Rabi Oscillations Revival Induced by Time Reversal: A Test of Mesoscopic Quantum Coherence

Authors: T. Meunier, S. Gleyzes, P. Maioli, A. Auffeves, G. Nogues, M. Brune, J. M. Raimond, and S. Haroche

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Quantum mechanics is all about information. Who has it? Who doesn't? Where is it going? Modern experimental developments now allow us to follow the flow of information when single atoms (both real and artificial) interact with their environment. The coupling between an atom and the quantized electromagnetic field in its environment leads to many fascinating phenomena important in the history of quantum mechanics, including first of all, spontaneous emission of photons. If an atom is placed in an excited state $|e\rangle$, it will emit a photon and irreversibly fall to a lower state $|g\rangle$ in a characteristic time T_1 (on the scale of nanoseconds for visible light, milliseconds for transitions in the microwave region). This process is irreversible because of the continuous density of states available to the photon, which once emitted, flies off at the speed of light never to return.

Marvelous things happen however if the atom is placed inside a cavity which prevents the photon from escaping [1-3]. If the discrete photon modes of the cavity do not match the atom transition, then spontaneous emission can be strongly inhibited. If however one of the cavity modes lies close to the atom transition then the atom and cavity can coherently exchange energy back and forth by oscillating between

$$|e, 0\rangle \Longleftrightarrow |g, 1\rangle \, .$$

These oscillations can be detected by leaving the atom in the cavity for various lengths of time, then extracting it and measuring its state. The energy coherently swaps between the atom and cavity at rates which can greatly exceed the free space value of $1/T_1$. The smaller the cavity and the bigger the atom, the faster this rate can be. With relatively large circular Rydberg atoms in small 3D microwave cavities, this so-called vacuum Rabi rate Ω_0 can be of order 50 kHz even though $T_1 \sim 30$ ms in free space [2]. [With artificial atoms (Cooper pair boxes) in ultra-small quasi 1D cavities, a much higher rate of 12 MHz has been demonstrated [3] but the values of T_1 are much smaller, $\sim 5\mu$s.] If the cavity does not start in the vacuum state, but rather already contains n photons when the excited atom is introduced, then the rate of swapping is enhanced from Ω_0 to $\sqrt{n}\Omega_0$.

One interesting circumstance explored by Meunier et al., is where the cavity contains, not a Fock state with definite n, but rather a coherent state with definite phase and uncertain n. Since the Rabi swapping rate varies with n, the oscillations of the different photon number components of the state get out of phase with each other and destructively interfere after about $\sqrt{n}$ oscillations. This apparent irreversibility is happening even though the photons are not escaping. It is not truly irreversible however because after about n oscillations, there is a kind of Poincaré recurrence in which constructive interference is partially revived. Borrowing ideas from NMR refocussing (spin echo methods) Meunier et al. managed to force an early revival of the oscillations by applying at time T what in quantum computing parlance is known as a 'phase gate' to the atom which puts a relative phase of π between the ground and excited states. This changes the sign of the coupling between the atom and the cavity and effectively 'reverses time' causing the oscillations to revive at time $2T$. The slightly reduced amplitude of the revival is a measure of the 'true' irreversiblity caused by photons escaping from the cavity due to its finite Q. This irreversiblity occurs despite the fact that a weak drive continuously maintains the coherent state of the microwaves in the cavity. This is because the photons which leak out carry away information about the atomic state which could be measured by an outside observer. [There are analogies here to the NMR concepts of entropy preserving spin-spin interactions and entropy increasing spin-lattice interactions, with the photon field inside the cavity playing the role of the other spins.]

This experiment works in a kind of mesoscopic regime for the photon number. The larger is n, the slower is the initial decay of the coherent oscillations and the longer is the Poincaré recurrence time. (The unit of time used by Meunier et al. contains an explicit factor of $1/\sqrt{n}$.) But if n is too large, the rate of irreversible escape of photons from the cavity dominates.

Coherent control of mesoscopic systems is of great current interest in the AMO and condensed matter communities, both for advancing our understanding of dynamics at the quantum/classical boundary and for learning how to manipulate quantum information.

More information about the cQED group at ENS can be found at:
http://www.lkb.ens.fr/recherche/qedcav/english/englishframes.html

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