

59% probability of having an astrophysical origin.³

Multimessenger astrophysics

Detecting more TDEs and better establishing their relationship to high-energy neutrinos should be possible as early as next year. The Vera C. Rubin Observatory, previously named the Large Synoptic Survey Telescope, is currently being built in Chile. Once it sees first light, its wide-field Simonyi Survey Telescope will have the capability of photographing the entire sky every few nights.

If the TDE–neutrino association is true, TDEs would have to be extremely efficient particle accelerators. The energies of high-energy neutrinos are many orders of magnitude higher than can be reached in even the most impressive

terrestrial particle accelerators, and they reach Earth largely unperturbed.

High-energy neutrinos, therefore, are a natural part of a multimessenger astrophysical laboratory. They can't be controlled or replicated as in a traditional lab experiment, but they can be used to study high-energy processes and test fundamental ideas about particle physics.

For example, some of the densest and most energetic conditions in the universe are found in supernovae. Because neutrinos are very light and only interact by the weak nuclear force, they can pass through the dense core of a supernova and probe the conditions there.

Neutrinos are also theoretically expected to be produced during neutron star mergers. None were seen after the

2017 binary neutron star merger in which gravitational waves and a gamma-ray burst were observed (see “The era of multimessenger astronomy begins,” *PHYSICS TODAY* online, 16 October 2017). Nevertheless, the hunt for them continues. And should any be detected, they may offer bits of information about the density of a neutron star merger and how energy is dissipated from it.

Alex Lopatka

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A triatomic molecule is laser cooled and trapped

Molecules that stretch, bend, and rotate offer many new avenues for ultracold physics experiments. But they're also harder to control.

In March 2020, as the world was grappling with the implications of the COVID-19 pandemic, John Doyle and colleagues at Harvard University were faced with the bleak prospect of shutting down their experiments on ultracold atoms and molecules, perhaps indefinitely. So they turned their physics expertise to a rather different but more timely set of problems: Could N95 masks, in perilously short supply at the time, be decontaminated and reused?¹ And how could the risks of airborne disease transmission be most effectively mitigated in a laboratory or office setting?²

Through their work, they helped Harvard develop a plan to safely and quickly reopen its research labs—including their own, shown in figure 1. “By June 2020 we were working at 70% capacity,” says Doyle, “and a couple months after that we were back to essentially 100%. Although we didn't have any visitors during the shutdown, we enjoyed the opportunity for quiet and concentration.”

That opportunity has paid off. In one of a steady stream of papers published since the start of the pandemic, they've now demonstrated the laser cooling and magneto-optical trapping of calcium monohydroxide (CaOH), the first three-

atom molecule to be so cooled and trapped.³ The extension of ultracold techniques to larger molecules promises to make possible new experiments in quantum information, tests of fundamental physics, and more.

Will the cycle be unbroken?

Laser cooling and trapping of atoms is a decades-old technology that garnered the 1997 Nobel Prize (see *PHYSICS TODAY*, December 1997, page 17). In its simplest form, it works by optical cycling: An atom repeatedly absorbs and emits photons as it hops between its ground and excited electronic states. Each absorbed photon imparts some momentum, which counters the atom's thermal kinetic energy, thereby slowing and cooling it.

The success of that method hinges on getting the atom to reliably return to its ground state. If there's some other low-lying state that it can relax into instead, researchers need to add another laser to repump the atom from that state; if the atom ever ends up in a so-called dark state that isn't repumped, the cooling cycle ends and the atom is lost from the experiment. The easiest atoms to laser cool are therefore those with the simplest energy-level structures, mostly

alkali metals such as potassium and rubidium and alkaline earth metals such as calcium and strontium.

Extending ultracold methods from atoms to molecules is useful for a wide range of experiments. Some of those experiments are obvious, such as studying chemical reactions in the quantum regime (see the article by Debbie Jin and Jun Ye, *PHYSICS TODAY*, May 2011, page 27); others are less so, such as searching for hypothetical supersymmetric particles that might endow the electron with a permanent electric dipole moment (see the article by Dave DeMille, *PHYSICS TODAY*, December 2015, page 34).

But all the challenges of laser cooling atoms are compounded in molecules, which possess not only electronic quantum states but also quantized rotations and bond vibrations. The veritable continuum of low-lying states would, in the general case, require many dozens of repumping lasers to keep under control.

Because of the difficulty of cooling molecules directly, most ultracold-molecule researchers build their molecules from atoms that are already cooled. Although that approach works well, it yields exotic, weakly bound molecules such as KRb (see *PHYSICS TODAY*, February 2020, page 12) and Sr₂ (see *PHYSICS TODAY*, October 2019, page 18) that are essentially unknown outside of ultracold research.



FIGURE 1. A THICKET of optical elements directs the laser beams that cool and trap the triatomic molecule calcium monohydroxide. Laser cooling and magneto-optical trapping of atoms is standard practice, and a few groups have succeeded in cooling and trapping diatomic molecules. But never before has a three-atom molecule received the same treatment. (Photo by Loïc Anderegg.)

But some special molecules can be cooled directly without too much trouble. The trick is to find a molecule whose ground and excited electronic states have nearly the same equilibrium shape. (For diatomic molecules, the “shape” is merely the length.) The molecule can be cycled between those states without stretching it, and most molecules reliably relax to the vibrational ground state. Occasionally they might end up with one or a few quanta of vibrational energy, but a small number of repumping lasers can coax them back to the vibrationless state.

Two molecules that fit the bill are strontium monofluoride and calcium monofluoride. In each case, the alkaline earth metal atom—Sr or Ca—has an extra electron that doesn’t participate in the metal-fluorine bond. Exciting that electron doesn’t change the bond length much at all. Both molecules can be laser cooled with just a handful of additional repumping lasers. (See *PHYSICS TODAY*, January 2010, page 9.)

Importantly, there are multiple tiers of what’s meant by “laser cooling.” Because of their extra electrons, SrF and CaF aren’t stable enough to be carried around in bottles; they have to be synthesized from their constituent atoms in a molecular beam. It’s relatively straightforward to apply lasers perpendicular to the molecular beam to cool the molecules’ transverse motion while they hur-

tle along at some 100 m/s—and for some applications, that form of cooling is enough.

For experiments that require lower temperatures or optical lattices, however, researchers need to catch the molecules in a trap, which requires first slowing the molecular beam to a virtual stop. To do so with just lasers, they need to get the molecules to cycle more than 10 000 photons without ever landing in a dark state. That challenging feat, even for diatomic molecules, has been achieved by only a handful of groups in the world so far.

The bends

Going from two atoms to three introduces another important degree of freedom: Not only can triatomic molecules stretch and rotate, but they can also bend. The bending mode gives rise to some potentially interesting new effects. For example, in strontium monohydroxide, it so happens that three quanta of bending have almost exactly the same energy as two quanta of the Sr–O stretch. That accidental degeneracy makes the SrOH spectrum potentially sensitive to some postulated types of dark matter.

For another example, exciting the bending mode breaks an otherwise linear molecule’s linear symmetry. A bending molecule therefore has quantized rotational motion not just from tumbling

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end over end but also from turning like a spindle about the molecule's length. For complicated quantum mechanical reasons, molecules that possess angular momentum about their internuclear axes are extremely easy to align with an applied field. That capability comes in handy in searches for the electron electric dipole moment, use of the molecules as qubits, and more.

But the bending mode introduces the same challenge to laser cooling as a diatomic molecule's stretching mode does: It creates more vibrational states into which the molecule might relax and break the optical-pumping cycle. Fortunately, the same advantage of SrF and CaF also applies to CaOH (which Doyle and colleagues chose over SrOH simply because its transitions lie at more convenient laser frequencies): The Ca atom's extra electron doesn't participate in bonding, so most molecules relax into the vibrational ground state. But a few relax into states excited in the Ca–O stretch, the bend, or both.

Doyle and colleagues transversely cooled CaOH in a molecular beam just before the start of the pandemic. It took six lasers, one to drive the main transition and five to repump vibrationally excited states.⁴ That scheme cycled an average of about 1000 photons per molecule. To reach the 10 000-photon threshold required to slow the beam to a stop, the researchers had to add six more laser frequencies, for a total of 12, as depicted in figure 2a.

Fortunately, the molecules don't all fall into a dark state after the same number of cycles. The mean number of photons cycled, plotted in figure 2b, is the number of photons scattered per molecule before the number of molecules is reduced by a factor of $e \approx 2.718$. So even though the 12 lasers cycle an average of just 12 000 photons per molecule, only slightly more than the 10 000 needed to stop the beam, they still leave more than $\frac{1}{3}$ of the molecules available to be caught in the magneto-optical trap.

Bigger and bigger

Bending and Ca–O stretching aren't the only vibrational modes available to CaOH. There's also stretching of the OH bond, which the Harvard researchers' laser scheme doesn't address at all. But that's because it didn't need to: Optically cycling CaOH molecules almost never

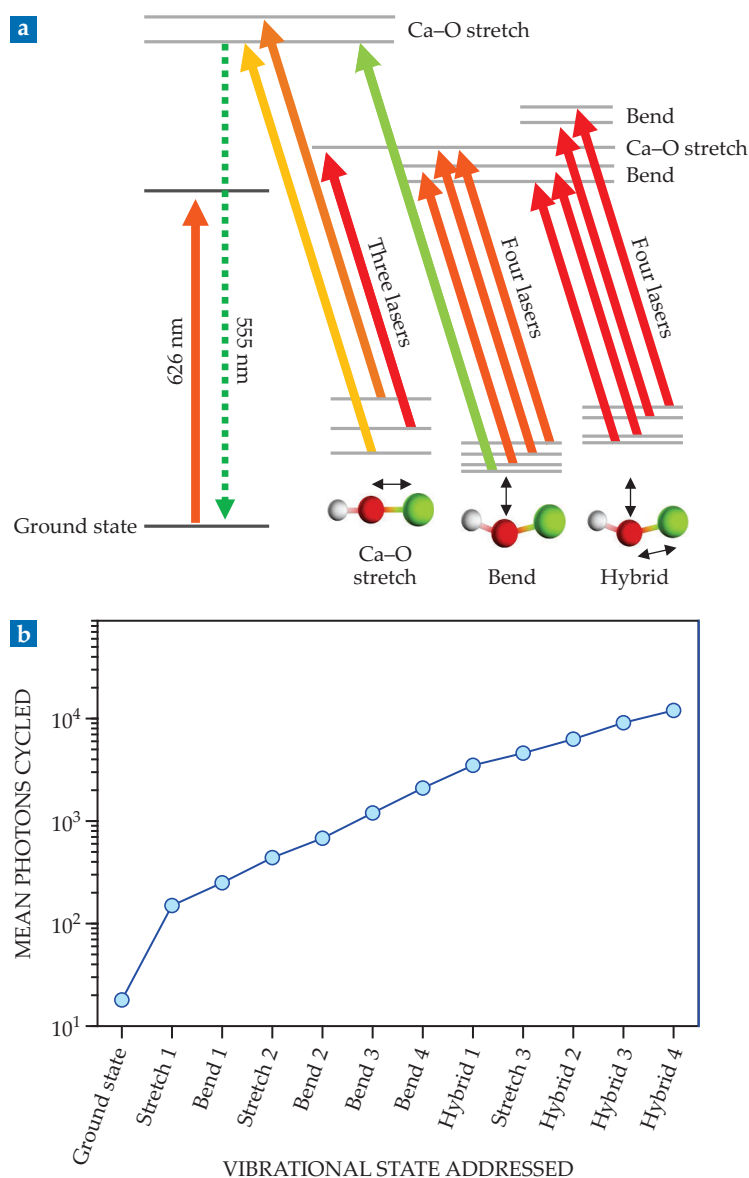


FIGURE 2. TWELVE LASERS combine to laser cool calcium monohydroxide. **(a)** The 626 nm laser cycles the molecule between the ground and electronically excited states, and 11 more lasers repump molecules that relax into vibrationally excited states. **(b)** The blue circles show the cumulative number of photons cycled as each new repumping laser is added. A six-laser scheme (from “ground state” through “bend 3”) cycles just 1000 photons per molecule. But using all 12 lasers increases that number to 12 000—enough to slow and trap the molecular beam. (Adapted from ref. 3.)

end up with any quanta of O–H stretching motion. It's intuitively easy to understand why. The cycling excitation is centered on the Ca atom, which is physically separated from the OH bond. The two parts of the molecule simply have little to do with each other.

That line of reasoning would seem to imply that laser-coolable molecules can be made arbitrarily large: Just attach a Ca (or Sr) atom to an O atom to just about anything. As with CaOH, one could

optically excite the unpaired electron, repump a few stretching and bending vibrational states, and leave the rest of the molecule alone.

The reality is almost certainly not so simple. Larger molecules have greater mass, so they'd have to cycle more photons to be slowed to a stop. And the sheer density of states of large molecules can introduce complicating effects, such as the coupling of disparate vibrational modes of similar energy.

Nevertheless, preliminary research suggests that the outlook for laser cooling larger molecules is good. Theory groups led by Anna Krylov, Svetlana Kotochigova, and Anastassia Alexandrova have analyzed the vibrational structures of many candidate molecules, and they predict that coolable molecules can incorporate some rather large organic structures, including benzene rings.⁵ On the experimental side, Doyle and colleagues have already done transverse in-beam cooling of calcium monomethoxide (CaOCH_3), although they still have a long way to go before they can catch that molecule in a trap.⁶

Cooling larger molecules would introduce even more richness to cold-molecule experiments. For example, if researchers could cool a molecule that breaks mirror symmetry, they could investigate whether the laws of physics treat such asymmetric molecules differently from their mirror-image counterparts. More broadly, by bringing all the well-known power of chemistry to bear on the ultracold regime, researchers could design ultracold molecules with shapes and properties to suit any purpose. “We don’t know whether our techniques are as broadly applicable as that,” says Doyle. “That’s a frontier scientific question.

We’re very interested in seeing what’s possible.”

Johanna Miller

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X-ray imaging shows how a 17th-century painting lost its color

When an arsenic sulfide pigment chemically degraded, it stripped the painting’s yellow rose of visible details.

As beautiful as they are to look at, art masterpieces are not eternal. For example, pigments and binders in oil paintings inexorably degrade. Light, humidity, and temperature fluctuations are the usual culprits, but exposure to certain cleaning solvents during conservation and the mixing of incompatible pigments by the artist can also render paint unstable over time.

The task of conservation scientists is to understand the chemical reactions that cause the degradation in order to answer three questions: How was the painting made, how did it originally appear, and how did it change—either naturally or by intervention? Those questions are not entirely backward-looking. By reconstructing how a painting deteriorates, conservators may be able to forestall further damage and better preserve it.

Paintings conservator and doctoral student Nouchka De Keyser (Rijksmuseum, University of Amsterdam, and University of Antwerp), her advisers Katrien Keune and Koen Janssens, and their colleagues have scientifically addressed all three questions in their analysis of a yellow rose in Abraham Mignon’s mid-17th-century painting *Still Life with Flowers and a Watch*,¹ shown in figure 1. Mignon painted his yellow roses with the mineral orpiment (As_2S_3), used by artists



FIGURE 1. STILL LIFE WITH FLOWERS AND A WATCH (left), by Abraham Mignon, oil on canvas (c. 1660–79), Rijksmuseum. **(a)** In its current form, the central yellow rose appears flat and lifeless. **(b)** The map of arsenic distribution reveals the element’s presence throughout the rose and Mignon’s original painted details. X-ray powder diffraction identifies the arsenic in the form of transparent lead arsenates rather than the original yellow-orange mineral orpiment (arsenic sulfide). (Adapted from ref. 1.)

since antiquity to give a bright and vibrant appearance. But orpiment can be problematic. Over time, the mineral can severely discolor, changing the look of painted orange draperies, lemons, yellow flowers, and golden metal in old masterworks.

Many artists, possibly including Mi-

gnon, were aware of those and the mineral’s other problems—it dries poorly, is incompatible with other pigments, and is extremely toxic. Yet it remained widely used until the 18th century. And orpiment was not the only troublesome pigment. In Vincent van Gogh’s 1888 painting *The Bedroom*, for instance, the fading