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# Bringing quantum mechanics to life: from Schrödinger's cat to Schrödinger's microbe

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## ABSTRACT

The question whether quantum mechanics is complete and the nature of the transition between quantum mechanics and classical mechanics have intrigued physicists for decades. There have been many experimental breakthroughs in creating larger and larger quantum superposition and entangled states since Erwin Schrödinger proposed his famous thought experiment of putting a cat in a superposition of both alive and dead states in 1935. Remarkably, recent developments in quantum optomechanics and electromechanics may lead to the realisation of quantum superposition of living microbes soon. Recent evidence also suggests that quantum coherence may play an important role in several biological processes. In this review, we first give a brief introduction to basic concepts in quantum mechanics and the Schrödinger's cat thought experiment. We then review developments in creating quantum superposition and entangled states and the realisation of quantum teleportation. Non-trivial quantum effects in photosynthetic light harvesting and avian magnetoreception are also discussed. At last, we review recent proposals to realise quantum superposition, entanglement and state teleportation of micro-organisms, such as viruses and bacteria.

## ARTICLE HISTORY

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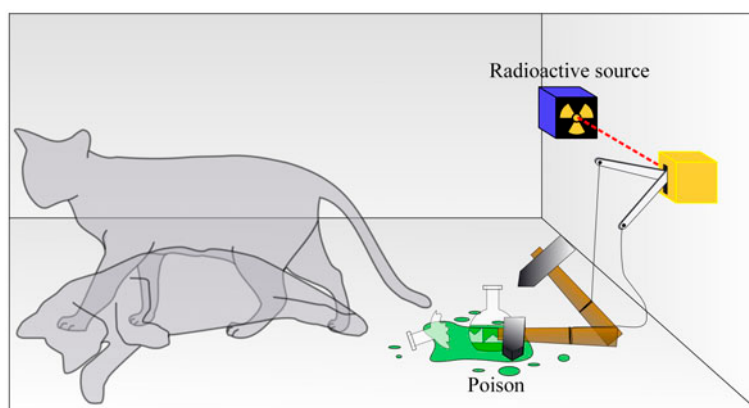
## KEYWORDS

Schrödinger's cat; quantum superposition; quantum entanglement; quantum teleportation; quantum biology

## 1. Introduction

At the beginning of the twentieth century, quantum theory was invented in order to explain puzzling phenomena related to the black body radiation and atomic emission spectra, which troubled physicists at that time. After Max Planck introduced the concept of energy quantisation to explain the spectrum of the black body radiation in 1901 [1], Albert Einstein suggested the existence of light quanta (photon) to explain the photoelectric effect [2]. There had been a long debate on whether light was a wave or a group of particles since the age of Isaac Newton. Einstein's concept of photon provided the quintessential example of wave-particle duality, which was later generalised to all matter by Louis de Broglie in 1924. The de Broglie wavelength of a particle is  $\lambda = h/p$ , where  $h$  is the Planck constant, and  $p$  is the momentum of the particle. From 1925 to 1927, quantum mechanics was finally formulated into precise mathematical equations, including the Heisenberg equation and the Schrödinger equation. In general, it is not possible to predict the outcome of a single measurement determinately in quantum mechanics, unless the system is in an eigenstate of the measurement bases.

Quantum mechanics has predicted many counterintuitive phenomena which are forbidden in classical mechanics. Since the discovery of quantum mechanics, there were debates on its interpretation. One of the most famous debates was between A. Einstein and N. Bohr during 1920s and 1930s. In a landmark paper [3], Einstein, Podolsky, and Rosen (EPR) showed that because of the entanglement between distant particles, either the locality was broken (implied faster-than-light correlation), or the quantum theory was incomplete. Schrödinger exchanged letters with Einstein on the EPR article. Einstein told Schrödinger that the state of an unstable gunpowder could be in the superposition of both exploded and unexploded states. Schrödinger further extended this idea to living systems, such as a cat [4]. He proposed to put a living cat in a sealed chamber, wherein a poison may kill the cat depending on the state of a radioactive atom (Figure 1 [5]). So the macroscopic state of the cat was entangled with the microscopic state of the radioactive atom. After waiting for a certain time, the atom had half chance to be decayed. We can write the wave function of the system as



**Figure 1.** Scheme of the Schrödinger's cat thought experiment proposed in 1935 [4]. A cat, a radioactive source and a bottle of poison are sealed in a box. If an atom in the radioactive source decays, it would trigger a device to release the poison to kill the cat. Thus, the living state of the cat is entangled with the decay state of an atom. At certain time, the atom is in superposition of decay or not decay state, so the cat is simultaneously alive and dead, which violates our common sense. If we open the box, the superposition state of the cat will collapse to either definitely alive or definitely dead in the Copenhagen interpretation. Figure adapted from Wikimedia [5].

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{alive}\rangle_{\text{cat}}|\text{undecayed}\rangle_{\text{atom}} + |\text{dead}\rangle_{\text{cat}}|\text{decayed}\rangle_{\text{atom}}). \quad (1)$$

Following the Copenhagen interpretation of quantum mechanics, the cat would be both alive and dead until it was observed. Nowadays, a Schrödinger's cat state is generally referred to a quantum superposition state of a macroscopic system that contains multiple degrees of freedom. The states of different degrees of freedom are entangled in a cat state [6].

Schrödinger's initial purpose of proposing this thought experiment [4] was to illustrate the absurdity of the Copenhagen interpretation of quantum mechanics, which remains one of the most received interpretations today. The Schrödinger's cat thought experiment stimulated physicists to propose alternative interpretations of quantum mechanics, such as the many-worlds interpretation initiated by Everett [7]. Following the many-worlds interpretation, the world is split into two worlds when the Schrödinger's cat is observed. In one world, the cat is alive. But in the other world, the cat is dead. Although the many-worlds interpretation tries to avoid the conflicts between quantum and classical worlds, it is almost impossible to be experimentally tested. After proposing the cat thought experiment, Schrödinger became interested in explaining biology from the perspective of quantum physics, and wrote a book titled 'What is life?' in 1944 [8]. This book had a great influence, and stimulated the enthusiasm to search for genetic molecules (such as DNA) in 1950s.

Experimental physicists have tried to realise larger and larger quantum superposition and entangled states for many years. The superposition of microscopic particles, such as electrons and atoms, are relatively easy to be

generated. There were remarkable progresses in this direction in the past two decades. In 1996, the Schrödinger's cat state was realised with a trapped cold ion [6]. A few years later, a matter wave interferometer for  $C_{60}$  molecules was realised [9]. Then, the size of macroscopic quantum systems increased rapidly with the development of quantum optomechanics and electromechanics. In 2010, a mechanical vibration mode of a 30  $\mu\text{m}$  long, 740 nm thick thin film ('quantum drum') was cooled to the quantum regime by a cryostat, and prepared into quantum superposition states by coupling it with a superconducting qubit [10]. Since the mechanical resonator in the quantum regime is already bigger than many microbes, quantum superposition of an entire small organism, such as a virus or a bacterium, seems to be feasible as proposed recently [11,12]. With the help of a superconducting circuit, the state of a living microbe may also be teleported to another microbe [12]. It was proposed that a microbe in a quantum coherent state would represent a new category of cryptobiosis [13]. Meanwhile, some organisms seem to be able to harness quantum coherence in biological processes, such as photosynthetic light harvesting and avian magnetoreception, to gain a biological advantage [14,15].

In this review, we will briefly summarise experimental and theoretical progresses in realising Schrödinger's cat states, and quantum phenomena in biological systems. In Section 2, basic concepts in quantum physics and quantum information, Schrödinger's cat thought experiment and relating proposals are introduced. In Section 3, we discuss experimental progresses in quantum superposition and entanglement. We first review how to realise quantum superposition and entanglement in microscopic systems, from single atoms to complex molecules. Then, we discuss recent experiments of generating

quantum superposition and entanglement in optomechanical and electromechanical systems. In Section 4, we discuss how to realise quantum teleportation with photons, trapped ions, and solid state systems. In Section 5, we review several biological processes such as photosynthesis and avian magnetoreception, in which quantum coherence may play an important role. In Section 6 and 7, we discuss two proposals that aim to realise quantum superposition with living micro-organisms. The scheme to teleport the internal state of a micro-organism is also reviewed.

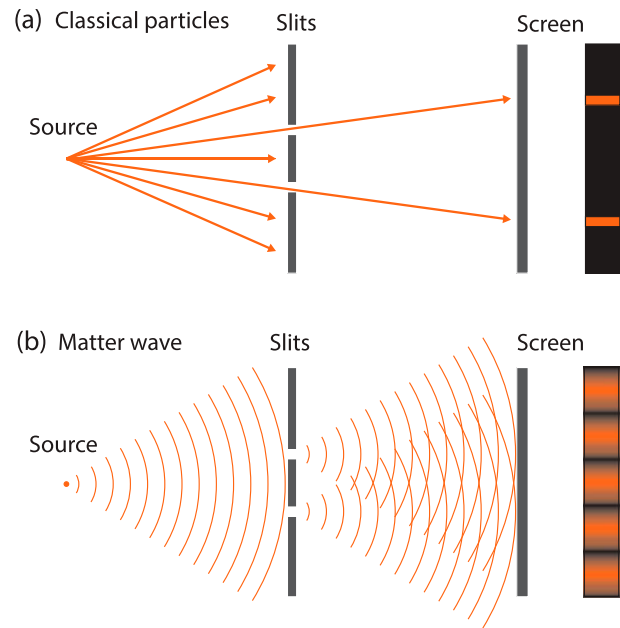
## 2. Quantum phenomena

In this section, we first introduce basic concepts and terminologies in quantum mechanics and quantum information science. We then introduce the Schrödinger's cat thought experiment and several related thought experiments.

### 2.1. Basic concepts in quantum mechanics

An experiment that can drastically distinguish classical mechanics and quantum mechanics would be the Young's double-slit experiment with atoms (or other small particles) (Figure 2). In such an experiment, atoms emitting from a small source with negligible size pass through a thin metal plate with two open slits. For simplicity, we assume all atoms have the same kinetic energy and mass. In classical mechanics, each atom has a deterministic trajectory. It can only be at one location at a given time. So an atom may be blocked by the plate, or pass through one of the slit. Because we have two open slits on the plate, we will see two stripes of atoms on the screen (Figure 2(a)). In quantum mechanics, however, atoms can have wave behaviours. An atom can pass through both 'up' and 'down' slits at the same time, which is the state superposition principle. We can write the two possible spatial states after an atom passing through the double slits as  $|\text{up}\rangle$  and  $|\text{down}\rangle$ . Because of the superposition principle, these two spatial states can form a new superposition state  $|\phi\rangle = c_1|\text{up}\rangle + c_2|\text{down}\rangle$ . The wavefunction of an atom evolves following the Schrödinger equation. The 'up' and 'down' parts of the wavefunction expand, overlap, and finally form an interference pattern on the screen (Figure 2(b)). Traditionally, the superposition principle was only used for microscopic particles, such as electrons, atoms and molecules. Recent experiments showed that it can also be applied for macroscopic systems, such as micro-mechanical resonators [10].

By applying the superposition principle mathematically, a quantum bit (qubit), a fundamental concept in



**Figure 2.** Different expectations of the Young's double-slit experiment with atoms in classical mechanics and quantum mechanics. (a) In classical mechanics, each atom has a deterministic trajectory. Only atoms go through one of the slits can reach the screen. We will see two stripes of atoms on the screen because of the two open slits on the blocking plate. (b) In quantum mechanics, an atom can exhibit wave behaviours. It can go through both the 'up' and 'down' slits at the same time. We will see an interference pattern of atoms on the screen.

quantum information science, can be defined. Just like a classical bit has a state either 0 or 1, a qubit can be in state  $|0\rangle$  or  $|1\rangle$ . Unlike the classical bit, a qubit can also be in the state

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad (2)$$

which is an arbitrary superposition of  $|0\rangle$  and  $|1\rangle$ . After measurement, the qubit could be either in  $|0\rangle$  state with probability  $|\alpha|^2$ , or in  $|1\rangle$  state with probability  $|\beta|^2$ . The complex numbers  $\alpha$  and  $\beta$  must fulfill the normalisation condition  $|\alpha|^2 + |\beta|^2 = 1$ . Generally speaking, a qubit state is a unit vector in a two-dimensional vector space.

Based on the superposition principle, entanglement was introduced and discussed by Einstein et al. [3]. They found that two particles could be prepared in a special state that cannot be described by two separated individual particle states, no matter how far the particles were separated. In other words, these two particles seemly correlate with 'spooky action at a distance' [16]. The debates on the EPR paradox led John Bell to define an inequality to distinguish a theory with local hidden variables from the quantum mechanics [17]. Experimental tests of the Bell inequality have continued for more than 40 years, in order to close all known loopholes. In 2015, three experiments, which were performed with nitrogen-vacancy centres and single photons systems, closed all

known loopholes and verified the Bell inequality. They excluded local hidden variable theories [18–20] and proved the faster-than-light correlation in quantum entanglement experimentally.

Before defining an entangled state, we should first introduce the concept of separable states. Let's focus on two qubits  $A$  and  $B$ , whose Hilbert spaces are  $H_A$  and  $H_B$ . For the whole system that includes two qubits, the Hilbert space is  $H_A \otimes H_B$ . If two qubits are in pure states  $|\psi_A\rangle = \alpha_A|0\rangle_A + \beta_A|1\rangle_A$  and  $|\psi_B\rangle = \alpha_B|0\rangle_B + \beta_B|1\rangle_B$ , the system of the composite system is  $|\psi\rangle_{AB} = |\psi_A\rangle \otimes |\psi_B\rangle = (\alpha_A|0\rangle_A + \beta_A|1\rangle_A) \otimes (\alpha_B|0\rangle_B + \beta_B|1\rangle_B)$ , which is a separable state. However, the most general states of the composite system is

$$|\psi\rangle_{AB} = \sum_{i,j=0}^1 c_{i,j} |i\rangle_A \otimes |j\rangle_B, \quad (3)$$

which cannot always be represented in the form of product states. For a state that is inseparable, we call it an entangled state.

Let's take a Bell state  $\frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)$  as an example of entangled states. The reduced density matrix for either  $A$  or  $B$  is totally mixed. Let an observer Alice measure the system  $A$ , and observer Bob measure the system  $B$  on the computational bases  $|0\rangle$  and  $|1\rangle$ . Both Alice and Bob will get random outcomes 0 or 1. If we combine their outcomes together, however, we will find that these outcomes are totally correlated. When Alice gets the outcome 0, Bob must get the outcome 1, and vice versa. Unlike classical bits, we can also measure the qubits on the superposition basis  $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$ . The outcomes between  $A$  and  $B$  are also totally correlated, no matter how large the separation between the two qubits. Therefore, the entangled states can only be described for the whole system, other than the individual subsystems.

As the speed of correlation in quantum entanglement is much faster than the light speed, can it be used for faster-than-light communication? Unfortunately, the answer is no. The next question is, can we use this correlation as a resource in communication? The answer is yes. In 1993, quantum teleportation was proposed [21]. In quantum teleportation, quantum entanglement is used as a resource for transferring an unknown quantum state from one location to another without physically moving the particles that the state is stored. The quantum teleportation also requires the assistance of classical communication. Therefore, the speed of information transmission cannot be faster than the speed of light in quantum teleportation. We will discuss more details of the quantum teleportation protocol in Section 4.1.

## 2.2. Schrödinger's cat thought experiment

Here we discuss the Schrödinger's cat thought experiment and review relating thought experiments. The original version of the Schrödinger's cat thought experiment [4] is shown in Figure 1. A cat is in a sealed chamber, along with a flask of poison which may kill the cat. There is also a tiny bit of radioactive material. In an hour or so there is a 50% possibility that an atom may decay and a 50% possibility that no decay occurs. A Geiger counter, once it measures a radioactive decay event, would trigger a lethal device that releases the poison and kills the cat. In other words, the cat's living state is entangled with the atomic state. The wave function of the system is  $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{alive}\rangle_{\text{cat}}|\text{undecayed}\rangle_{\text{atom}} + |\text{dead}\rangle_{\text{cat}}|\text{decayed}\rangle_{\text{atom}})$ . Following the Copenhagen interpretation, the alive or dead state of the cat is not determined before we open the chamber and observe the cat. When we open the chamber, however, the state of the cat becomes definitely alive or definitely dead. As an extension to the EPR paradox, the Schrödinger's cat thought experiment shows the possibility to entangle a macroscopic system with a microscopic system. It also reveals the incompleteness of the measurement theory in the Copenhagen interpretation. It seems that the life of the cat is determined by the observer.

Since the cat thought experiment was proposed, several interpretations have been proposed to resolve this paradox. A famous one is the many-worlds interpretation[7]. The many-worlds interpretation treats the whole universe as a wavefunction. Unlike the Copenhagen interpretation, the many-worlds interpretation does not treat measurement as a non-unitary process, and denies the wavefunction collapse. When a measurement is performed, all the different outcomes are obtained, and each outcome is in a different world. When we open the chamber and observe the Schrödinger's cat, the universe will split into two different ones. The alive and dead cats will be in different universes. Both universes are real in the many-worlds interpretation.

An interesting extension of the Schrödinger's cat thought experiment is to add an observer in the chamber to observe the cat's state. In this way, the quantum mechanics is applied to ourselves, especially our consciousness, and leads to even stranger conclusions [22–24]. The key point is that we can communicate with the observer inside the chamber before we open it. We may ask the observer whether the cat is in a definite state (can be dead or alive). If the observer answers 'Yes', we may undo the experiment since the evolution is reversible in quantum mechanics. We should note that the answer of the observer does not collapse the wavefunction to a definite 'dead' or 'alive' state as we still do



not know whether the cat is dead or alive from the answer. If the cat is dead, we may make it alive again by reversing the quantum process. So the poison is back into the bottle, the atom does not decay, and the observer does not remember seeing a dead cat. However, for the observer inside the chamber, his observation should make the cat's wave function collapse. His answer is the proof of it. In this way, a contradiction appears.

Doing such experiments with a cat is impossible right now. Therefore, people started to realise quantum superposition using relatively small objects. Up to now, single atoms, molecules with many atoms, and even micrometer-scale mechanical resonators have been prepared into quantum superposition states. Some of them were even generated into entangled states. We will summarise these progresses in Section 3. Schemes to realise quantum superposition of living micro-organisms, such as viruses and bacteria, have been proposed [11,12]. Ref. [12] also discussed how to teleport the internal electron spin state of a living bacterium to the internal electron spin state of another remote bacterium. In Section 6 and 7, we will review these proposals and related experimental progresses.

### 3. Experimental developments in quantum superposition and entanglement

In this section, we will first discuss the experimental developments in superposition and entanglement of atoms and molecules. Then we will discuss quantum behaviours of larger objects, such as optomechanical systems.

#### 3.1. Matter wave interferometry

In quantum mechanics, Young's double-slit experiment (Figure 2) is commonly used to study the wave feature of matter, which is also a proof of the quantum superposition of particle spatial states after the double slit. Double-slit experiments have been repeated with larger and larger particles. The first example was the double-slit experiment with single electrons, which was demonstrated more than 40 years ago [25]. In 2002, this experiment was selected as the most beautiful experiment in physics by 'Physics World' [26].

Unlike electrons, neutral atoms carry no charge and have shorter wavelengths. The matter wave interference experiment with atoms was first reported in 1991 [27]. In the experiment, metastable helium atoms were used, which have a relatively large de Broglie wavelength due to their small mass. Besides, the metastable helium atoms can be easily detected by an optical method. The scheme of the experiment is shown in Figure 3(a). An intense

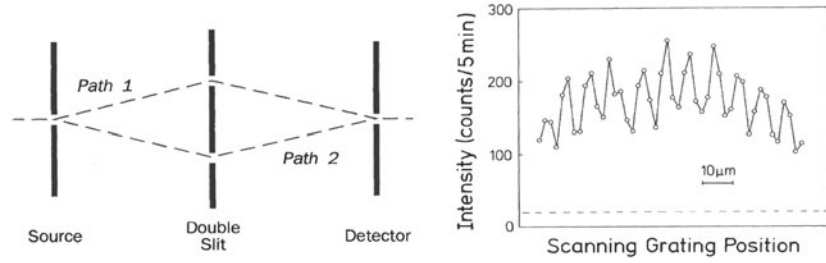
atomic beam of helium was produced by supersonic gas expansion. Most of the atoms (90%) were prepared into  $2^1S_0$  state. The mean velocity  $v_0$  of the atomic beam could be controlled by changing the gas reservoir temperature. Therefore, the mean de Broglie wavelength could be controlled. For example, when the reservoir temperature is  $T = 83$  K, the de Broglie wavelength is  $\lambda_{dB} = 1.03$  Å. The atoms first passed through a slit with a width of  $s_1 = 2$  µm. After travelling a distance  $L = 64$  cm, they passed through two 1-µm-wide slits, separated by 8 µm. The density profile of atoms was detected in a plane located another  $L' = 64$  cm behind the double slit. We expect a modulated intensity distribution with a periodicity  $dx = L'\lambda_{dB}/d$  and the envelop with a full width of  $2L'\lambda_{dB}/s_2$ , where  $d$  and  $s_2$  are the distance between the slits and the width of the double slits, respectively. Figure 3(b) shows the experimental results when the wavelength is  $\lambda_{dB} = 1.03$  Å. The average distance between two maximum is  $7.7 \pm 0.5$  µm, which agrees with the theoretical prediction.

It is more challenging to realise matter wave interferometers for molecules [28]. The first experimental paper in this direction was published in 1999 by Zeilinger's group [9], who realised the double-slit interference experiment using  $C_{60}$  molecules. As the mass of a  $C_{60}$  molecule is much larger than that of a helium atom, the de Broglie wavelength of the  $C_{60}$  molecular beam is much smaller. It is only 5 pm for a  $C_{60}$  molecule moves at 100 m/s. In this experiment, the slit separation was reduced to 100 nm, which was much smaller than the slit separation in the atomic experiment. The interference fringes were separated around 50 µm at 1 m behind the grating. Later, similar experiments were realised for larger molecules, such as  $C_{70}$  [29], and tetraphenylporphyrin (TPP) [30]. Comparing to atoms, these complex molecules have much larger masses. Thus they can be used to test the quantum superposition principle and study decoherence theories in much larger mass regime.

#### 3.2. Trapped ions

While quantum superposition states of atoms and molecules have been demonstrated with Young's double-slit experiments, a different experimental set-up is required to generate entangled states, which better corresponds to the Schrödinger's cat state. The first such experiment was done using trapped ions by Monroe et al. about 20 years ago [6]. In that experiment, the internal hyperfine state of the ion was entangled to the motional state of the ion to create the Schrödinger's cat state [6].

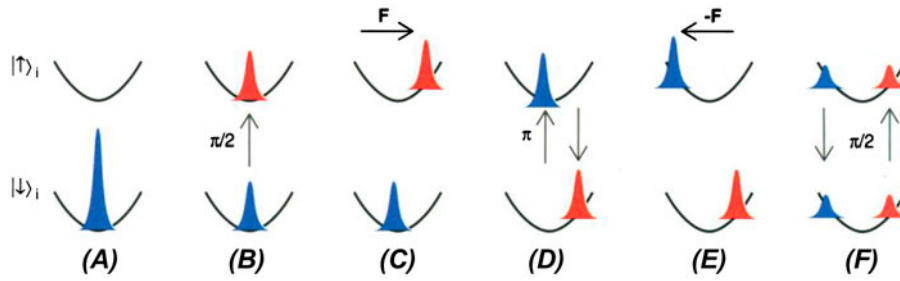
As shown in Figure 4, a trapped  $^9\text{Be}^+$  ion was first cooled to the quantum ground state by laser cooling. Then a pair of off-resonant lasers were used to coherently



(a) A double-slit interferometer for atoms [27]. The atoms can go through two different paths from the source to the detector. The distance between the source and the detector is 128 cm.

(b) Measured atomic density profile at the detector plane [27]. It was monitored with a  $8 \mu\text{m}$  scanning grating slit. The dashed line is the detection background.

**Figure 3.** Young's double-slit experiment with helium atoms. Reprinted with permission from [27]. Copyright (1991) by the American Physical Society.



**Figure 4.** Evolution of the spatial atomic wave packet entangled with the internal hyperfine states  $|\downarrow\rangle$  and  $|\uparrow\rangle$ . The area of the wave packets corresponds to the probability of the atom at the given internal state. (A) The ion is initially at the motional quantum ground state and internal state  $|\downarrow\rangle$ . (B) The wave function is split by a  $\pi/2$  pulse on the internal level. (C) The  $|\uparrow\rangle$  wave packet is excited to a coherent state  $|\alpha = 3\rangle$  with force  $F$ . (D) The  $|\downarrow\rangle$  and  $|\uparrow\rangle$  wave packets are exchanged by a  $\pi$ -pulse. (E) The  $|\uparrow\rangle$  wave packet is driven to a coherent state  $|\alpha = -3\rangle$  with force  $-F$ . This state corresponds to a Schrödinger's cat state. (F) The  $|\downarrow\rangle$  and  $|\uparrow\rangle$  wave packets are combined by a  $\pi/2$  pulse on the carrier for detection. Figure adapted from [6]. Reprinted with permission from AAAS.

manipulate its internal hyperfine and external motional states. The preparation was divided into 6 steps. After the step (E), the atom was prepared into the following entangled state [6]:

$$\Psi = \frac{|x_1\rangle|\uparrow\rangle + |x_2\rangle|\downarrow\rangle}{\sqrt{2}}, \quad (4)$$

where coherent states  $|x_1\rangle = |\alpha e^{-i\phi/2}\rangle$  and  $|x_2\rangle = |\alpha e^{i\phi/2}\rangle$  denote classical-like spatial wave packet states of the trapped ion,  $|\downarrow\rangle$  and  $|\uparrow\rangle$  represent the internal hyperfine states of the trapped  $^9\text{Be}^+$  ion [6]. The position separation of  $|x_1\rangle$  and  $|x_2\rangle$  was around 80 nm, which was larger than both the size of the individual wave packets (7 nm) and the size of the atom (1 Å). The mean number of vibrational quanta was  $\langle n \rangle = \alpha^2$ . In order to verify the superposition of the Schrödinger's cat state, the coherent wave packets were recombined in the step (F) to the following state

$$\Psi = |\downarrow\rangle|S_+\rangle - i|\uparrow\rangle|S_+\rangle, \quad (5)$$

with

$$|S_{\pm}\rangle = \frac{|\alpha e^{-i\phi/2}\rangle \pm e^{i\delta}|\alpha e^{i\phi/2}\rangle}{2}. \quad (6)$$

The populations of  $|\downarrow\rangle$  and  $|\uparrow\rangle$  depended on the motional phase difference  $\phi$  between the two wave packets. Thus the interference between two wave packets could be measured by detecting the probability that the ion was in  $|\downarrow\rangle$  (or  $|\uparrow\rangle$ ) internal state.

The key features of this experiment [6] include: (i) The motion of the trapped ion was controlled with well-defined amplitude and phase; (ii) the spatial spreading of individual wave packets of the atomic motion is small compared to the separation between the two wave packets. As we will see, the idea of this experiment has been adopted in quantum optomechanics and electromechanics.

### 3.3. Quantum optomechanics and electromechanics

Optomechanics (electromechanics) studies the interaction between light (circuit current) and a mechanical

resonator. Cooling a macroscopic mechanical resonator to the quantum regime, with a mean thermal phonon number less than 1, is one of the core issues in quantum optomechanics and electromechanics. The quantum ground state cooling requires the final temperature  $T < \hbar\omega_m/k_B$ , where  $\omega_m$  is the angular frequency of the mechanical oscillator,  $\hbar = h/2\pi$ , and  $k_B$  is the Boltzmann constant. If a mechanical resonator has a high resonant frequency, e.g. 1 GHz with  $\hbar\omega_m/k_B \sim 50$  mK, the quantum regime can be approached by putting it into a state-of-the-art cryogenic refrigerator ( $T \sim 20$  mK). For mechanical systems with resonant frequencies less than 1 GHz, other cooling methods such as cavity sideband cooling are required to bring them to the quantum regime.

In 2010, quantum ground state cooling of a macroscopic mechanical resonator was realised by conventional cryogenic refrigeration [10]. As shown in Figure 5(a), a micromechanical resonator with a resonant frequency at 6.1 GHz and a length of about 30  $\mu\text{m}$  was cooled to 25 mK with cryogenic refrigeration. The suspended thin film resonator consisted 150 nm  $\text{SiO}_2$ , 130 nm Al, 330 nm AlN and 130 nm Al. This 6.1 GHz mode corresponded to the dilatational vibration (the change of the thickness) of the thin film structure. As we know, the ground state of this mechanical mode can be reached once its temperature is below 0.1 K. The AlN film in the structure is piezoelectric. Therefore, the oscillation of the resonator generated a electric signal, and vice versa. In order to verify the ground state cooling of the resonator, quantum-limited measurement of the resonator was performed by a superconducting qubit, which was connected to the resonator through a circuit. The mean thermal phonon number was estimated to be  $\langle n_m \rangle < 0.07$ . As shown in Figure 5(b), the qubit was first excited, and then swapped its state with the mechanical resonator. The qubit was in its excited state at the maximum point in Figure 5(b). The minimum points corresponded to the situation when the qubit excitation was transferred to the resonator. If the qubit was prepared to be a superposition state initially, the mechanical resonator would also be in a superposition state by swapping their states. The fitted relaxation time for this mechanical resonator was 6.1 ns, in good agreement with its measured mechanical quality factor of  $Q = 260$ .

In 2011, sideband cooling of a mechanical resonator to the quantum regime was achieved in both electromechanical and optomechanical systems [31,32]. In the electromechanical experiment [31], a micro-mechanical membrane, with a resonant frequency at 10 MHz and  $Q = 3.3 \times 10^5$  was embedded into a superconducting microwave resonator. This 10 MHz mode corresponded to the center-of-mass vibration of the membrane. The

motion of mechanical resonator would shift the frequency of the microwave resonator. By placing the system in a cryogenic refrigerator at 15 mK and driving the red (low frequency) sideband of the microwave resonator, the mechanical resonator at 10 MHz was cooled to the quantum regime with a mean thermal phonon number  $0.34 \pm 0.05$ . The 100 nm-thick aluminium membrane vibrated just like the membrane of a drum. Thus, we may consider it as a ‘quantum drum’. Recently, the same group cooled the mechanical mode to a mean thermal phonon number around 0.1 and prepared the mechanical mode to squeezed states by quantum non-demolition measurements [33]. The quantum superposition of a mechanical resonator has been prepared, and the matter wave interference pattern has been observed in this system.

## 4. Experimental developments in quantum teleportation

In scientific fictions, teleportation describes the hypothetical transfer of an object between two distant locations without physically moving it along a path. In 1970s, the television series *Star Trek* brought the concept of teleportation to living rooms. The name of quantum teleportation was inspired by teleportation. However, in quantum teleportation, we can only teleport information, rather than a physical object [21]. In other words, quantum teleportation is a form of communication. In this section, we will introduce the basic quantum teleportation protocol. Then we will discuss experimental realisations of quantum teleportation in various systems, such as photons, trapped ions (atoms), and circuit QED.

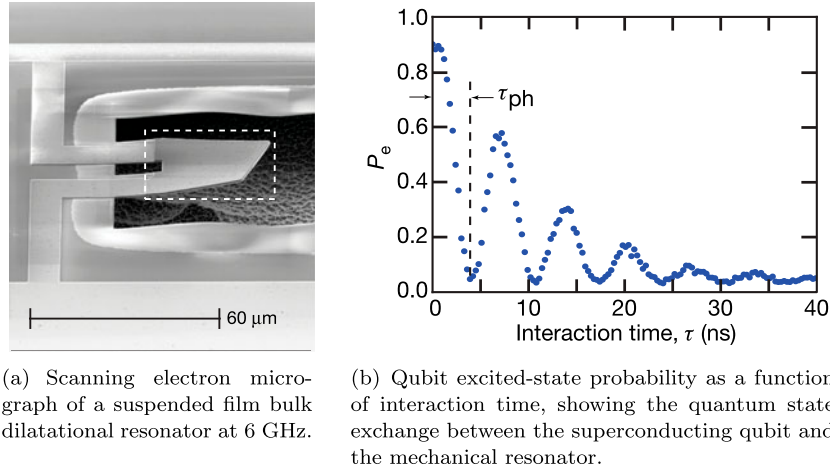
### 4.1. Quantum teleportation protocol

As we mentioned in Section 2.1, quantum teleportation uses entanglement as a resource to transfer quantum information between distant locations [21]. It needs the help of classical communication, but does not need to move the physical particles in which the quantum information is stored. After teleportation, the information stored in the original location is destroyed. Therefore, the quantum non-cloning theorem is obeyed. Here, we discuss the teleportation of a qubit as an example (Figure 6).

We assume that a qubit state  $|\phi_1\rangle = \alpha|0\rangle_1 + \beta|1\rangle_1$  is stored in particle 1. In order to teleport the qubit to another particle, we should prepare an EPR entangled state of a composite system of particles 2 and 3. We consider a specific case

$$|\Psi_{2,3}^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_2|1\rangle_3 - |1\rangle_2|0\rangle_3). \quad (7)$$





**Figure 5.** Ground state cooling and quantum superposition of a mechanical resonator. Reprinted by permission from Macmillan Publishers Ltd: Nature [10], copyright (2010).

Initially, Alice has the qubit  $|\phi_1\rangle$ . In order to teleport the qubit, one particle (2) of the EPR pair is given to Alice, and the other particle (3) is sent to Bob. Then Alice performs a Bell measurement on both particles 1 and 2. The bases of the measurement are

$$\begin{aligned} |\Psi_{12}^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|0\rangle_1|1\rangle_2 \pm |1\rangle_1|0\rangle_2), \\ |\Phi_{12}^{\pm}\rangle &= \frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2 \pm |1\rangle_1|1\rangle_2). \end{aligned} \quad (8)$$

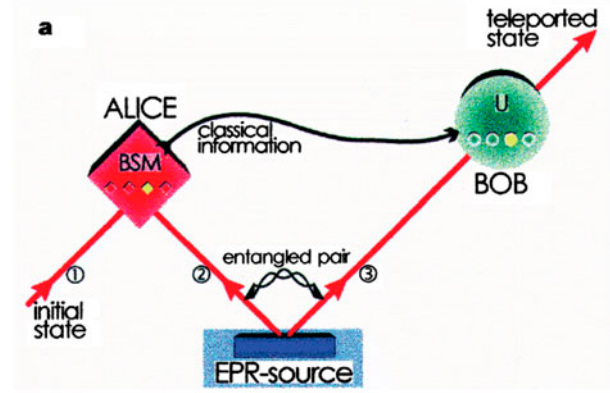
The three-particle state before the Bell measurement is

$$\begin{aligned} |\Psi_{123}\rangle &= \frac{\alpha}{\sqrt{2}}(|0\rangle_1|0\rangle_2|1\rangle_3 - |0\rangle_1|1\rangle_2|0\rangle_3) \\ &+ \frac{\beta}{\sqrt{2}}(|1\rangle_1|0\rangle_2|1\rangle_3 - |1\rangle_1|1\rangle_2|0\rangle_3) \end{aligned} \quad (9)$$

We can rewrite this three-particle state (Equation (9)) in the Bell bases (Equation (8)):

$$\begin{aligned} |\Psi_{123}\rangle &= \frac{1}{2} [\Psi_{12}^{-}(-\alpha|0\rangle_3 - \beta|1\rangle_3) \\ &+ \Psi_{12}^{+}(-\alpha|0\rangle_3 + \beta|1\rangle_3) + \Phi_{12}^{-}(\beta|0\rangle_3 + \alpha|1\rangle_3) \\ &+ \Phi_{12}^{+}(-\beta|0\rangle_3 + \alpha|1\rangle_3)] \end{aligned} \quad (10)$$

Each of the four measurement outcomes in the Bell bases has probability 25%. The Bell measurement will project the particle 3 to one of the four different states, according to the measurement outcome. The four states are



**Figure 6.** Principle of quantum teleportation. Alice has a quantum system (qubit 1) in an initial state  $|\phi_1\rangle$ , which she wants to transfer to Bob. An EPR source produces a pair of entangled photons 2 and 3, and sends photon 2 to Alice, photon 3 to Bob. Then Alice performs a joint Bell measurement on the initial qubit 1 and the ancillary photon 2. This measurement projects them to one of four different entangled states. She then sends the outcome to Bob through classical channel. Based on the classical information, Bob can perform a local operation on photon 3 and reproduce the initial state  $|\phi_1\rangle$ . Bob does not need to know the state  $|\phi_1\rangle$  in order to reproduce it. Reprinted by permission from Macmillan Publishers Ltd: Nature [34], copyright (1997).

$$\begin{aligned} |\phi_3^1\rangle &= -|\phi_1\rangle, \quad |\phi_3^2\rangle = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} |\phi_1\rangle, \\ |\phi_3^3\rangle &= \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} |\phi_1\rangle, \quad |\phi_3^4\rangle = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} |\phi_1\rangle. \end{aligned} \quad (11)$$

These states are simply related to the original qubit state  $|\phi_1\rangle$  that Alice has. Once Alice tells Bob her measurement outcome by classical communication, Bob can apply a local operation on the particle 3 to restore the qubit 1. However, after the Bell measurement, the information in particle 1 is erased. As the operations in

teleportation are linear, the protocol can be extended to multiple qubits.

#### 4.2. Quantum teleportation realisations

In order to realise quantum teleportation, we need to be able to generate and analyse quantum entanglement, which are challenging. Several years after quantum teleportation was proposed [21], Zeilinger's group realised it with entangled photons [34]. They generated entangled photon pairs by parametric down-conversion and used two-photon interferometry to analyse entanglement and perform the Bell measurement.

The principle of quantum teleportation experiment is shown in Figure 6 [34]. The entangled photons 2 and 3 were produced by parametric down-conversion. An incoming photon went through a nonlinear crystal, which converted it spontaneously to two photons in the entangled state  $|\Psi_{2,3}^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_2|1\rangle_3 - |1\rangle_2|0\rangle_3)$ . Here we denote  $|0\rangle$  and  $|1\rangle$  as horizontally and vertically polarised photonic states, respectively.

In order to perform the Bell measurement on photons 1 and 2, they must be indistinguishable. Firstly, they were made indistinguishable in time. Then, the photons were sent through a spectral filter to reduce their linewidth and enhance their coherence time to be longer than the pump pulse duration. Finally, they were sent through a 50:50 beam splitter to perform the Bell measurement. The setup in Ref. [34] could only detect one of the four Bell states. If photons 1 and 2 were indistinguishable and in an antisymmetric state, both detectors of the two output ports of a beam splitter would detect them simultaneously. In this way, the photons 1 and 2 were projected into the antisymmetric state  $|\Psi_{12}^-\rangle$ , which is the only Bell state in which the photons go to two ports of the beam splitter. Once the Bell measurement was successful, we knew the state of the photon 3 was  $|\phi_3^1\rangle = -|\phi_1\rangle$ . So the state of photon 1 was teleported to photon 3.

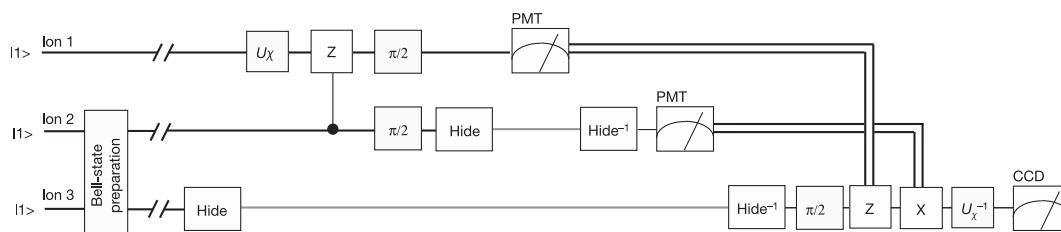
After the first demonstration, numerous quantum teleportation experiments with photonic systems have been performed. The first experiment was done without a complete two-photon Bell measurement. Teleportation could only be realised by selecting the measurement data after the experiment. In other words, the first teleportation experiment was based on post-selection. In 1998, unconditional quantum teleportation was proposed and realised using squeezed-state entanglement [35,36]. Teleporting two degrees of freedom (spin and orbital angular momentum) of a single photon was demonstrated in 2015 [37]. The teleportation distance has also been greatly increased in the last two decades. The longest distance of teleportation is more than 100 km right now [38,39].

Comparing to photonic qubits, atomic or solid state qubits can be stored for longer times. If we can realise quantum teleportation with atomic or solid state qubits, the transferred information will be available after the teleportation for further experiments. Besides, the teleportation in these systems could be deterministic, without post selection. The deterministic quantum teleportation between ions was reported by two groups in 2004, using  $^9\text{Be}^+$  [41] or  $^{40}\text{Ca}^+$  [40] ions. A scheme to teleport the quantum state of ion 1 to ion 3 is shown in Figure 7. Unlike photons, we cannot use two-particle interferometry to accomplish the Bell measurement because it is difficult to have a beam splitter for atomic and solid state qubits. Fortunately, the Bell measurement can also be realised by performing controlled quantum logic gates and measurements on the qubits [42].

The similar method was later adopted in solid state systems, such as superconducting circuits [43], nitrogen-vacancy (NV) centres in diamond [44], and etc. In order to increase the teleportation distance between qubits, photon interference and post-selection methods were used for preparing entanglement between distant trapped ion or solid state qubits [44,45]. The entanglement distribution between two NV centres qubits separated by 1.3 km has been achieved [18]. Loophole-free Bell test has also been performed in this setup [18]. With the goal to realise quantum internet in future, teleportation between different types of qubits has been studied. Quantum teleportation between light and atomic ensemble, [46] between light and solid state quantum memory [47], and between photon and phonon [48] have been demonstrated.

#### 5. Quantum coherence in biological processes

As discussed in previous sections, quantum coherence and entanglement have been observed in various systems, such as trapped ions, mechanical resonators, superconducting circuits, etc. They are crucial resources for quantum information processing. It is natural to ask whether quantum physics plays a nontrivial role in biology [14,15]. It is widely known that quantum mechanics is the basic rule of chemical processes. However, it is not clear what is the role of quantum mechanics in biological (physiological) process. In this section, we will review recent progresses in this direction. It has been found that biological systems can perform certain tasks (such as photosynthesis) more efficiently, or realise a function (such as magnetoreception in some avian species [14]) that cannot be done classically by harnessing quantum coherence and entanglement.



**Figure 7.** Quantum teleportation from ion 1 to 3. Ions 2 and 3 are initially prepared to a Bell state. The state to be teleported is encoded in ion 1 by the operation  $U_x$ . In order to realise Bell measurement between ion 1 and 2, we need to perform a controlled-Z gate followed by a  $\pi/2$  rotation and a state detection on ion 1 and ion 2. Based on the measurement results (classical information) of both ions 1 and 2, the state of ion 1 prepared by the operation  $U_x$  could be reconstructed in ion 3. Double lines in the figure represent the classical information channels. Reprinted by permission from Macmillan Publishers Ltd: Nature [40], copyright (2004).

### 5.1. Photosynthesis

Photosynthesis is one of the most important biological processes. It provides energy to almost all life on the Earth. In a typical photosynthetic process as shown in Figure 8, a photon is first absorbed by a light-harvesting antenna and creates an exciton. The exciton is then transferred to a reaction centre where the excitation energy is transformed into a more stable chemical energy. The remarkable experimental observation is that almost all of photon energy absorbed by the antenna is transferred to the reaction centre. The lifetime of electronic excitation is only on the order of 1 ns. Photosynthesis usually performs at temperatures above 273 K. Therefore, we may treat the exciton transfer as a classical random walk, e.g. the Förster model. In this model, the exciton transfer between different sites is incoherent. The superposition or coherence effects are neglected.

In 2007, Engel et al. reported that quantum coherence exists in both the energy transfer in the Fenna-Matthews-Olson (FMO) complex [49] and the reaction centre in photosynthesis [50]. FMO is a specialised structure through which the excitation energy is transferred to the reaction centre. The experiment was initially performed at a cryogenic temperature 77 K. Later experiments shown that the coherence in excitation transfer exists even near room temperature [51–53], as shown in Figure 8. One may ask why quantum coherence exists during the exciton transfer, and what is the role of it. The simple answer is to increase the energy transfer efficiency. A high transfer efficiency may be very important for life species that live in a weak light environment, e.g. green sulphur bacteria [51].

Numerous theoretical models have been proposed to explain how and why excitation energy transfer is more efficient using quantum coherence. For example, some models treat the environment as a Markovian thermal bath [54,55]. Each site in the FMO complex interacts with an independent environmental bath. It was found that by

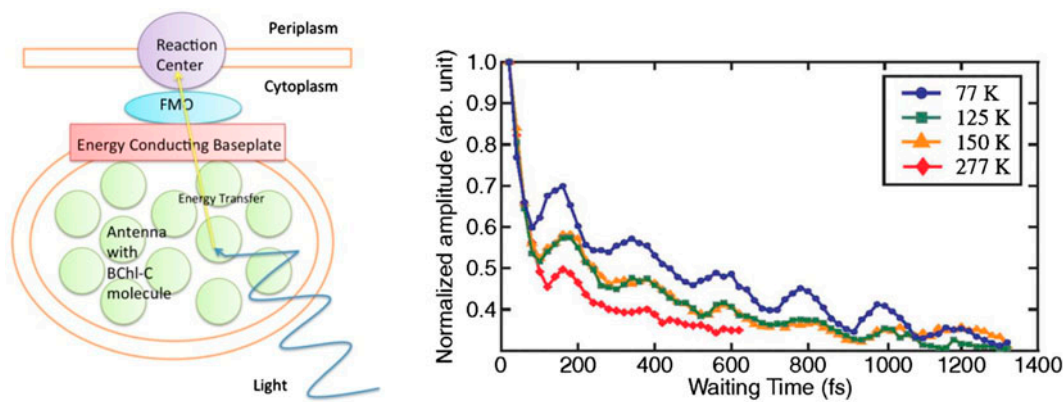
combining the coherence of excitation transport and the thermal noise, the excitation may easily escape a local potential minima of the FMO and move to the reaction centre. There were also works on studying the effects of the molecular geometric structure on the efficiency of energy transport [56]. Ref. [57,58] studied a dimer structure of light-harvesting complex 2 (LH2), and found that both dimerisation and dark states could increase the energy transfer efficiency.

Recent analysis showed that the quantum enhancement of the transport efficiency might be only a few percent [59]. Thus, it is still not clear whether quantum coherence is essential for photosynthesis. Some papers proposed classical models that can also have quantum-like oscillation behaviours [60]. More studies are needed to clarify the role of quantum coherence in photosynthesis [61,62].

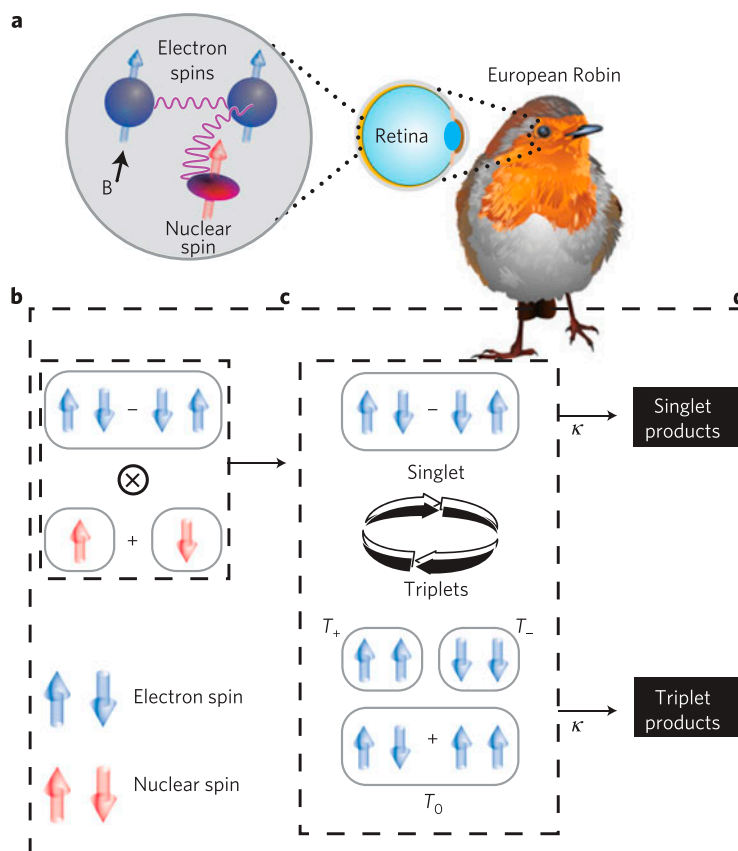
### 5.2. Avian magnetoreception

Another widely studied candidate of nontrivial quantum phenomena in living systems is avian magnetoreception [63]. Some migrating animal species use the weak magnetic field of the Earth for navigation. The mechanisms of magnetoreception vary from species to species. Behavioural experiments of certain species, such as European robins, show that their navigation is based on both the light and the external magnetic field [65,66]. These evidences support the so-called radical-pair (RP) mechanism [14,67], which is shown in Figure 9 [14].

A radical pair is a pair of bound molecules that each has an unpaired electron. As shown in Figure 9 [14], the RP mechanism contains three steps. In the first step, a molecule, such as a cryptochrome protein, in a bird's eye absorbs a photon and generates a spatially separated electron pair. Usually, the generated pair is in the singlet state before electron transfer. The singlet state will evolve



**Figure 8.** The left figure shows the transfer of an exciton from an antenna that absorbs light to the reaction centre in photosynthesis. The right figure shows that the quantum coherence persists for longer than 300 fs in photosynthesis at 277K. The left figure is adapted from Wikimedia [64], and the right figure is adapted from Ref. [52].



**Figure 9.** The avian quantum compass. (a) A schematic of the RP mechanism for magnetoreception which may explain the navigation of European robins. RP mechanism is thought to happen in proteins named cryptochromes in the retina. It contains three main steps. First, light-induced electron transferred from one radical-pair-forming molecule to an acceptor molecule creates a radical pair. (b,c), Second, the singlet and triplet states convert between each other, which is determined by the external and internal magnetic couplings. (d) Third, the singlet and triplet pairs recombine into singlet or triplet products, which could be detected through biological ways. Reprinted by permission from Macmillan Publishers Ltd: Nature Physics [14], copyright (2013).

due to the interaction with the external magnetic field of the Earth and the hyperfine interaction with the internal nuclear spins. Then the singlet and triplet states

convert to each other. Finally, the singlet and triplet pairs recombine. The rate of the recombination depends on the spin states of the separated charges, which also affect the



reaction products of the radical pairs. The recombination rate should be slower than the singlet-triplet conversion speed to allow the RP mechanism to happen. The singlet and triplet products are biologically detectable in principle. By detecting the relative weight of the singlet and triplet products, the angle of the external magnetic field can be determined. In this way, a magnetic compass is formed in a bird's eye.

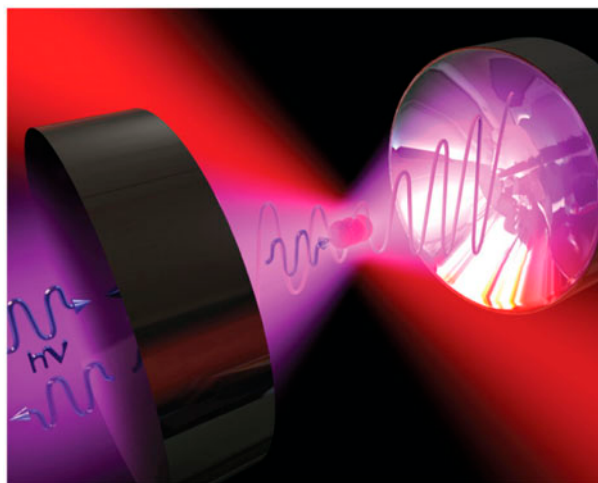
Spin singlet and triplet states are highly entangled states, and are equivalent to Bell states. There are many studies on how quantum coherence and entanglement will enhance the performance of the RP mechanism. Using density-matrix equation and quantum measurement theory, Kominis explained the RP mechanism by quantum zeno effects [68]. Cai et al. studied how quantum control could enhance or reduce the performance of compass in the RP mechanism, and studied the role of entanglement in this mechanism [69]. In the theoretical investigation by Gauger et al. [70], it was found that superposition and entanglement could be maintained in this system for tens of microseconds in a 'warm and wet' biological environment. Later, Cai et al. found that the sensitivity of the chemical compass based on the RP mechanism could be greatly enhanced by quantum criticality of the environment [71].

There were many experiments that investigated the sensitivity of the RP mechanism in detecting an external magnetic field. In most experiments [14,72], the requirements of high magnetic strength sensitivity (around  $50 \mu\text{T}$ ) and high angular sensitivity for avian magnetoreception cannot be fulfilled at the same time. Recently, Hiscock et al. studied a modified RP model that involved multinuclear radical pairs [73]. They found that the output contained a very sharp feature, which could greatly increase the angular sensitivity. The magnetic strength used in this experiment was also comparable to that of the Earth.

## 6. Towards quantum superposition of an optically levitated micro-organism

The quantum coherence in biological processes mentioned in the former section is still at the molecular scale. Can we create quantum superposition of an entire organism as proposed by Schrödinger in 1935? Can we entangle a macroscopic state of an entire living organism to a microscopic state of an atom or an electron to make a close analogue of the Schrödinger's cat thought experiment? Remarkably, these long-sought goals in quantum mechanics may be realisable with the state-of-the-art technologies [11,12].

In 2009, Romero-Isart et al. proposed to optically levitate a virus in vacuum inside an optical cavity to create



**Figure 10.** An optically levitated micro-organism, such as a virus, inside a high-finesse optical cavity in vacuum for creating quantum superposition states. Figure adapted from Ref. [11].

quantum superposition states of a virus (Figure 10) [11]. A virus levitated in high vacuum will be well isolated from the environment. By trapping it in an optical cavity, its motion can be coupled to the photon in the cavity, which can be used to cool its centre-of-mass (CoM) motion to the quantum ground state and create superposition states (Figure 10). While Schrödinger's cat proposal was a pure thought experiment, this intriguing proposal of a levitated virus increased our hope to create quantum superposition of a living organism in a laboratory. Romero-Isart et al. pointed out that this would be possible because (i) living micro-organisms have been optically trapped in liquids; (ii) some micro-organisms can survive in a vacuum environment; (iii) the size of viruses and some other smallest micro-organisms is comparable to the laser wavelength; (iv) some micro-organisms are transparent. Romero-Isart et al. proposed that a good example of virus for creating a quantum superposition state will be a tobacco mosaic virus which has a rod-like shape about  $50 \text{ nm}$  wide and  $1 \mu\text{m}$  long [11]. Because of its shape, a tobacco mosaic virus will also be a good candidate to study rotational and torsional cooling. Currently, the main difficulty to realise this proposal is to optically levitate a virus in high vacuum without significant heating due to light absorption. The optical absorption coefficients of organisms are typically much larger than that of pure silica optical fibres [74].

While optical levitation of a living micro-organism in vacuum has not been realised yet, there have been many experimental progresses in levitated optomechanics with inorganic dielectric particles [75]. In 1975, Ashkin and Dziedzic optically levitated glass spheres and oil droplets with diameters about  $20\text{-}\mu\text{m}$  in high vacuum [76]. In 2010, Li et al. demonstrated feedback cooling of the

centre-of-mass motion of an optically trapped silica microsphere from room temperature to about 1.5 mK in high vacuum [77]. Parametric cooling [78] and cavity cooling [79–81] of pure dielectric particles (silica and silicon) have also been demonstrated. It is expected that quantum ground state cooling of a levitated pure dielectric particle will be realised soon.

Let us consider an optically trapped nanoparticle (or a virus) inside an optical cavity as shown in Figure 11(a). The angular frequency of the mechanical vibration of the nanoparticle along the  $z$ -axis is  $\omega_m$ . The resonant angular frequency of the cavity without the nanoparticle is  $\omega_{C0}$ . For a nanoparticle much smaller than the wavelength of the laser, we can use the Rayleigh approximation. Because of the nanoparticle, the cavity resonant frequency shifts by an amount [11]

$$\delta\omega_C(\mathbf{r}) = -\frac{1}{2} \frac{\int_{V(\mathbf{r})} (\epsilon_r - 1) \mathbf{E}^2(\mathbf{r}') d^3\mathbf{r}'}{\int \mathbf{E}^2(\mathbf{r}') d^3\mathbf{r}'} \cdot \omega_{C0}, \quad (12)$$

where  $\mathbf{E}(\mathbf{r}')$  is the electric field of the cavity mode,  $\epsilon_r$  is the relative dielectric constant of the nanoparticle, and  $V(\mathbf{r})$  is its occupied space. Because the cavity mode is a standing wave,  $\delta\omega_C(\mathbf{r})$  depends on the location  $\mathbf{r}$  of the nanoparticle in the cavity. The amplitude of  $\delta\omega_C(\mathbf{r})$  is maximised when the nanoparticle is at an antinode of the cavity mode, and will be 0 if the nanoparticle is at a node of the cavity mode. Because the frequency shift depends on the position of the nanoparticle, the vibration (phonon) of the nanoparticle is coupled to the photon in the cavity. The typical quantum optomechanical coupling is [11]

$$H_{OM} = \hbar g (a_m^\dagger + a_m)(a_c^\dagger + a_c), \quad (13)$$

where  $a_m^\dagger$  ( $a_m$ ) are the creation (annihilation) phonon operators,  $a_c^\dagger$  ( $a_c$ ) are operators that create (annihilate) a photon in the cavity, and  $g = \sqrt{n_{ph}}g_0$  is the coupling strength. Here  $n_{ph}$  is the number of photons in the cavity and  $g_0$  is the coupling strength between a single photon and a single phonon.

This optomechanical interaction Hamiltonian (Equation 13) can be used to cool a levitated nanoparticle. To cool the centre-of-mass motion of the levitated nanoparticle, we can choose the laser detuning to be  $\Delta \equiv \omega_L - \omega_C = -\omega_m$ , where  $\omega_L$  is the frequency of the cooling laser,  $\omega_C$  is the resonant frequency of the cavity, and  $\omega_m$  is the frequency of the centre-of-mass motion of the nanoparticle (Figure 11(b)). By using rotating wave approximation under the condition  $\omega_m \gg g$ , we get the effective interaction Hamiltonian as [12]

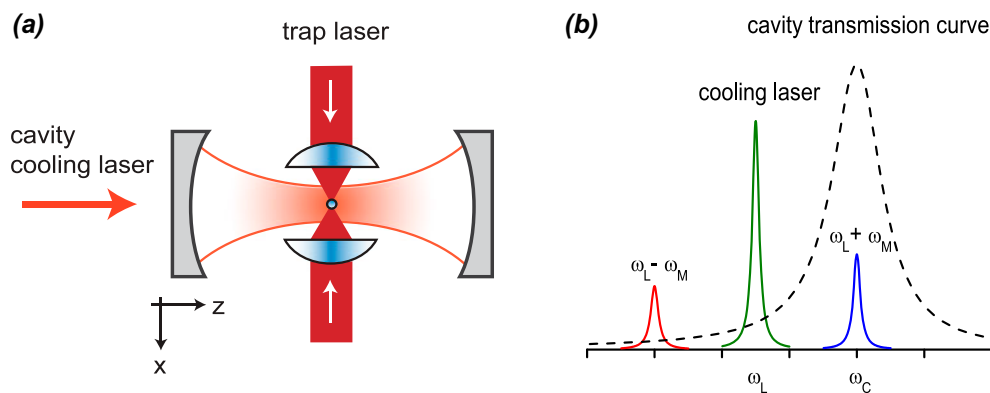
$$H_{\text{eff}} = \hbar g a_m^\dagger a_c + \hbar g a_m a_c^\dagger. \quad (14)$$

As shown in Figure 11(b), the motion of the nanoparticle will modulate the laser field in the cavity and generate two sidebands, one at frequency  $\omega_L - \omega_m$  and the other at frequency  $\omega_L + \omega_m$  [82]. If the laser detuning is  $\Delta = -\omega_m$ , then the high-frequency sideband  $\omega_L + \omega_m = \omega_C$  will be on resonant of the optical cavity and can leak out of the cavity. On the other hand, the low-frequency sideband  $\omega_L - \omega_m$  is detuned further away from the resonant frequency of the cavity. On average, the emitted photons will have higher energy than the photons entering to the cavity. Thus, the photons will carry away the kinetic energy from the nanoparticle. So the motion of the nanoparticle will be cooled. To achieve ground state cooling, we need to satisfy the resolved sideband limit, i.e.  $\omega_m > \kappa \gg \gamma_m$ . Here  $\kappa$  is the line width of the optical cavity, and  $\gamma_m$  is the decay rate of the mechanical oscillation of the nanoparticle.

A more interesting task is to create a quantum superposition state of a levitated nanoparticle (or virus). An example superposition state will be  $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ , where  $|0\rangle$ ,  $|1\rangle$  are the ground and the first excited state of the centre-of-mass vibration of the nanoparticle, respectively. A method is to use a single-photon state. The interaction Hamiltonian (Equation 14) can swap the state of the photon in the cavity to the state of the mechanical motion of the levitated nanoparticle. If the single photon is in a superposition state of entering or not entering to the cavity, its superposition state will be mapped to the mechanical motion of the nanoparticle. Thus the nanoparticle will be prepared in a superposition state. Romero-Isart et al. later proposed a different method to create superposition states with larger spatial separations by using two optical cavities [83]. In 2013, Yin et al. proposed to use electron spin-optomechanical coupling to create large spatial superposition states of a levitated nanodiamond [84,85]. Recently, optical trapping and electron spin control of nanodiamonds in vacuum have been demonstrated [86–88].

## 7. Towards quantum superposition, entanglement, and state teleportation of a micro-organism on an electromechanical oscillator

In 2015, Li and Yin proposed to create quantum superposition and entangled states of a living micro-organism by putting a small bacterium or a virus on top of an electromechanical oscillator, such as a membrane embedded in a superconducting microwave resonant circuit (Figure 12) [12]. Using an electromechanical oscillator instead of optical levitation in vacuum, this approach avoids the heating due to laser absorption. Electromechanical oscillators imbedded in superconducting circuits have been



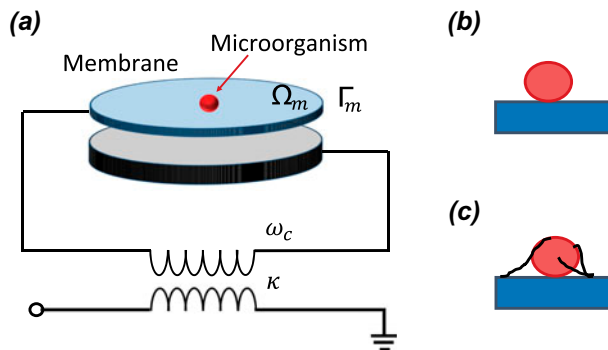
**Figure 11.** (a) Scheme of cavity cooling of a levitated nanoparticle. (b) Principle of cavity cooling. To achieve cooling, the angular frequency of laser  $\omega_L$  should be smaller than the resonant angular frequency of the cavity  $\omega_C$ .  $\omega_M$  is the angular frequency of the centre-of-mass motion of the levitated nanoparticle. Figure adapted from Ref. [82] (With permission of Springer).

cooled to quantum ground state by several groups [10,31, 89–94]. Advanced control techniques of superconducting circuits, including quantum teleportation with superconducting circuits, have also been demonstrated [43]. In addition, most micro-organisms can survive in the cryogenic environment, which is required to use the superconducting circuits. Micro-organisms will be frozen in a cryogenic environment. But they can be still living and become active after thawing [95]. Cryopreservation is a standard technology for preserving biological samples for long periods and is used clinically worldwide [95]. Most micro-organisms can be preserved for several years in cryogenic environments without losing vitality [96]. Even some organs can be preserved at cryogenic temperatures [97]. At millikelvin temperatures, the sublimation speed of water ice is negligible. It is only about 0.06 nm per hour at 128 K [98], and decreases further when the temperature decreases. So a micro-organism can be exposed to ultrahigh vacuum without sublimation at millikelvin temperatures.

In the following subsections, we will first review the scheme to create quantum superposition states of the centre-of-mass motion of a micro-organism on an electromechanical oscillator. We will then discuss how to create quantum entanglement between the internal state and the centre-of-mass motion of a micro-organism. At the end, we will discuss how to teleport the quantum state (centre-of-mass motion or internal state) of a micro-organism to another micro-organism.

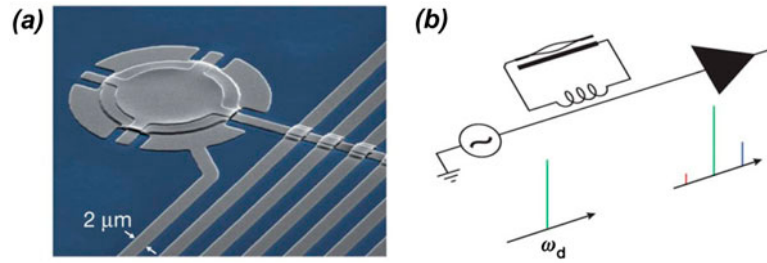
### 7.1. Center-of-mass motion

As proposed in Ref. [12], we can create quantum superposition states of a small micro-organism by putting it on a membrane oscillator (Figure 12). Figure 13 shows a 15- $\mu\text{m}$ -diameter aluminium membrane with a thickness



**Figure 12.** Schrödinger's microbe. (a) Scheme to create quantum superposition states of a micro-organism by putting it on top of an electromechanical membrane coupled to a superconducting LC circuit. (b) A bacterium with a smooth surface. (c) A bacterium with pili on its surface. Figure adapted from Ref. [12].

of 100 nm that has been cooled to quantum ground state by sideband cooling with a superconducting inductor-capacitor (LC) resonator [31]. The experiment [31] was performed in a cryostat at 15 mK. The fundamental vibration mode frequency of this membrane is about 10 MHz. Its mechanical quality factor is about  $3.3 \times 10^5$ . The mass of the membrane is 48 pg ( $2.9 \times 10^{13}$  Da), which is larger than those of many micro-organisms. Besides ground state cooling, coherent state transfer between the membrane and a travelling microwave field [90], and entanglement between the motion of the membrane and a microwave field [89] have been realised. These developments provide the toolbox for creating quantum superposition states of a small micro-organism. The masses of some common small micro-organisms are listed in Table 1. From Table 1, it is clear that the mass of the aluminium membrane used in Ref. [31] is about four orders larger than the mass of ultra-small bacteria [99–105]. A good example of cells that are suitable for performing



**Figure 13.** An aluminium membrane cooled to the ground state. (a) A scanning electron microscope (SEM) image showing the aluminium (grey) electromechanical circuit. A 15-μm-diameter aluminium membrane with a thickness of 100nm is suspended 50 nm above a lower electrode. The membrane's vibration modulates the capacitance of the superconducting microwave circuit. (b) A coherent microwave drive (left,  $\omega_d$ ) inductively coupled to the circuit acquires modulation sidebands (red and blue in the plot below) owing to the thermal motion of the membrane. The upper sideband is amplified with a Josephson parametric amplifier (filled triangle, right). Reprinted by permission from Macmillan Publishers Ltd: Nature [31], copyright (2011).

**Table 1.** Comparison of masses of some viruses and bacteria to the mass of a membrane oscillator ( $M_{\text{mem}} = 48$  pg) that has been cooled to the quantum ground state in Ref. [31]. Table adapted from Ref. [12].

Micro-organism	Typical mass (pg)	$m/M_{\text{mem}}$ ( $M_{\text{mem}} = 48$ pg)
Bacteriophage MS2	$6 \times 10^{-6}$	$10^{-7}$
Tobacco mosaic virus	$7 \times 10^{-5}$	$10^{-6}$
Influenza virus	$3 \times 10^{-4}$	$10^{-5}$
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	$10^{-2}$

this experiment is a mycoplasma bacterium. Mycoplasma bacteria are ubiquitous and their sizes are small [103]. We can utilise techniques developed in cryo-electron microscopy to prepare the system in a cryogenic environment [106].

As shown in Figure 12(a), a bacterium or virus can be put on top of an electromechanical membrane oscillator. Its mass  $m$  is assumed to be much smaller than the mass of the membrane  $M_{\text{mem}}$ . For simplicity, it will be better to use micro-organisms with smooth surfaces (Figure 12(b)), although micro-organisms with pili (hair-like structures) on their surfaces (Figure 12(c)) will also work as long as the vibration frequencies of the pili are different from the vibration frequency of the superconducting membrane.

At millikelvin temperatures, the mechanical properties of a frozen micro-organism will be similar to a glass particle, while its chemical properties are quite different. A frozen micro-organism will stick on the membrane due to attractive van der Waals force. 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 [107]. This is about  $10^7$  times larger than the gravitational force on a 1 μm particle. So, the micro-organism will move together with the membrane. The oscillation frequency of the membrane oscillator will change by roughly  $-\Omega_m m / (2M_{\text{mem}})$ , where

$\Omega_m$  is the intrinsic oscillation frequency of the membrane. This small frequency shift will not significantly affect the ground state cooling of the membrane. The change of the quality factor  $Q$  of the membrane oscillator due to a small micro-organism ( $m/M_{\text{mem}} \ll 1$ ) will also be negligible. The frequencies of internal vibration modes of the main body of a small bacterium (larger than 1 GHz for a bacterium smaller than 1 μm) are much larger than the frequency of the centre-of-mass motion of the electromechanical membrane which is about 10 MHz. Thus the internal vibration modes of the main body of a bacterium will not couple to the centre-of-mass vibration of the membrane. If the bacterium has pili on its surface (Figure 12(c)) [108], the situation will be more complex. One can avoid this problem by embedding the pili in water ice.

We assume the frequency of the centre-of-mass motion of the micro-organism and the membrane together to be  $\omega_m$ , which is close to  $\Omega_m$ . The motion of the membrane alters the frequency  $\omega_c$  of the superconducting LC resonator. The frequency  $\omega_c$  can be approximated with  $\omega_c(x) = \omega_0 + Gx$ , 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



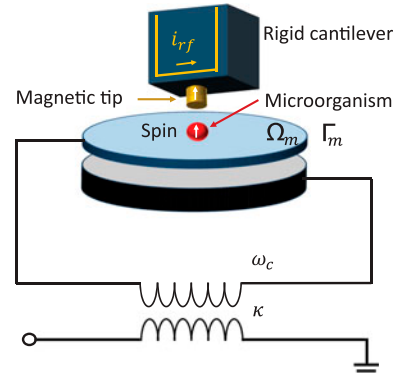
photon number operator, and  $x_0 = \sqrt{\hbar/2M_{\text{mem}}\omega_m}$  is the zero point fluctuation for mechanical mode. We denote the single-photon coupling constant  $g_0 = Gx_0$ . The LC resonator can be driven strongly with frequency  $\omega_d$  to enhance the effective coupling between LC resonator and mechanical oscillator. We assume that the steady state amplitude  $\alpha$  of the LC mode is much larger than 1. So the effective coupling strength will increase to  $g = \alpha g_0$ . The detuning can be freely chosen to satisfy the requirements of different applications. For ground state cooling, we choose  $\Delta = -\omega_m$ . Then we get the effective interaction Hamiltonian as [109]  $H_{\text{eff}} = \hbar g a^\dagger a_m + \hbar g a a_m^\dagger$ , which is basically the same as Equation 14.

Once the mechanical mode is cooled down to the quantum regime by cavity sideband cooling [31], we can prepare the mechanical superposition state of a bacterium by the method of quantum state transfer between the mechanical mode and the LC microwave mode. For example, we can first generate the superposition state  $|\phi_0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$  for LC mode  $a$  with assistance of a superconducting qubit. Here  $|0\rangle$  and  $|1\rangle$  are vacuum and 1 photon Fock state of the LC mode  $a$ . After interaction time  $t = \pi/g$ , the mechanical mode will be in the superposition state  $|\phi_0\rangle$ .

## 7.2. Internal states of a micro-organism

Key features of a micro-organism that are different from a glass bead include its ability of metabolism and its complex internal states. It will be interesting to create superposition state of the internal state of a micro-organism [12]. A suitable internal state of a micro-organism is the electron spin of a radical (or transition metal ion) in the micro-organism. Radicals are routinely produced during metabolism or by radiation damage. The electron spin of a glycine radical  $\text{NH}_3^+\dot{\text{C}}\text{HCOO}^-$  has a relaxation time  $T_1 = 0.31$  s and a phase coherent time  $T_M = 6$   $\mu\text{s}$  at 4.2 K [110]. The phase coherent time increases when the temperature decreases. Moreover, we can use universal dynamic decoupling to increase the coherent time  $T_M$  by several orders, approaching  $T_1$  [111]. Thus we expect the coherent time of the electron spin of a glycine radical to be much longer than 1 ms at millikelvin temperatures. In the original Schrödinger's cat thought experiment, the macroscopic 'alive' or 'dead' state of a cat was entangled with the microscopic state of a radioactive atom. As an analogue, we can entangle the centre-of-mass motion of an entire micro-organism to a microscopic internal state of the micro-organism.

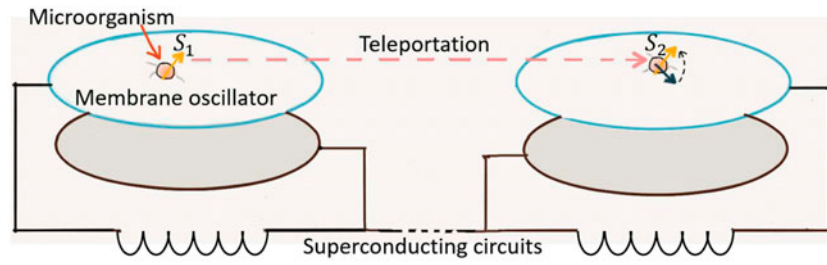
As shown in Figure 14, in order to couple the internal spins states of a micro-organism to the centre-of-mass motion of the Micro-organism, a magnetic field gradient is applied. Above the micro-organism, there is



**Figure 14.** Scheme to couple the electron spin of a radical in a micro-organism to its centre-of-mass motion with a magnetic field gradient created by a nearby ferromagnetic tip. A microwave signal  $i_{rf}$  can be used to control the state of the electron spin. The centre-of-mass motion of the membrane is also coupled to the microwave photon in the superconducting LC circuit. Figure adapted from Ref. [12].

a ferromagnetic tip mounted on a rigid cantilever, which produces a magnetic field  $\mathbf{B}$  with a large gradient. This scheme to couple the spin state and the centre-of-mass motion of a micro-organism is similar to the scheme used in magnetic resonance force microscopy (MRFM) [112–114]. Recently, single electron spin detection with a MRFM [112], and a MRFM at 30 mK has been demonstrated [114].

The oscillation of membrane induces a time-varying magnetic field on electrons in the micro-organism. We define the single phonon induced frequency shift  $\lambda = g_s \mu_B |\mathbf{G}_m| x'_0 / \hbar$ , where  $x'_0$  is the zero field fluctuation of micro-organism, and  $\mathbf{G}_m = \partial \mathbf{B}(\vec{x}_1) / \partial \vec{x}_1$ . Here we assume that the magnetic gradient is (un)parallel to both the magnetic field  $\mathbf{B}(\vec{x}_1)$  and the mechanical oscillation. The  $z$  axis is defined along the direction of  $\mathbf{B}(\vec{x}_1)$ . We apply a microwave driving with frequency  $\omega'_d$ , which is close to the electron 1's level spacing  $\omega_1 = g \mu_B B(\vec{x}_1)$ . In a micro-organism, there are usually more than one radicals. 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. With the help of a large magnetic gradient, the microwave can be on resonant (or near resonant) of only one electron spin [112]. So we can neglect the effects of other electron spins in the micro-organism. To make sure the electron spin is initially in the ground state at 10 mK, its energy level spacing should be larger than 500 MHz, which is much larger than the mechanical oscillator frequency. To achieve strong coupling, we can drive the system with a strong microwave at angular frequency  $\omega_1$  with a Rabi frequency  $\Omega'_d = \omega_M$ . Then the interaction Hamiltonian will be [12]



**Figure 15.** Scheme to teleport the quantum state of a micro-organism to another micro-organism with the help of two electromechanical oscillators and superconducting circuits. Both the centre-of-mass motion state and the internal state of the micro-organism can be teleported.

$$H_I = \hbar\lambda\sigma_+a_m + \hbar\lambda\sigma_-a_m^\dagger, \quad (15)$$

where  $\sigma_\pm = \sigma_z \pm i\sigma_y$ . The spin qubit is defined on the eigenstates of  $\sigma_x$ .

This interaction Hamiltonian is similar to Equation 14. We can generate entangled state and transfer quantum states between electron spin 1 and the mechanical mode  $a_m$  with this Hamiltonian (15). Similar to the scheme initially proposed for creating quantum superposition state of a nanodiamond with a built-in electron spin, we can prepare the spin of the free electron of a radical to be in a superposition state  $|s\rangle = \frac{1}{\sqrt{2}}(|-\frac{1}{2}\rangle + |+\frac{1}{2}\rangle)$ . With a magnetic field gradient, we can use the interaction Hamiltonian to transfer the spin superposition state to a spatial superposition state, and vice versa. Because of the small vibration amplitude of the high-frequency membrane used in Ref. [31], the spatial separation of the two states will be very small ( $10^{-14}$  m). To further increase the spatial separation of the superposition state of a micro-organism, one can attach the micro-organism to a magnetically levitated superconducting microsphere [115–118] instead of a fixed membrane in future. With that method, superposition of two states separated by about 500 nm should be feasible [115].

### 7.3. Quantum state teleportation of a micro-organism

Beyond the Schrödinger's cat thought experiment, we can also teleport the centre-of-mass motion state and internal electron spin state between two remote micro-organisms (Figure 15) [12]. Since internal states of an organism contain information, this provides an experimental scheme for teleporting information or memories between two organisms.

We consider two remote micro-organisms, which are attached to two separate mechanical resonators integrated with LC resonators. They are connected by a superconducting circuit as demonstrated in Ref. [43]. Quantum teleportation based on superconducting circuits has been demonstrated recently [43]. The two

mechanical resonators will be first cooled down to the motional 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 micro-organism and mechanical resonator is prepared to a superposition state  $|\psi_1\rangle = \alpha|0\rangle_{m1} + \beta|1\rangle_{m1}$ , where  $\alpha$  and  $\beta$  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 [109]. Then by transferring the state  $a_2$  to the mechanical mode  $a_{m2}$  of the second micro-organism 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  $a_{m2}$  [21]. 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  $a_{m1}$  [43].

The internal electron spin state of a micro-organism can also be teleported to another micro-organism using superconducting circuits [43]. We can first transfer the internal electron spin state of micro-organism 1 to its mechanical state with Hamiltonian (15) [84,85]. We then teleport it to the mechanical state of the remote micro-organism 2. Finally, we transfer the mechanical state of micro-organism 2 to its internal electron spin state. In this way, we achieve the quantum teleportation between internal electron spin states of two micro-organisms. In future, this method can be extended to entangle and teleport multiple degrees of freedom [37,119,120] of a living organism at the same time.

## 8. Conclusion

In conclusion, we have reviewed experimental and theoretical progresses related to Schrödinger's cat thought experiment. After a brief introduction to basic concepts in quantum mechanics, we review experimental demonstrations of quantum superposition, entanglement and teleportation. We then discuss recent developments in

investigating quantum phenomena in living organisms. Several experimental evidences show that quantum coherence and entanglement are important for certain biological functions, such as photosynthesis and magnetoreception. A better understanding of the role of quantum mechanics in photosynthetic processes can also help us to improve the energy efficiency of artificial photosynthetic devices for clean energy. Recently, it was proposed that quantum superposition, entanglement and state teleportation of a micro-organism are feasible with state-of-the-art technologies. Once realised experimentally, they would allow us to study some fundamental questions in quantum mechanics, such as the role of observation and the transition between quantum mechanics and classical mechanics. Quantum teleportation of the states of an organism may find applications in future [121].

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