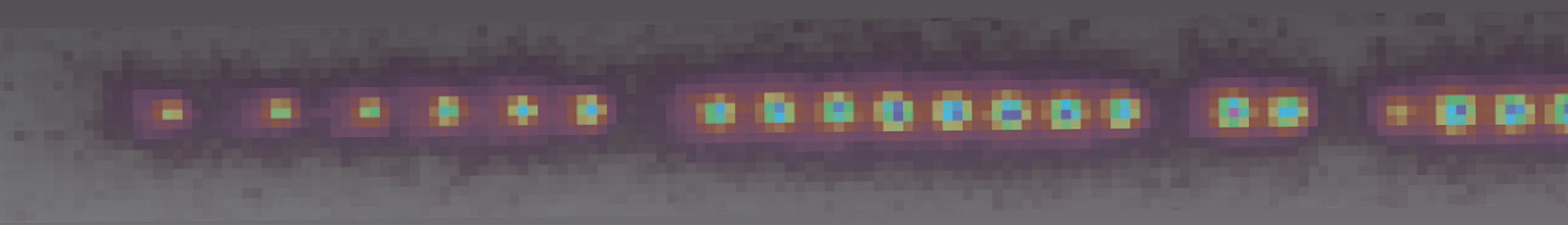


Quantum Information with Trapped Strontium Ions

Dana J. Berkeland

Something wonderful happens when small numbers of ions are trapped in a linear Paul (radiofrequency, or rf) trap and laser-cooled. The ions become nearly motionless and line up neatly along the trap axis—each confined to its own tiny space of about 100 micrometers or less in any direction. Because the ions are frozen in place, experimental physicists can continually observe them for up to months at a time and gain uncommon insight into the quantum realm.

For example, single ions exhibit quantum-mechanical effects that could never be observed in a large ensemble of ions or neutral atoms. A large field of study in quantum optics has in fact emerged with the development of ion traps (Thompson et al. 1997). In addition, the internal transitions of a nearly motionless ion are only slightly affected by Doppler shifts, and the ion can be superbly isolated from unwanted electric fields and noisy magnetic fields. This characteristic makes a trapped ion a useful testing ground for many physical theories that predict very small shifts of the atomic energy levels (Berkeland et al. 1999). Finally, a focused laser beam can interact first with one specific ion, then a different one—a capability that means we can control complicated interactions between states of a particular ion and between different ions. For this reason, the ion trap has shown considerable promise as the basis for a quantum computer. (See the article "Ion-Trap Quantum Computation" on page 264.)

In this article, I discuss some of our activities with trapped and laser-cooled ions. I focus on an experiment that provides a fundamental test of quantum-mechanical randomness but also mention a spectroscopy experiment that is a prerequisite to the development of a quantum logic gate. For background material, see the previously mentioned article, "Ion-Trap Quantum Computation," which discusses the operational principles of a linear Paul trap and laser cooling.

We conduct our experiments using singly ionized strontium atoms. Figure 1(a) is an illustration of our linear Paul trap (Berkeland 2002). Most of the trap has been created with off-the-shelf components and requires no precise or otherwise demanding machining to assemble. This feature is significant because it shows that ion trapping with linear traps can be an accessible technology for groups with limited resources.

Figure 1(b) shows the transitions we use in the strontium ion $^{88}Sr^{+}$. We use the 422-nanometer transition to Doppler-cool the ions. We also collect the 422-nanometer fluorescent light from the decay of the $P_{1/2}$ state and focus it onto a detector to image the ions. Light at 1092 nanometers drives the $D_{3/2} \leftrightarrow P_{1/2}$ transition to prevent the atoms from pooling in the long-lived $D_{3/2}$ state, in which they would not scatter any 422-nanometer light. A 674-nanometer diode laser drives transitions between the $S_{1/2}$ ground state and the $D_{5/2}$ state, which lives an average of 0.35 seconds. This transition can be used to couple the $S_{1/2}$ and $D_{5/2}$ states of the ion with its motional states, any of which may be used as qubits in a quantum computer. The $S_{1/2} \leftrightarrow D_{5/2}$ transition is also driven

About forty strontium ions lined up in our linear Paul trap are visible because they scatter laser light. The apparent gaps are due to other ions that do not scatter the light.

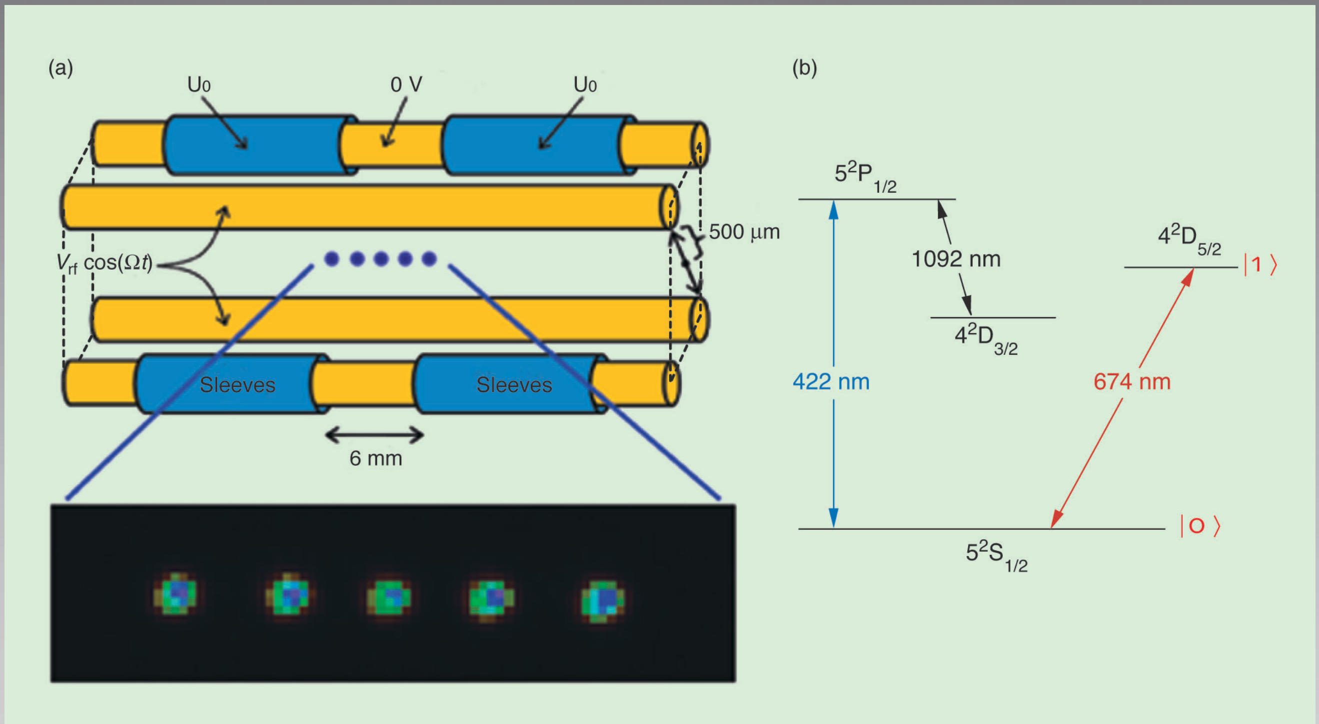


Figure 1. Strontium Ion Linear rf Paul Trap

(a) A schematic of the linear trap depicts five $^{88}Sr^+$ ions along its axis (not to scale). The ions in this trap are confined radially in a time-averaged potential that is created by applying 100 V at a frequency of 7 MHz to the two electrodes shown. The other two electrodes are held at a constant potential. The tubular electrodes (labeled "sleeves") are held at constant potentials up to 100 V, relative to the other electrodes, to stop the ions from leaking out of the ends of the trap. The picture of five Sr^+ ions was made by focusing the 422-nm light scattered from the ions onto an intensified charge-coupled-device camera. The ions are spaced about 20 μm from each other. (b) The diagram shows the relevant energy levels of Sr^+ and the corresponding transitions (not to scale). We use 422-nm light from a frequency-doubled diode laser to Doppler-cool the ions and collect the scattered 422-nm light to detect the ions. A fiber laser generates 1092-nm light that keeps the ions from becoming stuck in the long-lived $D_{3/2}$ state. A very stable diode laser at 674 nm drives the narrow $S_{1/2} \leftrightarrow D_{5/2}$ transition.

so that quantum jumps can be observed in the experiments discussed next.

Quantum Randomness

In the article "A New Face for Cryptography" on page 68, the authors describe the quantum cryptography project at Los Alamos. Cryptography applications, whether classical or quantum, require strings of numbers (typically 1s and 0s) that are as random as possible. Generating random numbers, however, is not a trivial matter. In fact, the random number generators found in various computer programs are do not yield very random numbers because they are based on algebraic processes that are intrinsically deterministic.

It is generally accepted that producing strings of truly random numbers requires measuring the random outcome of a quantum-mechanical process. One example of a random

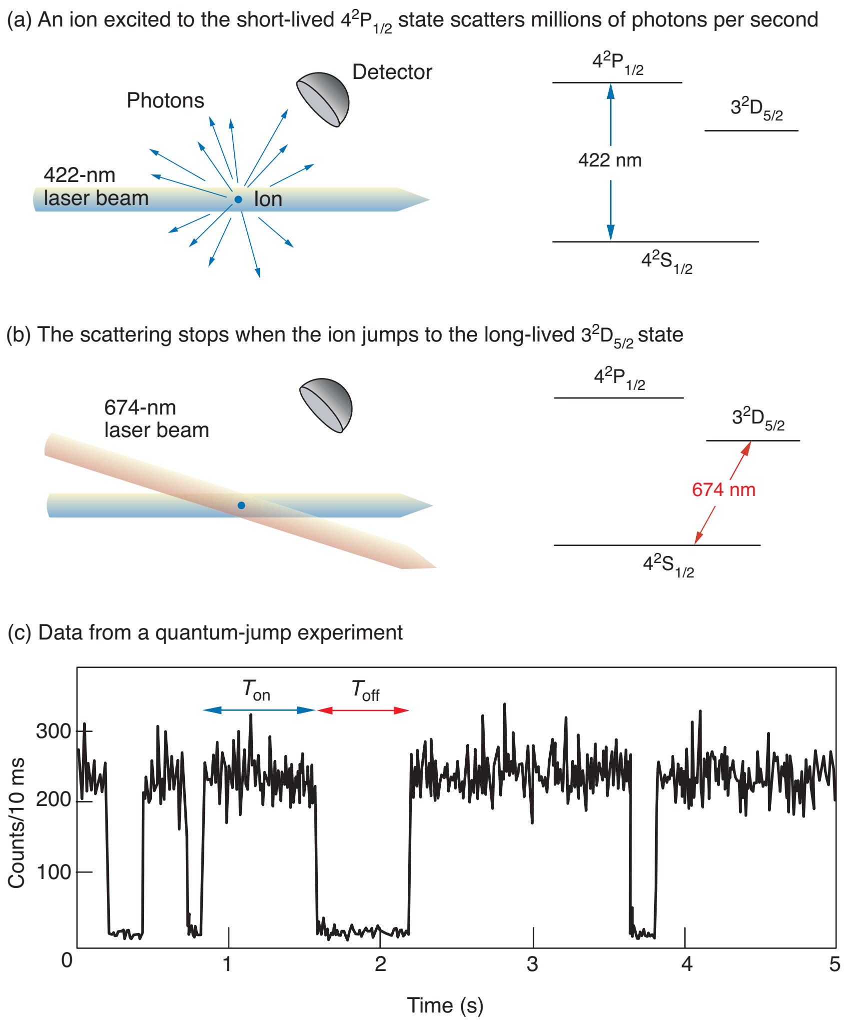


Figure 2. Quantum Jumps in a Single Trapped $^{88}Sr^+$ Ion

(a) When illuminated by 422-nm radiation, a single strontium ion will cycle between the $S_{1/2}$ and $P_{1/2}$ states and will scatter millions of photons per second. Some of the scattered light can be collected with a simple optical detector in order to monitor the state of the ion. (b) If the ion is simultaneously illuminated with 674-nm radiation, it will occasionally undergo a transition ("quantum jump") from the $S_{1/2}$ state to the long-lived $D_{5/2}$ state. The scattered light then disappears. (c) This plot shows typical data from the quantum-jump experiment. When the count rate is over 50 counts per 10 ms, the atom is cycling between the $S_{1/2}$ and $P_{1/2}$ states. When the count rate suddenly falls to less than 50 counts per 10 ms, the atom has made a transition into the $D_{5/2}$ state. We continuously monitor the ion's scattering rate for nearly an hour to observe tens of thousands of these transitions.

outcome is a photon hitting a beam splitter (Jennewein et al. 2000). The photon has a probability to either pass through the optic or reflect off it, and only a measurement determines its fate. Another example is the decay of radioactive nuclei, which emit, say, alpha particles at unpredictable times (Silverman et al. 2000). Although both those processes are believed to be random, they suffer from one major drawback in a test of their statistics: As in any experimental setup, all the detectors have physical limitations. Therefore, we cannot be sure that we would detect every photon or alpha particle. It is possible that some nonrandom processes might be overlooked in analyzing the incomplete data set.

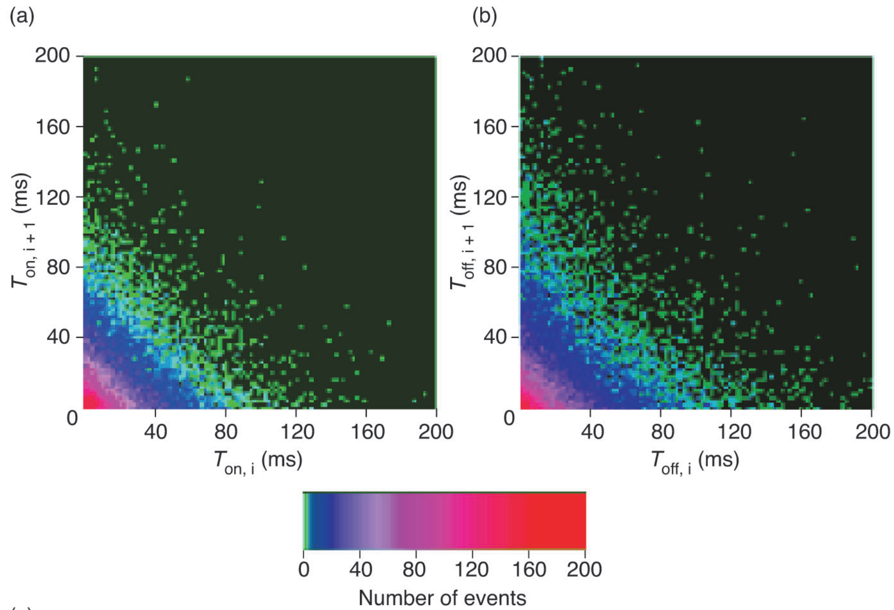
In contrast, a very clean way to test the statistical nature of quantum processes is to analyze the behavior of an atom undergoing quantum jumps (Erber 1995). Quantum jumps are the sudden transitions from one quantum state to another. As Figure 2 shows, a strontium ion in the $S_{1/2}$ ground state will absorb a photon from a laser tuned to 422 nanometers and "jump" to the $P_{1/2}$ excited state. Because the $P_{1/2}$ state is short-lived, the ion quickly returns to the $S_{1/2}$ state by emitting a 422-nanometer photon in a random direction. Once it returns to the $S_{1/2}$ state, the ion can absorb and emit another photon, and because the lifetime of the $P_{1/2}$ excited state is so short, the ion will scatter millions of photons per second. We can detect enough of the scattered light with an optical system to observe the ion but not enough to determine every time the ion jumps to and from the $P_{1/2}$ state.

To directly observe quantum jumps, we simultaneously illuminate the ion with a 422- and a 674-nanometer laser light. In addition to jumping to the $P_{1/2}$ state, now the ion can also jump to the $D_{5/2}$ state. As soon as that transition occurs, the ion will stop scattering 422-nanometer light. The scattered light will return the moment the ion has left the $D_{5/2}$ state. As Figure 2 shows, we can very easily record every time a single ion makes a transition to the $D_{5/2}$ state and every time it returns to the $S_{1/2}$ state. According to quantum theory, the exact times of those transitions are completely unpredictable. Surprisingly, this prediction has not been tested with data sets comprising much more than about a thousand consecutive events. It is important to test very large sets of data because it is harder to make a nonrandom series of numbers appear random if the series is very long.

Many tests can be used to determine the degree of randomness in a string of data. Figure 3(a) shows the result of one such test applied to our quantum-jump data (Itano et al. 1990). A single atom was continuously monitored until it had made over 34,000 transitions in and out of the $D_{5/2}$ state. We record the length of each time period $T_{on,i}$, during which the atom continually scatters 422-nanometer photons, and the length of each subsequent time period $T_{off,i}$, during which the ion scattered no photons because it was in the $D_{5/2}$ state. For example, in the figure, the values of T_{off} are $T_{off,1}$ = 0.23 second, $T_{off,2}$ = 0.1 second, $T_{off,3}$ = 0.61 second, and $T_{off,4}$ = 0.17 second.

We then sift through the data to determine the number of times a particular pair of values ($T_{off,i}$, $T_{off,i+1}$) occurs and make the color-coded plot shown in Figure 3(a). The symmetry and shapes of these graphs reflect several important characteristics of the data. For example, a pair of values, say ($T_{off,i}$, $T_{off,i+1}$) = (0.23 second, 0.1 second), is just as likely to occur as the pair (0.1 second, 0.23 second)—a long period of fluorescence is no more likely to be followed by a short one than a short period is likely to be followed by a long one. Essentially, plots like these indicate that the ion has no memory of what it was doing just the briefest moment before it fluoresces. This fundamental feature of quantum processes has not previously been tested precisely. It is also exactly what one would like to see in a random number generator.

We can easily convert the quantum-jump data into a string of 1s and 0s. If $T_{on,i}$ is more than a set amount of time, we assign to that event the value 0. Likewise, if $T_{on,i}$ is less than this time, we will assign the value 1 to the event. Figure 3(b) gives an



(c)

Set 1

4	2	18	86	14	8	52
16	10	10	22	78	146	196
180	84	134	6	52	2	32
72	34	76	112	12	16	2
82	28	6	54	4	170	38
22	42	78	6	22	2	186
32	82	66	48	30	54	32
4	16	32	28	126	34	74

Set 2

1	1	1	0	1	1	0
1	1	1	1	0	0	0
0	0	0	1	0	1	0
0	0	0	0	1	1	1
0	1	1	0	1	0	0
1	0	0	1	1	1	0
0	0	0	0	0	0	0
1	1	0	1	0	0	0

Figure 3. Analyzing Quantum-Jump Data

The scatter plots show consecutive periods that the ion spends (a) scattering 422-nm photons ($T_{on,i}$, $T_{on,i+1}$) and (b) not scattering 422-nm photons ($T_{off,i}$, $T_{off,i+1}$). Because these graphs are symmetric about their diagonal axis, we can tell that the ion is just as likely to spend a long time scattering photons followed by a short time scattering photons as it is to spend a short time followed by a long time scattering photons. This is one of many indications that the ion has no memory of when it has made a transition between the $S_{1/2}$ and $D_{5/2}$ states. (c) The quantum-jump data can also be converted to digital data. The first set of numbers shows a string of consecutive times spent in the $D_{5/2}$ state ($T_{off,i}$). If the ion spends 30 ms or more in the $D_{5/2}$ state, the event is assigned a value of 0. Otherwise, the event is assigned a value of 1. These assignments are shown in set 2. With strings of tens of thousands of these digital numbers, we can use established protocols to test the randomness of our quantum-jump data.

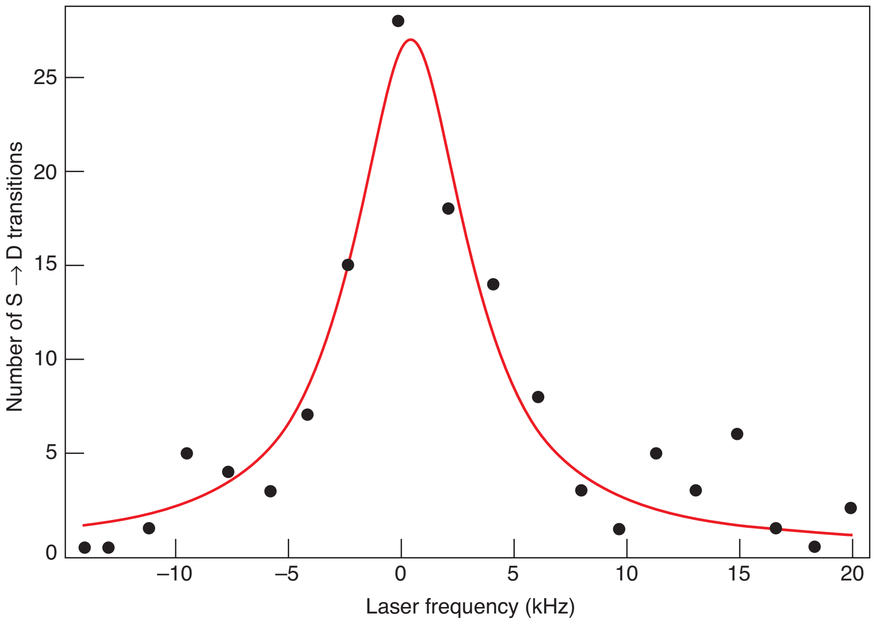


Figure 4. Measurement of the Laser Linewidth
The plot shows data taken from the narrow sideband of the $S_{1/2} \leftrightarrow D_{5/2}$ transition in a single trapped $^{88}Sr^{+}$ ion. The solid line is a Lorentzian line shape that is fitted to the data. In one laser probe cycle, the atom starts in the $S_{1/2}$ state. Next, the cooling light is turned off while the 674-nm light is pulsed on for 0.001s. Then the cooling light is turned on again, and we see if any 422-nm light is scattered into the detector. If not, then the 674-nm laser has successfully transferred the ion to the $D_{5/2}$ state. This process is repeated 100 times for each laser frequency.

example of this conversion for a typical set of data.

Digitizing our data lets us use some of the established protocols that test the randomness of digital data. (One such standard is outlined in the U.S. Federal Information Processing Standards publication 140-2). An example of such a test is the following: In a string of 1s and 0s, we count how many times the two-digit patterns (0,0), (0,1), (1,0) and (1,1) appear. We then compare these numbers with the values expected for an ideal, random sequence. It is easy to calculate how likely it is that the measured sets of values differ from the expected ones, so that we can decide whether or not our quantum-jump data are random according to the given protocol. We are collecting continuous sequences of data, tens of thousands of events long, that can be used for these tests.

Quantum Computing

We are also beginning some of the tasks that are prerequisites to making a quantum logic gate with a trapped ion. Perhaps the most critical step is coherently driving transitions between specific qubit states. In the experiments we are considering, the strontium $S_{1/2}$ ground state corresponds to the qubit state $|0\rangle$, whereas the $D_{5/2}$ excited state corresponds to the $|1\rangle$ qubit state. The stable 674-nanometer diode laser couples the qubit states to each other and to states of the ion's quantized external motion that would also be qubit states (Monroe et al. 1995).

The stability of the laser is one of several parameters that can limit the performance of a quantum computer. If the laser frequency and phase were constant, we could almost always complete quantum logic operations perfectly. For example, starting with the ion in the $S_{1/2}$ state, we could reliably create a specific superposition of the $S_{1/2}$ and $D_{5/2}$ states:

$$\left|S_{1/2}\right\rangle = \frac{\left|S_{1/2}\right\rangle + i\left|D_{5/2}\right\rangle}{\sqrt{2}} \quad . \tag{1}$$

However, if the phase or frequency of the laser is not perfectly stable while this operation is taking place, the result of the operation may be, for example,

$$\left|S_{1/2}\right\rangle = \frac{0.99\left|S_{1/2}\right\rangle + i1.01\left|D_{5/2}\right\rangle}{\sqrt{2}} \tag{2}$$

In this case, the new wave function has a small phase error. If this operation is repeated many times, the accumulations of these small errors could invalidate the results of a quantum computation. Because every laser has a nonzero linewidth (proportional to the laser's frequency), such errors are inevitable. One way to reduce the likelihood of introducing the errors is to perform the logic operation quickly, that is, faster than the typical time scales of the frequency fluctuations of the laser, although it is easier to perform a quantum-gate operation slowly. Thus, it is critical that the laser be very stable with its linewidth as small as possible.

We have measured our laser linewidth using a procedure related to the quantum-jump experiment described earlier. First, we turn off the 422-nanometer light, letting the ion decay to the $S_{1/2}$ state. Then we illuminate the ion with a pulse of 674-nanometer laser light. (The 422-nanometer light remains off during this step, because that light will perturb the $S_{1/2}$ state and broaden the $S_{1/2} \leftrightarrow D_{5/2}$ transition.) We then determine whether or not the laser has driven the atom from the $S_{1/2}$ to the $D_{5/2}$ state by shining the

422-nanometer light on the ion. We detect light scattered by the ion if it is not in the $D_{5/2}$ state, but only background light (the small amount of light scattered off the trap and vacuum chamber) if the ion is in the $D_{5/2}$ state. Figure 4 shows the number of times the 674-nanometer laser transfers the ion to the $D_{5/2}$ state as the laser frequency is scanned over one of the motional sidebands of the $S_{1/2} \leftrightarrow D_{5/2}$ transition. The figure also shows the result of fitting a Lorentzian-shaped curve to these data. From the shape of the fitted curve and from a few key experimental parameters, we can determine that the laser linewidth is about 4 kilohertz or less, which is about one percent of one billionth of the absolute frequency of the laser light (445 terahertz).

This laser linewidth is sufficiently narrow so that we can perform specific, coherent operations on qubit states. However, to perform the operations needed for a quantum logic gate, the ions must be cooled much more than they are at present, so that the quantum state of the ion can be initialized to the ground state of its motion. We are currently working toward this goal and on further narrowing the linewidth of the 674-nanometer laser. In addition, we are working on or anticipate performing several other quantum-optics experiments. The apparatus presented here, along with ion traps in general, can facilitate significant contributions to the field of quantum information and quantum computation. ■

Acknowledgments

I would like to thank Richard Hughes for suggesting the study of the randomness of quantum jumps and for his indispensable role in bringing ion-trap technology to the field of quantum information and quantum computation at Los Alamos. In addition, I am grateful to Daisy Raymondson for her work on some of the laser systems used in this experiment and to the Los Alamos Summer School for initially bringing her to Los Alamos.

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Dana J. Berkeland has performed a wide variety of experiments in atomic and optical physics. She received her Ph.D. from Yale University in 1995 after precisely measuring Stark shifts in lithium and cesium and measuring the ground-state Lamb shift in hydrogen to an accuracy of 6 parts per million. This measurement, performed with Malcolm Boshier, was at the time the most precise measurement of the quantity. Dana spent three years as a National Research Council postdoctoral fellow at the National Institute of Standards and Technology in Boulder, Colorado, where she evaluated a trapped-mercury-ion microwave frequency standard to a fractional accuracy of 3×10^{-15} (making it one of the most accurate frequency standards in the world). In 1998, she came to Los Alamos National Laboratory as a J. Robert Oppenheimer postdoctoral fellow to build a laboratory for quantum-optics experiments with trapped strontium ions and became a technical staff member in 2000. She has over a decade of experience in building and developing laser systems and related optics. Dana has over seven years of experience in building and working with ion trapping systems.