NOBEL PRIZE IN PHYSICS 2012: BUILDING AND CONTROLLING SCHRÖDINGER'S CAT

EL PREMIO NOBEL DE FÍSICA 2012: OBTENCIÓN Y CONTROL DEL GATO DE SCHRÖDINGER

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The Nobel prize in physics 2012 was awarded to Serge Haroche and David J. Wineland for having independently designed and performed groundbreaking experiments on individual quantum systems without destroying their quantum state. These measurements explore the foundations of quantum mechanics and they make real the thought experiments conceived, during the first half of the 20th century, by the founding fathers of quantum theory.

El premio Nobel de Física 2012 fue otorgado a los científicos Serge Haroche y David J. Wineland por haber diseñado y llevado a cabo, de manera independiente, experimentos revolucionarios sobre sistemas cuánticos individuales sin destruir su estado cuántico. Estas mediciones exploran los fundamentos de la mecánica cuántica y hacen realidad los experimentos mentales concebidos, durante la primera mitad del siglo XX, por los padres fundadores de la teoría cuántica.

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“There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe there ever was such a time. There might have been a time when only one man did, because he was the only guy who caught on, before he wrote his paper. But after people read the paper, a lot of people understood the theory of relativity in some way or other, certainly more than twelve. On the other hand, I think I can safely say that nobody understands quantum mechanics.”

Richard P. Feynman, *The Character of Physical Law*

On October 9th, 2012, the Royal Swedish Academy of Sciences announced that the Nobel prize in physics had been awarded to Serge Haroche (Collège de France and École Normale Supérieure, Paris, France) and David Jeffrey Wineland (National Institute of Standards and Technology and University of Colorado, Boulder, U.S.A.) for their “ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems” [1]. The laureates (see Figure 1) represent a research field known as *quantum optics*, which embraces the study of light-matter interaction at a fundamental level. This is the second time that this field was present in the award ceremony at Stockholm, after the American physicist Roy J. Glauber shared the prize in 2005 for his contribution to the theory of optical coherence.

Figure 1: Top panel: Prof. Serge Haroche, Collège de France and École Normale Supérieure. Bottom panel: Dr. David Wineland, National Institute of Standards and Technology and University of Colorado. Copyright © The Nobel Foundation 2012 [2]; Artist: Lena Cronström; Calligrapher: Annika Rücker; Book binder: Ingemar Dackéus; Photo reproduction: Lovisa Engblom.

During the last decades, Serge Haroche and David Wineland have led their own research groups, which have independently designed and implemented new experimental techniques that enable the measurement and control of individual quantum systems with high precision. Unravelling the scientific careers of both Nobel laureates reveals many illustrious names of the history of physics. Professor Serge Haroche, for example, completed his Ph.D. on optical pumping experiments and dressed atom formalism under the supervision of Claude Cohen-Tanoudji (Nobel prize, 1997) and spent a year as a visiting post-doc within the team directed by Arthur Leonard Schawlow (Nobel prize, 1981), working in quantum beats excited by dye lasers and studying the time evolution of states superposition. On the other hand, Dr. David Wineland did his Ph.D. under the supervision of Norman Foster Ramsey Jr.

(Nobel laureate, 1989) at Harvard University. His Ph.D. thesis was devoted to the atomic deuterium maser and how to control the environment in a very precise way in order to achieve long-lived superposition of hyperfine states. He then moved to Hans Dehmelt's (Nobel laureate, 1989) group at the University of Colorado at Boulder, where he experimented with trapped electrons and ions.

The work of last year's laureates addresses the foundations of quantum physics, the theory developed in the 1920s to describe the microscopic constituents of matter (light, atoms, nuclei and elementary particles), which has proven itself to be extremely successful in explaining atomic-scale phenomena. But quantum theory poses a tremendous challenge to the common sense based on our everyday experience, since its conclusions are often counter-intuitive. One of the founders of quantum mechanics, the Danish scientist Niels Bohr, said: "For those who are not shocked when they first come across quantum theory cannot possibly have understood it" [3]. Our intuition, for example, is that objects can only directly affect other bodies that are right next to them. If an object influences another which is not in its vicinity, then such effect must be indirect (it has to be transmitted by means of a chain of events, each of them involving only interactions between neighboring entities). This locality persists in the case of interactions between macroscopic distant objects, which provide examples of the above mentioned sequential spanning of the distance between the interacting bodies (they are mediated by the propagation of electric currents, electromagnetic waves, etc.), and it is expressed mathematically in the theory of fields. Quantum mechanics, oppositely, comprises a non-local vision of correlated behavior of separated entities with no intermediary via a property called *entanglement*. Since the laws of quantum physics have also to account for our everyday experience, the manifestation of phenomena such as non-locality and the transition between the quantum and the classical worlds, are among the central questions to be addressed by the theory.

The boundaries between quantum and classical mechanics have been investigated by many physicists since the early 1930s. This work gave rise to many famous paradoxes such as the Photon box, the Schrödinger's cat or the Einstein-Podolsky-Rosen, designed to explore the limits of the quantum theory by means of the so-called *thought experiments*, which reached its highest expression in the debates between Niels Bohr and Albert Einstein on the basic postulates of the quantum theory. The Schrödingers cat paradox [4] is illustrated in Figure 2: a cat in a sealed box, whose life or death depend on the state of a subatomic particle. Inside the box, there are two possible scenarios: either

i) the atom has not yet decayed and the cat remains alive

or

ii) it has already decayed causing the death of the cat.

Hence, without opening the box, the entire system formed by the cat and the atom is found to be in a superposition of states where the cat is at the same time death and alive.

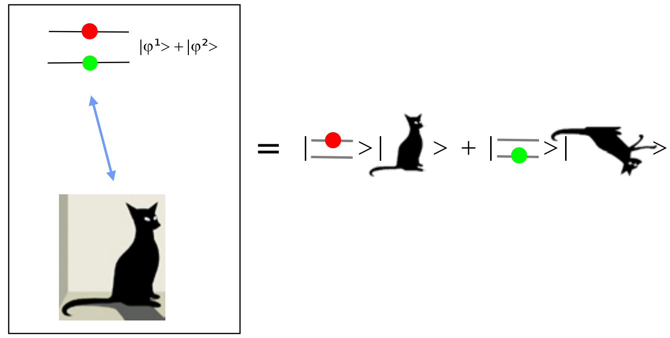

Figure 2: Illustration of the Schrödinger's cat paradox: an atom, a bottle containing a deathly poison and a cat are placed inside a sealed box. The quantum system (atom) is in a superposition of states $|\varphi_1> + |\varphi_2>$. When the box is opened (act of measurement), the state of the atom collapses in one of the two states $|\varphi_1>$ or $|\varphi_2>$ with equal probability. If the atom undergoes a transition from the state $|\varphi_1>$ to the state $|\varphi_2>$, a mechanism that opens the bottle is activated leading to the death of the cat. Otherwise, the cat remains alive. Therefore, without opening the box, the entire system is in a superposition of states where the cat (macroscopic system) is, with equal probability, death and alive.

In quantum mechanics, the system is described by a wavefunction which is a superposition of the two possible states of its constituents. The common goal of the thought experiments conceived during the early years of quantum mechanics was to anticipate the consequences of some of the hypothesis of the quantum theory, rather than actually perform the experiments. Nevertheless, the experimental methods devised by the research groups led by Haroche and Wineland allow the observation of several phenomena resembling those considered in the cornerstone thought experiments [5, 6].

As was pointed out during the Award Ceremony, in the Presentation Speech delivered by the Chairman of the Nobel Committee for physics, and also by the Nobel laureates themselves, their approaches were complementary to each other. A schematic representation of the basic experimental set-ups is shown in Figure 3:

1. David Wineland's workgroup used electrostatic traps to capture individual ions. The trapped particles were cooled, measured and controlled using light photons. As for the cat inside the box, the system can be put in a superposition of states, corresponding to two distinct values of the energy of oscillation.
2. The researchers in the team led by Serge Haroche captured single photons between two perfectly reflecting mirrors. The photons are kept in the cavity long enough to be measured, employing highly excited atoms which travel across the trap.

One of the most exciting features of these experiments is that they accomplish the long-standing dream of individually addressing quantum systems. The investigation of quantum properties of matter has been coined as "post-mortem physics", since traditional ways to perform a measurement on a quantum object will lead to the destruction of the state.

The remarkable experiences conducted by both Haroche and Wineland overcome the vanishing of the quantum behavior upon observation, something previously thought to be impossible. Erwin Schrödinger, the author of the most popular formulation of quantum mechanics, expressed: “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. (...) In the first place it is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo. We are scrutinising records of events long after they have happened”. The kind of experiments awarded with the Nobel Prize 2012 are known as *quantum non demolition measurements*. Although the theory of the quantum non demolition measurements was grasped already from the very beginning of quantum physics, it was not until the 1990s that they have been implemented [7].

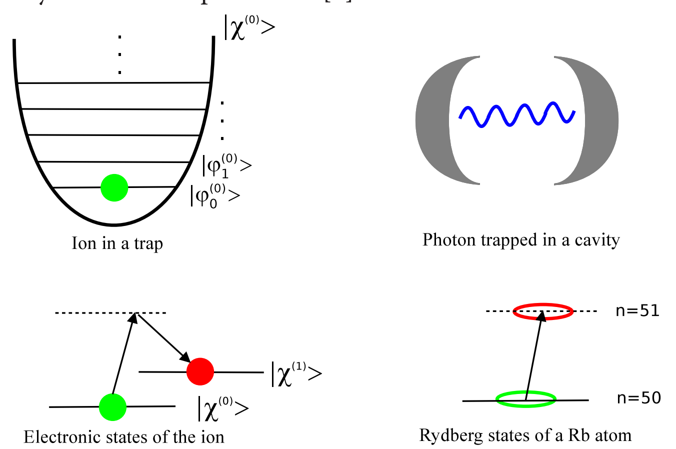

Figure 3: Illustration of the two kinds of experiments performed by D. Wineland (left) and S. Haroche (right). On the left, an ion is captured in a harmonic electrostatic trap. Its quantum state (both the electronic state and the vibrational motion) is controlled using light photons. On the right, a single photon (or a few photons) is (are) trapped inside a microwave cavity long enough to perform several measurements on it (them). The state of the field is measured and controlled by the interaction with highly excited rubidium (Rb) atoms.

To give an idea of how far it is acting on a single photon for hundreds of miliseconds, from our everyday experience, let’s say that during this interval of time, on average, approximately 2.8×10^{20} photons reach every square meter on Earth’s surface on a clear day. In other words, if photons would strike the surface of the Earth individually, separated by 100 miliseconds, it will take more than 600 times the age of the universe for such amount of photons to hit the surface. The processes we witness in our daily life involve huge numbers of microscopic entities. Under such conditions, the predictions of quantum theory can be shown to reduce to that of classical physics. This feature eliminates the possibility to encounter macroscopic objects in a state superposition, thereby ruling out the occurrence of paradoxical experiences such as a cat which can be simultaneously dead and alive.

The non-demolition measurements carried out by Serge Haroche use an extremely sensitive probe: an atom whose outermost electron is placed in a combination of two highly excited Rydberg states. The electron in this specific superposition of states can be roughly imagined as spinning around the atomic nucleus, giving rise to an average density distribution which is asymmetrical along the orbit. This distribution is characterized by a dipole moment which governs the interaction with the microwave field inside the cavity. The size of the Rydberg atom is about 125 *nm* (1 $nm = 10^{-9}$ m), nearly one thousand times larger than typical atoms in their ground state. Since the transition frequency between the two adjacent Rydberg states is not resonant with that of the electromagnetic field, the atom traverses the cavity without absorbing the photon, their interaction merely shift the electron distribution. Indeed, the atom initially settled at the excited state e in absence of the field (i.e., in presence of “0” photons), described by the wavefunction $|e,0>$, evolves into a superposition of states when passing through the cavity:

$$|e,0> \rightarrow \cos\left(\frac{\Omega t}{2}\right)|e,0> + \sin\left(\frac{\Omega t}{2}\right)|g,1> , \qquad (1)$$

where Ω represents the resonant Rabi frequency [8]. Equation (1) means that, at the exit of the cavity, the particle can be found in the initial state or in the ground state g after interacting with one photon (the latter is described by the wavefunction $|g,1>$).

The phase shift of the dipole moment

$$\Delta\Phi(N) = N\phi_0 = N\frac{\Omega^2 t}{2\delta} \qquad (2)$$

emerges as a consequence of the differences in the interaction between the photon and the Rydberg electron in each of the excited states. δ is the Stark shift between the two adjacent Rydberg states, provoked by the interaction with the field, and ϕ_0 is the phase shift per photon accumulated during time t. The shift $\Delta\Phi$ is proportional to the photon number N. In this way, measuring $\Delta\Phi$ allows to non-destructively count the number of photons inside the cavity [9].

One of the most fascinating spin-offs of this work, has been the assessment of the validity of the quantum description of the phenomena underlying the Schrödinger’s cat paradox: a large system (in this case, a coherent superposition of field states) coupled to a single atom evolves into a situation consistent with our expectations (a classical mixture of dead and alive states) [10, 11]. The lifetime of the cat state is extremely short: for an electromagnetic field comprising a small number of photons, it takes a few tens of miliseconds for the interaction with the environment to annihilate the initial superposition of states [10]. Since decoherence can be demonstrated to operate much faster as the size of the system increases, there is again no point in looking for such superposition for truly macroscopic objects.

Wineland and coworkers have also developed experimental techniques to transfer a quantum superposition of electronic states to a quantum superposition of vibrational modes of the ion in the trap [12]. The procedure is illustrated in Figure 4. The method involves the electronic excitation of the trapped particle from the lowest energy level within the vibrational manifold corresponding to the ground electronic state (step 1) followed by the de-excitation by a red-shifted laser pulse (step 2). The corresponding superposition of vibrational states can be further transferred to other ions inside the trap, which share the same vibrational energy levels. Hence, a Schrödinger's cat-like superposition of states can be transferred to the vibrational modes of a relatively small number of charged atoms without destroying it, and this is the basis of quantum gates based on trapped ions.

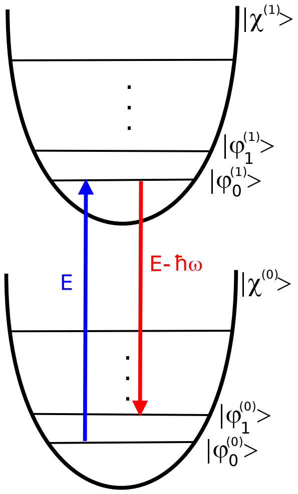

Figure 4: Step 1: Creating the electronic superposition of states (blue arrow). As a result, the system occupies simultaneously the vibrational ground states $|\varphi_0^{(0)}>$ and $|\varphi_0^{(1)}>$ corresponding, respectively, to the electronic states 0 and 1. As in the case of the Schrödinger's cat paradox, the superposition of states reads $|\Psi> = |\chi^{(0)}>|\varphi_0^{(0)}> + |\chi^{(1)}>|\varphi_0^{(1)}>$. E is the energy of the excitation laser. Step 2: Transferring the superposition to the vibrational degree of freedom (red arrow). The total wavefunction is now $|\Psi> = |\chi^{(0)}>|\varphi_0^{(0)}> + |\chi^{(0)}>|\varphi_1^{(0)}>$. $\hbar$ is the Dirac constant while ω denotes the oscillation frequency of the trapped ions.

One of the most recurring inquiries about Haroche's and Wineland's works is that of the potential applications of their discoveries. The manipulation of individual quantum systems is considered as a milestone for the manufacturing of quantum computers [13, 14], a new generation of devices which is expected to dramatically speed up the handling of data operations with respect to classical machines. Albeit futurist, such predictions are encouraged by the nowadays standard application of quantum mechanical principles into the assembling of nanoscale devices and also by experimental success in executing basic computational operations on a very small number of quantum bits [12, 15].

On the other hand, the importance of the findings in fundamental science can not be judged only in terms of promising applications. They can be found useful in domains for which their relevance was not immediately evident. Laser technology, for example, is ubiquitous in modern life: it is used in equipment such as DVD players, printers, scanners, as well as in surgery, industrial cutting and welding, etc. Such variety of uses could hardly be envisaged at the time when its theoretical foundations were established. During the lecture given by Professor Serge Haroche on April 25th, 2013, as part of the programme of the official opening of the Dresden Center for Nanoanalysis, he made the following example: even when Edward Purcell (Nobel Prize in physics, 1952) discovered the Nuclear Magnetic Resonance and he was a leading expert on this field, it would be extremely difficult for him to foreseen the application of this phenomenon in medicine, and even more to imagine that it would be routinely used as a tool in medical imaging.

Nonetheless, there are already technological applications which benefit from the precision standards set by the quantum measurements carried out in the facilities of the National Institute of Standards and Technology in Boulder. They have build atomic clocks which are a hundred times more accurate than the current standard ones, i.e., they are able to measure time with an uncertainty of less than one part in 10^{17} [16, 17]. This means that these new atomic clocks would get delayed or advanced by one second in about 140 millions of years. Widespread technologies such as the Global Positioning System, already requires time intervals to be determined within an accuracy of nanoseconds ($1\ ns = 10^{-9}\ s$). On the other hand, the spherical mirrors constructed by the Paris group, made of a very reflecting superconducting material cooled down to very low temperatures, are currently the best mirrors of the world allowing the photons to bounce back and forth nearly one million times. They may also find interesting applications in the near future.

In the meantime, the research results accumulated during the last decades by the workgroups of Serge Haroche and David Wineland and the advances they made on experimental techniques, have opened the door for the direct examination of the scientific principles underlying the behavior of isolated photons and atoms. As a consequence, some of the analysis regarding fundamental concepts of quantum mechanics, that were considered once as having only theoretical or philosophical interest, are now amenable for testing and direct observation. Their endeavours represent a major contribution to modern physics and are expected to remain among the most influential ones in the years to come.

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