

tered by varying the magnetic field. The effect of that variation is more complicated, however, as it also changes the bulk filling factor and, with it, the number of quasiparticles in the central zone. Biasing the antidot can also change the number of enclosed quasiparticles.

According to Stern and Halperin's analysis, if the quasiparticles are non-abelian, the period of the oscillation will depend on whether the number of enclosed quasiparticles is odd or even. This surprising odd-even behavior comes from the quasiparticles' shared degeneracy that ordinary, abelian quasiparticles lack.

Das Sarma, Freedman, and Nayak's NOT gate is not much more complicated. It contains an additional antidot and an additional pair of tunneling electrodes.

Universal computation

Even before topological quantum computing looked as though it might be feasible, Kitaev's paper inspired theorists to explore its properties. In 2000, Freedman and Kitaev, working with Michael Larsen and Zhengang Wang of Indiana University, proved that topological and qubit-based quantum computers are equivalent or, rather,

that each can faithfully simulate the other.

Another development concerns the FQH state at a filling factor of 12/5. The state was observed for the first time last year by Jian-Sheng Xia of the University of Florida and his collaborators, but its properties were anticipated earlier. In a 1999 paper, Read and Edward Rezayi of the California State University in Los Angeles identified the Moore-Read state as the second in a series of states. The third member, at a filling factor of 12/5, has nonabelian quasiparticles.

Xia observed the 12/5 state at a temperature of 9 mK, which, from the practical point of view, makes the state less attractive than the 5/2 state. However, to theorists, the 12/5 state would make a better topological quantum computer. No matter how one winds quasiparticles around each other in the 5/2 state, the Hilbert space isn't dense enough to yield even the minimum number—two—of the logic gates needed for computation.

That's not the case for quasiparticles in the 12/5 state. Indeed, in a recent paper, Nicholas Bonesteel, Layla Hormozi, and Georgios Zikos of Florida State University and Steven Simon of Lucent Technologies' Bell

Labs provide a recipe for constructing logical operations by manipulating triplets of quasiparticles.⁶ Figure 1 shows their conditional NOT gate.

However, because of its much wider gap, the 5/2 state will most likely be the first to be manipulated in the lab. Freedman and Kitaev are investigating ways to compensate for the state's computational shortcomings by modifying device architecture.

Back in 1993, when he was a graduate student at Princeton University, Nayak chose to work on the quantum Hall effect for his thesis. "I just thought it was an incredibly cool, beautiful subject," he recalls. "The idea it could be useful beyond a good measure of the fine-structure constant didn't cross my mind."

Charles Day

References

1. A. Yu. Kitaev, <http://arXiv.org/abs/quant-ph/9707021>.
2. S. Das Sarma, M. Freedman, C. Nayak, *Phys. Rev. Lett.* **94**, 166802 (2005).
3. A. Stern, B. I. Halperin, <http://arXiv.org/abs/cond-mat/0508447>.
4. P. Bonderson, A. Kitaev, K. Shtengel, <http://arXiv.org/abs/cond-mat/0508616>.
5. C. de C. Chamon et al., *Phys. Rev. B* **55**, 2331 (1997).
6. N. E. Bonesteel, L. Hormozi, G. Zikos, S. H. Simon, *Phys. Rev. Lett.* (in press).

Trapping Ions in Pairs Extends the Reach of Ultraprecise Optical Spectroscopy

Thanks to techniques borrowed from quantum computation, once-unsuitable ions can now be used for atomic clocks.

In standards labs around the world, physicists are building and testing the next generation of atomic clocks. Like their cesium-based forebears, the new clocks keep time by locking onto atomic resonances. To deliver high accuracy, a resonance must be sharp, but it must also be stable.

Because high frequency brings high stability, clockmakers seek optical transitions. And because the environment undermines stability, they work with single atoms or ions isolated in traps.

Spectrally speaking, the singly charged aluminum cation looks ideal for making an atomic clock. One of its hyperfine transitions ($^1S_0 \rightarrow ^3P_0$), has a Q of 2×10^{17} and barely wavers under the influence of stray electric and magnetic fields that leak from lab equipment.

But aluminum has an unfortunate drawback. Unlike the current favorite ions of atomic clockmakers—stron-

tium, ytterbium, and mercury—aluminum lacks a convenient transition for removing kinetic energy. If the ion remains too restless after being isolated in its trap, its motion shifts and smears the clock transition's superlative sharpness.

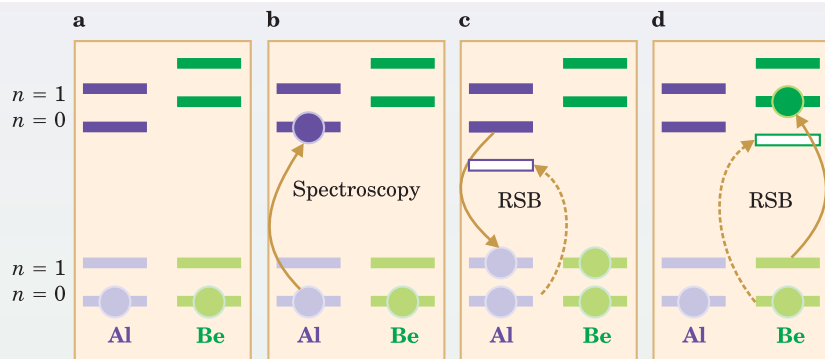
Now, David Wineland and his collaborators at NIST's campus in Boulder, Colorado, have demonstrated an ultraprecise method of frequency determination that doesn't require a fortuitous coincidence of clock and cooling transitions in the same species. Instead, the NIST group picks two different ion species.¹ One ion provides the clock transition, while the other provides the cooling transition. Thanks to the ions' Coulomb coupling, the cooling ion not only removes excess energy from both ions, but also acquires then divulges the probability amplitudes of the clock ion's quantum state. From those amplitudes, the clock transition's frequency is derived.

The NIST team is already running an atomic clock based on aluminum and beryllium ion pairs, but the method works for other combinations and has other applications. With an anticipated precision of 1 part in 10^{18} , the method can potentially validate the most exacting calculations of quantum electrodynamics, measure the nuclear charge radius of short-lived isotopes, and test if nature's fundamental constants vary in time.

Motional modes

Piet Schmidt, who is now at the University of Innsbruck in Austria, Till Rosenband of NIST, and Christopher Langer, a graduate student at the University of Colorado, set up and ran the first demonstration of the paired-ion method. For the experiment, which took place early this year, they paired $^{27}\text{Al}^+$ with $^9\text{Be}^+$. The aluminum ion's prime clock transition $^1S_0 \rightarrow ^3P_0$ is somewhat difficult to work with. To test their method, the NIST group chose instead a different transition, $^1S_0 \rightarrow ^3P_1$.

When trapped together, the two



A sequence of three laser pulses excites an $^{27}\text{Al}^+$ ion and faithfully transfers the probability amplitudes of its internal state to a $^9\text{Be}^+$ ion for subsequent detection. (a) Initially, the two ions are in their respective ground states and in the lowest ($n = 0$) sublevel of their mutual motional modes. (b) A laser pulse excites the $^{27}\text{Al}^+$ ion to create a superposition of its ground and excited states. This is the transition whose frequency the experiment aims to measure. The transfer of probability amplitudes takes place in two steps. (c) First, a red sideband (RSB) pulse stimulates the excited-state component of the $^{27}\text{Al}^+$ ion's superposition. It drops into the ground state's $n = 1$ sublevel. Even though it would have the same energy, the transition from the $^{27}\text{Al}^+$ ground state to the first excited state's $n = -1$ sublevel can't happen, because the substate doesn't exist. In a sense, the external state of the $^9\text{Be}^+$ ion is now a copy of the internal state of the $^{27}\text{Al}^+$ ion after the first laser pulse. (d) In the second transfer step, an RSB pulse excites the $^9\text{Be}^+$ ion from the ground state's $n = 1$ sublevel, which it shares with the $^{27}\text{Al}^+$ ion. Again, because the $n = -1$ sublevel doesn't exist, the RSB pulse can't excite $^9\text{Be}^+$ from the ground state's $n = 0$ sublevel. (Adapted from ref. 1.)

positively charged ions repel each other while the trap's potential pushes them together. That coupling puts the ions in shared motional modes whose quantized levels (labeled $n = 0, 1$, and so on) split the ions' ground and excited states (see figure 1a).

In a typical trapped-ion spectroscopy experiment, an ion is irradiated with a series of pulses from a laser whose frequency is stabilized by a high-finesse cavity. The laser's frequency is stepped up in value from below the expected resonance to above it. At each frequency, the probability of absorption—and the corresponding point on the resonance curve—is determined through the ion's fluorescence.

Because an ion either fluoresces or doesn't, several hundred measurements are taken at each frequency to evaluate the probability. Once the resonance curve has been sampled, the laser frequency is electronically steered to the ion's resonance and a device called a frequency comb determines its value (see the article by James Bergquist, Steven Jefferts, and Wineland, *PHYSICS TODAY*, March 2001, page 37). What makes the NIST approach different is that a second ion, not the clock ion itself, manifests the resonance.

The procedure begins with the ions in their ground states (figure 1a). Next, the ions are irradiated with a

laser pulse tuned close to the $^{27}\text{Al}^+$ target transition. The outcome (figure 1b), is a two-state superposition between the $^{27}\text{Al}^+$ ground and excited states with probability amplitudes α and β , respectively. Transferring those amplitudes intact from the clock ion to the cooling ion is the key to the NIST method. Here's how it works.

After the $^{27}\text{Al}^+$ ion has been excited, the ions are irradiated again—this time with what's called a red sideband pulse. As figure 1c shows, the RSB pulse is tuned to stimulate the transition of $^{27}\text{Al}^+$ from its first excited state to the ground state's $n = 1$ sublevel. Now the ions' motional coupling comes into play. A second RSB pulse (figure 1d) hits the ions—this time tuned to excite $^9\text{Be}^+$ from the $n = 1$ sublevel of its ground state to the $n = 0$ sublevel its first excited state.

The final pulse, not shown in figure 1, stimulates the emission of fluorescence photons from the $^9\text{Be}^+$ whenever the $^9\text{Be}^+$ is in the ground state. The fluorescence rate forms the resonance curve.

The motional modes faithfully transfer α and β not just because they link the two ions. Because the $n = -1$ mode doesn't exist, the first RSB pulse can't excite $^{27}\text{Al}^+$ from its $n = 0$ ground state, nor can the second RSB pulse excite $^9\text{Be}^+$ from its $n = 0$ ground state. As a result, the probability amplitudes engendered by the first pulse remain

intact, despite two subsequent pulses.

During the experiment, the $^{27}\text{Al}^+$ ion acquires kinetic energy from ambient electric fields. To avoid blurring the clock transition line—and, indeed, to put the ion into its ground state at the beginning of the procedure—the excess kinetic energy is removed by $^9\text{Be}^+$ through the ions' coupled motion.

Applications

With just one electron, the helium ion is simple enough that its energy levels can be calculated with extreme precision. Like aluminum, it's also hard to cool on its own. Two experiments performed last year exemplify how the NIST paired-ion method could bring the calculations into closer, possibly decisive, confrontation with data.

In the short-lived neutron-rich isotope ^6He , the extra neutrons occupy an extended halo that shifts the isotopes' atomic spectra. Almost all the shift comes from the halo's mass, but the halo's charge volume also contributes.

Last year, a team from Argonne National Laboratory in Illinois trapped ^6He atoms and ^4He atoms, compared the frequency of their $^3S_1 \rightarrow ^3P_2$ transition, and deduced the nuclear charge radius of ^6He to be $2.054 \pm 0.014 \text{ fm}$.² That value was accurate enough to rule out some models of nuclear structure, but not all them.

Helium also provides a route to measure the Rydberg constant and its possible variation in time. Earlier this year, Stephan Schiller, Bernhard Roth, and Ulf Fröhlich of the University of Düsseldorf in Germany succeeded in cooling ensembles of several thousand helium ions in a trap by coupling them to an ensemble of several thousand beryllium ions.³ Schiller hopes to apply the NIST paired-ion approach to single pairs of helium and beryllium ions. Using helium to measure the Rydberg constant would complement values obtained from hydrogen.

The course of basic research is hard to predict and sometimes surprising. The paired-ion method exploits techniques the NIST researchers had developed to manipulate ions for quantum computation. Those techniques, in turn, grew out of their work on atomic clocks.

Charles Day

References

1. P. O. Schmidt et al., *Science* **309**, 749 (2005).
2. L.-B. Wang et al., *Phys. Rev. Lett.* **93**, 142501 (2004).
3. B. Roth, U. Fröhlich, S. Schiller, *Phys. Rev. Lett.* **94**, 053001 (2005). ■