Decoherence Dynamics of Complex Photon States in a Superconducting Circuit

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Quantum states inevitably decay with time into a probabilistic mixture of classical states, due to their interaction with the environment and measurement instrumentation. We present the first measurement of the decoherence dynamics of complex photon states in a condensed-matter system. By controllably preparing a number of distinct, quantum-superposed photon states in a superconducting microwave resonator, we show that the subsequent decay dynamics can be quantitatively described by taking into account only two distinct decay channels, energy relaxation and dephasing. Our ability to prepare specific initial quantum states allows us to measure the evolution of specific elements in the quantum density matrix, in a very detailed manner that can be compared with theory.

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Quantum coherence provides the fundamental distinction between quantum and classical states, and is at the root of much of the non-intuitive behavior of quantum systems; quantum coherence also provides the central impetus for trying to build a quantum computer. Coherence is however extraordinarily delicate, decaying as a quantum system interacts with its environment, or vanishing as the result of even a simple measurement. A quantitative understanding of the decoherence process is critically important for predicting the behavior of quantum systems. The harmonic oscillator is a particularly compelling system for such studies, as an oscillator includes an infinite number of energy levels, from which arbitrarily complex states may be created, yet theories for decoherence in this system are especially simple. Harmonic oscillators are also generic, as they map into a large number of different physical systems: A highly useful example is the electromagnetic resonator, which is central to a number of approaches to building a quantum computer [1, 2, 3, 4, 5], serving as a quantum memory element or a communication bus. The recent development of techniques for generating and measuring arbitrarily complex quantum states in a harmonic oscillator [3, 4, 5, 6, 10, 11] presents the intriguing possibility of exploring the detailed time evolution of these complex states, allowing testing of the theories of decay dynamics [12, 13, 14, 15, 16].

Decoherence of complex harmonic-oscillator states has been studied in previous experiments [13, 14, 16]. The effect of energy decay was measured using Schrödinger cat states by observing loss of interference fringes [13, 16] or by directly filming the Wigner function [14]. Dephasing was measured by injecting noise and then observing the loss of interference fringes for specially prepared states [13]. Here we describe a series of experiments in which we prepare specific, complex, quantum-superposed photon states in an electromagnetic resonator, and then monitor the decay dynamics of its density matrix. By selectively preparing certain types of states, we can highlight the decay of various elements in the density matrix, in particular off-diagonal ones describing phase coherence, for a precise comparison with theory. For the first time, the time decay of various off-diagonal elements are explicitly measured and compared to theory, which show a unique and simple signature. We also demonstrate that energy decay and dephasing can be measured simultaneously: Surprisingly, dephasing rates can be extracted even when it is not dominant, indicating the precision of our measurement. In characterizing a superconducting resonator circuit, our experiment measures an unexpected dephasing rate that is 30 times slower than energy decay. To perform these experiments, we have measured the decay of more than 13 unique off-diagonal elements, for the superposed photon Fock states $|0\rangle + |n\rangle$, $n = 1$ to 8, for the states $|m\rangle + |3\rangle$, $m = 1, 2$, and for the Schrödinger cat states.

Our experiment is performed using a half-wavelength coplanar waveguide resonator made from superconducting aluminum [10, 11, 12]. The cavity has a resonance frequency of 6.971 GHz, and is weakly coupled through a capacitor to an external microwave source. Non-classical photon states are generated and measured via a second weak capacitive coupling to a superconducting phase qubit, whose state can be manipulated using a second microwave source, and measured quickly with single-shot fidelity near unity ($\sim 90\%$) $[19]$. The strong non-linearity of the qubit allows complete control of the resonator photon state $[11]$. The qubit has an energy relaxation time $T_{1q}$ $\sim$ 300 ns and a phase coherence time $T_{2q}$ $\sim$ 120 ns, whereas the resonator has an energy relaxation time $T_1$ $\sim$ 2.4 $\mu$s, similar to previous devices [12, 20].

A single measurement of the qubit state gives an outcome of $|g\rangle$ or $|e\rangle$; by repeating the state preparation and measurement, typically hundreds of times, we determine the probability $P_e$ for the qubit excited state. Tomography of the resonator state involves measuring this prob-
ability for a range of resonator preparation parameters, followed by a photon swap with the qubit, as described below.

Non-classical resonator states are generated with qubit pulse sequences similar to those in previous experiments [11], which are based on the Law/Eberly protocol [17]. The resonator state is subsequently measured after a variable delay time \( 0 \leq t \leq 15 \mu s \) by first displacing the resonator with a coherent microwave pulse, which is characterized by a complex amplitude \( \alpha \), where \( |\alpha|^2 \) corresponds to the average photon number. The qubit is then brought into resonance with the resonator for a variable interaction time \( \tau \), allowing photon exchange between the two, after which the qubit state is measured. Because the resonator-qubit swapping frequency depends on photon number \( n = 0, 1, 2, \ldots \), a measurement of the excited qubit state \( |\alpha\rangle \) versus \( \tau \) is used to determine the photon occupation probabilities \( P_n(\alpha) \) in the resonator. In a prior publication [11] we measured the full Wigner distribution \( W(\alpha) \) from the parity \( \sum_n (-1)^n P_n(\alpha) \) at thousands of points in the complex phase space \( \alpha \). Here we instead use a much more efficient sampling for \( \alpha \), of only 60 points in total, arranged as two concentric circles with radii \( |\alpha| = 1.10 \) and 1.45, from which we calculate the density matrix and reconstruct the Wigner distribution [21]. The resulting readout fidelity is close to that obtained with full Wigner tomography, with the increased uncertainty (~2%) mostly coming from the smaller sample size.

The decay dynamics of a harmonic oscillator quantum state are described by a Markovian master equation that assumes uncorrelated energy relaxation and dephasing processes [18]. The density matrix element \( \rho_{mn} \) in the Fock state basis obeys

\[
\frac{d\rho_{mn}}{dt} = - \left[ \frac{m+n}{2T_1} + \frac{(m-n)^2}{T_\phi} \right] \rho_{mn} + \sqrt{(m+1)(n+1)} \frac{T_1}{T_\phi} \rho_{m+1,n+1},
\]

where \( T_1 \) and \( T_\phi \) are the resonator energy relaxation and dephasing times, respectively. For \( m = n \), Eq. (1) reduces to the master equation for photon number (Fock) state decay [12], with the \( n \)-photon Fock state lifetime given by \( T_{nn} = T_1/n \). For the off-diagonal elements \( m \neq n \), dephasing causes \( \rho_{mn} \) to decay at an additional rate proportional to the square of the distance from the diagonal. In both cases, decay proceeds along the diagonal \( \rho_{mn} \rightarrow \rho_{m-1,n-1} \rightarrow \rho_{m-2,n-2} \rightarrow \cdots \) (see Fig. 3).

The decoherence for the Fock state superpositions \( |0\rangle + |3\rangle \) is
coherent state \( |\alpha = \sqrt{5}\rangle\), created by driving the resonator with a classical pulse to an average photon number of \( |\alpha|^2 = 5 \). During state evolution, the coherent peak is observed to move toward the origin at a rate consistent with \( T_1 \), while the Wigner distribution remains that of a coherent state, as expected from theory with \( T_\phi \gg T_1 \).

Figure 4 also shows the decay of the odd (c) and even (d) Schrödinger cat states. These states are created from a superposition of coherent states \( |\alpha = i\sqrt{2}\rangle \pm |\alpha = -i\sqrt{2}\rangle \), where the even (odd) cat is for the plus (minus) sign, and consists of a superposition of even (odd) number photon states in the Fock-state basis. In the experiment, the photon numbers are truncated above \( n = 6 \). As seen in the figure, the cat states feature a Wigner distribution with two peaks, corresponding to the coherent states displaced from the origin, but with quantum interference fringes between them. The even and odd cats have opposite fringe patterns, as expected. The interference fringes disappear at \( \approx 1\,\mu s \), indicating the loss of phase coherence mostly due to energy relaxation. The two coherent peaks begin to merge at \( \approx 3\,\mu s \), indicating a complete energy decay of the system towards a vacuum state.

Movies of the decay dynamics for all the states mentioned here are available online [22]. In all these states, movies constructed from the experimental data agree well with simulations based on the measured initial den-
FIG. 4: Evolution of (a) the state $|0\rangle + i|2\rangle + |4\rangle$, (b) the coherent state $|\alpha = \sqrt{2}\rangle$, (c) the odd Schrödinger cat state $|\alpha = i\sqrt{2}\rangle - |\alpha = -i\sqrt{2}\rangle$, and (d) the even Schrödinger cat state $|\alpha = i\sqrt{2}\rangle + |\alpha = -i\sqrt{2}\rangle$. Movies of the evolution for all states can be viewed online [22].

In conclusion, we have measured the evolution of a number of non-classical photon states, prepared and measured in a microwave electromagnetic resonator using a superconducting phase qubit. The deterministically-generated states have non-zero off-diagonal elements in their density matrices, and we find that their time evolution is in excellent agreement with theoretical predictions based on the Markovian master equation, both in the sequence of elements and the individual decay rates. While decay from energy loss is in good quantitative agreement with theory, we can only conclude that the decay due to dephasing is consistent with theory, due to the comparatively small effect of dephasing in this system ($T_\phi \gg T_1$).

We also find that movies of decoherence for all the states we prepared and monitored are in excellent agreement with simulations.

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