A superconducting qubit as a quantum transformer routing entanglement between a microscopic quantum memory and a macroscopic resonator

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We demonstrate experimentally the creation and measurement of an entangled state between a microscopic two level system and a macroscopic superconducting resonator where their indirect interaction is mediated by an artificial atom, a superconducting persistent current qubit (PCQB). We show that the microscopic two level system, formed by a defect in an oxide layer, exhibits an order of magnitude longer dephasing time than the PCQB, while the dephasing time of the entangled states between the microscopic two level system and macroscopic superconducting resonator is significantly longer than the dephasing time in the persistent current qubits. This demonstrates the possibility that a qubit of moderate coherence properties can be used in practice to address low decoherence quantum memories by connecting them to macroscopic circuit QED quantum buses, leading future important implications for quantum information processing tasks.

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The twentieth century saw the discovery of one of the most fundamental and far reaching theories ever developed, quantum mechanics. Quantum mechanics provides a set of principles describing physical reality at the atomic level of nature and is critical to our understanding of how atomic devices work. It has important implications for the processing of information at this atomic level and in fact allows for a paradigm shift to quantum information processing. Quantum mechanics provides a fundamentally different computational model by employing features not present in a classical world, most notably superposition and entanglement. Such coherence properties however are not restricted to the microscopic world. Quantum coherence in macroscopic objects have been observed in a number of physical systems, which are usually referred as macroscopic quantum coherence effects. These effects can be most prominent in solid-state systems like engineered superconducting electronic systems \( \text{[1]} \). We can now design quantum circuits on a controllable scale, making quantum mechanics available as a technological resource. As an example, circuit quantum electrodynamics experiments \( \text{[2–4]} \) have demonstrated the coupling of artificial two-level systems (qubits) to single photons in macroscopic superconducting resonators. Other researchers have demonstrated \( \text{[5, 6]} \) the use of such resonators as versatile quantum buses \( \text{[7–9]} \) to couple distant qubits, leading to experimental demonstrations of quantum algorithms \( \text{[10]} \) and Bell violations \( \text{[11]} \). In the longer term, with the promising developments in highly integrated nanotechnologies, these are going to be important to construct superconducting quantum information processors. However imperfections, defects will degrade the performance of such devices. One particular defect of recent interest are microscopic two level systems (TLS) inside the barriers of Josephson junctions. These are individual quantum objects \( \text{[12–17]} \), usually acting as an inevitable noise source, however they can also be used as proxies for engineered qubits \( \text{[18]} \), their long coherence time making them a good proxy for quantum memories, despite their limited controllability \( \text{[19]} \). This leads to the natural question of how to access, manipulate and control TLSs. It is essential for TLSs to be able to coherently interact with other quantum objects within our system generating entanglement in between the two systems. Of particular interest would be to create entanglement between the TLS and the macroscopic resonator. However, neither of these objects directly couple to one another and so would need to be mediate by the superconducting qubits. In this letter, we introduce and experimentally demonstrate a new design of entangling gate between TLS and the resonator via superconducting qubits. Given the short coherence time of the superconducting qubits, it is curious to know if it would be only extremely short lived due to the coupling with the short-lived superconducting qubits.

This letter demonstrates the entanglement of a single microscopic TLS and a engineered open ended superconducting coplanar stripline of length \( l_{\text{res}} = 7.1 \text{ mm} \), the geometry of which is depicted in Fig. \( \text{[II]} \). These systems are off-resonant and coupled weakly directly, but both interact strongly with a persistent current qubit (PCQB) \( \text{[20]} \) in a four Josephson junction configuration \( \text{[21]} \), depicted in Fig. \( \text{[III]} \), when tuning the PCQB into resonance. A mutual
inductance between the qubit and the resonator, created by placing the qubit directly on the substrate and resonator segment in a metallization layer above, isolated by a SiO$_2$ layer couples the zero point fluctuation current of the resonator to the qubit persistent current. The electric scheme in Fig. 1(c) contains the qubit loop including the junctions with Josephson energies $E_J$, $4E_J$ and $\alpha E_J$, where $\alpha = 0.72$, forming the persistent current qubit, coupled to the control line and the stripline resonators fundamental mode with a wavelength $\lambda = 2\pi_{\mathrm{res}}$, represented by a resonant circuit formed by an inductance and a parallel capacitance. The qubit is coupled to the TLS by the electric field in one of the capacitances shunting a junction, displayed in Fig. 1(d). Such TLS are imperfections in the oxide, first explicitly observed in phase qubits \[12\]. A trapped elementary charge tunnels between stable positions, illustrated in Fig. 1(c).

The PCQB transition frequency $\nu_{QB}$ is controlled during the experiments by magnetic flux threading the PCQB loop, which is the sum of a constant magnetic flux $\Phi_0$, generated by a solenoid, and a time-varying flux $\Phi(t)$, induced by a current $I(t)$ through an on-chip control line coupled to the qubit by a mutual inductance. The operating point is set to $\Phi_{\text{ext}} = 3\Phi_0/2 + \delta\Phi_{\text{ext}}$, where $\Phi_0 = \hbar/(2e)$ is the superconducting flux quantum and $\delta\Phi_{\text{ext}} \ll \Phi_0$. At this bias two macroscopically distinct current states exist, corresponding to a persistent current $I_p \approx \pm300$ nA, circulating clockwise or counterclockwise. The magnetic energy of these two states corresponds to a frequency of $\epsilon(t) = \pm I_p(\Phi(t) + \delta\Phi_{\text{ext}})/\hbar$. The Josephson junctions parameters generate a tunnel element between the two states of $\Delta = 3.2$ GHz. The PCQB Hamiltonian takes the form $H_{QB} = \hbar(\Delta \sigma_{x, QB} + \epsilon(t)\sigma_{z, QB})/2$, where $\sigma_{x, QB}$ and $\sigma_{z, QB}$ are the normal Pauli matrices, so that the transition frequency is given by $\nu_{QB} = \sqrt{\Delta^2 + \epsilon^2(t)}$. The measured spectrum after a long AC pulse $I(t) = I_{rf}\cos(2\pi\nu_{rf}t)$ with small amplitude $I_{rf}$ applied to the control line is plotted in Fig. 2 as a function of $\delta\Phi_{\text{ext}}$, where the frequency was swept for each magnetic field to acquire the spectrum of the qubit. The qubit readout is achieved by a measurement DC-SQUID, where after completing any qubit control sequence, in this case a long rf pulse, a possible switching event of the measurement DC-SQUID is recorded. Repeating this sequence 10000 times enables to estimate the qubit excitation probability.

While the dispersion relation on the coarse scale fits the qubit dispersion relation, the insets show avoided crossings at the microscopic TLS transition frequency $\nu_{TLS} = 6.17$ GHz and the resonators fundamental frequency $\nu_{\text{res}} = 8.97$ GHz. The splitting of the avoided crossing at $\nu_{\text{res}}$ is $2\nu_{\text{res, QB}} = 112$ MHz, (corresponding to a coupling strength $g_{\text{res, QB}} = 157$ MHz in the canonical base of the qubit). The TLS is presumably contained in a Josephson junction barrier, indicated in Fig. 1(b). The coupling of a charged TLS and a persistent current qubit was described in \[16\], where the maximum possible coupling strength was found to be $g_{\text{TLS, QB}} = \Delta\phi_m d/t$, where $\phi_m$ is the phase difference associated with the persistent current states, which is on the order of unity, $t \approx 0.6$ nm the oxide layer thickness and $d \approx 0.03$ nm the distance between the stable locations, so $g_{\text{TLS, QB}} \leq 200$ MHz. The experimentally observed splitting at $\nu_{\text{TLS}}$ is $2\nu_{\text{TLS, QB}} = 54$ MHz, corresponding to a coupling strength of $g_{\text{TLS, QB}} = 55$ MHz in the qubits canonical base. The TLS frequency $\nu_{\text{TLS}}$ fluctuated between the acquisition of the spectrum in Fig. 2 and the experiments described below, which we attribute to a fluctuation of the surrounding electric field \[15\].

During the time-domain experiments a constant external magnetic flux $\delta\Phi_{\text{ext}} \approx 4\Phi_0$ is applied, corresponding to $\nu_{QB} = 7.92$ GHz. Before beginning any pulse sequence the system is kept at $I = 0$ for approximately 800 $\mu$s. After this time the system has relaxed to its thermodynamic equilibrium state, governed by the qubit energy $\hbar\nu_{QB}$ and effective
electronic qubit temperature of approximately 130 mK, corresponding to an excited state population of the qubit of about 5%, subsequently ignored in the discussion of the sequences[22]. The system is then in the $|0,0,0\rangle$ state, where the first subspace denotes the PCQB state, the second denotes the TLS state, and the third denotes the resonator state. Each of the sequences depicted in Fig. 3(a)-(c) begins with a qubit spin flip by a resonant $\pi$-pulse with a duration $\tau_0 = 4 \text{ ns}$ and with an amplitude determined in a Rabi experiment, preparing the system in the $|1,0,0\rangle$ state. The input current applied to the on-chip control line is defined by a piecewise function[24] by the pulse lengths $\tau_i$ and the quasi-dc pulse heights $I_{dc,i}$, corresponding to a qubit transition frequency $\nu_{QB,i}$. We represent the pulse sequences as shown in Fig. 3(a)-(c) and model the system in the qubit and TLS eigenbase by the approximate Hamiltonian $H_{\text{total}} = \hbar (\nu_{QB}(t) |1/2\rangle\langle 1/2| + \nu_{TLS} |1/2\rangle\langle 1/2| + \nu_{TLS,QB} |1\rangle\langle 1| + \nu_{res, QB} (\sigma^+_{QB} |a\rangle \langle a| + \sigma^-_{QB} |a\rangle \langle a|) + \nu_{res} (\sigma^+ \langle a| \sigma^- \langle a| + \sigma^- \langle a| \sigma^+ \langle a|) + \nu_{res} (\sigma^+ \langle a| \sigma^- \langle a| + \sigma^- \langle a| \sigma^+ \langle a|)$. We first characterize the qubit-TLS interaction as shown in Fig. 3(a) by bringing the excited qubit on resonance for a time $\tau_{TLS}$, allowing us to determine $\nu_{TLS, QB}$ and the time $\tau_{\text{SWAP}} = 1/(8 \nu_{TL S, QB})$ needed for performing a $\sqrt{\text{SWAP}}$ operation. After this operation the TLS and the qubit are in the entangled state $(|1,0,0\rangle + |0,1,0\rangle)/\sqrt{2}$. This state is an entangled state between the qubit and the TLS, named Bell-$\Phi^+$-state. To transfer the entanglement the resonator qubit-resonator interaction is characterized equivalently in Fig. 3(b) and the time $\tau_{\text{SWAP}} = 1/(4 \nu_{res, QB})$ corresponding to a $\sqrt{\text{SWAP}}$-operation is determined, in which the qubit state and the single-photon state are exchanged, making the state $|0,0,1\rangle$.

A combination of these two operations yields the pulse sequence in Fig. 3(c). The first quasi-dc pulse tunes the qubit in resonance with the TLS for a time $\tau_1 = \tau_{\text{SWAP}}$, generating the entanglement and the second pulse brings qubit in resonance with the resonator for a time $\tau_2 = \tau_{\text{SWAP}}$, transferring the Bell state between the qubit and the TLS to a Bell state between the TLS and the resonator $(|0,1,0\rangle + |0,0,1\rangle)/\sqrt{2}$. After this the qubit is taken off resonance for a time $\tau_3$. During this period the $(|0,1,0\rangle + |0,0,1\rangle)/\sqrt{2}$ state evolves according to a multi-spin Zeeman Hamiltonian as $(\exp(i 2 \pi \nu_{TLS} \tau_3) |1,0,0\rangle \langle 1,0,0| + \exp(i 2 \pi \nu_{res} \tau_3) |0,0,1\rangle \langle 0,0,1|)/\sqrt{2} = \exp(i 2 \pi \nu_{TLS} \tau_3) (|0,1,0\rangle \langle 0,1,0| + \exp(i \varphi) |0,0,1\rangle \langle 0,0,1|)/\sqrt{2}$, where $\varphi = 2 \pi \nu_{res} - \nu_{TLS}$. As a result, the occupation oscillates between the $\Phi^+$ state and the $\Phi^+$ state, so varying $\tau_3$ probes this coherent phase evolution. Bringing the qubit and the resonator in resonance for a time $\tau_4 = \tau_{\text{SWAP}}$ swaps the resonator state back to the qubit. The last pulse brings the qubit on resonance with the TLS for $\tau_5 = \tau_{\text{SWAP}}$ generating another $\sqrt{\text{SWAP}}$-operation and projecting the Bell-$\Phi$-states into the state $\cos(\varphi) |1,0,0\rangle + \sin(\varphi) |0,1,0\rangle$, resulting in an oscillating qubit excitation probability. We plot the measured excitation probability in Fig. 3(c) as a function of $\tau_5$ between 20 ns and 21 ns. Fitting using a robust least-squares method yields frequency of 2.935 GHz ± 22 MHz, which matches the frequency difference between the TLS and the resonator. In Fig. 3(a) we show the qubit excitation probability over $\tau_5$ ranging from 20 ns to 60 ns in steps of 100 ps. For comparison, the results of Ramsey pulse sequences are shown, in which memory sequence consisting of two SWAP operations with...
FIG. 4. (a) Coherent oscillation of the qubit excitation acquired by Ramsey (memory) sequences on the TLS and the resonator, and the entanglement sequence in Fig. 2 as a function of time between the pulses. (b) demodulated oscillation amplitudes; dashed lines indicate fits to exponential decays.

a varied time delay is inserted, probing the coherence of the resonator and the TLS. The Fourier transform (not shown) of the data in Fig. 4(a) exhibits only a single dominant peak for each of the signals. Demodulating the signal into amplitude and phase yields a resonator frequency \( \nu_{\text{res}} = 8.97 \) GHz, a TLS transition frequency of \( \nu_{\text{TLS}} = 6.05 \) GHz, and an entangled state oscillation frequency of \( \nu = 2.92 \) GHz, all to a precision better than 10 MHz and fulfilling the relation \( \nu_{\text{res}} - \nu_{\text{TLS}} = \nu \).

Fitting the oscillation amplitudes, plotted in Fig. 4(b), to exponential decays yields characteristic decay times and amplitudes \( A_0 \) at \( \tau_3 = 0 \) for each of the coherent signals. Each of these oscillation amplitudes is proportional to twice the absolute value of the corresponding off-diagonal element in the density matrix. For the entangled state, \( A_0 = 0.2 \), where the proportionality factor is set by the transfer efficiency \( \eta \) of the corresponding states in the disentanglement gate. Under the condition that only a single photon is input into the system, which is fulfilled in the present experiment, the concurrence as a usual entanglement measure is given by twice the absolute value of this density matrix element. Hence, regardless of the numerical value of this factor, any finite oscillation amplitude corresponds to a finite entanglement. In numerical simulations we estimate \( \eta \approx 0.6 \) taking into account the Qubit dephasing with a dephasing time of \( t_{2,\text{QB}} = 14.8 \) ns, and the experimental pulse shaping limitations, yielding a concurrence for \( \tau_3 = 0 \) of \( C = A_0/\eta = 0.33 \). This is a conservative estimation, since the experimental \( \eta \) is likely to be lower. Independent of the absolute value of the concurrence, we can probe its decay over time. A naive interpretation yields that the decay can be described by a single decay rate, induced by relaxation and dephasing of the off-diagonal entangled state density matrix elements and should be the sum of the decay rate of the two subsystems Ramsey decay rates. However, the memory dephasing times of \( 73 \pm 8 \) ns for the resonator and \( 106 \pm 16 \) ns for the TLS yield an expected characteristic decay time of the entangled state of \( 43 \pm 6 \) ns, which deviates from the experimental value of \( 28 \pm 4 \) ns. This suggests a mechanism for a collective decoherence, which could be a direct coupling between the resonator and the TLS or the indirect coupling via the qubit, which participates in the resonator state due to the significant ratio of \( \nu_{\text{res,QB}}/(\nu_{\text{QB}} - \nu_{\text{res}}) \).

To conclude, we have shown an extremely heterogeneous quantum experiment consisting of three effective qubits, in which a PCQB acts as a transformer between a stripline resonator and a microscopic TLS inside one of the qubits Josephson junctions. We use this qubit to generate, mediate and measure entanglement between the two other systems. The frequency of the entangled state matches the predicted relations exactly, and the amplitude, equivalent to the concurrence, decays over a timescale dominated by the relaxation of the resonator. Overall we show that the qubit itself acts mainly as a mediator and participates only weakly in the entangled states dynamics, by observing a the entangled state coherence time significantly longer than the qubit dephasing time. This demonstrates that a single active element, even with a short coherence time, can be used as a mediator to generate entanglement between passive quantum systems otherwise isolated from the environment.
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