The 2012 Nobel Prize in Physics

Manipulation at the Single-Particle Quantum Level

Vasant Natarajan

The 2012 Nobel Prize in Physics has been awarded jointly to Serge Haroche and David J Wineland "*for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems*". In this article, we discuss how the experiments of the two Laureates have taught us how to study single quantum particles – using photons to study single atoms in the case of Wineland, and using atoms to study single photons in the case of Haroche. Their work may some day lead to a superfast quantum computer.

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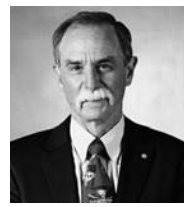
Quantum mechanics describes the weird world of microscopic particles, which is completely different from the macro world that we are used to in our daily lives. Perhaps the most defining characteristic of that world is that it is *discrete* – hence the name *quantum* – as opposed to the continuous nature of physics at the macrolevel. The discreteness of the microscopic world was first introduced to science by Planck in 1900 with his explanation of the blackbody spectrum. Since then, we have understood that discreteness is an inherent feature of both matter (atoms, or a collection of them) and its interactions (light in the form of photons, for example).

This year's Nobel Laureates – Serge Haroche and Dave Wineland shown in *Figure* 1 – are being honored for experiments that show the "quantum" behaviour of nature at the microlevel. In this article, I will highlight just a few points that demonstrate this discreteness.

Keywords
2012 Nobel Prize, quantum computation, ion traps, single photons.

First, the experiments of Wineland. From the time of Bohr, we know that atoms have discrete energy levels, and can make a transition from one level to another – a so-called quantum jump. If the first level is an excited state, and the second level is the ground state, the transition is through the process of spontaneous emission with a rate determined by the lifetime of the upper state. What Wineland and his team showed in 1986 was the observation of a quantum jump of a single atom held in a Paul trap. The Paul trap (the invention of which won the Nobel Prize for Wolfgang Paul in 1989) uses radio-frequency fields to confine a charged particle, a single Hg^+ ion in this case. The ground state of the ion is an S state, and the first resonance line is the $S \rightarrow P$ transition, which is driven by a laser. There is also a metastable D state that lies in between the two levels. It is metastable (or long-lived) because the transition to the ground state is forbidden by selection rules.

Serge Haroche



David J. Wineland

Figure 1. The winners of the 2012 Nobel Prize in Physics.

The experimental demonstration of quantum jumps now proceeds as follows. The ion is irradiated with laser light driving the first resonance line. As it absorbs and emits the light, the ion shines with resonance fluorescence, which can be imaged with a CCD camera or some photodetector. The ion in this condition is called 'bright'. The signal is nearly continuous because the lifetime of the excited P state is only about 2 ns, much faster than the response time of any photodetector. Once in a while, the ion goes into the metastable D state (with a lifetime of 0.1 s), and becomes 'dark'. Dark because the ion in the metastable state cannot absorb the first-resonance radiation, and the fluorescence signal goes off. The signal comes on again when the ion decays back to the ground state. Therefore, the fluorescence signal as a function of time shows on and off periods, with *sudden transitions* between the two – a direct and beautiful demonstration of quantum jumps. The statistical average of all the off periods over a long observation time gives the lifetime of the D state.

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The ion used in the above study was *laser cooled*. Laser cooling itself is a clever idea that was first proposed for trapped ions by Wineland and Dehmelt (Nobel Prize in 1989 for the invention of the Penning trap), and independently for neutral atoms by Hänsch and Schawlow (both also Nobel Laureates – Hänsch in 2005 for the invention of the laser frequency comb, and Schawlow in 1981 for the development of laser spectroscopy). Laser cooling is an idea where the force from light (remember a photon of wavelength λ carries a momentum of h/λ) is used to reduce the kinetic energy of the atom that absorbs it. The $S, P, D, F \ldots$ energy levels that we talked about earlier refer to the *internal* degrees of freedom, whereas the kinetic energy refers to the *external* degrees of freedom. In a trap, the potential holding the ion is harmonic (to leading order). And again, unlike a classical harmonic oscillator, the energy of a *quantum* harmonic oscillator can only take discrete values. Elementary quantum mechanics teaches us that the energy levels of a harmonic oscillator of frequency ω form a set of evenly-spaced levels, with the energy of the nth level equal to $(n + 1/2)\hbar\omega$. In fact, this led Dehmelt to coin the colorful word *geonium* to describe an electron held in a Penning trap, because it was an electron bound to the earth, or like the hydrogen atom with the nucleus replaced by the trap. The energy levels in the trap are like the vibrational levels of a molecule.

Laser cooling in the trap is also called sideband cooling. This is because the trapped particle is frequency modulated by the oscillatory motion in the trap. The entire analysis has been presented in detail in my earlier article on Robert Dicke[1]. Briefly, the spectrum (like the Fourier transform of any fm modulated wave) shows a fundamental frequency ω_0, and evenly spaced sidebands at $\omega_0 \pm n\omega_{\rm t}$, where $\omega_{\rm t}$ is the trap-oscillation frequency. Laser cooling is achieved by tuning the laser to the lower motional sideband, i.e., at $\omega_0 - \omega_{\rm t}$, as shown in *Figure* 2.

[1] Robert Dicke and Atomic Physics, *Resonance*, Vol.16, No.4, pp.322–332, 2011.

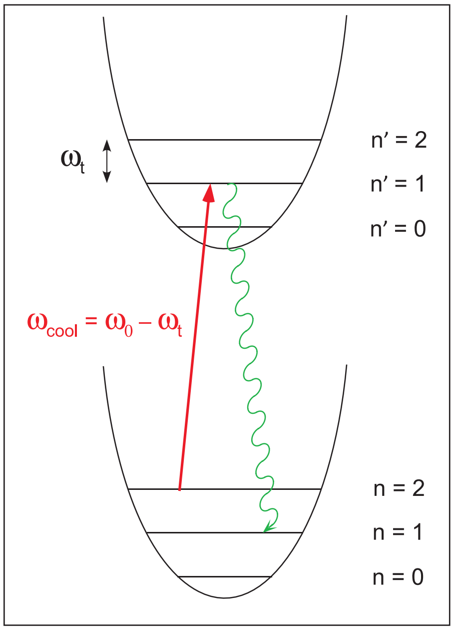

Figure 2. Principle of sideband cooling. The motional degrees of freedom in the trap are quantized to form a set of evenly spaced levels separated by ω_t. The cooling laser is tuned to the lower motional sideband, i.e., at $\omega_0 - \omega_t$, so that the ion loses one quantum of vibrational energy in each absorption–emission cycle.

In effect, the cooling laser drives a Raman transition to a lower vibrational level. After each absorption–emission cycle, the ion (on average) loses one quantum of motional energy. Successive cycles can actually take the ion to the lowest quantum state, with only what is called the zero-point motion as determined by the Heisenberg uncertainty principle. This was also first demonstrated by Wineland and his group in 1989.

A laser-cooled ion in a trap is a spectroscopist's dream. It is usually inside an ultra-high vacuum (UHV) chamber, so that perturbations due to collisions with background atoms is negligible. It is cold, therefore the second-order Doppler effect is negligible. And the cold ion is usually tightly confined, meaning that its spatial spread is much smaller than the wavelength of its emission. Such a confined ion is said to be in the Lamb–Dicke regime, and its emission is *recoilless*, which is important for next-generation optical clocks. Such a precise clock (with a fractional uncertainty below 7×10^{-15}), again based on a single laser-cooled Hg^+ ion, was first demonstrated by Wineland and his group in 2001.

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We thus see that a single trapped ion is useful for many fundamental experiments, and has therefore been used for many studies on the foundations of quantum mechanics. The latest application, and one that is mentioned explicitly in the Nobel citation, is the field of quantum computing. The bits in a quantum computer, called *qubits*, can take on any superposition of 0 and 1, while that of a classical computer can only be one of the two. This feature, along with other quantum mechanical aspects like entanglement, can be exploited to compute some things much faster than can be done classically. The trapped laser-cooled ion is an almost ideal qubit because it is a single particle that is free from perturbations, and its energy levels can be addressed very precisely using lasers. The 0 and 1 state of the qubit are the ground and a metastable state, respectively. Ca^+ ions in a linear Paul trap are now the species of choice for such applications because the laser cooling transition is accessible with a low-cost diode laser. Several groups worldwide (including mine) are doing experiments on Ca^+ ions for quantum computing applications. In *Figure* 3, I show the CCD image of a string of 11 laser-cooled Ca^+ ions in a Paul trap. All the ions are bright, except the 9th one that is dark. The image is from the group of Guenter Werth (student of Paul) at the University of Mainz in Germany.

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So far we have seen how to use photons to manipulate single particles of matter. Haroche's experiments are complementary in the sense that he and his team use atoms to manipulate single photons, thereby demonstrating the quantum nature of light. The quantized

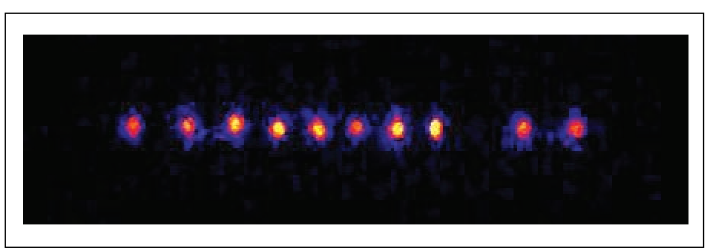

Figure 3. CCD image of the fluorescence from a string of 11 laser-cooled Ca^+ ions trapped in a linear Paul trap. The signal shows that all the ions are bright, except the 9th one that is dark. The image is from the group of Guenter Werth at the University of Mainz in Germany.

EM field is like quantizing a harmonic oscillator, except that instead of the position and velocity oscillating in a harmonic oscillator, it is the electric and magnetic fields that oscillate in a light wave. The detailed theory for getting quantized photons from the classical fields is called *quantum electrodynamics* (QED)[2].

[2] Vasant Naarajan, 'What is a Photon?', *Resonance*, Vol.18, No.1, pp.39–50, 2013.

For understanding the experiments of Haroche, two features are important. One is that they use *circular Rydberg* atoms of Rb. These are atoms that have a large value of the principal quantum number n (about 50), and the largest possible value of the orbital quantum number l, i.e., $n-1$. Such an atom is circular in the sense that the valence electron is represented by a wave packet in a circular orbit. The nucleus and the inner electrons are far enough away that the potential seen by the outer electron is equal to that of the hydrogen atom, and the simple Bohr model can be used to explain most of its features. Some of these features are that the atom has a very large magnetic moment, and a long radiative lifetime for transitions.

The second important aspect of their experiments is the use of *cavity quantum electrodynamics* (cavity QED). The transition that they use is at 51.1 GHz from $n = 50$ to $n = 51$, accessed inside a superconducting microwave cavity – two niobium spherical mirrors in a Fabry–Perot configuration cooled to a temperature of about 1 K. At this temperature, the number of thermal photons is about 0.1. It is an extremely high-Q cavity, in the sense that a photon bounces back and forth between the mirrors for 1 ms before decaying. More importantly, the interaction of the Rydberg atom with the cavity is so strong that it overwhelms all dissipative coupling to the environment. And the radiative lifetime of the transition is 30 ms, much longer than other time scales.

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The non-destructive measurement of a single photon proceeds as follows. Rydberg atoms are sent through

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the microwave cavity. The cycle of photon absorption and emission during the interaction causes a shift in the phase of the atomic wavefunction, the so-called Rabi oscillation. The cavity is first *prepared* by sending an atom in the upper state. The interaction time is adjusted for a phase shift of $\pi/2$, corresponding to a quarter Rabi oscillation: a $\pi/2$ pulse in the terminology of NMR. It leaves the cavity in a superposition state with 0 or 1 photon; 0 if the atom is in the upper state, and 1 if the atom is in the lower state. A second 'meter' atom performs a *non-demolition* measurement of the state of the cavity. The interaction time is now adjusted for a phase shift of 2π, i.e., a full Rabi oscillation. The measurement is non-destructive because the state of the cavity is the same before and after the measurement. The phase of the meter atom is measured using fringes in an atom interferometer, with a set of Ramsey pulses. The fringe pattern shifts by π depending on whether the cavity has 1 photon or 0.

Before you wonder what it means to interact with 0 photons, let me explain that this is another peculiarity of quantum mechanics. The zero-point motion for a harmonic oscillator that we encountered before, translates to fluctuations of the E and B fields in the quantized EM field. Thus the mean value of the fields is zero, but the mean squared (or the rms value) is not zero. The interaction with this 'vacuum' causes what is called a *vacuum Rabi oscillation*.

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We can now see that this same setup can be used to perform an analogue of the quantum jump, but this time for photons. The cavity is used to store one microwave photon for a long time. The meter atom shows a Ramsey fringe pattern corresponding to the presence of one photon. The fringe pattern shifts *suddenly* when the photon dies, a quantum jump in the life of the photon. This is what Haroche and his group showed in 2007, nicely complementing the quantum jump experiments

Figure 4. Photograph from the 1995 Gordon conference in New Hampshire showing me with 4 (future) Nobel Laureates. Circled faces from the left: Wolfgang Ketterle, myself, Bill Phillips, Eric Cornell, Dave Pritchard (my advisor), and Dave Wineland. Serge Haroche and Norman Ramsey were at the preceding Gordon conference in 1993.

nicely complementing the quantum jump experiments of Wineland with atoms.

The two names mentioned above, Rabi and Ramsey, are both Nobel Laureates – Rabi in 1944 for development of magnetic-resonance spectroscopy, and Ramsey in 1989 for improving the resonance method using separated oscillatory fields. They are my grand advisor and great grand advisor, respectively. Therefore, I feel a genealogical affinity for precision measurements.

I would like to close with a personal anecdote about Dave Wineland. I was doing my PhD at MIT on precision mass measurements using single ions in a Penning trap. Shortly after I started my work, Dave visited the lab. I did not know who he was then. As with any visitor, I excitedly described the principle of the Penning trap, and the physics behind my experiment. At each stage, he nodded appreciatively and appeared eager to listen to what I had to say. It was only after he left that a co-student told me that I was explaining about traps to the father of ion traps! Never once did Dave let on that I was telling him stuff that he knew. But that is Dave Wineland, one of the most unassuming people that I know, always making you feel that you are smarter than him. The Nobel could not have happened to a nicer person.

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