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Quantum superposition, entanglement, and state teleportation of a microorganism on an electromechanical oscillator

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Abstract Schrödinger's thought experiment to prepare a cat in a superposition of both alive and dead states reveals profound consequences of quantum mechanics and has attracted enormous interests. Here we propose a straightforward method to create quantum superposition states of a living microorganism by putting a small cryopreserved bacterium on top of an electromechanical oscillator. Our proposal is based on recent developments that the center-of-mass oscillation of a 15-μm-diameter aluminum membrane has been cooled to its quantum ground state (Teufel et al. in Nature 475:359, 2011), and entangled with a microwave field (Palomaki et al. in Science 342:710, 2013). A microorganism with a mass much smaller than the mass of the electromechanical membrane will not significantly affect the quality factor of the membrane and can be cooled to the quantum ground state together with the membrane. Quantum superposition and teleportation of its center-of-mass motion state can be realized with the help of superconducting microwave circuits. More importantly, the internal states of a microorganism, such as the electron spin of a glycine radical, can be entangled with its center-of-mass motion and teleported to a remote microorganism. Our proposal can be realized with state-of-the-art technologies. The proposed setup is a quantum-limited magnetic resonance force microscope. Since internal states of an organism contain information, our proposal also provides a scheme for teleporting information or memories between two remote organisms.

Keywords Quantum superposition · Quantum entanglement · Quantum teleportation · Schrödinger's cat · Electromechanical Oscillator · Cryopreserved microorganism

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1 Introduction

In 1935, Erwin Schrödinger [1–3] proposed a famous thought experiment to prepare a cat in a superposition of both alive and dead states. He imagined that a cat, a small radioactive source, a Geiger counter, a hammer and a small bottle of poison were sealed in a chamber. If one atom of the radioactive source decays, the counter will trigger a device to release the poison. So the state of the cat will be entangled with the state of the radioactive source. After a certain time, the cat will be in superposition of both alive and dead states. The possibility of an organism to be in a superposition state is counterintuitive and dramatically reveals the profound consequences of quantum mechanics. Besides their importance in studying foundations of quantum mechanics, quantum superposition and entangled states are key resources for quantum metrology and quantum information [4]. Furthermore, the explanation of how a "Schrödinger's cat" state collapses is the touchstone of different interpretations of quantum mechanics. While many-worlds interpretations propose that there is no wave function collapse [5, 6], objective collapse theories [7–10] propose that the wave function collapse is an intrinsic event that happens spontaneously.

The "Schrödinger's cat" thought experiment has attracted enormous interest since it was proposed 80 years ago [4]. Many great efforts have been made to create large quantum superposition states. Superposition states of photons, electrons, atoms, and some molecules have been realized [11]. Wave-like energy transfer through quantum coherence in photosynthetic systems has been observed [12, 13]. Recent developments in quantum optomechanics [14–17] and electromechanics [18–25] provide new opportunities to create even larger superposition states experimentally [26]. In 2009, Romero-Isart et al. [27] proposed to optically trap a living microorganism in a high-finesse optical cavity in vacuum to create a superposition state. That paper increased our hope to experimentally study the quantum nature of living organisms [1–3, 28, 29]. Meanwhile, Li et al. [30] demonstrated optical trapping of a pure silica microsphere in air and vacuum and cooling its center-of-mass motion from room temperature to about 1.5 mK in high vacuum [31]. Recently, parametric feedback cooling [32] and cavity cooling of pure dielectric nanoparticles [33–35] were also demonstrated. These are important steps toward quantum ground-state cooling of a levitated dielectric particle. Optical trapping of an organism in vacuum, however, has not been realized experimentally. The main difficulty is that the optical absorption coefficient [36] of organisms is much larger than that of a pure silica particle, which can lead to significant heating of an optically trapped microorganism in vacuum. Recently, Fisher [37] proposed that the nuclear spin of phosphorus can serve as the putative quantum memory in brains.

Here we propose to create quantum superposition and entangled states of a living microorganism by putting a small bacterium on top of an electromechanical oscillator, such as a membrane embedded in a superconducting microwave resonant circuit (Fig. 1). Our proposal also works for viruses. Since many biologists do not consider viruses as living organisms [29], we focus on small bacteria in this paper. Our proposal has several advantages. First, it avoids the laser heating problem as no laser is required in our scheme. Second, quantum ground-state cooling and advanced state control of an electromechanical oscillator integrated in a superconducting circuit have been realized experimentally [18–23, 25]. Quantum teleportation based on superconducting circuits has also been demonstrated

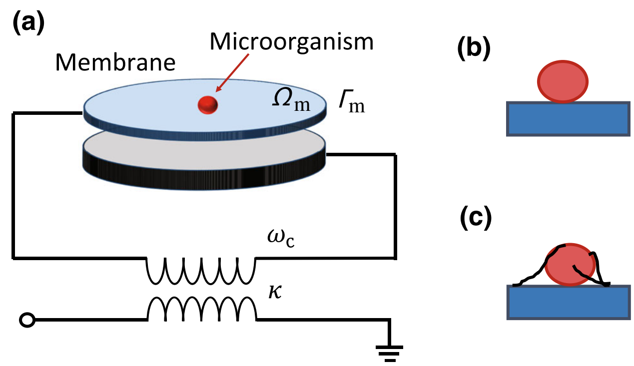

Fig. 1 (Color online) **a** Scheme to create quantum superposition states of a microorganism by putting a small bacterium or a virus with a mass of m on top of an electromechanical membrane oscillator with a mass of M_{mem}. The membrane is the upper plate of a capacitor embedded in a superconductor inductor–capacitor (LC) resonator. The LC resonator is coupled to a transmission line. The membrane has an intrinsic mechanical oscillation frequency of Ω_m and a linewidth of Γ_m when the microorganism is not on it. The LC resonator has a resonant frequency of ω_c and an energy decay rate of κ. Some microorganisms have smooth surfaces (**b**), while some have pili (hair-like structures) on their surfaces (**c**)

[38]. In addition, most microorganisms can survive in the cryogenic environment that is required to achieve ground-state cooling of an electromechanical oscillator. Although microorganisms are frozen in a cryogenic environment, they can be still living and become active after thawing [39]. Cryopreservation is a mature technology that has been used clinically worldwide [39]. Most microorganisms can be preserved for many years in cryogenic environments [40]. Even some organs [41] can be preserved at cryogenic temperatures. At millikelvin temperatures, a microorganism can be exposed to ultrahigh vacuum without sublimation of water ice. More importantly, the internal states of a microorganism, such as the electron spin of a glycine radical $NH_3^+\dot{C}HCOO^-$ [42, 43], can also be prepared in superposition states and entangled with its center-of-mass motion in the cryogenic environment. This will be remarkably similar to Schrödinger's initial thought experiment of entangling the state of an entire organism ("alive" or "dead" state of a cat) with the state of a microscopic particle (a radioactive atom).

We also propose to teleport the center-of-mass motion state and internal electron spin state between two remote microorganisms, which is beyond Schrödinger's thought experiment. Since internal states of an organism contain information, our proposal provides an experimental scheme for teleporting information or memories between two organisms. Our proposed setup not only can be used to study macroscopic quantum mechanics, but also has applications in quantum-limited magnetic resonance force microscopy (MRFM) for sensitive magnetic resonance imaging (MRI) of biological samples [44]. This will