DISTINGUISHED LECTURES

CONTRIBUTIONS to SCIENCE 9 (2013) 33-41 Institut d'Estudis Catalans, Barcelona, Catalonia
doi: 10.2436/20.7010.01.161 ISSN: 1575-6343 www.cat-science.cat

CONTRIBUTIONS to SCIENCE
OPEN ACCESS

The Nobel Prizes of 2012

The *Gedankenexperimente* of quantum mechanics become reality: On the 2012 Nobel Prize in Physics, awarded to Serge Haroche and David J. Wineland

Jordi Mompart
Optics Group, Department of Physics, Autonomous University of Barcelona, Bellaterra, Catalonia

Based on the lecture given by the author at the IEC, Barcelona, on December 18, 2012, and at the October Centre of Contemporary Culture, València, on January 28, 2013.

Correspondence:
Departament de Física
Facultat de Ciències
Universitat Autònoma de Barcelona
08193 Bellaterra, Catalonia
Tel. +34-935811652
Fax +34-935812155
E-mail: jordi.mompart@uab.cat

Received: 08.03.13
Accepted: 31.10.13

Summary. The development of quantum mechanics at the beginning of the 20th century constituted one of the greatest revolutions in the theoretical and experimental sciences as well as in philosophy, completely transforming the way we understand the world at both micro- and macroscales. In fact, as its founders pointed out, quantum mechanics is strongly counterintuitive to our classical way of thinking. To overcome this limitation, Erwin Schrödinger and Albert Einstein, among others, proposed a series of idealized experiments to illustrate the paradoxical behavior of quantum mechanics, with the best known being "Schrödinger's cat" and the "EPR paradox" (Einstein-Podolsky-Rosen paradox). These thought experiments, referred to by the German *Gedankenexperimente*, made use of the superposition principle and the entanglement of quantum systems to show the strange properties of quantum mechanics. However, they were somehow ridiculous proposals since, as indicated by Schrödinger himself, we would never be able to manipulate individual particles. The 2012 Nobel Prize in Physics was awarded to Serge Haroche and David J. Wineland, who, with extremely sophisticated experimental devices, are able to trap and manipulate individual photons and ions, respectively, thus allowing the *Gedankenexperimente* proposed at the beginning of quantum mechanics to become reality. In addition, these experiments set the foundations for a new field of research, quantum information science, and for the development of new applications, such as atomic clocks with unprecedented accuracy. These developments have signaled the beginning of a second quantum revolution.

Keywords: quantum optics · quantum mechanics · cavity quantum electrodynamics · trapping and cooling of ions

Resum. El desenvolupament de la mecànica quàntica a principis del segle XX va constituir una de les més grans revolucions tant en les ciències experimentals i en les ciències exactes com en la filosofia, i va modificar completament la manera d'entendre el món tant a nivell microscòpic com macroscòpic. De fet, tal com varen fer notar els seus fundadors, la mecànica quàntica és força contradictòria respecte a la nostra forma clàssica de pensar. Per superar aquesta limitació, Erwin Schrödinger i Albert Einstein, entre d'altres, van proposar una sèrie d'experiments ideals que mostraven el comportament paradoxal de la mecànica quàntica, entre els quals l'anomenat «gat de Schrödinger» i la «paradoxa EPR» (o paradoxa Einstein-Podolsky-Rosen) són els més coneguts. Aquestes propostes experimentals, que es coneixen amb el nom alemany de *Gedankenexperimente* (experiments mentals), feien ús del principi de superposició i de l'entrellaçament dels sistemes quàntics per mostrar les estranyes propietats de la mecànica quàntica. Tanmateix, com va indicar el mateix Schrödinger, es tractava de propostes ridícules perquè mai aconseguiríem manipular partícules individuals. El Premi Nobel de Física 2012 ha estat atorgat a Serge Haroche i David J. Wineland, que van ser capaços, mitjançant sofisticats dispositius experimentals, d'atrapar i manipular fotons i ions individuals, respectivament, tot fent realitat els *Gedankenexperimente* proposats als inicis de la mecànica quàntica. A més, aquells experiments van establir les bases per a un nou camp de recerca, la ciència de la informació quàntica, i per al desenvolupament de noves aplicacions com ara la construcció de rellotges atòmics de precisió anteriorment mai assolida. Aquests desenvolupaments han marcat l'inici de l'anomenada segona revolució quàntica.

Paraules clau: òptica quàntica · mecànica quàntica · electrodinàmica quàntica en cavitats · captura i refredament d'ions

The Royal Swedish Academy of Sciences awarded the 2012 Nobel Prize in Physics to Serge Haroche and David J. Wineland, "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems" (Fig. 1). Haroche, born in France in 1944, works at the Collège de France in Paris, and Wineland, a US citizen also born in 1944, at the National Institute of Standards and Technology in Boulder, Colorado. The 2012 Nobel Prize in Physics adds to a series of Nobel Prizes that have been awarded to quantum optics, a field of research in physics that deals with the interaction of light with matter, in which either one, or both, can be described by the laws of quantum mechanics. Quantum optics has developed in parallel with quantum mechanics and includes phenomena such as black-body radiation and the photoelectric effect, both of which are part of the foundations of quantum mechanics. Laser cooling and trapping techniques and the generation of squeezed states of light are two modern ap-

Fig. 1. Serge Haroche (left) and David J. Wineland (right). (Photos by Ulla Montan © The Nobel Foundation).

plications of quantum optics. Figure 2 shows the most recent previous Nobel Prize laureates whose research activities were in the field of quantum optics. These include in 2005, Roy Glauber, “for his contribution to the quantum theory of optical coherence”, and John L. Hall and Theodor W. Hänsch “for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique;” the 2001 Nobel Prize to Eric A. Cornell, Wolfgang Ketterle, and Carl E. Wieman “for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates;” and the 1997 Nobel Prize to Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips “for development of methods to cool and trap atoms with laser light.”

Science is a human activity that develops as a result of the strong and continuous efforts of many researchers around the world, whose endeavors benefit from the preceding research of their colleagues. It is non-stop, step by step collective work. In those countries that permanently support science, outstanding research groups and laboratories are created that are conducive to success and whose efforts are recognized by the scientific community. Quantum optics is a good example of excellent collective work extending over time. Haroche’s PhD supervisor was Cohen-Tannoudji, who received the Nobel Prize in Physics in 1997 for the development of novel techniques for trapping and cooling neutral atoms with laser light. Cohen-Tannoudji’s PhD supervisor was Alfred Kastler, who was awarded the 1966 Nobel Prize in Physics for the development of the optical pumping technique. On the other side of the Atlantic, Wineland’s PhD supervisor was Norman F. Ramsey, the 1989 Nobel laureate in Physics for the discovery of what is now called Ramsey spectroscopy. Ramsey’s PhD supervisor was Isidor Rabi, who received the Nobel Prize in Physics in 1944 for his contribution to the development of nuclear magnetic resonance. Standard experiments in quantum optics require highly sophisticated techniques that push technological frontiers, as exemplified by the creation of an extremely high quality vacuum to manipulate electrical, magnetic, and light fields with exceptional control, or to trap charged and neutral particles and cool them to temperatures nearly reaching absolute zero. Through their training at some of the best quantum optics laboratories in the world, Haroche and Wineland learned and developed these and other techniques that, later on, would allow them to follow their own careers and to become two of the most distinguished researchers in the quantum optics community. Some of their own PhD students might be future recipients of the Nobel Prize in Physics.

Fig. 2. Recent Nobel Prizes in Physics related to quantum optics. **Top row:** the 2005 laureates. **Middle row:** the 2001 laureates. **Bottom row:** the 1997 laureates. (Photos by Ulla Montan © The Nobel Foundation).

At the beginning of the 20th century, it was widely believed that quantum theory, at the time only recently introduced, was only applicable to systems formed by a large collection of particles, such that its predictions were of statistical nature. Indeed, experiments with single particles were simply not possible. Today, however, as explicitly shown by Haroche and Wineland, technology allows for the isolation, manipulation, and measurement of single particles. Thus, it is possible to investigate individual quantum systems, whose behavior is counterintuitive compared to classical ones, and to study the transition from quantum to classical regimes when dealing with mesoscopic systems. Indeed, Haroche and Wineland were awarded the 2012 Nobel Prize in Physics for their experiments with single (or few) photons and single (or few) ions, respectively. The experimental techniques and devices involving the manipulation of photons in cavity quantum electrodynamics have nothing to do with those being used for trapping and cooling individual ions; rather, they represent two different yet complementary approaches—Haroche traps single photons, manipulating and measuring them with Rydberg atoms, while Wineland traps single ions or a chain of ions (and their motional state), manipulating and measuring them with laser light. However, from a fundamental point of view the two quantum systems are quite similar since both can be modeled through the Jaynes-Cummings Hamiltonian [14], first proposed in 1963, which accounts for the dynamics of a two-level system interacting with a quantized harmonic oscillator (Fig. 3). In Haroche's experiments the quantized harmonic oscillator accounts for one single mode of the quantum electromagnetic field while in Wineland's experiments it describes the motional (vibrational) states of the trapped ion. $|g\rangle$ and $|e\rangle$ are the ground and excited states of the two-level atom, respectively, and $|n\rangle$ with $n = 0,1,2,\ldots$ are the energy eigenstates of the quantum harmonic oscillator. Ω is the so-called Rabi frequency, which accounts for the interaction strength of a laser field with the electric dipole moment of the two-level transition, and γ is the spontaneous decay rate from $|e\rangle$ to $|g\rangle$. Both systems have allowed investigation into some of the most fundamental issues emerging from quantum mechanics, including entanglement, non-locality, wave function collapse, and the transition from quantum to classical regimes through decoherence. In addition, these technologies have been used for quantum information science implementing single and two-qubit gates as well as quantum algorithms and, in the case of the cooling and trapping of ions, to design atomic clocks of the highest accuracy.

In the following, we review some of the outstanding scientific contributions that have come out of Haroche's and Wineland's experiments with individual quantum systems. Nevertheless, to understand the significance of their work, we first review some of the oldest and most fundamental problems in quantum mechanics, illustrated by the *Gedankenexperimente*, as well as several elementary issues in quantum optics, such as the (quantum) Rabi oscillations. We then describe the experiments of Haroche, Wineland, and coworkers, discussing the main results obtained with single photons and single ions and then pointing out some of the conclusions that can be drawn from them.

Gedankenexperimente in quantum mechanics

The term *Gedankenexperiment* was first introduced by the German physicist Ernst Mach and refers to the conceptual counterpart of a real experiment such that if the real experiment is not possible, then an idealized, purely imaginary one is conceived of in its place. *Gedankenexperimente*, in English, thought experiments, were proposed in the early years of quantum theory to make apparent some of its counterintuitive aspects. Two of these *Gedankenexperimente* became very famous: "Schrödinger's cat" [25] and the "EPR paradox," the latter referring to Einstein, Podolsky, and Rosen [10]. These two thought experiments exploit the quantum superposition principle, first identified by Dirac. In quantum mechanics, the quantum state of a system can evolve in a superposition of two or more orthogonal states, e.g., the wave function of a particle can be a superposition of two non-overlapping distant wave functions such that the particle is described as being in two different positions at the same time. In Paul Dirac's words referring to quantum states: "The original state must be regarded as the result of a kind of superposition of the two or more new states, in a way that cannot be conceived on classical ideas." [9]. In terms of the standard (Copenhagen) interpretation of quantum mechanics, the superposition principle states that, before the measurement, a quantum system is undetermined, collapsing (randomly) to a particular possibility

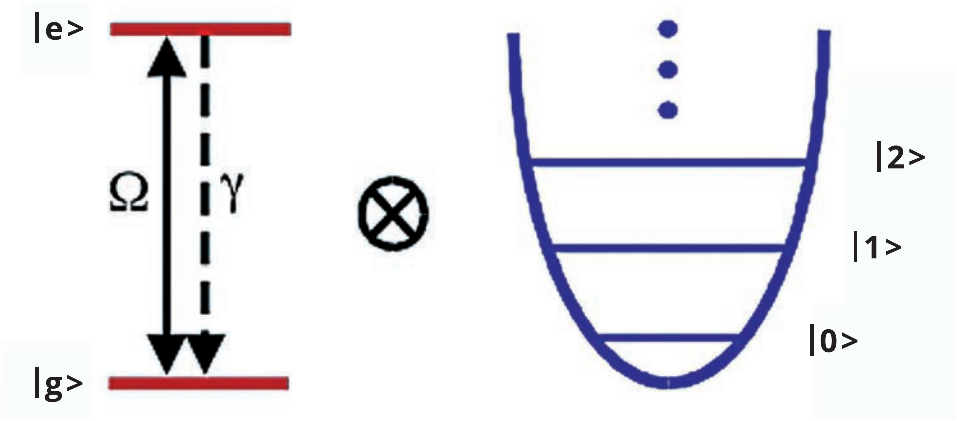

Fig. 3. Sketch of the Jaymes-Cummings model: two-level atom (in red) coupled to a quantized harmonic oscillator (in blue).

upon being measured. Einstein was extremely skeptical about the notion of a collapse, as in a conversation with William Hermanns he had stated: "God doesn't play dice with the world." [21].

"Schrödinger's cat" [25] was proposed in 1935 by the Austrian physicist Erwin Schrödinger. This thought experiment illustrates apparently contradictory aspects of the standard interpretation of quantum mechanics as applied to classical (macroscopic) objects. Let us place a living cat into a closed chamber together with a device that contains a radioactive substance such that, if a single atom of the radioactive substance decays, a relay mechanism will activate a hammer that, in turn, will break a vial containing a poison lethal to the cat. If at a given time the radioactive atom is in a superposition state of non-decaying and decaying states, then from the standard interpretation of quantum mechanics we conclude that the cat is in an alive-dead superposition. Obviously, if we open the door and check the actual state of the cat we will only obtain one of the two possible answers: alive or dead. However, before the measurement, quantum mechanics describes the full quantum system formed by the radioactive atom and the cat as a quantum superposition in which the cat, according to its wave function, is simultaneously alive and dead. This strange and counterintuitive conclusion from the standard interpretation of quantum mechanics was criticized by Einstein who, in conversations with Abraham Pais, asked: "Do you really think the moon is not there if you are not looking at it?" [21].

The "EPR paradox" [10] was, as it name implies, proposed by Albert Einstein, Boris Podolsky, and Nathan Rosen, in 1935. It was aimed at showing the incompleteness of quantum theory. In quantum mechanics, particles satisfy Heisenberg's uncertainty principle [12], which fixes a fundamental limit to the precision with which certain pairs of conjugate variables of a particle, such as its position and momentum, can be known simultaneously. In mathematical terms, the uncertainty principle applied to the particle's position and momentum reads $\Delta x \Delta p \geq \hbar/2$, where Δx and Δp are the uncertainty in the position and the momentum and $\hbar$ is the reduced Planck's constant. Contrary to classical systems, quantum particles cannot have a simultaneously well-defined position and momentum, which from Einstein's point of view was far-removed from reality. In a modern formulation of the "EPR paradox," two particles originating from the decay of a parental one are emitted towards two detectors such that the total energy, linear momentum, and angular momentum are conserved. Measuring the position of one of the particles and the momentum of the other, and bearing in mind the laws of conservation, the position and momentum of both particles can be deduced with accuracy, therefore violating Heisenberg's principle. The question raised by Einstein and coworkers is whether the particles' position and momentum were well-defined before the measurement, which would imply realism, or whether the measurement collapses the position and momentum of the particles, implying a "spooky" action at a distance between the two correlated (entangled) particles. The latter would mean that quantum mechanics is non-local. Today's most advanced tests of so-called Bell's inequalities [1] have indeed demonstrated the non-locality of quantum mechanics while leaving open the question of realism.

In this short review of the *Gedankenexperimente*, it is important to add that, as late as 1952, Schrödinger affirmed: "We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences..." [26]. However, rapid advancements in the technologies to isolate, manipulate, and measure individual quantum systems, developed by Haroche and Wineland among others, have shown that Schrödinger's statement is no longer valid. *Gedankenexperimente* are now real experiments being implemented in some of the world's most sophisticated quantum optics laboratories.

To explain how Haroche and Wineland have pushed technology to its present status and made real the most significant thought experiments, we need first to recall some of the basic principles of quantum optics. In the following, we describe the so-called Rabi oscillations (see [27] for a detailed review).

Rabi oscillations

Let us consider a two-level atom with ground state $|g\rangle$ and excited state $|e\rangle$ (Fig. 3 left) interacting with a monochromatic laser field that can be described in classical terms, whose amplitude and frequency are $\vec{E}_0$ and ω, respectively. We consider first the resonant case for which the laser frequency ω coincides with the transition frequency ω_0. Within the standard quantum optics approximations, the state vector for a two-level atom initially prepared in the ground state $|g\rangle$ is, as given in Dirac's notation:

$$|\psi(t)\rangle = a_g(t)|g\rangle + a_e(t)|e\rangle = \cos\left(\frac{\Omega t}{2}\right)|g\rangle - \sin\left(\frac{\Omega t}{2}\right)|e\rangle \tag{1}$$

where $a_g(t)$ and $a_e(t)$ are the complex probability amplitudes of the ground and excited states, respectively, and $\Omega = \vec{\mu}_o \cdot \vec{E}_0 / \hbar$ is the Rabi frequency, where $\vec{\mu}_o$ is the electric dipole moment of the two-level transition. The atomic populations of ground and excited states can be determined through $p_g(t) = a_g a_g^*$ and $p_e(t) = a_e a_e^*$, respectively, and oscillate at the Rabi frequency Ω.

For a two-level atom resonantly interacting with a single mode of the quantized electromagnetic field, as in Haroche's experiments, the quantum Rabi flopping of an atom initially prepared either in state $|\psi(0)\rangle_{g,n+1} = |g\rangle \otimes |n+1\rangle$ or state $|\psi(0)\rangle_{e,n} = |e\rangle \otimes |n\rangle$ is given, respectively, by:

$$|\psi(t)\rangle_{g,n+1} = \cos\left(\frac{\Omega_0\sqrt{n+1}t}{2}\right)g\rangle \otimes |n+1\rangle - \sin\left(\frac{\Omega_0\sqrt{n+1}t}{2}\right)e\rangle \otimes |n\rangle \qquad (2a)$$

and

$$|\psi(t)\rangle_{e,n} = \cos\left(\frac{\Omega_0\sqrt{n+1}t}{2}\right)e\rangle \otimes |n\rangle + \sin\left(\frac{\Omega_0\sqrt{n+1}t}{2}\right)g\rangle \otimes |n+1\rangle \qquad (2b)$$

where $|n\rangle$ is the number of photons of the quantized field and Ω_0 is the vacuum Rabi frequency. States with well-defined photon number are called Fock states, with $|n\rangle = |0\rangle$ as the vacuum state. Note that if the system is initially prepared in state $|e\rangle \otimes |0\rangle$ there will be Rabi oscillations at the vacuum Rabi frequency Ω_0, i.e., vacuum induces Rabi oscillations, while for an initial state $|g\rangle \otimes |0\rangle$ there will be no Rabi oscillations.

For the off-resonance case, the interaction between the two-level atom and the electromagnetic field yields level shifts that depend on the detuning, the number of photons in the cavity, and the state of the atom which, during the interaction, produces a state-dependent phase shift for both the atom and the electromagnetic field.

Haroche's experiments with single photons

In Haroche's experiments (Fig. 4), a two-level atom interacts with a quantized electromagnetic field that is typically prepared in a Fock state, e.g., the vacuum state $|0\rangle$, or in a coherent state, i.e., a particular superposition of Fock states that presents quasi-classical properties [27]. Since the quantized electromagnetic field in the cavity has a very small mean photon number, and in order to obtain sufficiently strong coupling, Haroche's experiments require the use of two-level atoms whose electric dipole moment is huge, e.g., circular Rydberg atoms.

A Rydberg atom is usually an alkaline atom whose active electron has been excited, by means of subsequent light pulses, to a bound state close to the continuum, i.e., it possesses a very high principal quantum number. The core electrons shield the active electron from the attractive Coulomb field of the nucleus such that it is effectively a hydrogen-like atom. Successive microwave photons are usually sent to the Rydberg atom to reach maximum orbital and magnetic quantum numbers for the state of the active electron such that its wave function becomes an almost classical one with a toroidal shape. If so, this atom is called a circular Rydberg atom. In Haroche's experiments, performed at the Laboratoire Kastler Brossel in Paris, circular Rydberg atoms are prepared whose principal quantum numbers are typically of 50 or 51. In this case, the electron describes a quasi-classical trajectory around the nucleus, whose radius is about 100 µm, resulting in an electric dipole moment about 1000 times larger than that of electric dipole transitions involving the ground and first excited states of the active electron. Note also that standard transition frequencies between circular Rydberg states are in the microwave range.

In Haroche's experiments, circular Rydberg atoms are sent one by one towards a microwave cavity, of a few centimeters length, whose longitudinal cavity mode frequency matches the transition frequency between two consecutive Rydberg states. Since this frequency is in the microwave domain, the cavity has to be cryogenically cooled down to temperatures as low as T = 1 mK, to reduce the presence of unwanted thermal photons. In addition, for either the Fock state or the coherent state introduced in the cavity to survive for the entire duration of the experiment, Haroche em-

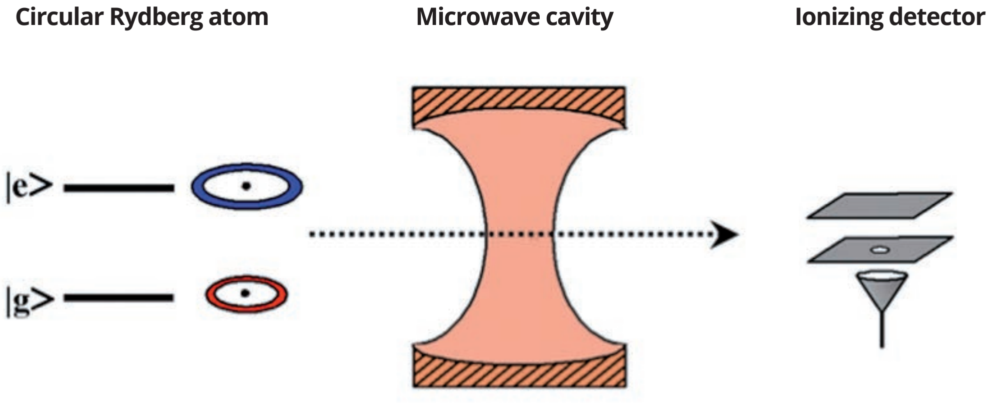

Fig. 4. Scheme of the experimental setup for Haroche's experiments. A two-level circular Rydberg atom is sent through a microwave cavity containing a quantized electromagnetic field. The output state of the atom is measured with an ionizing field detector.

ploys the highest grade mirrors, made of niobium, such that the photons' lifetime in the cavity is about 130 ms, i.e., the photons undergo 1.5 billion reflections before they are finally absorbed or transmitted through the mirrors; this corresponds to a total path length of 40,000 km, about the distance of the Earth's circumference. Note also that the lifetimes of circular Rydberg states are a few tens of ms, much longer than the typical time of flight of atoms between their excitation and detection, tens of µs in Haroche's experiments.

Finally, once the circular Rydberg atoms have crossed the microwave cavity, their state can be selectively detected with high efficiency by means of the ionizing field technique, since the amplitude of the ionization electric field varies substantially with the principal quantum number.

Let us consider now that an individual atom initially prepared in the excited state $|e\rangle$ of the two-level Rydberg transition is sent through the microwave cavity containing a resonant vacuum mode. Following Eq. (2b), the full system formed by the atom and the cavity mode will experience vacuum Rabi oscillations. If the atomic velocity is initially chosen such that the total duration of the interaction with the cavity mode is $\Omega_0 t = \pi/2$, then the output state of the full system will be:

$$\left|\psi(t_{output})\right\rangle = \frac{1}{\sqrt{2}}\left(|e\rangle \otimes |0\rangle + |g\rangle \otimes |1\rangle\right) \qquad (3)$$

That is, the output state corresponds to a correlated (entangled) state between the atomic and cavity states. Measurement of the atomic state with the ionizing field detector will cause its collapse (randomly) in either the ground or the excited Rydberg state, which, in turn, will collapse the cavity into the vacuum or the one-photon state, through a non-local influence. Hence, if the outgoing Rydberg atom is in the excited Rydberg state, the cavity will collapse to the vacuum state; if the atom is in the ground Rydberg state, the cavity will collapse to a Fock state containing one photon. The observation of non-local entangled states between atomic and photon number states was reported by Haroche and coworkers in [4,11].

Let us consider now that after the generation of the entangled state, as described by Eq. (3), and before any measurement takes place, a second identical atom initially prepared in its ground Rydberg state $|g\rangle$ is sent through the cavity at a velocity such that $\Omega_0 t = \pi$. Then, according to Eq. (2), the output state will be:

$$\begin{aligned}\left|\psi(t_{output})\right\rangle &= \frac{1}{\sqrt{2}}\left(|e\rangle_1 \otimes |g\rangle_2 \otimes |0\rangle - |g\rangle_1 \otimes |e\rangle_2 \otimes |0\rangle\right) \\ &= \frac{1}{\sqrt{2}}\left(|e\rangle_1 \otimes |g\rangle_2 - |g\rangle_1 \otimes |e\rangle_2\right) \otimes |0\rangle\end{aligned} \qquad (4)$$

where the subscript $i = 1,2$ refers to the first and second atom, respectively. Therefore, the output state of the system shows a non-local correlation between the atomic states of two circular Rydberg atoms, which indeed correspond to an EPR pair consisting of two massive particles [11]. Note that the two atoms become entangled through (successive) interactions with the cavity field but without directly interacting with each other.

Haroche and coworkers also have been able to trap coherent states of the electromagnetic field in a far detuned microwave interacting with a two-level atom in a superposition of two circular Rydberg states. In this case, the cavity field splits into a superposition of two coherent states with different phases, i.e., a Schrödinger's cat for the electromagnetic field is created [5]. Additionally, with his setup, Haroche is able to physically implement quantum non-demolition measurements [3], a quantum phase gate for quantum information tasks [22], entanglement between three atoms [23], teleportation of atomic states between two cavities [20], and the observation of a single-photon without destroying it [7].

Wineland's experiments with single ions

After finishing his PhD with Ramsey in 1970, Wineland held a postdoctoral position with the group of Hans Dehmelt, at the University of Washington, where he started working on electron and ion traps. Dehmelt and Wolfgang Paul, together with Ramsey, were awarded the 1989 Nobel Prize in Physics "for the development of the ion trap technique." In Wineland's experiments (Fig. 5A), an ion trap is created by a combination of static and oscillatory electric fields. Ions can be individually addressed with laser beams and their fluorescence registered with a CCD camera. The experiments are performed in ultrahigh vacuum and at extremely low temperatures, to isolate the ions from heat and unwanted surrounding radiation. With this approach, in 1981, Wineland and Itano were able to trap a single $^{24}Mg^+$ ion in a Penning trap [30].

Figure 5A shows the energy eigenstates of the system formed by the two internal levels of a single ion, $|g\rangle$ and $|e\rangle$, and the ion's motional state $|n\rangle$. In the Lamb-Dicke regime [27], a laser field can be appropriately tuned to a transition involving $\Delta n = -1,0,+1$ (corresponding, respectively, to the red, black, and blue double arrows in Fig. 5B), while spontaneous emission takes place predominantly into the channel $\Delta n = 0$. Therefore, assuming an initial state $|g,n\rangle$, it is possible to cool down the ion's motional degrees of freedom by the subsequent application of red- sideband laser pulses to reach state $|g,0\rangle$. The sideband cooling technique was first implemented by Wineland and coworkers using $^{198}Hg^+$ ions [8]. In addition, they reported the preparation of Fock, coherent, squeezed, and thermal states of motion for an isolated $^9Be^+$ ion [17].

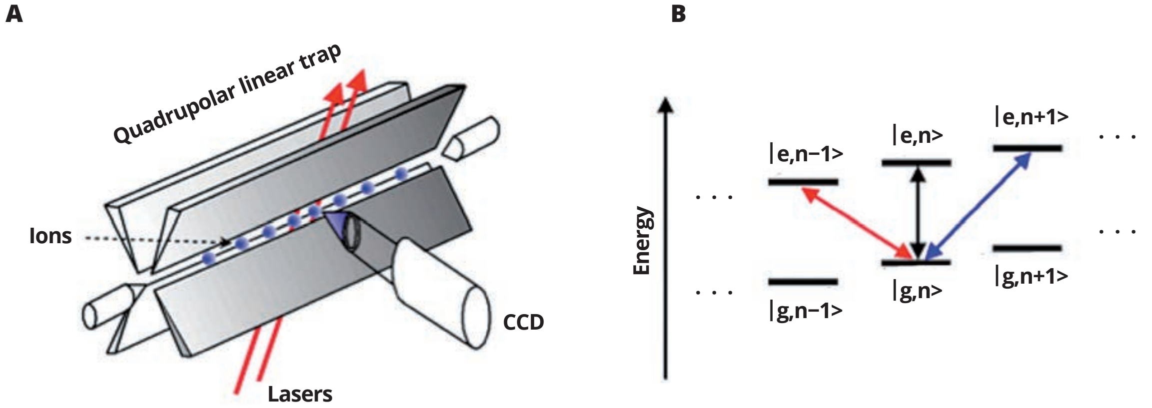

Fig. 5. (**A**) Scheme of the experimental setup for trapping single ions. Ions are placed in a row by means of a quadrupolar linear trap and its mutual Coulomb repulsion. The ions are individually addressed by laser fields and their fluorescence is registered with a CCD camera. (**B**) Relevant energy levels of the coupled system formed by the $|g\rangle \leftrightarrow |e\rangle$ two-level internal transition of the ion and its quantized motional states $|n\rangle$.

Following up on previous work from Cirac and Zoller [6], Wineland and coworkers also reported [18] the transfer of a quantum superposition between two electronic states of an ion to a quantum superposition between two of its motional states. Consider a single ion that is initially prepared in both the electronic and the motional ground states, i.e., $|\psi_0\rangle = |g\rangle \otimes |0\rangle$, that is coupled to state $|e\rangle \otimes |0\rangle$ with a laser pulse, as described in Eq. (1). After the laser pulse, the ion state will be in the general superposition $|\psi_1\rangle = (\alpha|g\rangle + \beta|e\rangle) \otimes |0\rangle$. If a red-sideband pulse fulfilling $\Omega t = \pi$ is applied to the ion, then only state $|e\rangle \otimes |0\rangle$ will evolve, performing half a Rabi oscillation with state $|g\rangle \otimes |1\rangle$ such that the final state will read $|\psi_2\rangle = |g\rangle \otimes (\alpha|0\rangle + \beta|1\rangle)$, i.e., the superposition in the internal degrees of freedom is transferred to the motional degrees of freedom. In a series of articles, Wineland and coworkers extended previous work to implement quantum gates [18,15], entangle two ions [29], and generate Schrödinger cat states with the individual [19] and collective [16] motional coherent states of the ions.

In 1977, George Sudarshan and Baidyanath Misra introduced the so-called quantum Zeno effect [28], which enables the dynamic evolution of a quantum system to be inhibited by applying frequent measurements. Wineland and coworkers were the first to report the observation of the quantum Zeno effect [13]. To do so, they considered ^{9}Be^{+} ions confined in a Penning trap with three internal levels in a V-type configuration. Starting with the ions in their internal ground state, a laser pulse was applied to one of the transitions of the V-type system such that, as expected, the excited population followed the dynamics described in Eq. (1), i.e., $p_e(t) = \sin^2(\Omega t/2)$. During this dynamic evolution, a series of light pulses were applied to the adjacent transition and the fluorescence associated with this transition was registered. The result was inhibition of the dynamic evolution to the excited state. Every time a fluorescence photon was emitted from the adjacent transition, the quantum state of the ion underwent a quantum jump that collapsed it into the ground state, i.e., frequent measurement of the fluorescence resulted in the inhibition of the excitation. Indeed, the first observation of quantum jumps from a single atom was that of Wineland and coworkers, using a trapped ^{198}Hg^{+} ion [2].

Although the experiments performed by Wineland (and by Haroche) and coworkers have been used to test some of the most fundamental issues of quantum mechanics and to implement the basic elements for quantum computation, it is important to note that the experimental techniques developed by these researchers have already had real applications. In particular, Wineland and coworkers have been able to construct the world's most accurate clock, by determining with a precision of 17 digits the ratio of Al^{+} and Hg^{+} single-ion optical clock frequencies [24]. The precision of this atomic clock is so high that the tiny effects of special and general relativity have to be taken into account to properly describe its dynamic behavior.

Concluding remarks

Haroche and Wineland, benefitting from their education and training in some of the best quantum optics laboratories in the world, have been able to conceive and put into practice novel techniques to isolate, manipulate, and measure individual quantum systems with the highest precision. Their work with single photons and single ions has enabled the study of many of the most fundamental issues in quantum mechanics, such as superposition, entanglement, non-locality, Schrödinger's cats, EPR pairs, wave function collapse, and decoherence, making real the *Gedankenexperimente* proposed at the beginning of the quantum mechanics era. Additionally, they have used their setups for applications related to high precision measurements, to the development of quantum computation implementing quantum gates and quantum algorithms, and to engineer the most accurate atomic clock in the world. The outstanding contributions of Haroche, Wineland, and their coworkers have come to define what some scientists justifiably call the second quantum revolution.

Acknowledgements. I thank my colleagues at the Quantum and Atom Optics Group of the Physics Department, Universitat Autònoma de Barcelona, and Dr. Luis Plaja, from the Universidad de Salamanca, for their careful reading of this manuscript and their constructive comments, which were indeed very useful to improve the quality of the final version. Finally, I especially thank Prof. Ramón Corbalán and Prof. Albert Bramon, from the Universitat Autònoma de Barcelona, for their continuous motivation in teaching quantum optics and quantum mechanics, respectively, to an entire generation of physicists.

For further information:

On the Nobel Prize in Physics 2012:

- Cirac I (2012) Premios Nobel de Física 2012. Revista Española de Física 26:8-9
- "The Nobel Prize in Physics 2012 - Advanced Information." Nobelprize.org. 22 Feb 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/advanced.html

On Haroche's experiments with single photons:

- Raimond JM, Brune M, Haroche S (2001) Colloquium: Manipulating quantum entanglement with atoms and photons in a cavity. Reviews of Modern Physics 73:565-582
- "Serge Haroche - Nobel Lecture: Controlling photons in a box and exploring the quantum to classical boundary." Nobelprize.org. 17 Feb 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/haroche-lecture.html

On Wineland's experiments with single ions:

- Leibfried D, Blatt R, Monroe C, Wineland D (2003) Quantum dynamics of single trapped ions. Reviews of Modern Physics 75:281-324
- David J. Wineland - Nobel Lecture: Superposition, entanglement, and raising Schroedinger's cat". Nobelprize.org. 18 Feb 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/wineland-lecture.html

References

1. Bell J (1964) On the Einstein Podolsky Rosen Paradox. Physics 1:195-200
2. Bergquist JC, Hulet RG, Itano WM, Wineland DJ (1986) Observation of quantum jumps in a single atom. Phys Rev Lett 57:1699-1702
3. Brune M, Haroche S, Raimond JM, Davidovich L, Zagury N (1992) Manipulation of photons in a cavity by dispersive atom-field coupling: Quantum-nondemolition measurements and generation of "Schrodinger cat" states. Phys Rev A45:5193-5214
4. Brune M, Schmidt-Kaler F, Maali A, Dreyer J, Hagley E, Raimond JM, Haroche S (1996) Quantum Rabi oscillation: A direct test of field quantization in a cavity. Phys Rev Lett 76:1800-1803
5. Brune M, Hagley E., Dreyer J, Maître X, Maali A, Wunderlich C, Raimond JM, Haroche S (1996) Observing the progressive decoherence of the "meter" in a quantum measurement. Phys Rev Lett 77:4887-4890
6. Cirac JI, Zoller P (1995) Quantum Computations with cold trapped ins. Phys Rev Lett 74:4091-4094
7. Davidovich L, Zagury N, Brune M, Raimond JM, Haroche S (1994) Teleportation of an atomic state between two cavities using nonlocal microwave fields. Phys Rev A50:R895-R898
8. Diedrich F, Bergqvist JC, Itano WM, Wineland DJ (1989) Laser cooling to the zero-point energy of motion. Phys Rev Lett 62:403-406
9. Dirac PM (1930) The principles of quantum mechanics. Clarendon-Press Oxford
10. Einstein A, Podolsky B, Rosen N (1935) Can quantum-mechanical description of physical reality be considered complete? Phys Rev 47:777-780
11. Hagley E, Maître X, Nogues G, Wunderlich C, Brune M, Raimond JM, Haroche S (1997) Generation of Einstein-Podolsky-Rosen pairs of atoms. Phys Rev Lett 79:1-5
12. Heisenberg W (1927) Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. Zeitschrift für Physik 43: 172–198
13. Itano WM, Heinzen DJ, Bollinger JJ, Wineland DJ (1990) Quantum Zeno effect. Phys Rev A41:2295-2300
14. Jaynes ET, Cummings FW (1963) Comparison of quantum and semi-classical radiation theories with application to the beam maser. Proc. IEEE 51:89–109
15. Leibfried D, DeMarco B, Meyer V, Lucas D, Barrett M, Britton J, Itano WM, Jelenković B, Langer C, Rosenband T, Wineland DJ (2003) Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. Nature 422:412-415
16. Leibfried D, Knill E, Seidelin S, Britton J, Blakestad RB, Chiaverini J, Hume DB, Itano WM, Jost JD, Langer C, Ozeri R, Reichle R, Wineland DJ (2005) Creation of a six-atom "Schrödinger cat" state. Nature 438:639-642
17. Meekhof DM, Monroe C, King BE, Itano WM, Wineland DJ (1996) Generation of Nonclassical Motional States of a Trapped Atom. Phys Rev Lett 76:1796-1799
18. Monroe C, Meekhof DM, King BE, Itano WM, Wineland DJ (1995) Demonstration of a fundamental quantum logic gate. Phys Rev Lett 75:4714-4717
19. Monroe C, Meekhof DM, King BE, Wineland DJ (1996) A "Schrödinger Cat" superposition state of an atom. Science 272:1131-1136
20. Nogues G, Rauschenbeutel A, Osnaghi S, Brune M, Raimond JM, Haroche S (1999) Seeing a single photon without destroying it. Nature 400:239-242
21. Pais A (1979) Einstein and the quantum theory. Rev Mod Phys 51:863-914
22. Rauschenbeutel A, Nogues G, Osnaghi S, Bertet P, Brune M, Raimond JM, Haroche S (1999) Coherent operation of a tunable quantum phase gate in cavity QED. Phys Rev Lett 83:5166-5169
23. Rauschenbeutel A, Nogues G, Osnaghi S, Bertet P, Brune M, Raimond JM, Haroche S (2000) Step-by-step engineered multiparticle entanglement. Science 288:2024-2028
24. Rosenband T, Hume DB, Schmidt PO, Chou CW, Brusch A, Lorini L, Oskay WH, Drullinger RE, Fortier TM, Stalnaker JE, Diddams SA, Swann WC, Newbury NR, Itano WM, Wineland DJ, Bergquist JC (2008) Frequency ratio of Al$^+$ and Hg$^+$ single-ion optical clocks; etrology at the 17th decimal place. Science 28:1808-1812
25. Schrödinger E (1935) Die gegenwärtige Situation in der Quantenmechanik. Naturwissenschaften 23:807-812
26. Schrödinger E (1952) Are there quantum jumps? Part II, Brit J Phil Sci 3:233-247
27. Scully MO, Zubairy MS (1997) Quantum optics. Cambridge University Press, UK
28. Sudarshan ECG, Misra B (1977) The Zeno's paradox in quantum theory. J Math Phys 18:756-763
29. Turchette QA, Wood CS, King BE, Myatt CJ, Leibfried D, Itano WM, Monroe C, Wineland DJ (1998) Deterministic entanglement of two trapped ions. Phys Rev Lett 81:3631-3634
30. Wineland DJ, Itano WM (1981) Spectroscopy of a single Mg$^+$ ion. Phys Lett A82:75-78