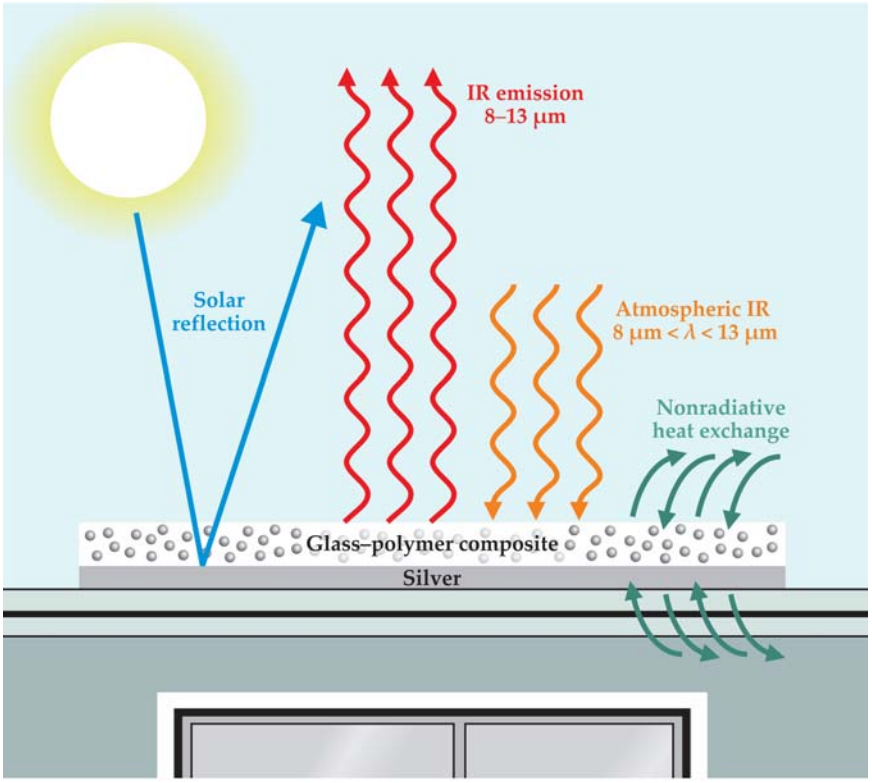

FIGURE 3. A GLASS–POLYMER COOLING PANEL, depicted here on the roof of a house, must emit more energy into space than it absorbs from other sources: from the Sun, from atmospheric thermal radiation, and from the environment via conductive and convective heat exchange. To keep the sunlight from warming the underlying roof, a film of silver reflects it away.

To best discharge heat into space, the film needs to face a clear, unobstructed patch of sky. Surrounding buildings, trees, clouds, and dirt on the film's surface could all compromise the cooling efficiency by emitting their own thermal radiation that the film then absorbs. Humidity, too, diminishes the atmosphere's transparency in the 8–13 μm window and reduces the cooling effectiveness. The Boulder researchers did their tests under nearly ideal conditions: on a series of clear, dry days in an open space in Arizona. "We want to get a better understanding of how atmospheric and geological conditions affect cooling," says Yang, "but that's not our area of expertise. And we're just starting to study the effects of dirt on the film."

A more immediate application could be adhering the film (without the silver backing) to the surfaces of photovoltaic cells, which can lose efficiency when they get too hot. The researchers expect that the material could be ready for market in as little as a year or two. Beyond radiative cooling, they emphasize the potential to draw on the existing body of research on photonics and spectral engineering to create inexpensive, mass-producible materials. Says Yin, "You don't need a cleanroom to make a photonic structure."

Johanna Miller

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Magnetic trap snares methyl radicals

The ability to isolate the important reaction intermediates at subkelvin temperatures could be a boon to cold chemistry.

By and large, physicists have succeeded in their quest to tame the atom. These days, atoms can be laser cooled to their ground states, stored in traps for minutes, and switched between internal states virtually at will. (See the article by Ignacio Cirac and Peter Zoller in PHYSICS TODAY, March 2004, page 38.)

Molecules, however, are wilder beasts. They are all but impervious to laser cooling, which demands a closed optical loop—that is, a sequence of photoexcitation and decay that can be repeated ad infinitum. Due to the additional degrees of freedom afforded by rotational and vibrational modes, molecules tend to decay unpredictably, often to states that can't be optically addressed. Inevitably, the loop breaks.

Over the years, experimenters have devised strategies to overcome the optical-loop problem: creating cold molecules *in situ* from cold, trapped clouds of reactive atoms (see the article by Debbie Jin and Jun Ye, PHYSICS TODAY, May 2011, page 27); cooling molecules "sympathetically" by letting them thermalize with cold atoms; closing optical loops by using RF fields to periodically reset molecules' internal states (see PHYSICS TODAY, January 2010, page 9). But those methods generally either work only in limited cases or yield gases that are too dilute for investigations of cold-molecule collisions, Bose–Einstein condensation, and other quantum phenomena of interest.

A fourth way to cool molecules into the quantum realm is simply to let them escape from a pressurized container into a vacuum. If the initial pressure is suitably high and the escape orifice suitably small, the temperature of the exiting molecules will fall to well below 1 K, cold enough that they behave more like waves than particles. For the experimenter set on interrogating them, however, there's a complication: The molecules will shoot from the orifice at roughly the speed of a rifle bullet.

In 2000 Gerard Meijer and his colleagues at the University of Nijmegen in the Netherlands showed that such beams could be slowed to a standstill using pulsed electric fields, provided the molecules had sufficiently strong electric

dipoles.[1] Now researchers led by Takamasa Momose (University of British Columbia, Vancouver, Canada) and David Carty (Durham University, UK) have pulled off an analogous feat on a molecule that has no electric dipole at all: They used pulsed magnetic fields to decelerate and trap a beam of methyl radicals cooled to their rotational ground state.[2] The new trapping technique can be applied not only to CH_3 but to any molecule with a magnetic moment—a class that includes essentially the entire family of reactive intermediates known as radicals.

Zeeman deceleration

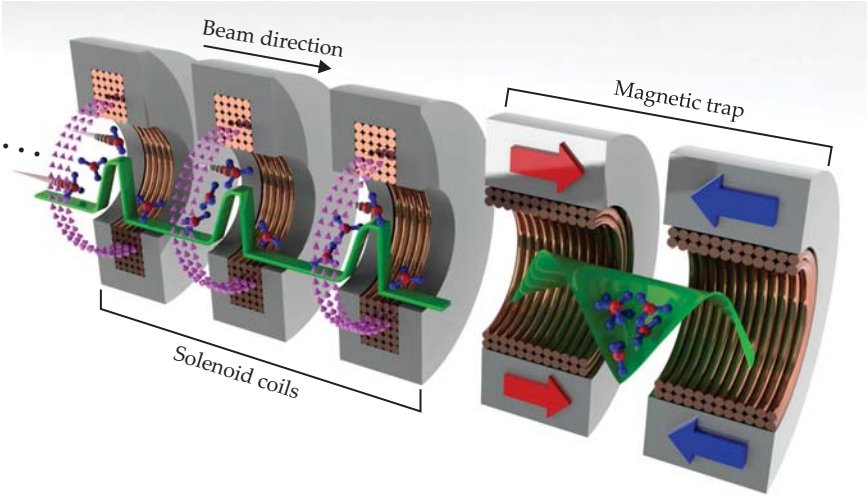
The concept behind the new decelerator and trap is nearly a decade old, developed by Frédéric Merkt and coworkers at ETH Zürich as a way to corral beams of paramagnetic atoms. When such beams are directed through the magnetic field of a solenoid coil, about half the atoms have their unpaired electron spin aligned antiparallel to the field. Those atoms are weakly repelled by the field due to the Zeeman effect, whereby the energy of an antiparallel state grows in proportion to an external field.

But that repulsion alone doesn't suffice to slow an atomic beam. A fast-moving atom's encounter with a localized magnetic field is like a fast-rolling ball's encounter with a mound: The atom expends kinetic energy climbing the magnetic potential but regains it during the ensuing descent. The trick with Zeeman deceleration is to switch the coil off just as the atoms arrive at the field's peak, so that the expended kinetic energy is permanently lost. By repeating that process with a succession of a dozen coils, each delivering 1 T pulses, Merkt and his coworkers could stop atoms entirely.

For nearly a decade now, Merkt's group has been using the approach to trap atomic hydrogen and deuterium. But stopping the heftier CH_3 radicals called for considerably greater braking force. Momose and his colleagues needed coils that could deliver pulses exceeding 4 T, on par with the strongest magnets in laboratory use. And they needed 85 of them.

The team's instrument, a meter-long cylinder lined with 4-mm-diameter solenoid coils, is partially illustrated in the figure on page 20. (The design is a modified version of an atom decelerator built by a University of Texas at Austin group led by Mark Raizen.[3]) At the outlet is a pair of opposing permanent magnets that serve as the trap. Near the inlet, a nozzle spouts CH_3 radicals in cold, bunched beams. The appropriate timing for each pulse could be calculated based on the gas's initial velocity, around 320 m/s. But coordinating the coils to fire with the requisite precision took considerable technical know-how. "We have to send 700 amps to each of the 85 coils for just a few microseconds at a time," Momose explains. "And we have to do it inside a vacuum. There are always dielectric breakdowns."

In all, it took six years to get the instrument working—three to decelerate molecules and another three to stop them. In a typical run the team captures some 50 000 molecules in the 1 mm^3 magnetic trap, where they can be held for about a second. The trapped gas is sufficiently dense to allow precise measurements of cross sections for collisions between CH_3 and assorted background gases; those measurements are already under way.



A FAST BEAM OF METHYL RADICALS can be slowed to a near standstill with a series of well-timed magnetic pulses from solenoid coils. Each pulse exerts a braking force on molecules with magnetic moments oriented antiparallel to the magnetic field. (The green curves indicate effective potentials for such a molecule as it travels, from left to right, through the device; purple triangles indicate the direction of the electric current.) As molecules exit the final coil, they can be trapped in the field of two ring-shaped permanent magnets, whose polarities are indicated by the red and blue arrows. The real-life implementation uses 85 4-mm-diameter coils, as opposed to the three shown here. (Adapted from ref. 2.)

"It would have been extremely difficult to trap methyl radicals using any other method," comments Edvardas Narevicius, whose group at the Weizmann Institute of Science has been developing a magnetic decelerator to simultaneously trap lithium and molecular oxygen.[4] "This is really a big step forward expanding the number of species that we can address."

Interstellar chemistry

On occasion, Momose cadges time at the Nobeyama Radio Observatory's 45 m telescope in Nagano, Japan. There he combs the space between stars for spectral lines produced by small hydrocarbon molecules, which are puzzlingly abundant in the interstellar medium. A possible explanation is that the rates of hydrocarbon-forming reactions are boosted by quantum tunneling through activation-energy barriers.

That's one reason Momose is especially excited about the newfound ability to isolate cold CH_3. He previously worked with researchers at Kyoto University in Japan to detect tunneling contributions to the methane-forming reaction $CH_3 + H_2 \rightarrow CH_4 + H$ in cryogenic hydrogen crystals. Now that CH_3 can be more comprehensively isolated from environmental influences, he hopes to measure those tunneling rates with far greater precision.

The ability to trap CH_3 also presents opportunities for fundamental physics. With the molecule in its rotational ground state, the researchers can make precise measurements of hyperfine transitions and parity-violating interactions. (See the article by David DeMille, PHYSICS TODAY, December 2015, page 34.) Ultimately, however, they hope to create a molecular gas that's cold enough and dense enough to form a Bose–Einstein condensate.

Momose thinks they should be able to cool their gas to submillikelvin temperatures via sympathetic cooling, "and then evaporative cooling should get us much lower, down to 1 microkelvin. Then the only missing part would be the density."

A BEC requires a phase space density of order 1, which would translate to a volumetric density about three orders of magnitude higher than the 5×10^7 cm^{-3} that Momose and company have achieved so far. "We'd probably need to build another decelerator," he muses. "So that would mean another three years."

Ashley G. Smart

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Why the ocean's carbon sink has gotten stronger

The past decade's slowdown of overturning boosted the ocean's ability to take up carbon dioxide, but the enforcement may not last.

In just over a century, the atmosphere's carbon dioxide concentration has risen from around 280 ppm to 400 ppm. That increase is a consequence of the burning of fossil fuels, conversion of forests into farm lands, and other human activities. Yet if all anthropogenic carbon stayed in the atmosphere, the rate at which atmospheric CO_2 concentration is presently increasing would be more than double its actual value. Instead, terrestrial plants, soils, and the ocean have taken up a significant tranche of the anthropogenic CO_2. (See the article by Jorge Sarmiento and Nicolas Gruber, PHYSICS TODAY, August 2002, page 30.) Some 30–40% of all anthropogenic CO_2 emitted since the late 18th century is thought to have been absorbed by the ocean.

The net flow of CO_2 across the air–sea boundary depends on the relative concentrations of the greenhouse gas in the ocean and the atmosphere. Attention has understandably focused on rising CO_2 levels in the atmosphere, but the ocean is no passive bystander. The 1990s saw a weakening of the ocean's carbon sink, which was attributed to the strengthening of westerly winds over the Southern Ocean, the waters encircling Antarctica.[1] Those winds combine with the Coriolis force to drive the northward flow of surface waters, which in turn draws carbon-rich deep waters to the surface. Puzzlingly, the ocean's carbon sink recovered in the 2000s even though the westerly winds remained strong.[2]

To tease out what other factors might be at play, Timothy DeVries at the University of California, Santa Barbara, Mark Holzer at the University of New South Wales in Australia, and François Primeau at the University of California, Irvine, took a look below the ocean surface. The researchers ran model simulations of the global ocean overturning circulation—the transport of surface waters downward and deep waters upward—for the 1980s, 1990s, and 2000s and then fed the results into an ocean carbon-cycle model. Their findings identify changes in the pace of circulation in the upper 1000 m of the global ocean as the primary driver of the observed trends in the ocean's net carbon uptake.[3]

The ups and downs

Global ocean overturning circulation involves water at all depths—from the surface down to the abyss some 4000–6000 m below—and operates at 1000-year time scales. (See the article by Adele Morrison, Thomas Frölicher, and Jorge Sarmiento, PHYSICS TODAY, January 2015, page 27.) For decadal variability in the ocean carbon sink, though, DeVries and his colleagues focused on the upper 1000 m of ocean, because deeper waters are unlikely to reach the surface in those time frames.

Ocean general-circulation models typically start with an at-rest ocean with some initial distribution of temperature and salinity. Turning on hydrodynamic and thermodynamic processes gets the waters moving, and then the model is stepped through time, often for thousands of simulated years, until an equilibrium circulation pattern emerges. Observational data serve mostly to set reasonable initial conditions.

DeVries and his colleagues opted for a different approach that places at center stage observational data for temperature, salinity, naturally occurring carbon-14, and chlorofluorocarbon distributions, each of which helps to reveal when a parcel of water last contacted the ocean surface. Chlorofluorocarbons, the ozone-depleting gases once widely used as refrigerants (see the article by Anne Douglass, Paul Newman, and Susan Solomon, PHYSICS TODAY, July 2014, page 42), are a particularly good tracer because their history in the atmosphere is well known