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Controlling the quantum - the Nobel Prize in Physics 2012

Jonathan Home, Institute for Quantum Electronics, ETH Zürich

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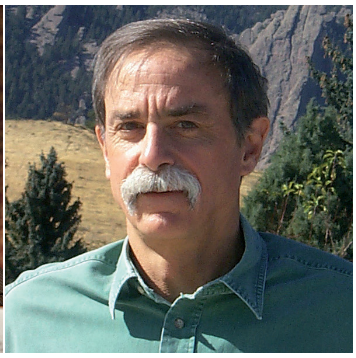

The award of the 2012 Nobel prize in Physics recognizes the contributions of Prof. Serge Haroche (left) and Dr. David Wineland (right) to the advancement of quantum mechanical control over single quantum systems. Any of us who remember first courses on quantum mechanics will remember having to accept counter-intuitive rules, in particular those that apply to sequential measurements made on a single quantum particle. Indeed the students in my Physics 3 lecture course recently demanded an example "of a real experimental measurement, where the result of the measurement corresponds to the state of the particle after the measurement", as quantum mechanics demands. In this regard, we find great company in the founders of quantum mechanics themselves, including Schrödinger, who mused that "we never experiment with just one electron or atom...", "In thought experiments we sometimes assume that we do; this invariably entails ridiculous consequences...". The Nobel prize rewards the laureates for playing a leading role in observing the "ridiculous" consequences in their experiments, forming the basis for atomic clocks and the pursuit of quantum computers.

The key to realizing such ideal measurements is in achieving an extremely high precision in the action of the measurement itself. To verify the predictions of quantum mechanics at the single-particle level, the quantum system must be stored for long enough that this can be done. The two laureates achieved this precision in two different systems, namely single atoms (Wineland), and a single mode of oscillation of light (Haroche). Prof. Haroche stores quantum states of light (including single "particle" states of light, which we call a photon) between two superconducting mirrors for times up to 1/6 of a second. He performs measurements on the trapped light by sending atoms one at a time between the mirrors. Each atom has an internal clock, for which the hands rotate at an extremely well specified speed. The rate at which time advances on these clocks is shifted depending on the intensity of the trapped light. By subsequent measurements of the atom, a single bit of information can be obtained conveying a small amount of information about the field intensity. Using many atoms, more information can be obtained, which allows the results of repeated measurements to be controlled and the behaviour predicted by quantum mechanics to be revealed.

Dr. Wineland's experiments have pioneered the trapping and laser cooling of singly charged atomic ions. The single atoms can be trapped for days by electric fields, and cooled and controlled using laser techniques which Wineland proposed and demonstrated. This resulted in the possibility to cool the motion of a single particle to a single quantum state, namely that in which the atom has no energy left (for a ball in a bowl, which is a classical analogue to the atom in its trap, the ball would not be moving any more, but would be at the bottom of the bowl). The ability to place an atom in a single quantum state provided the starting point for an exploration of a variety of other quantum states, including the closest states in form to those envisioned in Schrödinger's famous cat thought experiment, a postulated dead-and-alive object. In the ion case, the states are quantum mechanical superpositions of two very different states of the atom, where it is superposed between two oscillations with an amplitude of 80 nm which are out of phase. While this system is by no means a cat, these experiments mark the start of an adventure to explore the boundaries between the quantum and classical worlds.

The work of Wineland and Haroche has laid the basis for the active field of quantum information, for which the precise control of quantum states is a pre-requisite. A major goal for this field is to build a quantum computer, which would make use of the rules of quantum mechanics to compute certain tasks with an efficiency that no classical device could achieve. Towards this goal, quantum control is now performed in a wide range of systems, including photon, solid state systems and atoms and ions. Despite rapid progress, a quantum computer remains a long term goal, but techniques from quantum computation have already spread to other areas. One notable application of experimental quantum computation is seen in the trapped-ion atomic clocks developed in Wineland's group. A critical element of the current best ion clock is an elementary quantum logic "gate" between two ions, which transfers information from an ultra-stable transition in a single aluminium ion, and conveys it to a magnesium ion from where it can be easily read out by observing fluorescence. The systems are now the most accurate frequency references we have, with an accuracy such that a second would be lost or gained in 3.7 billion years.

Pictures from Wikipedia

Jonathan Home is an Assistant Professor in the Department of Physics at ETH Zürich. He received his PhD in 2006 in Oxford working with Prof. Andrew Steane, before taking up a Lindemann fellowship in the group of David Wineland at NIST in Boulder. He started a new group at ETH Zürich pursuing precision control of trapped ions in August 2010.