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Trapped-atom analysis pushes calcium-41 onto the radiometric dating scene FREE

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Christine Middleton

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fluorophore on a rotating kinesin stalk would be seen to take alternate steps of 6 nm and 10 nm, even though the stalk itself advances by a steady 8 nm each time.

When Hell and colleagues performed that experiment, the alternating step sizes are just what they found. The result isn't definitive evidence of a twirling mechanism—kinesin could still walk facing forward while twisting from side to side—but it doesn't rule it out.

Next steps

Both groups' MINFLUX experiments focus on tracking the position of a single fluorophore, with no information about the dynamics of anything else in the system. That capability works for studying kinesin, because the microtubules don't move much on the time scales of the experiments, even in living cells. But a more powerful tool would be one that simultaneously tracks the positions of two fluorophores that fluoresce in different colors. A two-color experiment could monitor protein interactions or conformations; with one fluorophore on each foot of a kinesin, it could settle the question of whether kinesin walks or twirls. "That's exactly what we're working on establishing next," says Ries.

For Hell, the next MINFLUX frontier is pushing the technique's resolution even further. The spatial resolution is already as good as it can be, because it's limited by the size of the fluorophore, but the temporal precision still has room to run. "The limiting factor is the fluorophore brightness," says Hell. A molecule that fluoresces more efficiently provides the same positional information in much less time. "With brighter fluorophores, we could get from one nanometer per millisecond down to one nanometer per ten microseconds," he says. "There's no reason that shouldn't be possible."

Johanna Miller

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Trapped-atom analysis pushes calcium-41 onto the radiometric dating scene

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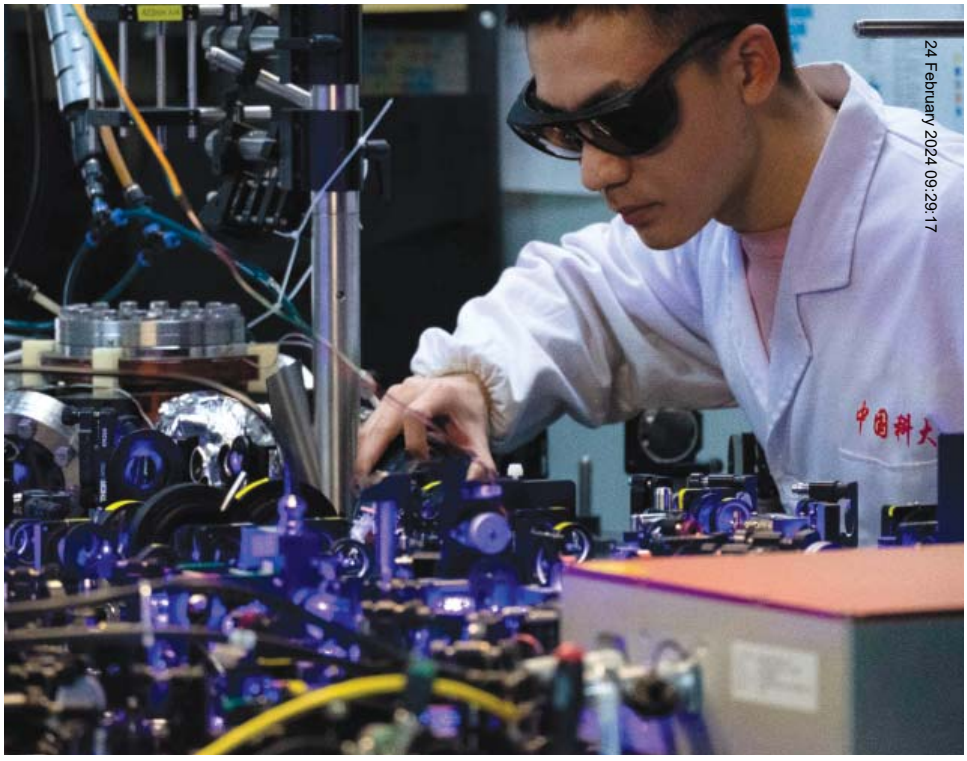

FIGURE 1. WEI-WEI SUN, a graduate student in the Laser Laboratory for Trace Analysis and Precision Measurements at the University of Science and Technology of China, adjusts the blue laser that slows and traps calcium atoms in the group's atom-trapping setup. (Courtesy of Wei-Wei Sun.)

When Willard Libby and colleagues developed radiocarbon dating in the late 1940s, they faced an experimental obstacle: No radiation detection tool was sensitive enough to detect carbon-14 at its expected environmental concentrations—about 1 out of every 10^{12} carbon atoms.

To overcome that obstacle, Libby and coworkers built a sample chamber surrounded by multiple Geiger counters and significant shielding. It removed some background signal and allowed them to calibrate for still more, thereby enabling them to pick out the ^{14}C signal.

As the field of radiometric dating has expanded to include isotopes with longer half-lives, lower abundances, and trickier contaminants, so has the range of experimental challenges. Calcium-41 was identified in the late 1970s as a potentially useful radioactive tracer for studying biochemical and geochemical cycles because of its prevalence in both biological organisms and Earth's crust. And because ^{41}Ca has a longer half-life than ^{14}C—nearly 100 000 years rather than around 5700 years—it could date older specimens. But its low natural baseline abundance, about 1 out of every 10^{15} Ca atoms, kept ^{41}Ca dating out of experimental reach.

Now Tong-Yan Xia, Wei-Wei Sun, and colleagues in Zheng-Tian Lu's group at the University of Science and Technology of China in Hefei have built an atom-trap trace analysis (ATTA) setup[1] (see figure 1) that can measure ^{41}Ca at abundances of less than 10^{-16}. They've demonstrated their system's ability to measure ^{41}Ca in natural samples of granite, seawater, and bone, and they are now collaborating with glaciologists and other experts to test the isotope as a tracer for radiometric dating.

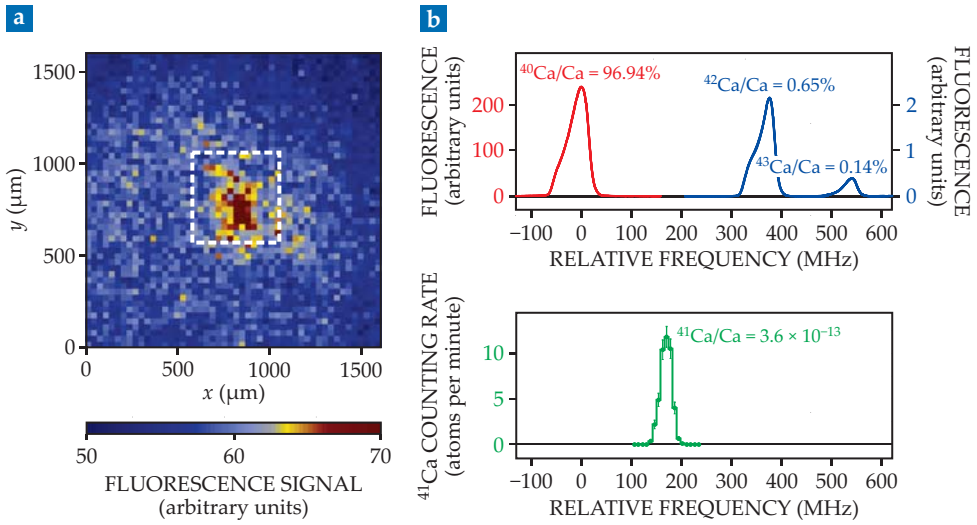

FIGURE 2. INDIVIDUAL CALCIUM-41 ATOMS are picked out of a Ca beam by atom-trap trace analysis. **(a)** The fluorescence from a single trapped ^{41}Ca atom is recorded as a CCD image. The pixels in the region of interest (ROI) are used to measure the signal. **(b)** When the laser frequency is tuned to be resonant with the electron transitions in ^{40}Ca, ^{42}Ca, or ^{43}Ca, the beam traps many atoms at once, which produces a bright fluorescent signal (top panel). But when it's tuned to ^{41}Ca, it rarely catches more than a single atom at a time (bottom panel). (Adapted from ref. 1.)

Isolating isotopes

A major disadvantage of using Geiger counters to measure a radioactive isotope's abundance is that the atoms are detectable only when they decay. So it revolutionized the field when researchers started using accelerator mass spectrometry (AMS) for carbon dating[2] in the 1970s. The technique uses a magnetic field to sort ions in a beam by mass, so researchers could measure the abundance of a particular isotope directly instead of waiting to detect a decay product. As a result, measurements take less time and can use much smaller samples.

A challenge for mass-spectrometry techniques is separating rare isotopes from common ones of the same mass. Radioactive ^{14}C may be easily distinguished from ^{12}C, but it's basically indistinguishable from nitrogen-14. To separate those isotopes, researchers have to give the species different charges so that they behave differently in the magnetic field. Carbon-14 atoms accept electrons to form a negatively charged beam, but ^{14}N atoms don't. So that technique solves the problem for carbon dating.

But for other elements, including Ca, the trick of making a negatively charged beam doesn't work well. That's where ATTA comes in.[3] Introduced in 1999, the technique filters atoms based on their electronic structure rather than their mass.

An ATTA sample is first vaporized in an oven to create a neutral beam of atoms. Those atoms are then slowed by Doppler cooling and, eventually, loaded into a magneto-optical trap so that their fluorescence can be imaged (see figure 2a).

The main reason why AMS measurements of ^{41}Ca can't reach natural environmental levels is because of potassium-41 contamination; the species have the same atomic mass, and even after purification, the stable isotope is always present at the same low level as ^{41}Ca. But the two have entirely different electronic structures. So when the ATTA laser is tuned to a ^{41}Ca transition, it has no effect on ^{41}K, and the contaminant is no longer an issue.

The problematic contaminants in ATTA are isotopes of the same element. Slightly different nuclear masses and dipole moments alter the isotopes' energy levels and shift the electronic transition frequencies. But those shifts can be small, so isolating a particular transition can be tricky.

Picking out a peak

Figure 2b shows the ATTA spectra for the four Ca isotopes that Xia, Sun, and their colleagues measured. When they tuned their laser to the resonance of the more abundant isotopes (top panel), they caught so many atoms in the trap at once that the measurement yielded only an overall fluorescent signal. But at the ^{41}Ca resonance, rarely was there more than one atom in the trap at a time, so the researchers could count individual atoms.

The fact that ATTA looks at only one isotope at a time differentiates it from typical spectroscopy measurements and is crucial for its success with rare isotopes. The ^{40}Ca fluorescence peak is 16 orders of magnitude taller than the ^{41}Ca peak, and the two are separated by only about 200 MHz. If they were measured together, the smaller peak would be completely swallowed by the tails of the larger one. Trapping the ^{41}Ca atoms separately allows them to be measured in isolation and their tiny peak to emerge.

For dating studies, though, the quantity of interest isn't just how many ^{41}Ca atoms are present; it's the ratio ^{41}Ca/Ca. To figure out the Ca beam's intensity, the researchers looked at the stable isotope ^{43}Ca, which has the same hyperfine structure as ^{41}Ca and is therefore trapped with a similar efficiency. Its isotopic abundance is 0.135%, which is too high for counting individual atoms. But the researchers extracted the trapping rate—how many atoms were caught per second—by turning the ^{43}Ca trap on and off and analyzing the slope of the fluorescent signal.

Lu was part of the team that first developed ATTA and has been successfully applying the technique for years to dating glacier ice cores with argon and krypton isotopes. (See the Quick Study by Lu, Physics Today, March 2013, page 74.) Noble gases present the same challenge

to AMS as Ca does—they don't form negative ion beams, so it's hard to separate the radioisotopes from more stable isotopes of the same nuclear mass.

So why did it take so long to apply ATTA to ^{41}Ca? Researchers, including Lu, did attempt those experiments shortly after the technique's development.[4] And it was successful in applications for which the concentration could be raised above the natural background level of about 10^{-15}. But it couldn't measure lower levels.

Lu credits advances in lasers in part for their current setup's improved performance: "Laser power is a lot higher, and laser frequency control is better—everything got better." Whereas it was difficult to pinpoint an isotope's transition frequency for cooling in earlier experiments, doing so is straightforward with modern lasers. Add to that an increase in power from about 60 mW to 3 W and an ATTA setup can reach a loading rate that is four orders of magnitude higher than it was in the technique's early days.

Advances over the past 15 years in modern cold-atom experimental techniques were also necessary to improve the trap's efficiency at capturing and holding atoms. One particularly important technique is so-called repumping: Each time an atom is excited in the Doppler-cooling process, it has a small chance of falling back to a state other than the ground state. When that happens, it can no longer be cooled by the laser and is lost. A repump laser directs the rogue atoms back to the ground state, thereby keeping more atoms around. It also helps the trap hold them long enough for imaging, which takes about 10 ms.

Going lower

The researchers measured the ^{41}Ca abundances in a series of samples that they made using commercially available Ca with a known ^{41}Ca abundance of 10^{-7} and an added dilutant. The measured abundances in those samples covered three orders of magnitude, from 4×10^{-13} to 5×10^{-16}, and had an error of about 12%.

The lowest abundance the researchers measured was that of the dilutant itself—Ca collected from deep in a mine. They determined the dilutant's ^{41}Ca abundance by adding known amounts of it to the commercial Ca and measuring the resulting samples with ATTA. That calibration yielded an abundance of $(8.4 \pm 3.5) \times 10^{-17}$, which agreed with the value the researchers found through ATTA measurements of the pure dilutant. And they expect to be able to reach still lower concentrations by strengthening the atom beam and improving the laser-cooling setup.

The researchers are already collaborating with other groups to explore geological applications for their device. One area of particular interest is exposure dating of glaciers. Calcium-41 is produced through the capture of cosmic-ray-induced neutrons by ^{40}Ca, but the process happens only in rock and soil within the top few meters of Earth's surface. So if rock gets buried under a glacier, the process stops, and the ^{41}Ca starts to decay. Measuring a newly exposed rock's ^{41}Ca/Ca ratio should therefore reveal how long it's been since the rock was last exposed.

A problem with that logic, though, is that baseline levels of ^{41}Ca vary considerably, so it's hard to establish the starting point from which the level declined. But that number is critical if researchers want to use the isotope for dating.

"We've been talking to experts," says Lu, "because we have this new tool, but we don't quite know what to do first." One potential starting point they've identified is collecting and measuring the ^{41}Ca concentration in water samples from various ocean bodies to see if it's uniform. The thinking is that even if there is local variation in the concentration, the currents might even it out, and then the water could serve as a baseline in certain situations.

But that theory still needs to be tested, and future applications are still uncertain. "We're just excited that now we can measure all kinds of samples and learn about ^{41}Ca and its distribution on Earth," says Lu. "We can now explore the world."

Christine Middleton

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