CrossMark

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

Tongcang Li · Zhang-Qi Yin

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

T. Li (✉)
Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA
e-mail: tcli@purdue.edu

T. Li
School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA

T. Li
Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA

T. Li
Purdue Quantum Center, Purdue University, West Lafayette, IN 47907, USA

Z.-Q. Yin
Center for Quantum Information, Institute of Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China

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

SCIENCE CHINA PRESS

Springer

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
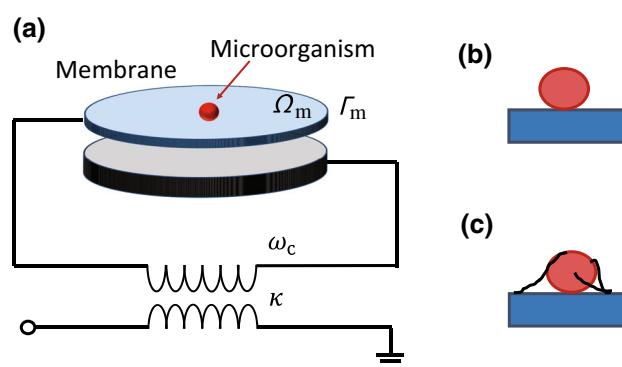

Fig. 1 (Color online) **a** Scheme to create quantum superposition states of a microorganism by putting a small bacterium or a virus with a mass of m on top of an electromechanical membrane oscillator with a mass of M_{mem}. The membrane is the upper plate of a capacitor embedded in a superconductor 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 $\mathrm{NH_3^+\dot{C}HCOO^-}$ [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

provide more than structural information that can be obtained by cryo-electron microscopy [45], which also requires the sample to be cooled to cryogenic temperatures to avoid sublimation of water ice in vacuum. This system can coherently manipulate and detect the quantum states of electron spins, which enables single electron spins that could not be read with optical or electrical methods to be used as quantum memory.

2 The model

Recently, a 15-μm-diameter aluminum membrane with a thickness of 100 nm has been cooled to quantum ground state by sideband cooling with a superconducting inductor–capacitor (LC) resonator [19]. Coherent state transfer between the membrane and a traveling microwave field [21], as well as entangling the motion of the membrane and a microwave field [20] have been realized. The experiment in Ref. [19] was performed in a cryostat at 15 mK. The mechanical oscillation frequency of this membrane is about 10 MHz, with a mechanical quality factor of 3.3×10^5. The mass of the membrane is 48 pg (2.9×10^{13} Da). As shown in Table 1, this mass is about four orders larger than the mass of ultra-small bacteria and even more orders larger than the mass of viruses [46–52]. We can use this membrane oscillator to create quantum superposition states of a small microorganism. Among different cells, mycoplasma bacteria are particularly suitable for performing this experiment because they are ubiquitous and their sizes are small [50]. In addition, they have been preserved at cryogenic temperatures [40]. It will also be interesting to create superposition states of prochlorococcus. Prochlorococcus is presumably the most abundant photosynthetic organism on the earth, with an abundance of about 10^5 cells/mL in surface seawater [51, 53]. It can be used to study quantum processes in photosynthesis.

As shown in Fig. 1a, we consider a bacterium or virus on top of an electromechanical membrane oscillator. We assume the mass of the microorganism m is much smaller than the mass of the membrane M_{mem}. Some microorganisms have smooth surfaces (Fig. 1b) while some other microorganisms have pili on their surfaces (Fig. 1c). For simplicity, it will be better to use microorganisms with smooth surfaces. One way to put a microorganism on top of an electromechanical membrane is to spray a small amount of microorganisms to air in a sealed glove box, and wait one microorganism to settle down on the electromechanical membrane. The process can be monitored with an optical microscope. After being cooled down to a cryogenic temperature, the microorganism can be exposed to high vacuum without sublimation of the water ice. Techniques developed in cryo-electron microscopy can be utilized here

[45]. The sublimation rate of water ice is only about 0.3 monolayers/h at 128 K with a sublimation energy of 0.45 eV [54]. The sublimation of water ice can be safely ignored at millikelvin temperatures.

At millikelvin temperatures, a frozen microorganism will be in a hard and brittle state like a glass. It will be stuck on the membrane due to van der Waals force or even stronger chemical bonds. The pull-off force between a 1 μm sphere and a flat surface due to van der Waals force is on the order 100 nN [55], which is about 10^7 times larger than the gravitational force on a 1 μm particle. So the microorganism will move together with the membrane as long as there is a good contact between them. The oscillation frequency of the membrane oscillator will change by roughly $-\Omega_{\text{m}} m / (2 M_{\text{mem}})$, where Ω_{m} is the intrinsic oscillation frequency of the membrane. The exact frequency shift depends on the position of the microorganism on the membrane. Nonetheless, this frequency shift will be small and will not significantly affect the ground-state cooling or other state control of the membrane when $m/M_{\text{mem}} < < 1$.

The change of the quality factor Q of the membrane oscillator due to an attached small microorganism ($m/M_{\text{mem}} < < 1$) will also be negligible. For a frozen bacterium with a smooth surface (Fig. 1b), the lowest internal vibration frequency can be estimated by the speed of sound in ice divided by half of its size. So the internal vibration modes of the main body will be larger than 1 GHz for a bacterium smaller than 1 μm. This is much larger than the frequency of the center-of-mass motion of the electromechanical membrane which is about 10 MHz. Thus these internal vibration modes of the main body of a bacterium will not couple to the center-of-mass vibration of the membrane. The situation will be a little complex for bacteria that have pili on their surfaces (Fig. 1c) [56]. For a very thin and long pilus, it is possible that its vibration frequency to be on the same order or even smaller than the center-of-mass vibration frequency of the electromechanical membrane. However, because the quality factors of both the pili and electromechanical membrane are expected to be very high at milikelvin temperatures, it is unlikely that their frequencies matches within their linewidths to affect the ground-state cooling of the center-of-mass mode of the membrane. One can also avoid this problem by embedding the pili in water ice.

3 Center-of-mass motion: cooling, superposition, and teleportation

We assume the frequency of the center-of-mass motion of the microorganism and the membrane together to be ω_{m}, which is almost the same as Ω_{m}. The motion of the membrane alters the frequency ω_{c} of the superconducting LC resonator. The frequency ω_{c} can be approximated with

Table 1 Comparison of masses of some viruses and bacteria to the mass of a membrane oscillator ($M_{mem} = 48$ pg) that has been cooled to the quantum ground state in Ref. [19]

Microorganism	Typical mass (pg)	m/M_{mem} ($M_{mem} = 48$ pg)
Bacteriophage MS2	6×10^{-6}	10^{-7}
Tobacco mosaic virus	7×10^{-5}	10^{-6}
Influenza virus	3×10^{-4}	10^{-5}
WWE3-OP11-OD1 ultra-small bacterium	0.01	10^{-4}
Mycoplasma bacterium	0.02	10^{-4}
Prochlorococcus	0.3	10^{-2}
E. coli bacterium	1	10^{-2}

These mass values are obtained from Refs. [46–52]

$\omega_c(x) = \omega_0 + Gx$, where x is the displacement of membrane, and $G = \partial \omega_c / \partial x$. The parametric interaction Hamiltonian has the form $H_I = \hbar G a^\dagger a \hat{x} = \hbar G \hat{n} x_0 (a_m + a_m^\dagger)$, where a (a_m) and $a^\dagger$ ($a_m^\dagger$) are the creation and annihilation operators for LC (mechanical) resonator, $\hat{n}$ is the photon number operator, and $x_0 = \sqrt{\hbar/2M_{mem}\omega_m}$ is the zero point fluctuation for mechanical mode. We denote the single-photon coupling constant $g_0 = Gx_0$.

In order to enhance the effective coupling between LC resonator and mechanical oscillator, the LC resonator is strongly driven with frequency ω_d and Rabi frequency Ω_d. The corresponding Hamiltonian reads $H_d = \frac{\Omega_d}{2} e^{-i\omega_d t} a$ +h.c.. The detuning between the driving microwave source and the LC resonator is $\Delta = \omega_d - \omega_0$. The steady-state amplitude can be approximated as $\alpha = \Omega_d/(2\Delta + i\kappa)$, where κ is the decay rate of the LC resonator. We assume that the steady-state amplitude α is much larger than 1. We expand the Hamiltonian with $a - \alpha$, and the total Hamiltonian reads

$$H = \hbar \Delta a^\dagger a + \hbar \omega_m a_m^\dagger a_m + \hbar g(a^\dagger + a)(a_m^\dagger + a_m), \quad (1)$$

where $g = \alpha g_0$. The detuning can be freely chosen to satisfy the requirements of different applications. In order to cool the membrane resonator, we choose $\Delta = -\omega_m$. By using rotating wave approximation under the condition that $\omega_m \gg g$, we get the effective equation as [57]

$$H_{eff} = \hbar g a^\dagger a_m + \hbar g a a_m^\dagger. \quad (2)$$

In order to cool the membrane oscillation to the ground state, the system should fulfill the sideband limit $\omega_m \gg \kappa, \gamma_m$, where γ_m is the decay rate of mechanical mode of the whole system [58, 59]. γ_m will be almost the same as the decay rate Γ_m of the mechanical mode of the electromechanical membrane alone when the frequencies of internal modes of the microorganism do not match the frequency of the electromechanical membrane. The master equation for the system is

$$\dot{\rho} = -i[H_{eff}, \rho]/\hbar + \mathcal{L}_a \rho + \mathcal{L}_{a_m} \rho, \quad (3)$$

where the generators are defined by $\mathcal{L}_a \rho = \kappa D_a \rho$, $\mathcal{L}_{a_m} \rho = (1 + \bar{n}_m)\gamma_m D_{a_m} \rho + \bar{n}_m \gamma_m D_{a_m^\dagger} \rho$, and the notation of the generators has Lindblad form $D_x \rho = 2x\rho x^\dagger - x^\dagger x \rho - \rho x^\dagger x$. In the limit that $\kappa \gg g$, we can adiabatically eliminate the a mode, and get the effective master equation

$$\dot{\rho} = \mathcal{L}_{a_m} \rho + \mathcal{L}'_{a_m} \rho, \quad (4)$$

where $\mathcal{L}'_{a_m} = \kappa' D_{a_m}$, and $\kappa' = g^2/\kappa$. We define the total generator $\mathcal{L} = \mathcal{L}_{a_m} + \mathcal{L}'_{a_m} = (1 + \bar{n}'_m)\gamma' D_{a_m} + \bar{n}'_m \gamma' D_{a_m^\dagger}$, where $\gamma' = \gamma + \kappa'$, and $\bar{n}'_m = \bar{n}_m \gamma/\gamma'$. As long as $\kappa' > \bar{n}_m \gamma$, the steady-state mean phonon number of mechanical resonator $\bar{n}'_m$ is less than 1, which is in the quantum regime. As a bacterium or virus are attached on the top of membrane, it is also cooled down to the quantum regime.

Once the mechanical mode is cooled down to the quantum regime, we can prepare the mechanical superposition state by the method of quantum state transfer between mechanical and LC resonators. For example, we can first generate the superposition state $|\phi_0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ for LC mode a with assistant of a superconducting qubit. Here $|0\rangle$ and $|1\rangle$ are vacuum and Fock state with 1 photon of mode a. Then, we turn on the beam-splitter Hamiltonian (2) between a and a_m. After the interaction time $t = \pi/g$, the mechanical mode will be in the superposition state $|\phi_0\rangle$. Here we suppose that the strong coupling condition $g > \bar{n}_m \gamma, \kappa$ fulfills. Therefore, the coherence of the superposition state $|\phi_0\rangle$ can maintain during the state transfer.

The quantum state of the center-of-mass motion of a microorganism can also be teleported to another microorganism using a superconducting circuit. Quantum teleportation based on superconducting circuits has been demonstrated recently [38]. We consider two remote microorganisms, which are attached to two separate mechanical resonators integrated with LC resonators. They are connected by a superconducting circuit as demonstrated in Ref. [38]. They are initially cooled down to the motional

SCIENCE CHINA PRESS

ground states. We use the ground state and the first Fock state $|1\rangle$ of both mechanical and LC resonators as the qubit states. The mechanical mode a_{m1} of the first microorganism and mechanical resonator is prepared to a superposition state $|\psi_1\rangle = \alpha|0\rangle_{m1} + \beta|1\rangle_{m1}$, where α and β are arbitrary and fulfill $|\alpha|^2 + |\beta|^2 = 1$. The LC resonator modes a_1 and a_2 are prepared to the entangled state $(|0\rangle_1|1\rangle_2 + |1\rangle_1|0\rangle_2)/\sqrt{2}$, through quantum state transfer, or post-selection [57]. Then by transferring the state a_2 to the mechanical mode a_{m2} of the second microorganism and mechanical oscillator, the LC mode a_1 entangles with mechanical mode a_{m2}. This entanglement can be used as a resource for teleporting the state in mechanical mode a_{m1} to the mechanical mode a_{m2} [60].

To do this task, we need to perform Bell measurements on mode a_1 and a_{m1}, which can be accomplished by a CPHASE gate between a_1 and a_{m1}, and Hadamard gates on a_1 and a_{m1} [38]. In order to realize the CPHASE gate, we tune the driving detuning $\Delta - \omega_m = \delta \ll \omega_m$. The effective Hamiltonian between a_1 and a_{m1} becomes

$$H'_{\text{eff}} = \hbar\delta a_1^\dagger a_1 + \hbar g a^\dagger a_m + \hbar g a a_m^\dagger. \tag{5}$$

In the limit $\delta \gg g$, we get an effective photon–phonon coupling Hamiltonian by adopting second order perturbation method,

$$H_{\text{pp}} = \hbar\frac{g^2}{\delta} a_1^\dagger a_1 a_{m1}^\dagger a_{m1}. \tag{6}$$

By turning on the Hamiltonian (6) for time $t = \pi\delta/g^2$, the CPHASE gate between a_1 and a_{m1} accomplishes. The state of the system becomes $|\psi\rangle = (\alpha|0\rangle_{m1}|0\rangle_1|1\rangle_{m2} + \alpha|0\rangle_{m1}|1\rangle_1|0\rangle_{m2} + \beta|1\rangle_{m1}|0\rangle_1|1\rangle_{m2} - \beta|1\rangle_{m1}|1\rangle_1|0\rangle_{m2})\sqrt{2}$. Then we perform two Hadamard gates on a_1 and a_{m1} modes, and project measurements on the basis $|0\rangle$ and $|1\rangle$. There are four different output $\{00, 01, 10, 11\}$, which are one-to-one mapping to the four Bell measurement basis. Based on the output, we can perform the specific local operation on the mode a_{m2} and recover the original state $\alpha|0\rangle + \beta|1\rangle$.

4 Internal electron spins: entanglement, detection, and teleportation

The internal states of a microorganism can also be prepared in superposition states and entangled with the center-of-mass motion of the microorganism at millikelvin temperatures. A good internal state of a microorganism is the electron spin of a radical or transition metal ion in the microorganism. Radicals are produced during metabolism or by radiation damage. Some proteins in microorganisms contain transition metal ions, which also have nonzero electron spins can be used to create quantum superposition

states. The smallest amino acid in proteins is glycine. The electron spin of a glycine radical $NH_3^+\dot{C}HCOO^-$ has a relaxation time $T_1 = 0.31$ s and a phase coherent time $T_M = 6$ μs at 4.2 K [42]. As shown in Fig. 4 of Ref. [42], the phase coherent time increases dramatically when the temperature decreases below 10 K. So it will be much longer at millikelvin temperatures. Moreover, universal dynamic decoupling can be used to increase the coherent time T_M by several orders, eventually limited by the relaxation time T_1 [61]. Thus we expect the coherent time of the electron spin of a glycine radical to be much longer than 1 ms at millikevin temperatures. The electron spin of some other radicals or defects in a frozen microorganism may have even longer coherence time at millikelvin temperatures.

As shown in Fig. 2, our scheme to couple the spin state and the center-of-mass motion of a microorganism with a magnetic tip is similar to the scheme used in MRFM. Recently, single electron spin detection with a MRFM [62], and nanoscale magnetic resonance imaging of the ^1H nuclear spin of tobacco mosaic viruses [44] have been realized. A MRFM using a superconducting quantum interference device (SQUID)-based cantilever detection at 30 mK has also been demonstrated [63].

As shown in Fig. 2, in order to couple the internal spins states of a microorganism to the center-of-mass motion of the microorganism, a magnetic field gradient is applied. Above the microorganism, there is a ferromagnetic tip mounted on a rigid cantilever, which produces a magnetic
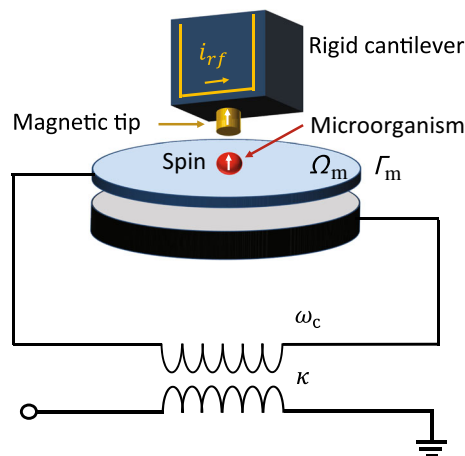

Fig. 2 (Color online) Scheme to couple the internal states of a microorganism to the center-of-mass motion of the microorganism with a magnetic gradient. A ferromagnetic tip mounted on a rigid cantilever produces a strong magnetic gradient. A RF current i_{RF} passing through a superconducting microwire generates a B_{RF} that excites an electron spin in the microorganism. Different from a typical MRFM apparatus, the cantilever is rigid, while the substrate (membrane) of the microorganism is flexible to oscillate in this setup

field $\boldsymbol{B}$ with a large gradient. In a microorganism, there are usually more than one radical that has unpaired electrons. Because the magnetic field is inhomogeneous, the energy splitting between electron spin states depends on the relative position between an electron and the ferromagnetic tip. The Hamiltonian for N unpaired electron spins reads

$$H_e = \sum_i^N \hbar g_s \mu_B \boldsymbol{S}_i(\vec{x}_i) \cdot \boldsymbol{B}(\vec{x}_i), \tag{7}$$

where $g_s \simeq 2$, μ_B is Bohr magneton, $\vec{x}_i$ is the position of the ith electrons, $\boldsymbol{S}_i$ is the spin operator for ith electrons spins. To make sure that the electron spin of interest is initially in the ground state at 10 mK, we suppose that the electron spin level spacings are larger than 500 MHz, which requires a magnetic field larger than 18 mT at the position of the radical. Because the finite size of the microorganism, the magnetic field at the position of membrane can be smaller than 10 mT, which is the critical magnetic field of aluminum. So the membrane can be made of aluminum [19] if necessary. However, superconducting materials (e.g., Nb) with a relative large critical magnetic field will be better for making the membrane and the RF wire [22, 63].

The oscillation of membrane induces a time-varying magnetic field on electrons in the microorganism. We define the single-phonon-induced frequency shift $\lambda = g_s \mu_B |\boldsymbol{G}_m| x_0'/\hbar$, where x_0' is the zero field fluctuation of microorganism, and $\boldsymbol{G}_m = \partial \boldsymbol{B}(\vec{x}_1)/\partial \vec{x}_1$. Here x_0' is different from x_0 of membrane. Usually, x_0' is two times larger than x_0 when the microorganism is at the center of the membrane. Here we assume that the magnetic gradient is (un)parallel to both the magnetic field $\boldsymbol{B}(\vec{x}_1)$ and the mechanical oscillation. The z-axis is defined along the direction of $\boldsymbol{B}(\vec{x}_1)$. We apply a microwave driving with frequency ω_d', which is close to the electron 1's level spacing $\omega_1 = g\mu_B B(\vec{x}_1)$. The Rabi frequency is Ω_d', which is tuned to near the mechanical mode frequency ω_m. In all electrons, the level spacing $\omega_2 = g\mu_B B(\vec{x}_2)$ of the second electron is closest to the first one. Under the condition that $g_s \mu_B |\boldsymbol{B}(\vec{x}_1) - \boldsymbol{B}(\vec{x}_2)| \gg |\Omega|$, we have $|\Omega| \ll |\omega_1 - \omega_2|$. Therefore, only electron 1 is driven by the microwave. We can neglect the effects of all other free electrons in microorganism. The Hamiltonian contains electron 1 and the motion of the membrane and the microorganism reads [64]

$$H_{eM} = \hbar\omega_m a_m^\dagger a_m + \frac{\Delta_e}{2}\hbar\sigma_z + \frac{\Omega_d'}{2}\hbar\sigma_x + \frac{1}{2}\hbar\lambda(a_m + a_m^\dagger)\sigma_z, \tag{8}$$

where $\Delta_e = \omega_d' - \omega_1$. We rotate the electron spin axis to diagonalize it, which has the effective level splitting $\omega_{\text{eff}} = \sqrt{\Delta_e^2 + \Omega_d'^2}$.

We first need to identify the position and frequency of an electron spin in the microorganism. We can search it by scanning the magnetic tip above the microorganism [62]. The microwaves driving the LC resonator and the electron spins are turned on with Rabi frequencies Ω_d and Ω_d', and frequencies ω_d and ω_d'. Once the electron spin resonance (ESR) reaches $\omega_{\text{eff}} = \omega_m$, the excitation of the electron spin could be efficiently transferred to the LC mode a, mediated with the mechanical mode a_m, and decay finally. We will observe the ESR signal on the output spectrum of the LC mode. Then we want to tune the Δ_e to be zero and maximize the spin-phonon coupling strength. First, we scan the frequency of the microwave on the electron spins, under the specific Rabi frequency Ω_d'. The ESR peaks appear in pair with the center frequency ω_1. Then we tune the frequency of the microwave drive on electron $\omega_d' = \omega_1$, the ESR should have only one peak. In this way, we find the resonant frequency ω_1 of the electron 1. The magnetic field $\boldsymbol{B}$ near the electron can be got from Eq. (7). Then we can identify the relative location between the electron 1 and the magnetic tip. This setup can also detect nuclear spins with lower sensitivity, which has broad applications [37, 44, 65].

Let us suppose that Δ_e has been tuned to be zero, and denote the operators $\sigma_\pm = \sigma_z \pm i\sigma_y$, The qubit is defined on the eigenstates of σ_x. In the limit $\lambda \ll \omega_m, |\Omega_d'|$, we set $\Omega_d' = \omega_m$ and the effective interaction Hamiltonian between electrons and the motion of microorganism is

$$H_I = \hbar\lambda\sigma_+ a_m + h.c.. \tag{9}$$

Here the rotating wave approximation is used. We may also set $\Omega_d' = -\omega_m$, and the effective Hamiltonian has the form

$$H_I' = \hbar\lambda\sigma_+ a_m^\dagger + h.c.. \tag{10}$$

If we use the parameters in Ref. [19], $\omega_m = 2\pi \times 10$ MHz, $M_{\text{mem}} = 48$ pg, we have $x_0 = 4.2 \times 10^{-15}$ m, and $x_0' \simeq 2x_0 = 8.4 \times 10^{-15}$ m. Under the magnetic gradient $|\boldsymbol{G}_m| = 10^7$ T/m, the single-phonon-induced frequency shift $\lambda = g_s \mu_B |\boldsymbol{G}_m| x_0'/\hbar = 14.8$ kHz. The mechanical decay rate $\gamma_m = 2\pi \times 32$ Hz. The effective mechanical decay under temperature 10 mK is $\bar{n}_m \gamma_m \simeq 20 \times 2\pi \times 32$ Hz $= 4.0$ kHz, which is much less than λ. Recently, a mechanical decay rate as low as $\gamma_m = 2\pi \times 9.2$ Hz was realized in a similar electromechanical membrane oscillator [66], which will be even better. The electron spin decay and dephase can be both less than kHz [42, 61], which is also much less than λ. Therefore, strong coupling condition is fulfilled. We can generate entangled state and transfer quantum states between electron spin 1 and the mechanical mode a_m with either Hamiltonian (9) or (10) [67, 68]. Thus this setup not only can detect the existence

of single electron spins like conventional MRFM [62], but also can coherently manipulate and detect the quantum states of electron spins. It enables some isolated electron spins that could not be read out with optical or electrical methods to be used as quantum memory for quantum information. To further increase the spatial separation of the superposition state of a microorganism, one can attach the microorganism to a magnetically levitated superconducting microsphere [69–71] instead of a fixed membrane in future.

The internal electron spin state of a microorganism can also be teleported to another microorganism using superconducting circuits [38]. We can first transfer the internal electron spin state of microorganism 1 to its mechanical state with either Hamiltonian (9) or (10) [67, 68]. We then teleport it to the mechanical state of the remote microorganism 2 as discussed in Sect. 3. Finally, we transfer the mechanical state of microorganism 2 to its internal electron spin state. In this way, we achieve the quantum teleportation between internal electron spin states of two microorganisms. In future, this method can be extended to entangle and teleport multiple degrees of freedom [72–74] of a living organism at the same time. Since internal states of an organism contain information, our proposal also provides an experimental scheme for teleporting information or memories between two remote organisms.

5 Conclusions

In summary, 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. The internal state of a microorganism, such as the electron spin of a glycine radical, can be entangled with its center-of-mass motion. Beyond "Schrödinger's cat" thought experiment, we also propose schemes to teleport the center-of-mass motion and internal states of one microorganism to another remote microorganism. Different from using simple inorganic samples, the use of a microorganism will allow this system to study defects and structures of proteins and other biologically important molecules. More importantly, our scheme can be used to study quantum wave function collapse due to biochemical reactions in future. At cryogenic temperatures, we can enable certain photochemical reactions with photons. For example, the wave-like energy transfer through quantum coherence in photosynthetic systems was first observed at a cryogenic temperature [12]. We can put a prochlorococcus, which is a photosynthetic organism, on top of an electromechanical oscillator and prepare its center-of-mass motion in a superposition state. We can then use one or a few photons to trigger the photosynthetic reaction of the prochlorococcus to study the effect of the internal biochemical reactions on the collapse of the superposition state of the center-of-mass motion of a microorganism.

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. Schrödinger E (1935) Die gegenwärtige situation in der quantenmechanik. Naturwissenschaften 23:807–812
2. Schrödinger E (1935) Die gegenwärtige situation in der quantenmechanik. Naturwissenschaften 23:823–828
3. Schrödinger E (1935) Die gegenwärtige situation in der quantenmechanik. Naturwissenschaften 23:844–849
4. Wineland DJ (2013) Nobel lecture: superposition, entanglement, and raising Schrödinger's cat. Rev Mod Phys 85:1103–1114
5. Everett H (1957) Relative state formulation of quantum mechanics. Rev Mod Phys 29:454–462
6. DeWitt BS (1970) Quantum mechanics and reality. Phys Today 23:155–167
7. Penrose R (1996) On gravity's role in quantum state reduction. Gen Rel Grav 28:581–600
8. Diósi L (1989) Models for universal reduction of macroscopic quantum fluctuations. Phys Rev A 40:1165–1174
9. Ghirardi GC, Rimini A, Weber T (1986) Unified dynamics for microscopic and macroscopic systems. Phys Rev D 34:470–491
10. Bassi A, Lochan K, Satin S et al (2013) Models of wave-function collapse, underlying theories, and experimental tests. Rev Mod Phys 85:471–527
11. Hornberger K, Gerlich S, Haslinger P et al (2012) Quantum interference of clusters and molecules. Rev Mod Phys 84:157–173
12. Brixner T, Stenger J, Vaswani HM et al (2005) Two-dimensional spectroscopy of electronic couplings in photosynthesis. Nature 434:625–628
13. Engel GS, Calhoun TR, Read EL et al (2007) Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. Nature 446:782–786
14. Aspelmeyer M, Kippenberg TJ, Marquardt F (2014) Cavity optomechanics. Rev Mod Phys 86:1391–1452
15. Chang DE, Regal CA, Papp SB et al (2010) Cavity opto-mechanics using an optically levitated nanosphere. Proc Natl Acad Sci USA 107:1005–1010
16. Yin Z-Q, Geraci AA, Li T (2013) Optomechanics of levitated dielectric particles. Int J Mod Phys B 27:1330018
17. Chan J, Alegre TPM, Safavi-Naeini AH et al (2011) Laser cooling of a nanomechanical oscillator into its quantum ground state. Nature 478:89–92
18. O'Connell AD, Hofheinz M, Ansmann M et al (2010) Quantum ground state and single-phonon control of a mechanical resonator. Nature 464:697–703
19. Teufel JD, Donner T, Li D et al (2011) Sideband cooling of micromechanical motion to the quantum ground state. Nature 475:359–363

20. Palomaki TA, Teufel JD, Simmonds RW et al (2013) Entangling mechanical motion with microwave fields. Science 342:710–713

21. Palomaki TA, Harlow JW, Teufel JD et al (2013) Coherent state transfer between itinerant microwave fields and a mechanical oscillator. Nature 495:210–214

22. Suh J, Shaw MD, LeDuc HG et al (2012) Thermally induced parametric instability in a back-action evading measurement of a micromechanical quadrature near the zero-point level. Nano Lett 12:6260–6265

23. Suh J, Weinstein AJ, Lei CU et al (2014) Mechanically detecting and avoiding the quantum fluctuations of a microwave field. Science 344:1262–1265

24. Wollman EE, Lei CU, Weinstein AJ et al (2015) Quantum squeezing of motion in a mechanical resonator. Science 349:952–955

25. Pirkkalainen JM, Damskägg E, Brandt M et al. (2015) Squeezing of quantum noise of motion in a micromechanical resonator. arXiv:1507.04209

26. Nimmrichter S, Hornberger K (2013) Macroscopicity of mechanical quantum superposition states. Phys Rev Lett 110:160403

27. Romero-Isart O, Juan ML, Quidant R et al (2010) Towards quantum superposition of living organisms. New J Phys 12:033015

28. Schrödinger E (2012) What is life?: with mind and matter and autobiographical sketches. Cambridge University Press, Cambridge

29. Bull JW, Gordon A (2015) Schrödinger's microbe: implications of coercing a living organism into a coherent quantum mechanical state. Biol Philos. doi:10.1007/s10539-015-9500-4

30. Li T, Kheifets S, Medellin D et al (2010) Measurement of the instantaneous velocity of a Brownian particle. Science 328:1673–1675

31. Li T, Kheifets S, Raizen MG (2011) Millikelvin cooling of an optically trapped microsphere in vacuum. Nat Phys 7:527–530

32. Gieseler J, Deutsch B, Quidant R et al (2012) Subkelvin parametric feedback cooling of a laser-trapped nanoparticle. Phys Rev Lett 109:103603

33. Kiesel N, Blaser F, Delic U et al (2013) Cavity cooling of an optically levitated submicron particle. Proc Natl Acad Sci USA 110:14180–14185

34. Asenbaum P, Kuhn S, Nimmrichter S et al (2013) Cavity cooling of free silicon nanoparticles in high-vacuum. Nat Commun 4:2743

35. Millen J, Fonseca PZG, Mavrogordatos T et al (2015) Cavity cooling a single charged levitated nanosphere. Phys Rev Lett 114:123602

36. Jacques SL (2013) Optical properties of biological tissues: a review. Phys Med Biol 58:R37

37. Fisher MPA (2015) Quantum cognition: the possibility of processing with nuclear spins in the brain. arXiv:1508.05929

38. Steffen L, Salathe Y, Oppliger M et al (2013) Deterministic quantum teleportation with feed-forward in a solid state system. Nature 500:319–322

39. Mazur P (1984) Freezing of living cells: mechanisms and implications. Am J Physiol 247:C125

40. Norman MC, Franck EB, Choate RV (1970) Preservation of mycoplasma strains by freezing in liquid nitrogen and by lyophilization with sucrose. Appl Microbiol 20:69–71

41. Fahy GM, Wowk B, Wu J et al (2004) Cryopreservation of organs by vitrification: perspectives and recent advances. Cryobiology 48:157–158

42. Hoffmann SK, Gramza M, Hilczer W (1995) Molecular dynamics of diglycine nitrate studied by phase memory relaxation time of glycine radical. Ferroelectrics 172:431–435

43. Zhou X, Cegelski L (2012) Nutrient-dependent structural changes in *S. aureus* peptidoglycan revealed by solid-state nmr spectroscopy. Biochemistry 51:8143–8153

44. Degen CL, Poggio M, Mamin HJ et al (2009) Nanoscale magnetic resonance imaging. Proc Natl Acad Sci USA 106:1313–1317

45. Adrian M, Dubochet J, Lepault J et al (1984) Cryo-electron microscopy of viruses. Nature 308:32–36

46. Spirin AS (2002) Ribosomes. Kluwer Academic Publishers, New York Chapter 16, Page 320

47. Fuerstenau SD, Benner WH, Thomas JJ et al (2001) Mass spectrometry of an intact virus. Angew Chem Int Ed 40:542–544

48. Ruigrok RW, Andree PJ, Hooft van Huysduynen RA et al (1984) Characterization of three highly purified influenza virus strains by electron microscopy. J Gen Virol 65:799–802

49. Luef B, Frischkorn KR, Wrighton KC et al (2015) Diverse uncultivated ultra-small bacterial cells in groundwater. Nat Commun 6:6372

50. Zhao H, Dreses-Werringloer U, Davies P et al (2008) Amyloid-beta peptide degradation in cell cultures by mycoplasma contaminants. BMC Res Notes 1:38

51. Partensky F, Hess WR, Vaulot D (1999) Prochlorococcus, a marine photosynthetic prokaryote of global significance. Microbiol Mol Biol Rev 63:106

52. Neidhardt FC (1999) Escherichia coli and salmonella: cellular and molecular biology. ASM Press, New York

53. Flombaum P, Gallegos JL, Gordillo RA et al (2013) Present and future global distributions of the marine Cyanobacteria *Prochlorococcus* and *Synechococcus*. Proc Natl Acad Sci USA 110:9824–9829

54. King GM, Schürmann G, Branton D et al (2005) Nanometer patterning with ice. Nano Lett 5:1157–1160

55. Heim LO, Blum J, Preuss M et al (1999) Adhesion and friction forces between spherical micrometer-sized particles. Phys Rev Lett 83:3328

56. Proft T, Baker EN (2009) Pili in Gram-negative and Gram-positive bacteria -structure, assembly and their role in disease. Cell Mol Life Sci 66:613–635

57. Yin ZQ, Yang WL, Sun L et al (2015) Quantum network of superconducting qubits through an optomechanical interface. Phys Rev A 91:012333

58. Wilson-Rae I, Nooshi N, Zwerger W et al (2007) Theory of ground state cooling of a mechanical oscillator using dynamical backaction. Phys Rev Lett 99:093901

59. Marquardt F, Chen JP, Clerk AA et al (2007) Quantum theory of cavity-assisted sideband cooling of mechanical motion. Phys Rev Lett 99:093902

60. Bennett CH, Brassard G, Crépeau C et al (1993) Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels. Phys Rev Lett 70:1895

61. de Lange G, Wang ZH, Ristè D et al (2010) Universal dynamical decoupling of a single solid-state spin from a spin bath. Science 330:60–63

62. Rugar D, Budakian R, Mamin HJ et al (2004) Single spin detection by magnetic resonance force microscopy. Nature 430:329–332

63. Vinante A, Wijts G, Usenko O et al (2011) Magnetic resonance force microscopy of paramagnetic electron spins at millikelvin temperatures. Nat Commun 2:572

64. Rabl P, Cappellaro P, Dutt MVG et al (2009) Strong magnetic coupling between an electronic spin qubit and a mechanical resonator. Phys Rev B 79:041302(R)

65. Cai JM, Jelezko F, Plenio MB et al (2013) Diamond based single molecule magnetic resonance spectroscopy. New J Phys 15:013020

66. Lecocq F, Clark JB, Simmonds RW et al (2015) Quantum non-demolition measurement of a nonclassical state of a massive object. arXiv:1509.01629

67. Yin ZQ, Li T, Zhang X et al (2013) Large quantum superpositions of a levitated nanodiamond through spin-optomechanical coupling. Phys Rev A 88:033614

68. Yin ZQ, Zhao N, Li T (2015) Hybrid opto-mechanical systems with nitrogen-vacancy centers. Sci China Phys Mech Astron 58:050303

69. Romero-Isart O, Clemente L, Navau C et al (2012) Quantum magnetomechanics with levitating superconducting microspheres. Phys Rev Lett 109:147205

70. Cirio M, Brennen GK, Twamley J (2012) Quantum magnetomechanics: ultrahigh-q-levitated mechanical oscillators. Phys Rev Lett 109:147206

71. Geim AK, Berry MV (1997) Of flying frogs and levitrons. Eur J Phys 18:307

72. Heilmann R, Gräfe M, Nolte S et al (2015) A novel integrated quantum circuit for high-order W-state generation and its highly precise characterization. Sci Bull 60:96–100

73. Sheng YB, Deng FG, Long GL (2010) Complete hyperentangled-Bell-state analysis for quantum communication. Phys Rev A 82:032318

74. Wang XL, Cai XD, Su ZE et al (2015) Quantum teleportation of multiple degrees of freedom of a single photon. Nature 518:516–519