Quantum Zeno Effect and Quantum Zeno Dynamics in Cavity Quantum Electrodynamics

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Abstract: We describe a cavity QED experiment on quantum Zeno effect with Rydberg atoms and a microwave superconducting cavity. We propose an implementation of quantum Zeno dynamics leading to promising methods for tailoring nonclassical field states.

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The coherent evolution of a quantum system can be blocked by repeated projective quantum measurements. The quantum Zeno efffect [1] (QZE) has been observed on a variety of two-level systems [2]. We have recently observed it on a harmonic oscillator in a Cavity Quantum ElectroDymamics experiment [3] using circular Rydberg states and a superconducting cavity [4].

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The cavity C, resonant at 51 GHz, behaves as an harmonic oscillator whose damping is extremely small. The lifetime of a photon stored in C is $T_c = 0.13$ s, a macrosopic time interval. During T_c, the field can be probed by many atoms crossing C at thermal velocities. They are prepared in a quantum superposition of two circular Rydberg states, e and g (principal quantum numbers 51 and 50 respectively). The $e \to g$ transition is tuned near resonance with C. The atom-cavity detuning is large enough to preclude any photon emission or absorption by the atom in C. However, the atom experiences light shifts in the cavity mode. They result in a phase-shift of the atomic coherence, proportional to the photon number n in C, that can be read out by a Ramsey atomic interferometer arrangement. Atoms extract information about the photon number without changing it. Sending a few tens of atoms through the cavity, we are able to measure the photon number in an ideal projective, quantum nondemolition way [5].

In our QZE experiment [3], the coherent evolution is produced by a classical resonant source S coupled to C. It injects repeatedly small amplitudes (corresponding to much less than one photon on the average). When S acts alone, these amplitudes add up coherently and result in the build-up of a sizeable coherent state in C, whose energy grows quadratically with time. Performing a QND field intensity measurement after each injection, we block this coherent runaway process. We have observed that the field remains close to the vacuum state as expected. The residual field growth is well modeled by a random walk in phase space.

Quantum Zeno dynamics [6] (QZD) takes place when the repeated projective measurement has multidimensional eigenspaces. The system's state, initially in one of these eigenspaces, remains confined in it by the repeated measurement, evolving under the action of the restriction of the free hamiltonian to this subspace. QZD can also be obtained by submitting the system to repeated unitary kicks, U_K, with multidimensional invariant subspaces. In this context, QZD is related to the 'bang-bang' control techniques [7].

We propose to implement QZD in a cavity QED experiment [8]. The corresponding set-up is under construction in the ENS laboratory. Slow ground state atoms are sent upwards towards C, in an atomic fountain arrangement. Near their turning point, the atoms are excited in a circular state. They interact with C for a long time, in the ms range, and are finally detected by field-ionization inside C.

The evolution is stroboscopic. At each step, S provides the free evolution of C by injecting in it a small amplitude. The atom is initially in the level h (circular state with principal quantum number 49). The $e \to g$ transition is tuned in resonance with C. Since h is far off-resonance, the levels $|h,n\rangle$ (atom in h with n photons) are impervious to atom-cavity

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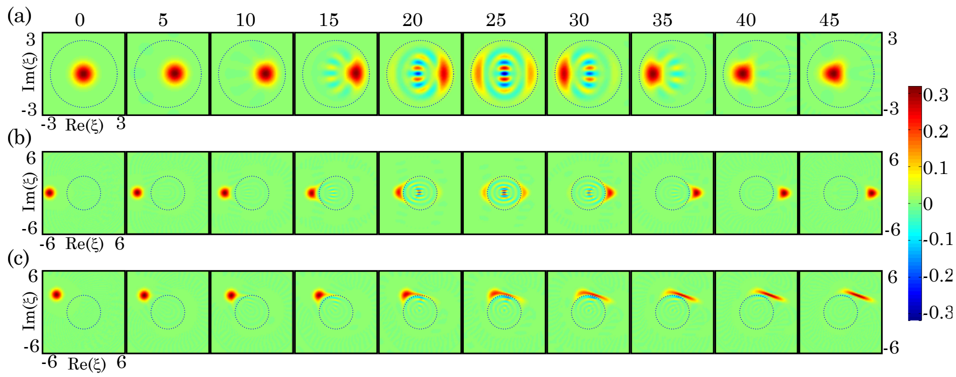

Fig. 1. (a) QZD dynamics in $\mathscr{H}_{<6}$ (from [8]). Field Wigner function $W(\xi)$ obtained after a number of steps indicated above. C is initially in $|0\rangle$. At each step, S injects an amplitude $\beta = 0.1$. The EC is plotted as a dashed line. The state oscillate inside the EC, going through mesoscopic quantum superpositions. (b) QZD dynamics in $\mathscr{H}_{>6}$, with an initial $\alpha = -5$ amplitude. (c) Off-axis collision on the EC, with an initial amplitude $\alpha = -4 + i\sqrt{6}$, generating a squeezed state.

coupling. The transition between $|h,n\rangle$ and the dressed states $|\pm,n\rangle = (|e,n-1\rangle \pm |g,n\rangle)/\sqrt{2}$ is probed by a source S'. The energy of the dressed states depends upon n. The transition corresponding to a single photon number s can thus be addressed selectively. Setting S' to perform a 2π Rabi pulse, we realize the transformation $|h,n\rangle \to (-1)^{\delta_{n,s}}|h,n\rangle$. The atom is left in h and the field state experiences the unitary $U_K = 1 - 2|s\rangle\langle s|$.

Under repeated actions of U_K, the field dynamics is blocked in its eigenspaces, either $\mathscr{H}_{<s}$ (generated by the Fock states from $|0\rangle$ to $|s-1\rangle$) or $\mathscr{H}_{>s}$ (photon number larger than s). The state $|s\rangle$ realizes a 'hard wall' between these subspaces, materialized in the phase plane as an 'exclusion circle' (EC) with radius $\sqrt{s}$. With $s = 1$, we retrieve the standard QZE.

We have investigated numerically this QZD [8]. It produces a variety of interesting effects, such as the generation of mesoscopic superposition states or of squeezed states (Fig. 1). Applying controlled displacements of the field, before and after the interrogation of the atomic transition, we obtain a QZD with an EC centered at an arbitrary point in phase space. With $s = 1$, we pin an arbitrary coherent component at a fixed position and leave all the other non-overlapping ones free to evolve under the action of S'. The EC is a 'phase space tweezer', comparable to the optical tweezers used to manipulate microscopic objects.

The field evolution can be induced by the tweezer itself. The blocked coherent state component follows the motion of the $s = 1$ EC when it moves slowly. Phase space tweezers can thus be used to move independently non-overlapping coherent components in a quantum superposition. They can enlarge cat states, quantum superpositions of components with different amplitudes. Using extra atomic levels, we can turn the method into a process synthezising, from the vacuum, an arbitrary superposition of an arbitrary number of nonoverlapping coherent components.

The numerical simulations can take into account the realistic experimental imperfections. We show that the planned experiment will allow the obervation and tailoring of QZD evolutions. We shall discuss the progress towards its realization.

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