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

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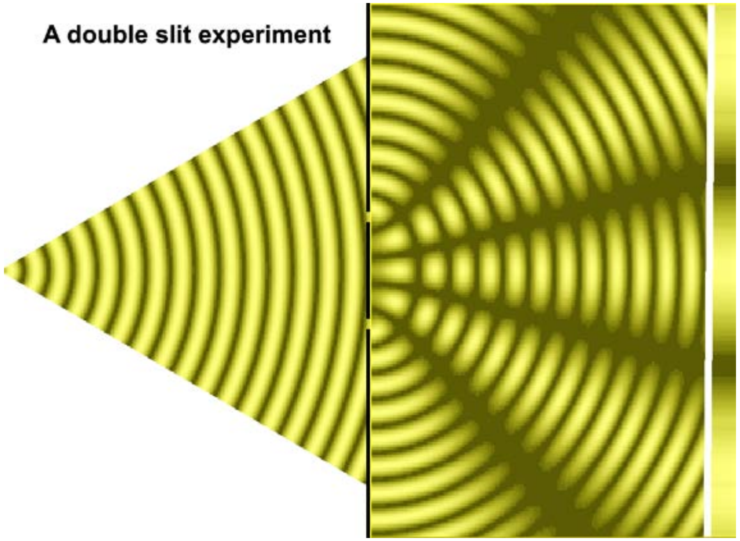
Contents

A classical particle v.s. wave

Where is the stone?

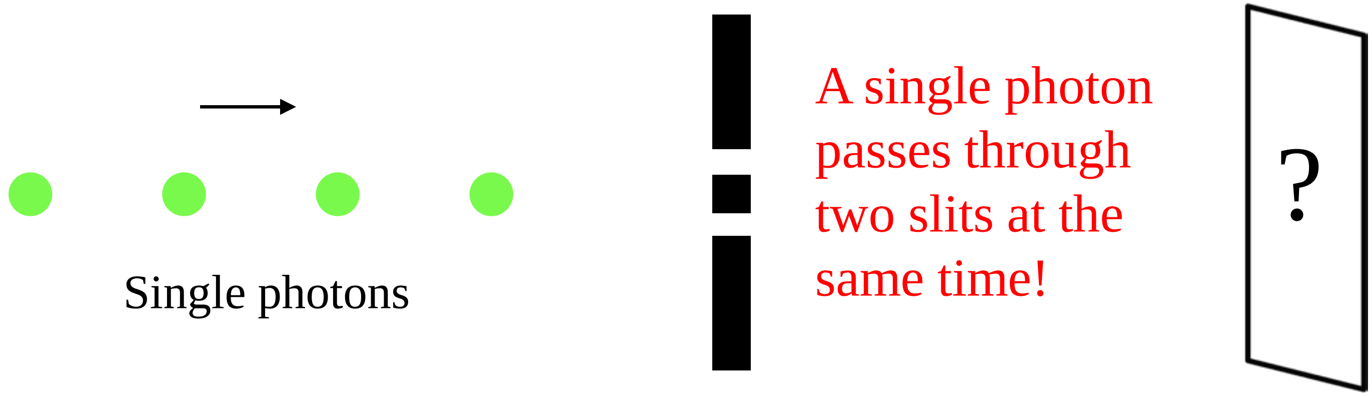
Where is the water wave?

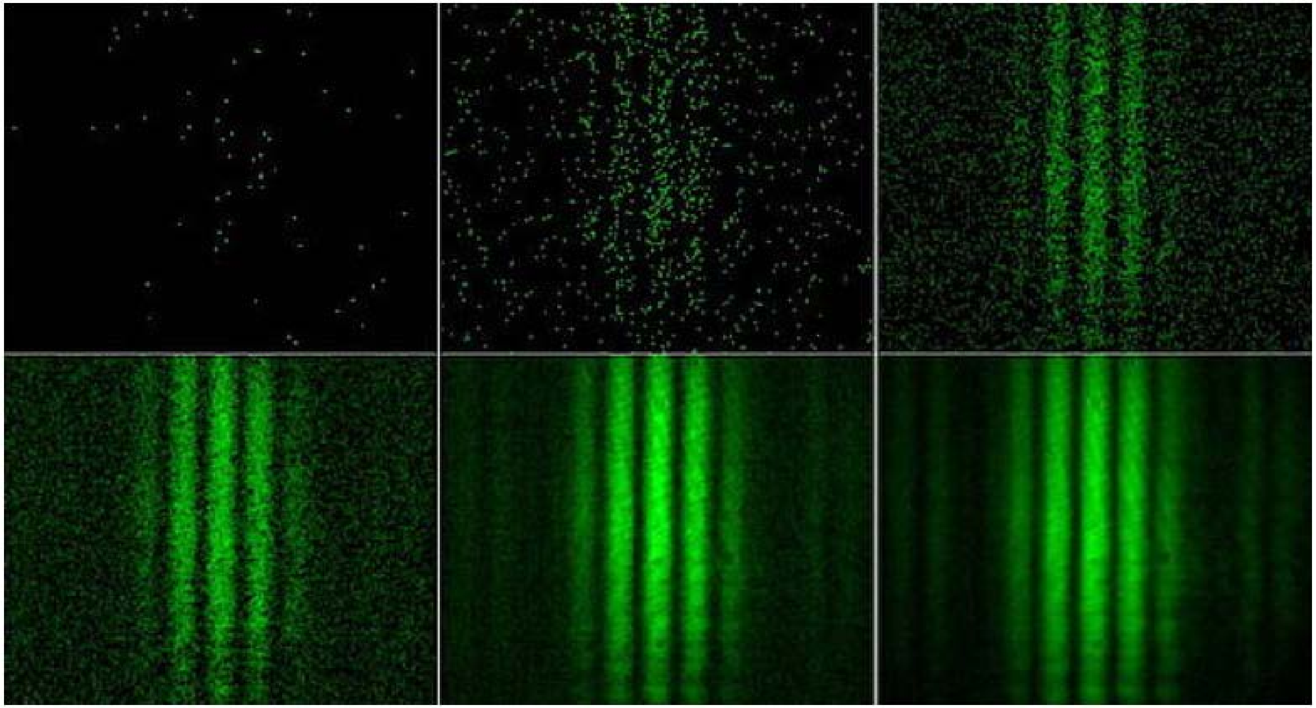
Interference of water waves



Interference is a manifestation of waves

Photon : a particle or a wave?



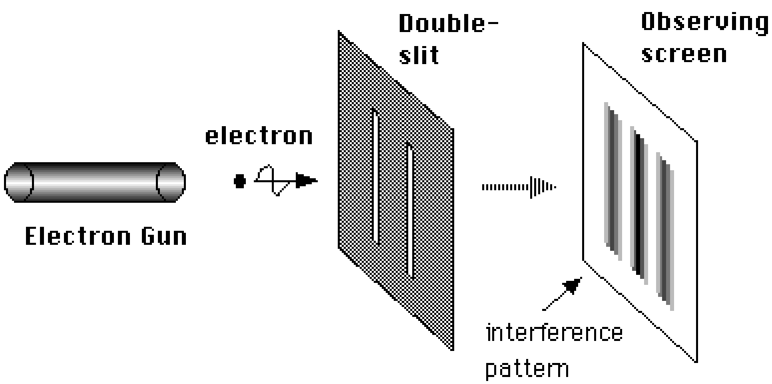


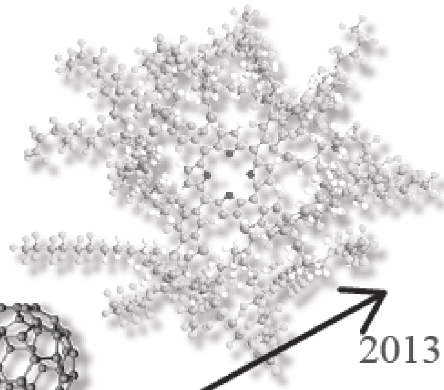
All matter can exhibit wave-like behavior.

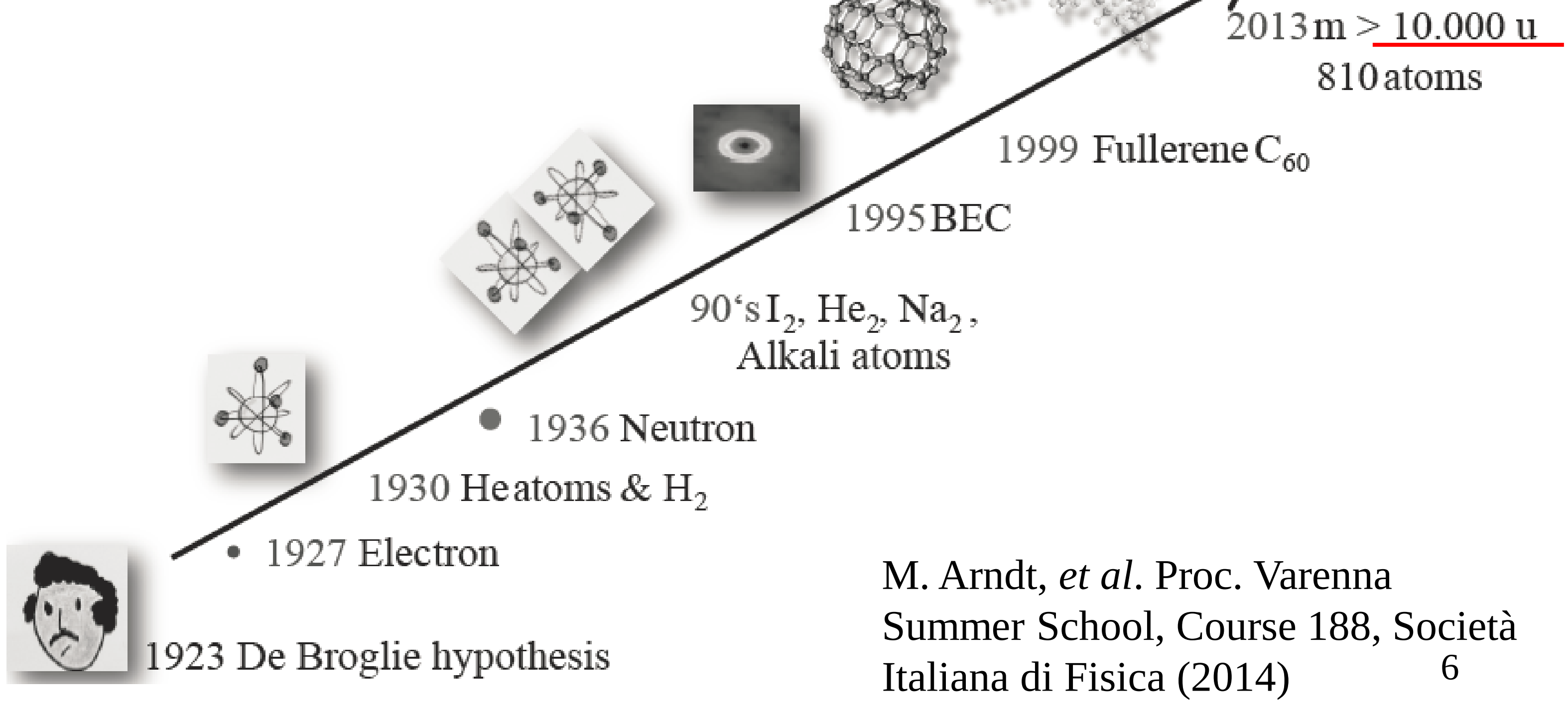
$$\lambda = \frac{h}{p}.$$

Louis de Broglie, 1923

Nobel Prize in Physics in 1929

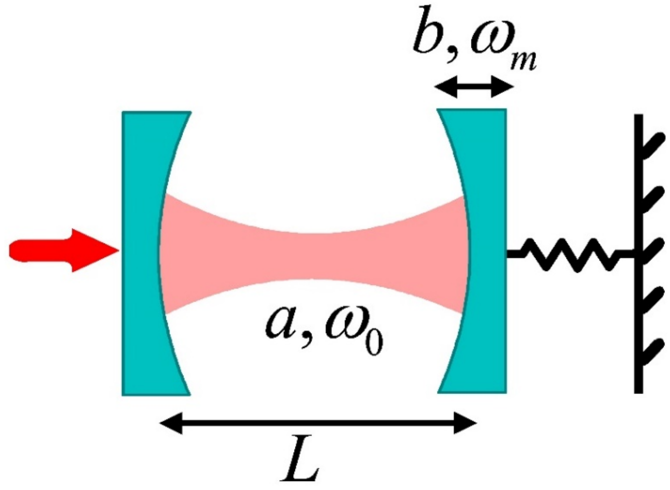






M. Arndt, *et al*. Proc. Varenna Summer School, Course 188, Società Italiana di Fisica (2014)

Introduction to optomechanics

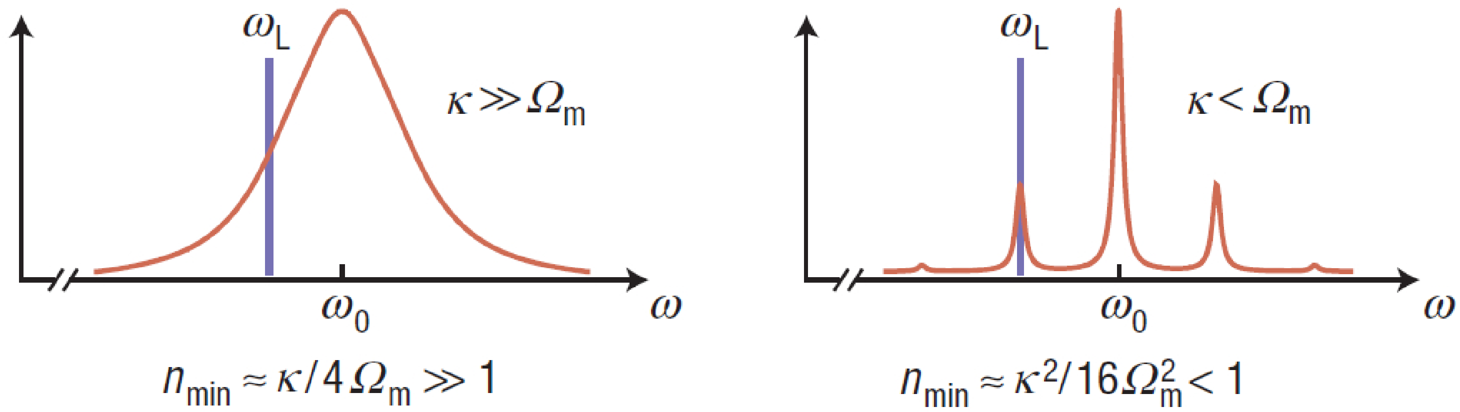


- The interaction Hamiltonian between cavity mode and mechanical mode is

$$\mathrm{H}_I = g a^\dagger a \left(b^\dagger + b\right)$$

- Ref: Rev. Mod. Phys. 86, 1391 (2014)

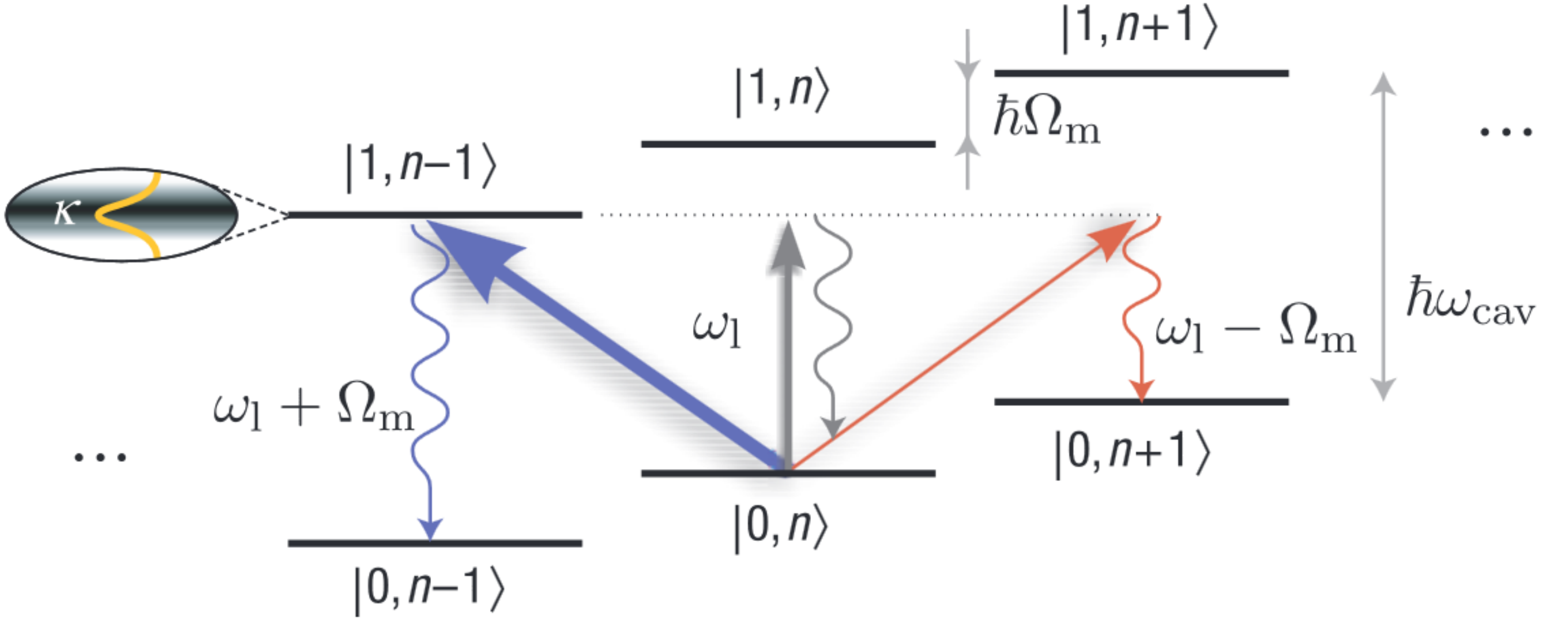
Sideband cooling of a mechanical resonator



- If the cavity decay rate is larger than the mechanical oscillation frequency, the final phonon number is larger than 1
- If the cavity decay rate is less than the mechanical oscillation frequency, the final phonon number is less than 1 (in quantum regime)

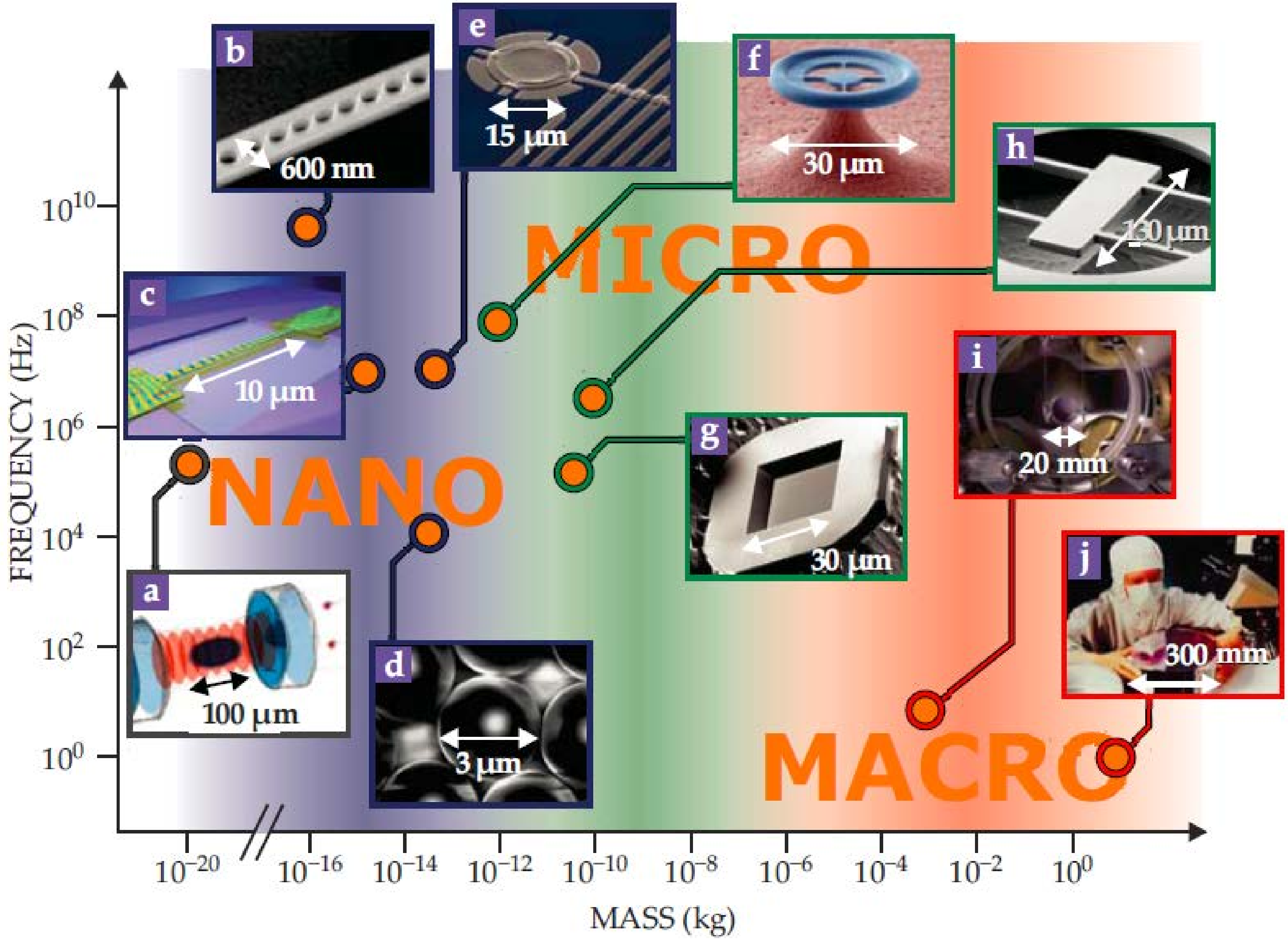
- In 2011, NIST and Caltech groups realized quantum ground state cooling in optomechanics/electromechanics

Sideband cooling



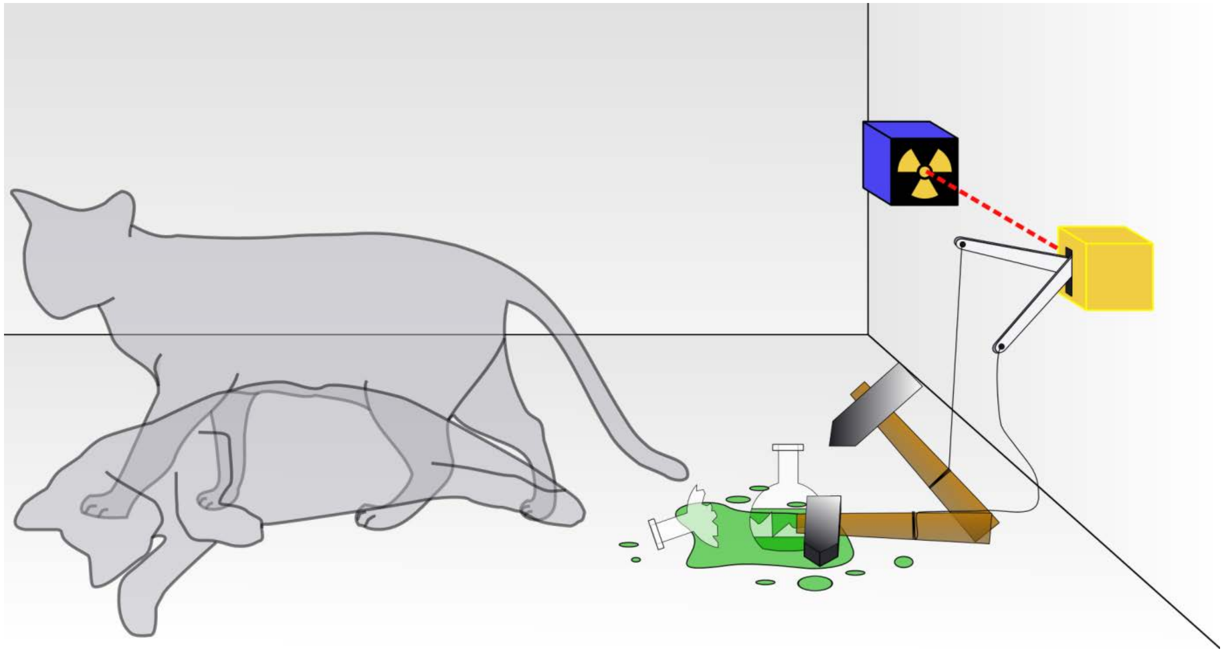
n: phonon number

Quantum optomechanics



"Quantum Optomechanics," M. Aspelmeyer, P. Meystre, and K. Schwab, Physics Today 65, 29 (2012).

Schrödinger's cat



Wikipedia

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{live}, 1\rangle + |\text{dead}, 2\rangle\right)$$

Erwin Schrödinger, 1935

The Copenhagen interpretation of quantum mechanics implies that after a while, the cat is simultaneously alive and dead. Yet, when one looks in the box, one sees the cat either alive or dead, not both alive and dead.

Debates and interpretations

- Schrödinger equation cannot explain
  - Wavefunction collapse.
- Decoherence
  - Interaction between system and environment
  - Gravity induced decoherence
- Many-worlds interpretation

- Superposition and mind
  -- Quantum suicide
  -- Quantum consciousness.
  -- Quantum long living

Bringing quantum mechanics to life

- 1944: “What is life” by E. Schrödinger

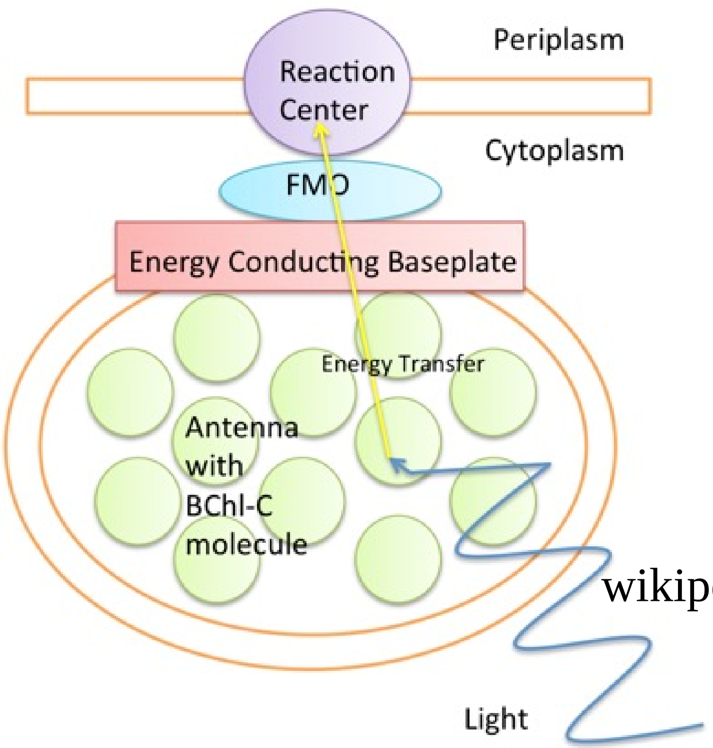
believed our body fully obeyed the laws of quantum mechanics

introduced the idea of an "aperiodic crystal" that contained genetic information in its configuration of covalent chemical bonds

Both James D. Watson and Francis Crick, co-discoverers of the double helix structure of DNA in 1953, credited Schrödinger's book with presenting an early theoretical description of how the storage of genetic information would work.

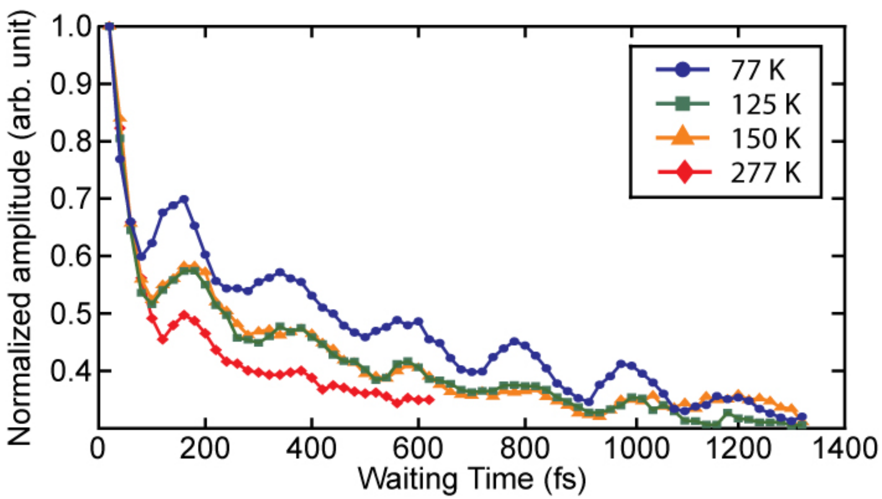
Quantum coherence in biological processes

Photosynthesis



wikipedia

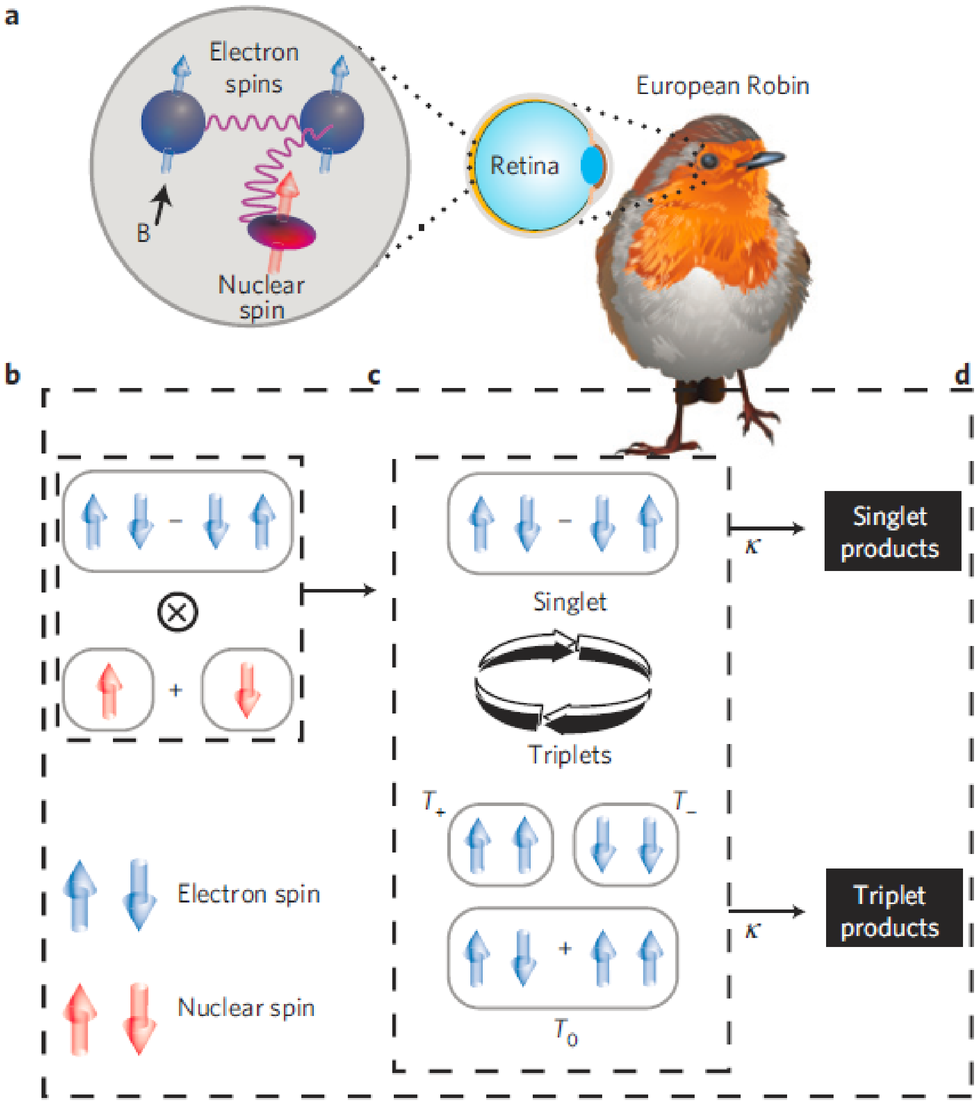
The transfer of an exciton from an antenna that absorbs light to the reaction center in photosynthesis.



G. Panitchayangkoon, et al. Proc. Natl Acad. Sci. USA 107, 12766-12770. (2010)

Expert at Purdue: Prof. Sabre Kais

Quantum coherence in biological processes

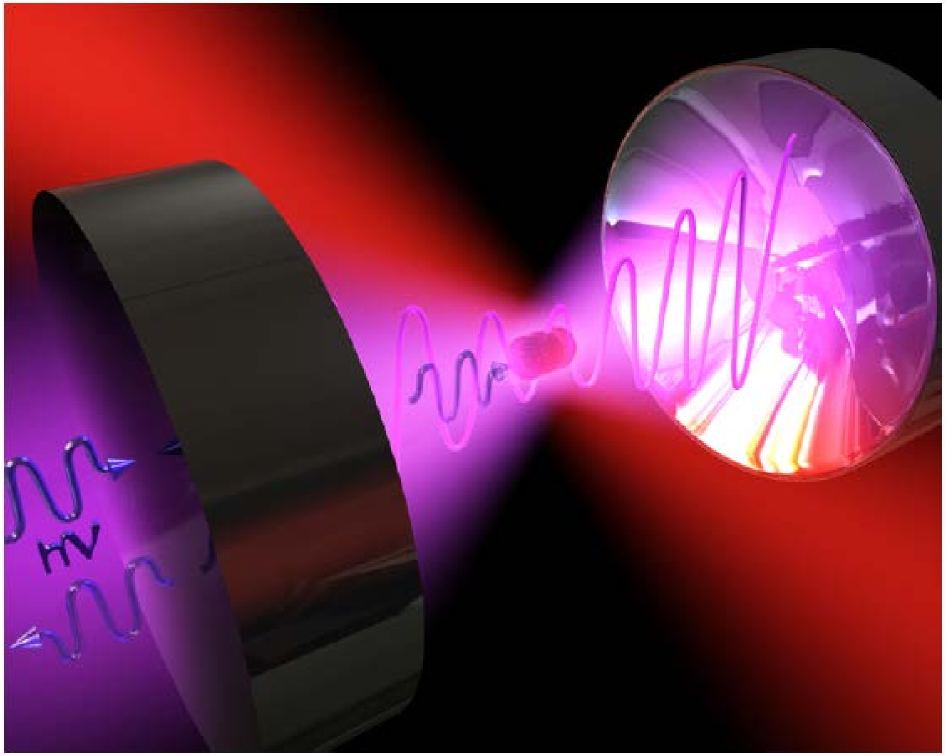


Avian magnetoreception

- First, light-induced electron transfer from one radical-pair-forming molecule to an acceptor molecule creates a radical pair.
- Second, the singlet (S) and triplet (T) electron-spin states inter-convert owing to the external (Zeeman) and internal (hyperfine) magnetic couplings.
- Third, singlet and triplet radical pairs recombine into singlet and triplet products, respectively, which are biologically detectable.

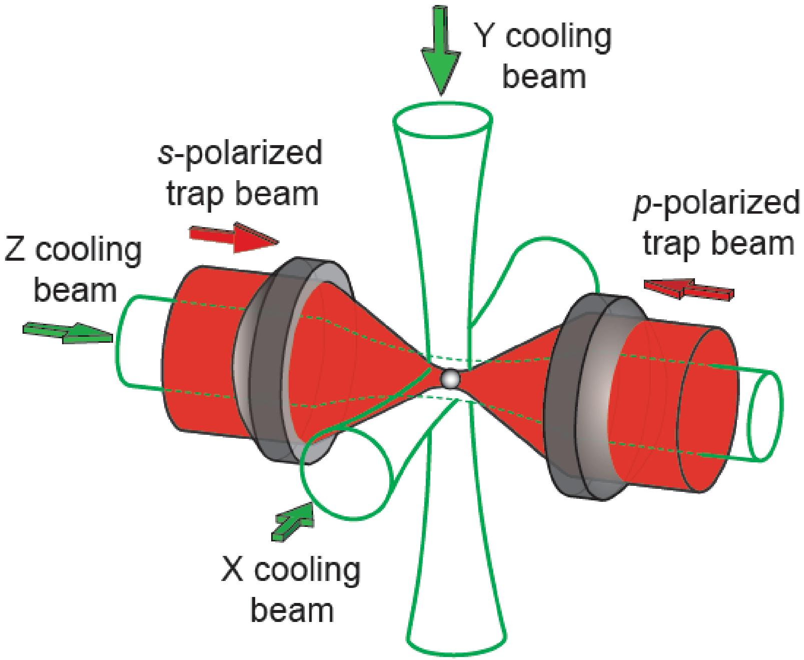
NATURE PHYSICS 9, 10 (2013)

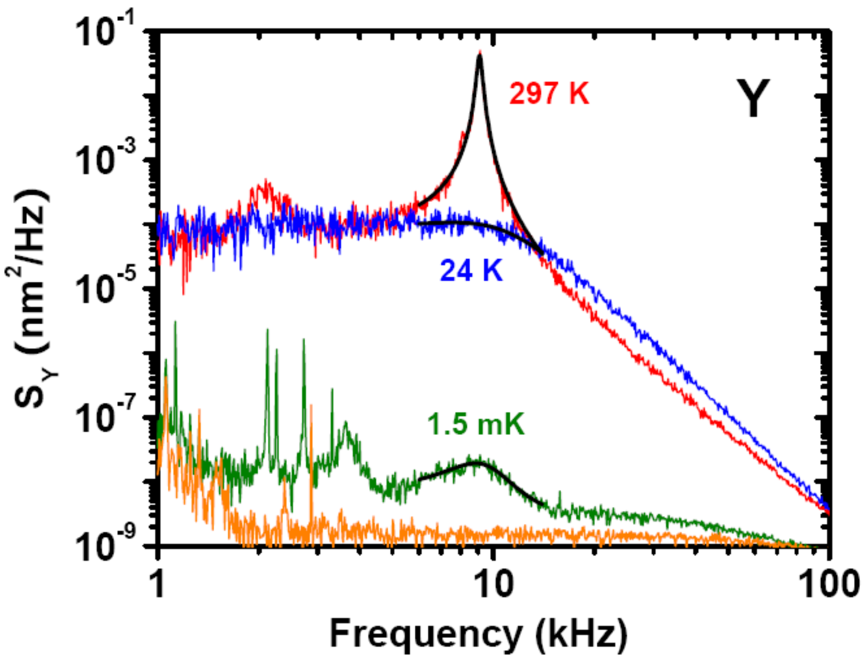
Towards quantum superposition of an optically levitated microorganism



O. Romero-Isart, M. L. Juan, R. Quidant, J. I. Cirac. ***New. J. Phys.*** 12 (2010), pp. 033015.

Feedback cooling

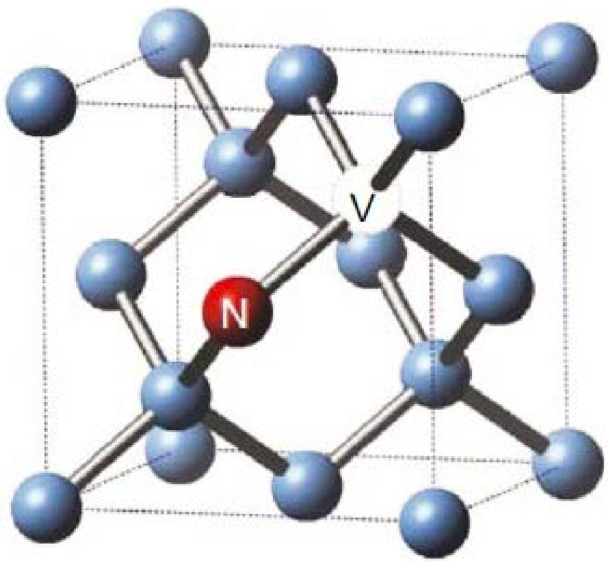


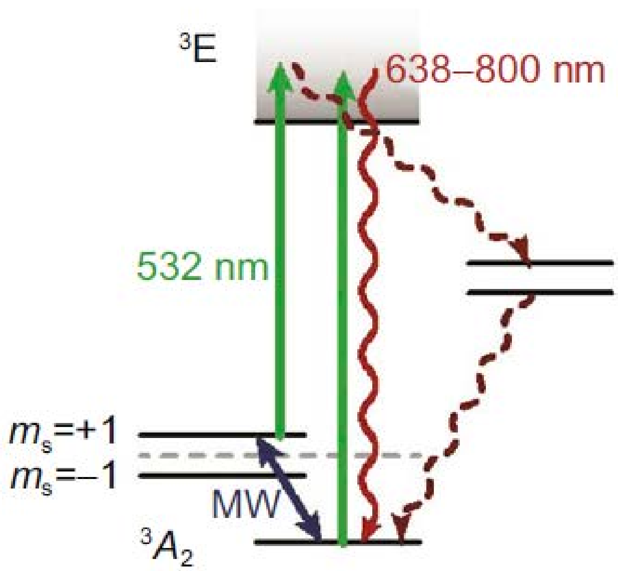


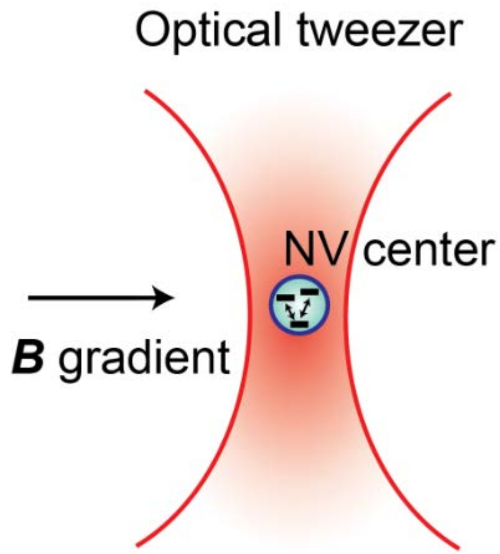
T. Li, S. Kheifets, D. Medellin, M. G. Raizen, **Science,** 328, 1673 (2010)

T. Li, S. Kheifets, M. G. Raizen. ***Nature Physics***, 7, 527 (2011)

A nanodiamond with a NV center: an artificial atom







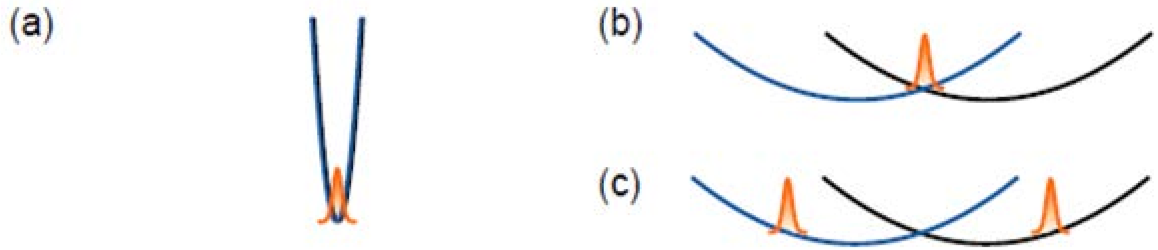
N. Bar-Gill, et al.. Nat. Commun., 3, 858 (2012).

Z.-Q. Yin, T. Li, X. Zhang, and L. M. Duan. Phys. Rev. A, 88, 033614 (2013).

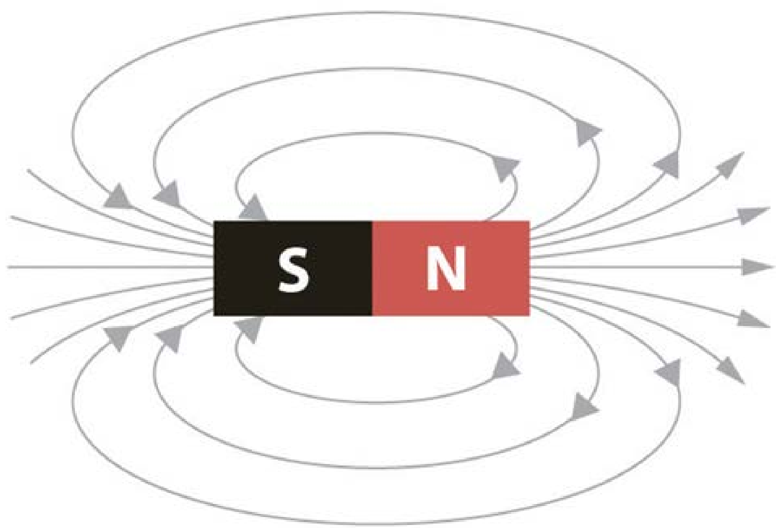
Schrödinger's cat state of a nanodiamond

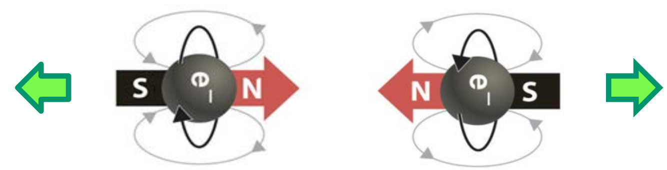
Electron spin

$$(|+1\rangle + |-1\rangle)/\sqrt{2}$$



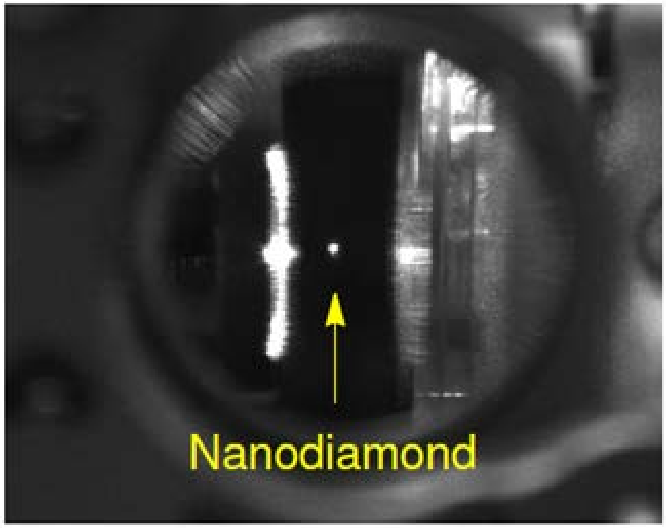
"Stern–Gerlach experiment" with a nanoparticle

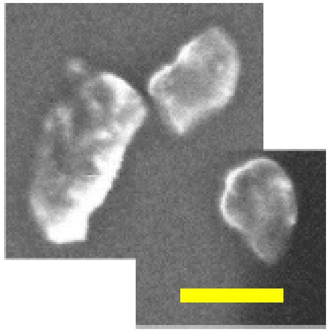




Z.-Q. Yin, T. Li, X. Zhang, and L. M. Duan. Phys. Rev. A, 88, 033614 (2013).

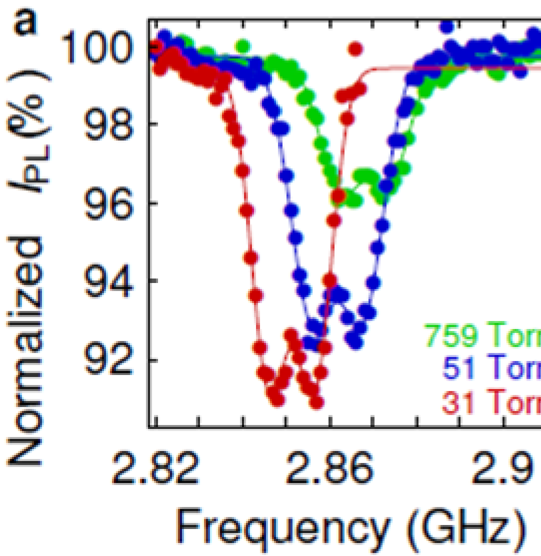
Our progresses at Purdue University





100 nm

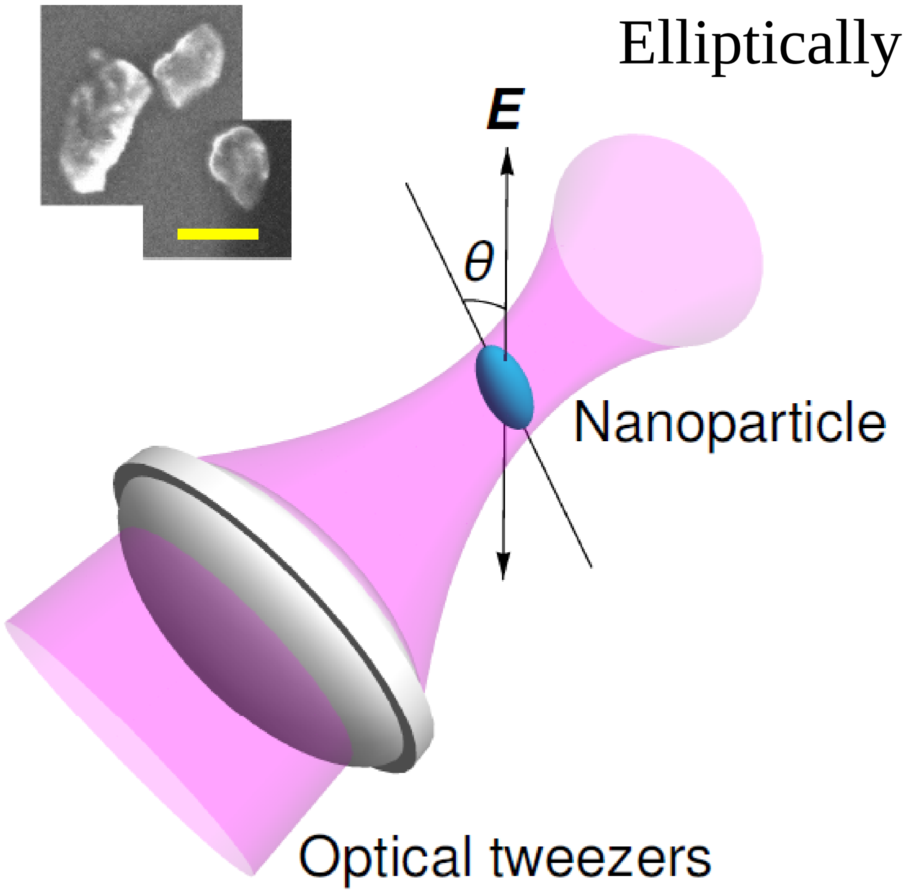
Electron spin resonance (ESR)

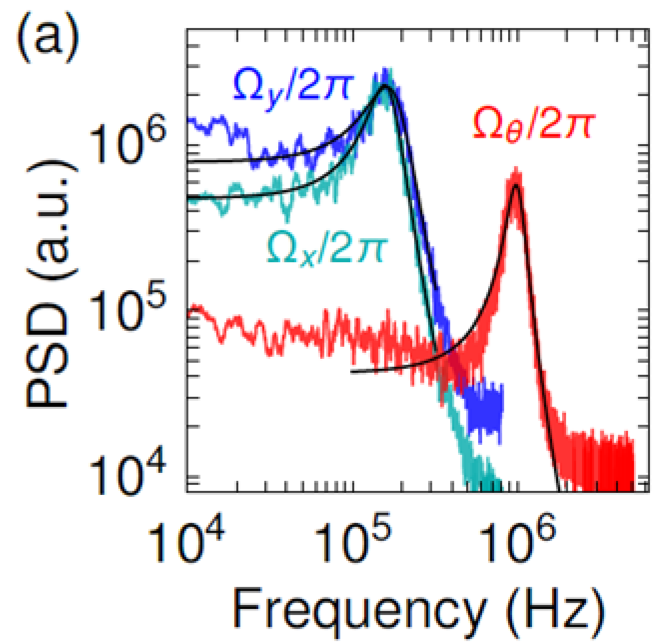


T. M. Hoang, J. Ahn, J. Bang, T. Li. ***Nature Communications*** 7, 12550 (2016)

Angular trapping and torsional optomechanics

Elliptically polarized





Linearly polarized

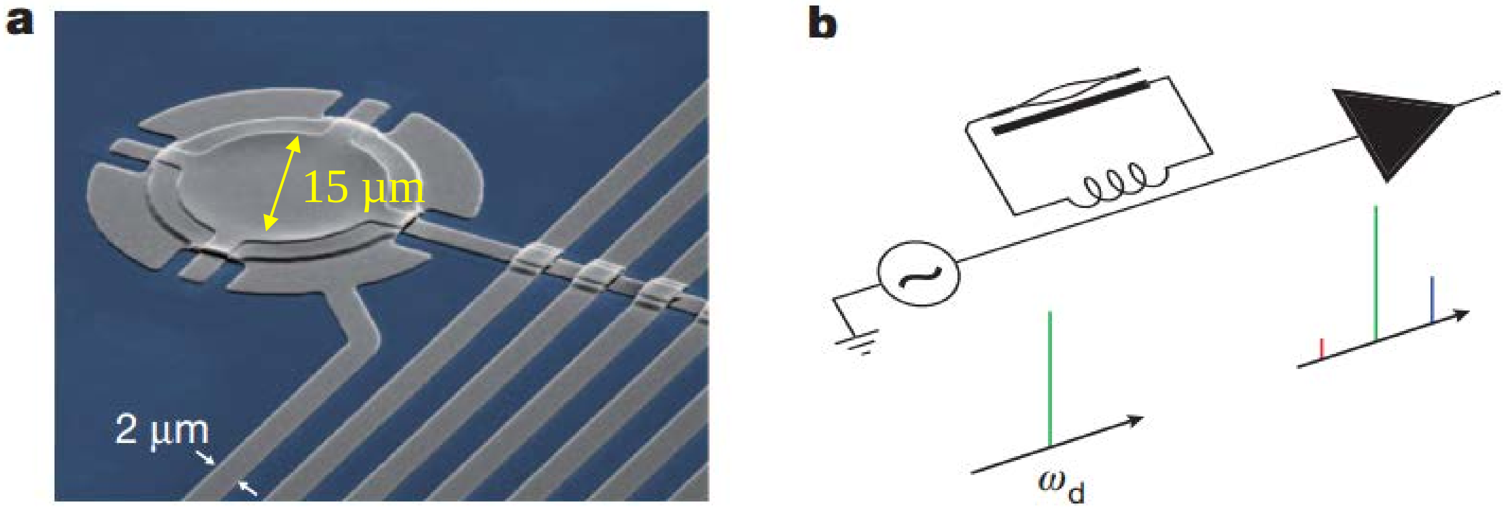
T. M. Hoang, Y. Ma, J. Ahn, J. Bang, F. Robicheaux, Z.-Q. Yin, T. Li. ***Phys. Rev. Lett.*** 117, 123604 (2016)

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

T. Li, Z.-Q. Yin. ***Science Bulletin***, 61:163–171 (2016).

Z.-Q. Yin, T. Li. ***Contemporary Physics*** (accepted) arXiv:1608.05322 (2016)

Electromechanical oscillators

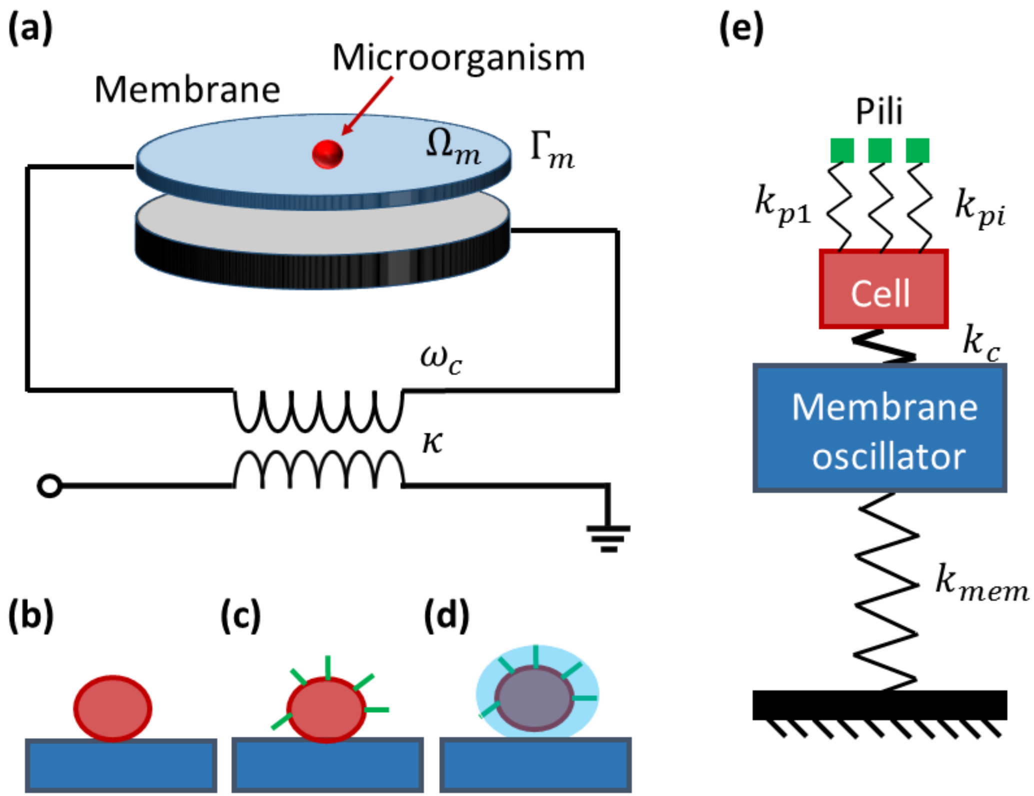


Quantum ground state cooling: J. D. Teufel et al, ***Nature*** 475, 359 (2011).

Entangling the motion of the membrane and a microwave field:
T. A. Palomaki, et al. ***Science*** 342,710 (2013)

Our scheme

Cryopreserved bacterium



T. Li, Z.-Q. Yin. ***Science Bulletin***, 61:163–171 (2016).

Quantum superposition of the center-of-mass motion

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}

- Most microbes can be cryopreserved without losing viability
- The mass of many microbes are much smaller than the mass of the metallic membrane that has been cooled to the quantum regime
- A microbe will stick to the membrane by van der Waals force.

T. Li, Z.-Q. Yin. ***Science Bulletin***, 61:163–171 (2016).

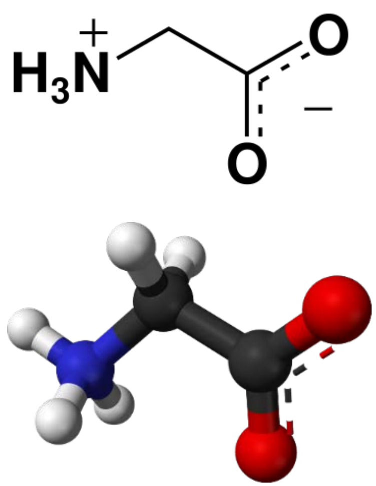
Why?

- **Have fun!**

- It is interesting to realize Schrödinger's cat state with a living organism.
- It can study the effects of biochemical (metabolic) processes on quantum superposition.
- It may provide the first step towards quantum superposition of living objects under physiological conditions.

Then?

Detect and study individual radicals



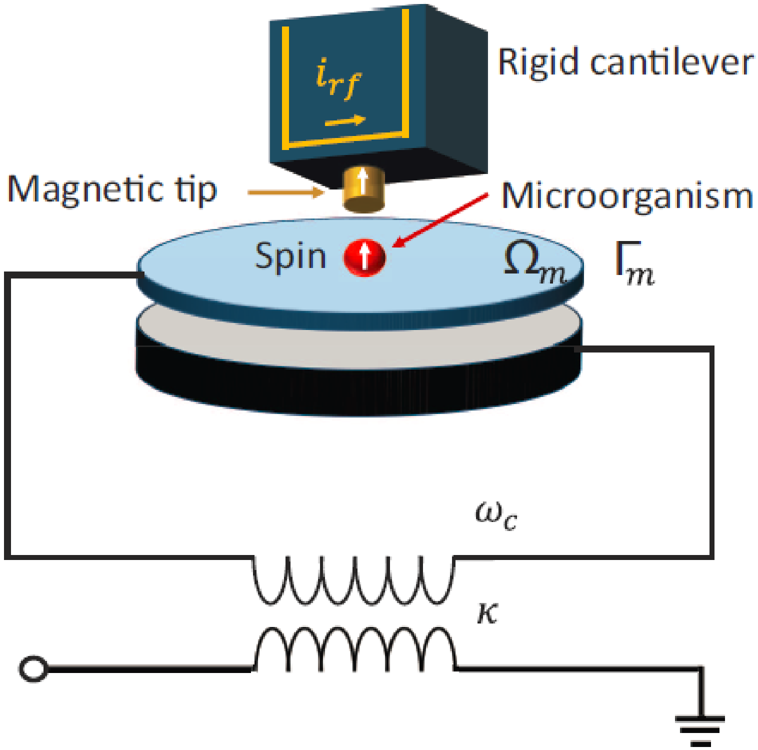
glycine radical

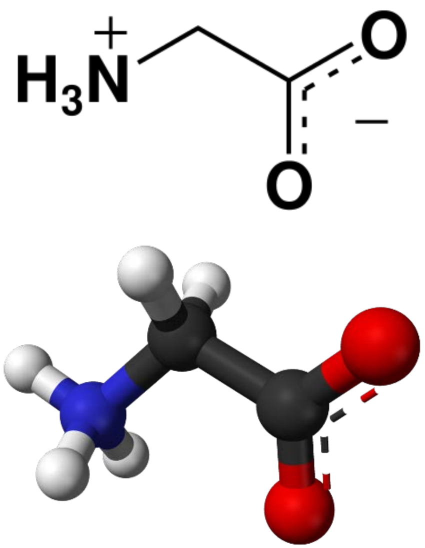
Radicals are produced during biochemical reactions, by radiation damage etc.

The protein structures are maintained when a bacterium is cryopreserved.

- The smallest amino acids is glycine.
- The relaxation time of the electron spin of a glycine radical is about 0.31 s at 4K, and the coherent time is 6 μs at 4K.
- The coherent time can be dramatically increased by reducing the temperature to 10 mK.
- We can also use dynamical decoupling to increase the coherent time.

Potential application: to detect single radicals





Glycine radical

T. Li, Z.-Q. Yin. ***Science Bulletin***, 61:163–171 (2016).

Hamiltonian of radical electrons in a magnetic field

$$H_e = \sum_{i}^{N} \hbar g_s \mu_B S_i(\vec{x}_i) \cdot B(\vec{x}_i)$$

- The magnetic field $B(\vec{x}_i)$ has a large gradient.
- The magnetic field should be larger than 18 mT to have a energy splitting larger than 500 MHz, which is required to maintain the spin in its ground state at 10 mK.
- We can use superconductor niobium (Nb), which has a critical magnetic field of 100 mT.

Magnetic gradient induced coupling

The single phonon-single spin coupling strength:

$$\lambda = g_s \mu_b |G_m| x_0' / \hbar$$

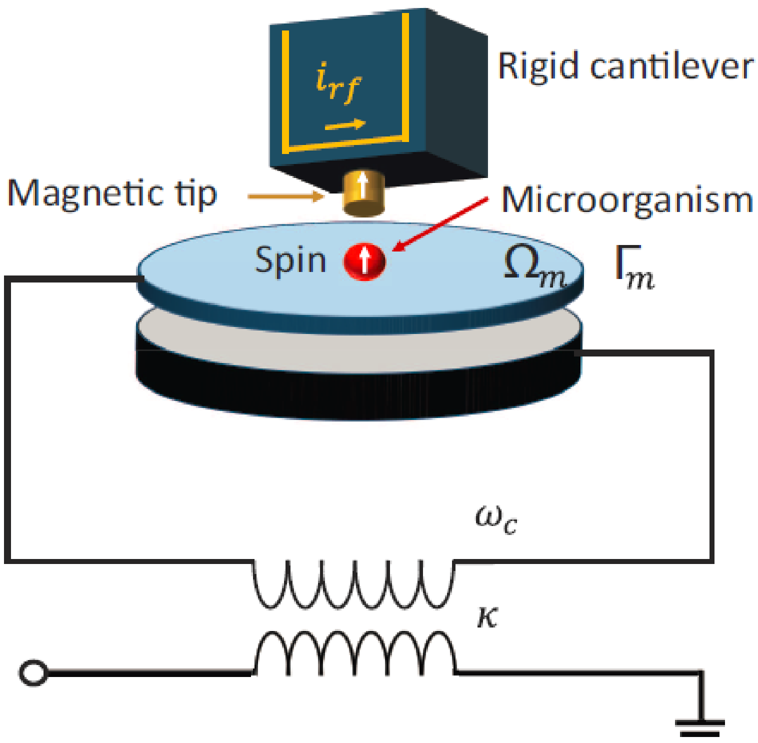
Where $G_m = \partial B(\vec{x}_i)/\partial \vec{x}_i$， x_0' is the amplitude of zero-point fluctuation.

We will apply a microwave drive. The frequency is close to the resonant frequency of an electron. The Rabi oscillation frequency is close to the mechanical frequency of the oscillator.

Due to the large magnetic field gradient, we only need to consider one electron:

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

Detecting radical electron spins



The energy splitting of electron spin states:

$$\omega_{eff} = \sqrt{\Delta_e^2 + \Omega_d'}$$

$$\Delta_e = \omega_d' - \omega_1$$

Nature **430**, 329-332 (15 July 2004)

Manipulating radical electrons spins

- Effective coupling Hamiltonian between electron spin and the mechanical vibration:

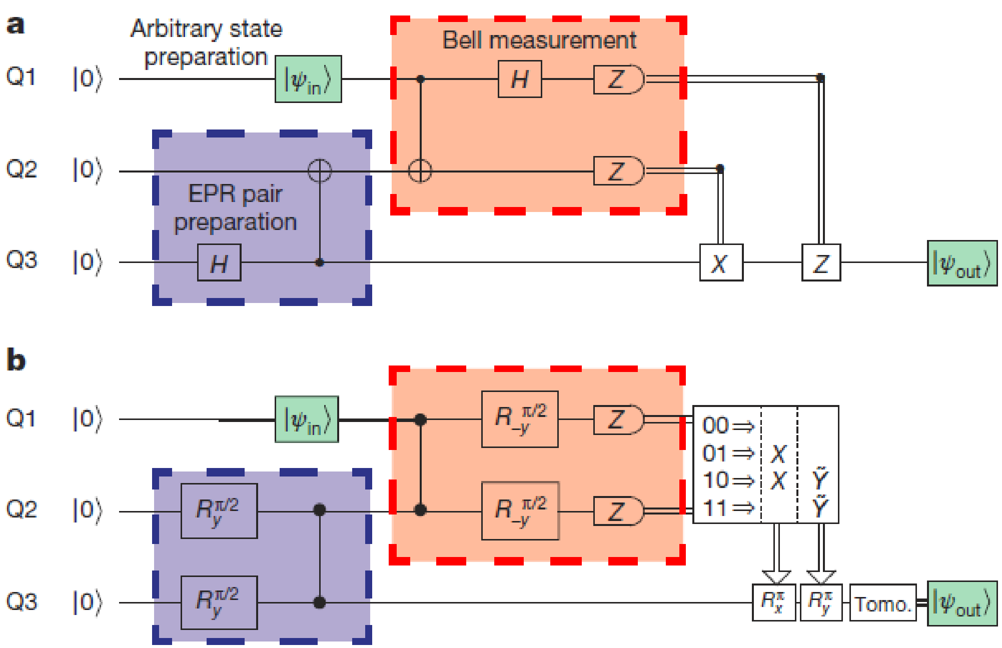
$$H_I = \hbar\lambda\sigma_+ a_m + h.c.$$

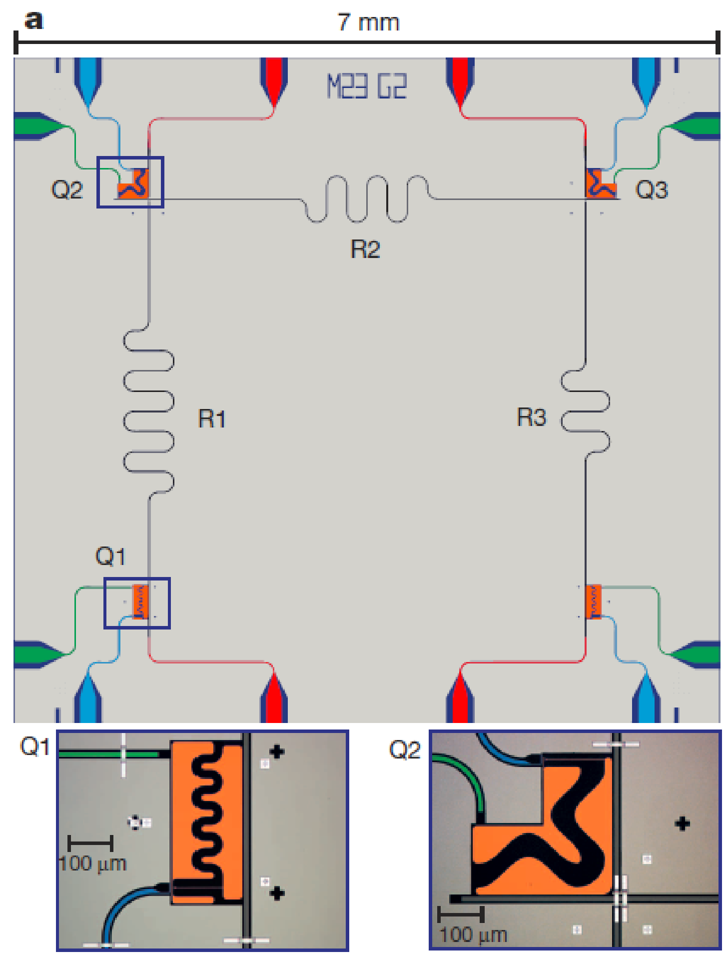
- State transfer and generation of entangled states.
- Can be used to probe the local environment of the electron spin.

- Parameters:

$$\omega_m = 2\pi \times 10MHz, x_0' = 8.4fm, G_m = 10^6\text{T/m}, \lambda = 14.8\text{ kHz}$$

Quantum teleportation with a superconducting circuit





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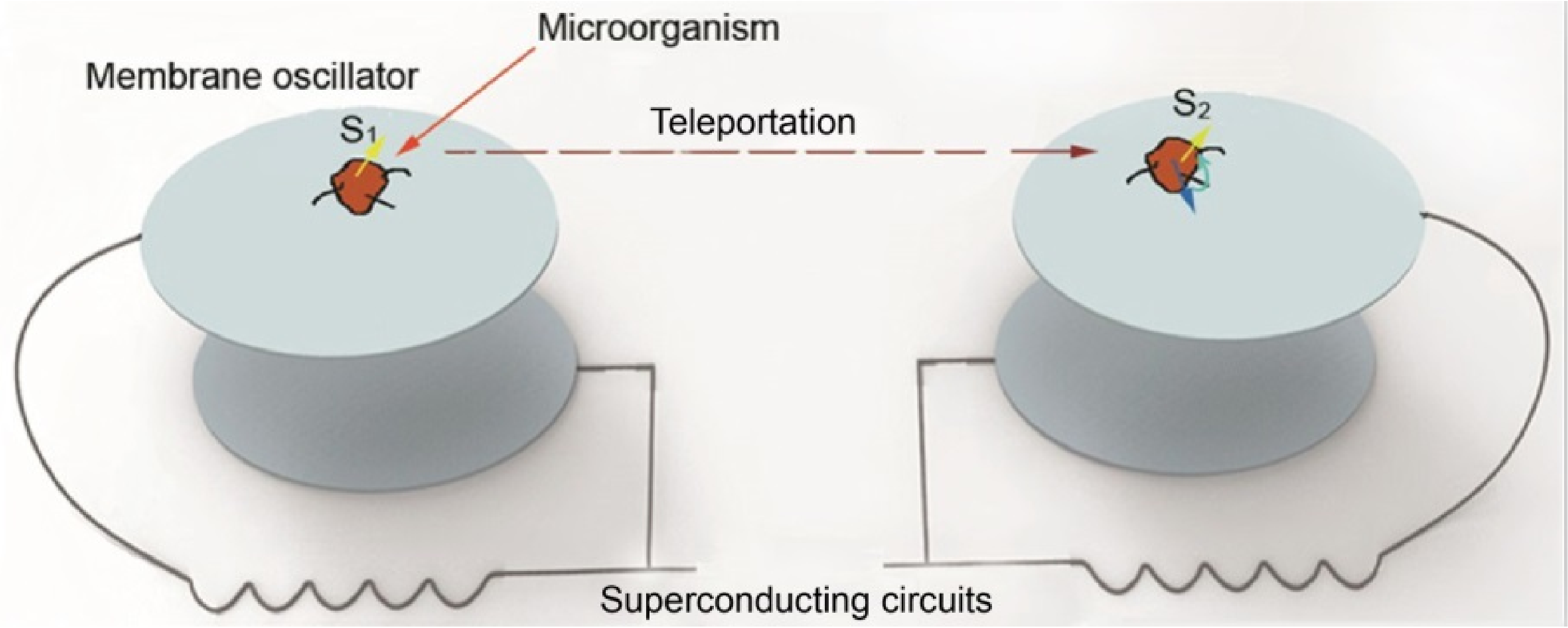
Quantum teleportation between two microbes



T. Li, Z.-Q. Yin. ***Science Bulletin***, 61:163–171 (2016).
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Forbes: 10 Quantum Truths About Our Universe

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PHYSICS

SHARING MEMORIES, THE QUANTUM WAY

PHYSICISTS REVEAL BOLD PLANS TO TELEPORT THE 'MEMORY' OF BACTERIA

In quantum physics, two particles can become entangled across vast distances, and even across time

PHOTO: SCIENCE PHOTO LIBRARY

We may still be a long way from Star Trek-style Vulcan mind melds, but we could soon be teleporting memories from one living thing to another. An international team from Purdue University, USA and Tsinghua University, China has published a paper detailing a potential method of teleporting quantum information, or 'memories', between two bacteria.

The technique relies on a phenomenon known as quantum superposition, in which particles exist in all possible states simultaneously until they are observed and fall into one known state. The most famous example of this was described in Erwin Schrödinger's famous thought experiment in which a cat is locked inside a box rigged with a poison delivery system triggered by a chunk of radioactive material. If the material decays, the poison is released and the cat dies; if the material doesn't decay, the poison stays put and the cat stays alive. But until the box is opened and we learn the fate of the cat, it is in a superposition of both alive and dead states.

ALBERT EINSTEIN FAMOUSLY DUBBED QUANTUM ENTANGLEMENT "SPOOKY ACTION AT A DISTANCE"

The experiment is also an example of another quantum mechanical phenomenon called entanglement. Famously dubbed "spooky action at a distance" by Albert Einstein, entanglement occurs when particles are connected in such a way that they their interactions can be predicted regardless of how far apart they are. In the Schrödinger's cat experiment, the state of the cat is said to be entangled with the state of the radioactive material. If we open the box and the cat is dead, we know the material has decayed.

In 2013, researchers at the University of Colorado successfully put an aluminium membrane into a superposition of states by rapidly vibrating it. By cooling a bacterium down to just above absolute zero to cut down its chemical activity and placing it on top of such a membrane, the team at Purdue believe they can put it into a superposition state, effectively meaning it will be in two places at once.

Next, they plan to take advantage of entanglement to join together information about the bacterium's internal state and motion and quantum teleport it to a second bacterium.

"We propose a straightforward method to put a microorganism in two places at the same time, and provide a scheme to teleport the quantum state of a microorganism," said researcher Tongcang Li. "I hope our unconventional work will inspire more people to think seriously about quantum teleportation of a microorganism and its potential applications in future."

Quantum teleportation has already been demonstrated with photons, atoms and superconducting circuits but so far, never with a living organism.

ABOVE: In a prior experiment, photons were guided from one diamond to another using optical equipment

BELOW: Tongcang Li of Purdue University in Indiana, who was involved in the research

PHOTOS: TU DELFT, ROY KALTSCHMIDT/BERKELEY LAB

HOW IT WORKS

BEFORE TELEPORTATION

Entanglement allows particles to be teleported from one place to another. The 'source' particle to be transported is allowed to interact with one of a pair of entangled particles, whose partner (the 'receiver') is then dispatched, physically, to the destination.

SENDER: SOURCE PARTICLE, ENTANGLED PARTICLE 1 (E1) ⟺ RECEIVER: ENTANGLED PARTICLE 2 (E2)

TELEPORTATION BEGINS

The 'source' then has all its properties beamed to the receiver by two routes: some directly, and some via the receiver's entangled partner. This circumvents the uncertainty principle, which forbids perfect knowledge of all a particle's properties simultaneously. The receiver particle now has the same properties as the source.

SENDER: SOURCE PARTICLE, ENTANGLED PARTICLE 1 (E1), MEASURES, INFO → RECEIVER: E2 ⟹ TRANSFORMS E2 INTO SOURCE PARTICLE

Thank you!