced in α decays. (Neutron capture by lithium-6 yields some ^{3}He, but the amount is negligible for most purposes.)

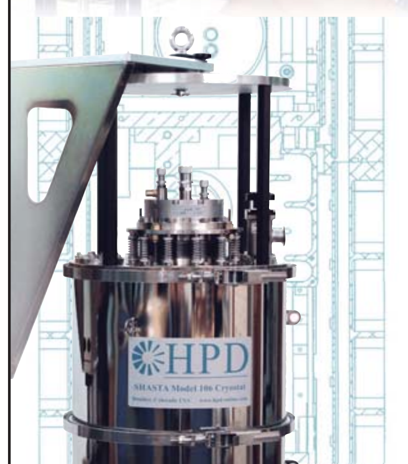
Much of Earth's He, primordial and radiogenic, remains trapped in the crust and mantle. When mantle material melts and reaches the surface, it degases, losing much of its He to the atmosphere. Higher ^{3}He/^{4}He ratios should therefore signal material that's remained relatively unexposed to the surface over geologic time. Indeed, the ^{3}He/^{4}He ratio is low for mid-ocean ridge minerals, which form from the mantle just beneath the crust, as shown in figure 1. The ratio is often higher on ocean islands, which form from plumes originating in the lower mantle.

Samples from several islands, including Hawaii, Iceland, Samoa, and the Galapagos, have been found to have especially high ^{3}He/^{4}He, more than 30 times that of air. But, as measured in 2003 by Finlay Stuart and colleagues, the Baffin Island rocks have the highest ratio ever found on Earth: up to 50 times that of air.[3] Those researchers concluded that the Baffin material was not from a pristine mantle reservoir, however, in part because of their Nd measurements.

Neodymium

Neodymium-142, the subject of Boyet and Carlson's 2005 investigation, is not normally a useful probe of a sample's geological history. Any place-to-place variation in the ^{142}Nd/^{144}Nd ratio would have to be caused by partial separation of ^{144}Nd and ^{146}Sm, ^{142}Nd's parent. Since the two Nd isotopes, both stable, behave virtually identically, the ^{142}Nd/^{144}Nd ratio has been locked in place ever since all the ^{146}Sm had decayed into ^{142}Nd, a few hundred million years after Earth's





formation. Indeed, all of Boyet and Carlson's terrestrial samples had the same $^{142}Nd/^{144}Nd$ ratio to within a few parts per million, the resolution of their measurement.

But Nd has another radiogenic isotope, ^{143}Nd, the daughter of the much longer-lived ^{147}Sm. Since much of Earth's original ^{147}Sm is still around, geological processes over the whole of Earth's history can and do separate ^{147}Sm and ^{144}Nd, yielding measurably different $^{143}Nd/^{144}Nd$ ratios over a much larger range of about one part per thousand.

If Earth's composition were chondritic, then primitive, undifferentiated mantle material would have a $^{143}Nd/^{144}Nd$ ratio of about 0.5126, the same as that of the chondrites. But since, as Boyet and Carlson found, the accessible part of Earth formed with more ^{146}Sm than the chondrites, it must also have had more ^{147}Sm. The expected $^{143}Nd/^{144}Nd$ for primitive terrestrial mantle thus works out to between 0.5129 and 0.5131.

As shown in the top panel of figure 2, the rocks from Baffin Island and from neighboring West Greenland do fall within the 0.5129–0.5131 range. When Stuart and colleagues measured those values in 2003, they inferred not that the samples were from a primitive reservoir but that they were mixtures of material from two different parts of the mantle, neither of which represented a primitive composition.

Lead

It was Jackson's idea to revisit the Baffin Island samples in light of Boyet and Carlson's ^{142}Nd results, by looking at Pb. Like Sm decaying into Nd, two particular isotopes of uranium decay into two isotopes of Pb through a series of α and β decays: ^{235}U into ^{207}Pb and ^{238}U into ^{206}Pb. All the intermediate elements in each decay chain have short half-lives, so the decay rate is governed by the U half-life: 700 million years for ^{235}U and 4.5 billion years for ^{238}U.

Unlike ^{146}Sm, neither U isotope has entirely decayed away, so the amounts of both radiogenic Pb isotopes, measured with respect to the nonradiogenic ^{204}Pb, can vary considerably from sample to sample. The key to making sense of the measurements is to realize that since the two U isotopes decay at different rates but otherwise behave almost identically, the $^{235}U/^{238}U$ ratio is a function of time but not of position. It follows that on a plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, a system that's been isolated for a time t will fall somewhere on a line, called an isochron, whose location depends on t. Where on the line it falls depends on the U/Pb ratio that the system started with.

As shown in the lower panel of figure 2, the Baffin and West Greenland samples are clustered around the 4.50-billion-year isochron, as expected for material that's been isolated since shortly after Earth's mantle formed. All of the other high-^3He samples fall well to the Baffin samples' right. That doesn't mean that their ages are given by the isochrons through those points, rather that at some point in their history—possibly during their journey through the mantle to the surface—they mixed with material of different composition.

As the world churns

If the Baffin samples are indeed from an ancient mantle reservoir, how could any part of the mantle have remained undifferentiated for so long? Many geoscientists once thought that the answer was easy. Studies of seismic-wave speeds reveal a pressure-induced phase boundary at a depth of 660 km; that boundary, it was thought, could be a barrier to mixing. If the upper and lower parts of the mantle never mixed, then the lower mantle would have remained pristine.

Subsequent seismic studies, however, have shown that picture to be far too simple. As new oceanic crust is created at the mid-ocean ridges, the old crust sinks, or subducts, beneath the neighboring tectonic plate and into the mantle, as shown in figure 1. The slabs of subducted crust appear to extend far past the 660-km discontinuity almost all the way to the core–mantle boundary. (See PHYSICS TODAY, August 1997, page 17.) Since the oceanic crust regenerates fairly quickly compared to the age of Earth—the time from creation to subduction is usually less than 200 million years—the subducted slabs should induce mixing of the whole mantle.

But it can't be mixed to the point of homogeneity. Even setting aside Jackson and colleagues' new work, the $^3He/^4He$ measurements make it clear that the mantle's composition is not uniform. The challenge for geophysical modelers is to reconcile the seismic measurements with the isotopic ones. Some models show every part of the mantle affected by mixing, but not uniformly.[4] They could explain the high $^3He/^4He$ ratios, but not the preservation of any primitive material.

Other models show primitive material preserved in pockets. For example, if the subducted crust is more than a few percent denser than the surrounding mantle, it sinks to and accumulates around the core.[5] As the dense pools build up, they could trap blobs of uncontaminated mantle material, possibly for billions of years.

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Putting quantum gases under the microscope

Microscopes with single-site resolution are vital for using ultracold atoms to simulate strongly correlated electrons in solids.

Many intriguing behaviors, such as high-temperature superconductivity, result from the strong interactions among particles in a many-body system. Theorists have explored those complex interactions with model Hamiltonians, but real-world defects make physical systems imperfect realizations of the models. And time and memory constraints limit computer simulations of quantum behavior to just a handful of atoms.

A tantalizing alternative is to use small clouds of atoms, typically tens of thousands, cooled to nanokelvin temperatures, to study the complex physics of strongly correlated systems. To simulate the structure of solids, researchers can trap atomic gases in a periodic array of optical potentials created by intersecting laser beams, much as eggs are confined by the corrugations of an egg carton. The optical arrays can be nearly defect free, and particle interactions can be tuned to explore the system behavior. Depending on whether the atom is a fermion or a boson, it might represent an electron or an electron pair. The simulations can possibly be extended to quantum spin systems, such as anti-