

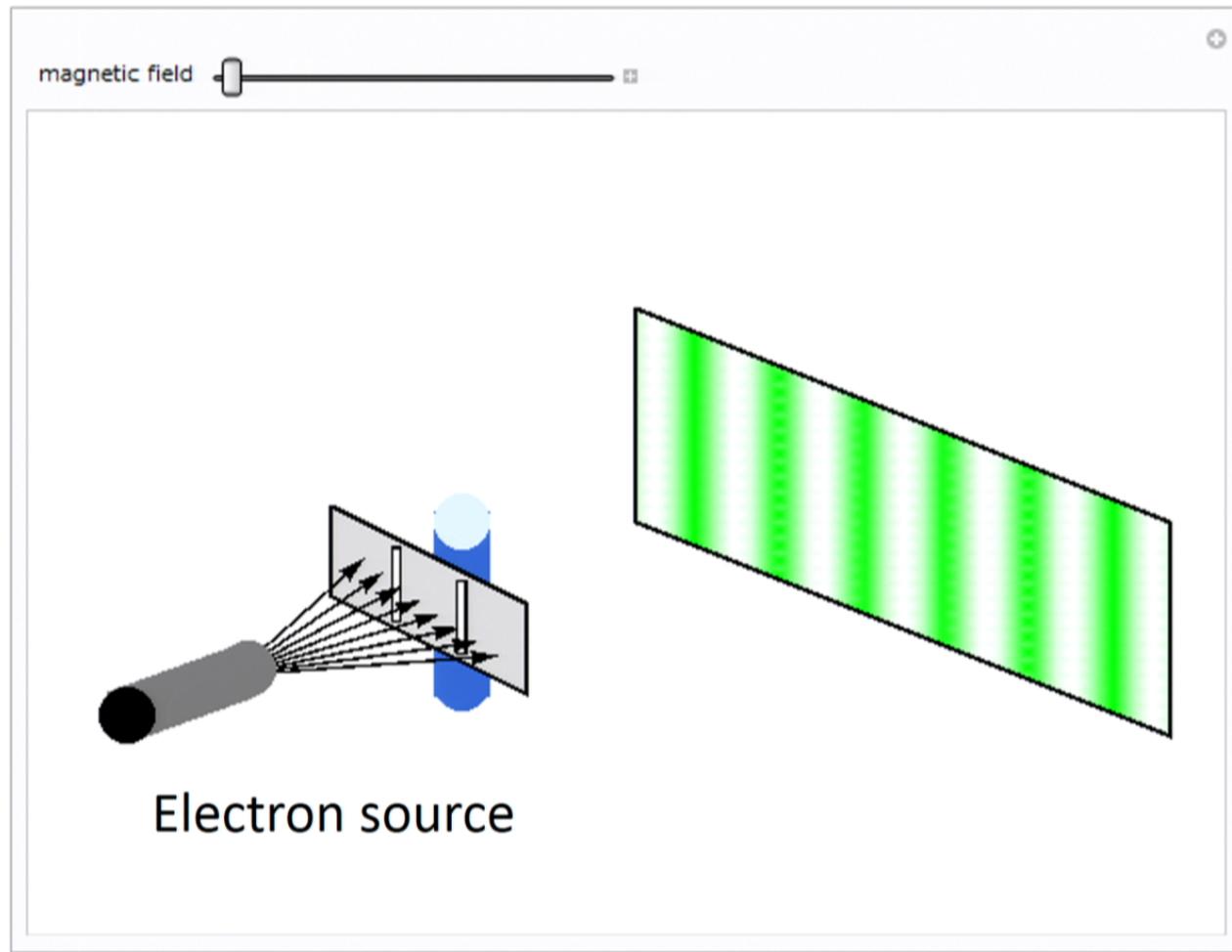
Title: Observation of Aharonov-Bohm effect with quantum tunneling

Date: Jun 20, 2016 02:30 PM

URL: <http://pirsa.org/16060038>

Abstract: Quantum tunneling is one such phenomenon that is essential for a number of devices that are now taken for granted. However, our understanding of quantum tunneling dynamics is far from complete, and there are still a number of theoretical and experimental challenges. The dynamics of the quantum tunneling process can be investigated if we can create a large tunneling region. We have achieved this using a linear Paul trap and a quantum tunneling rotor, which has resulted in the successful observation of the Aharonov-Bohm effect in tunneling particles. Also, this result shows that the spatially separated phonon can be interfered.

Aharonov-Bohm Effect



Credit: Mathematica

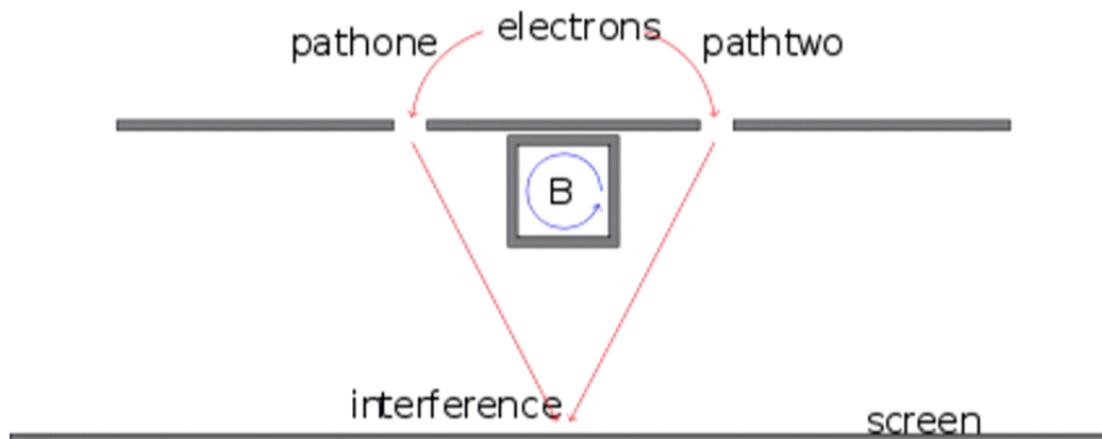
$$\hat{H} = \frac{1}{2m} (\hat{p} - qA(x, t))^2 + q\phi(x, t)$$

Gauge invariant condition

$$\longrightarrow \psi'(x, t) = \exp \left[i \frac{q}{\hbar} \Lambda(x, t) \right] \psi(x, t)$$

Two-path phase difference

$$\delta\phi = \frac{q}{\hbar} \int_P A \cdot dx - \frac{q}{\hbar} \int_{P'} A \cdot dx = \frac{q}{\hbar} \oint A \cdot dx = \frac{q}{\hbar} \int B \cdot d^2x$$



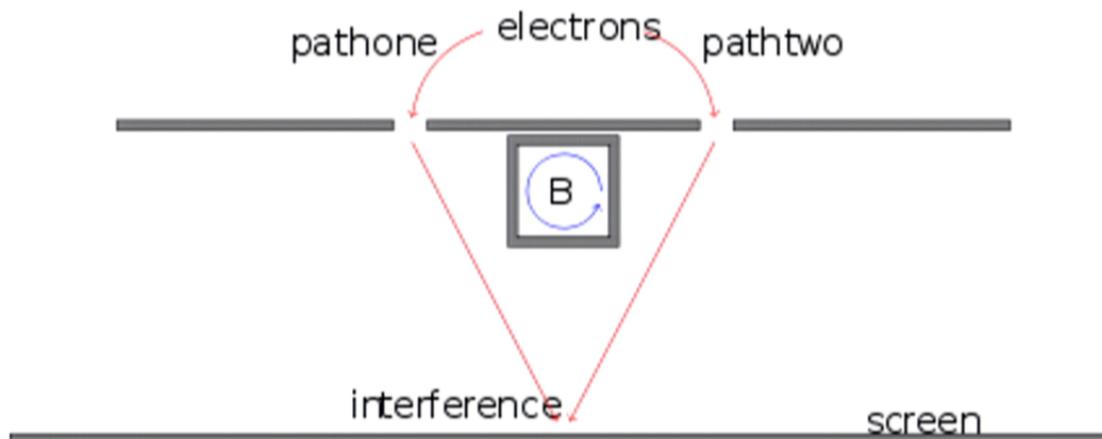
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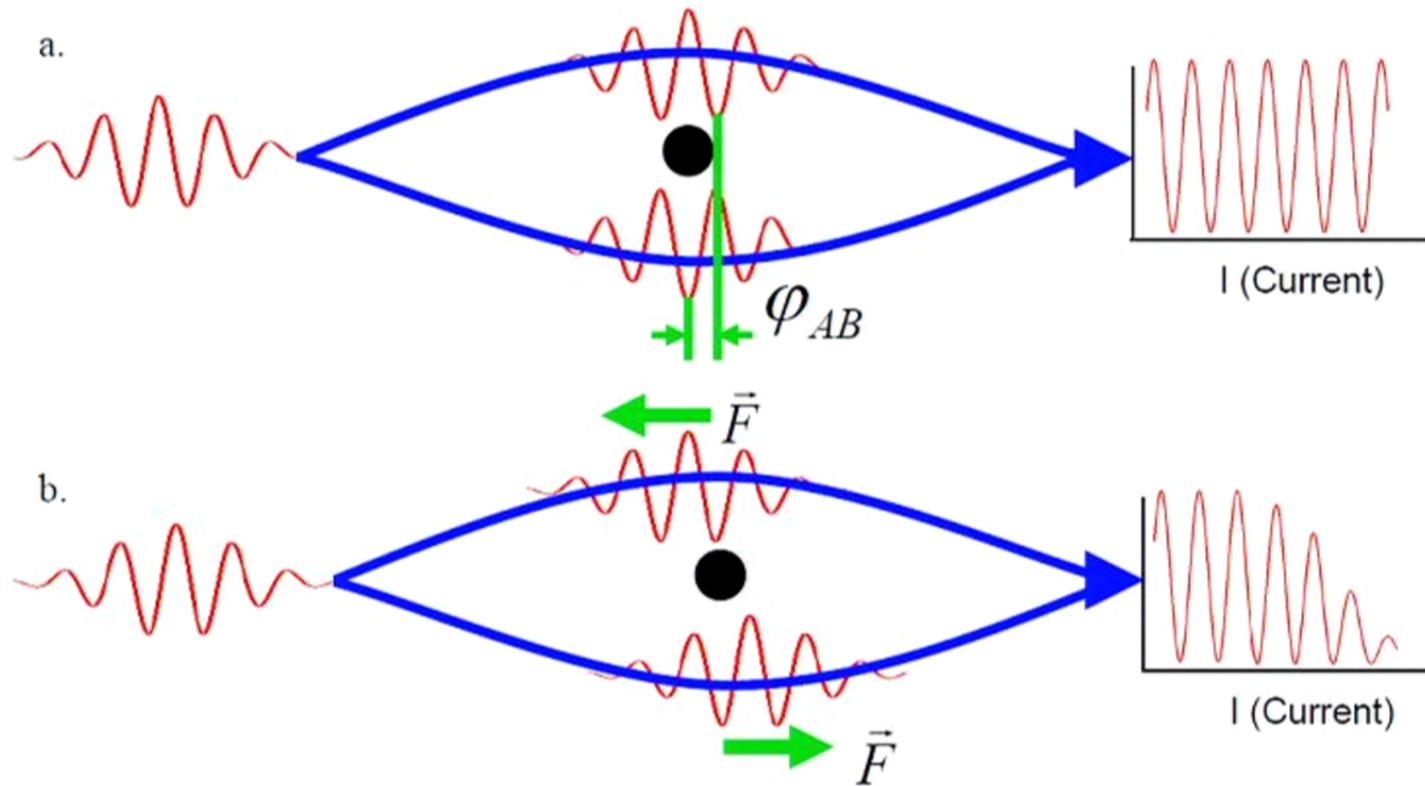
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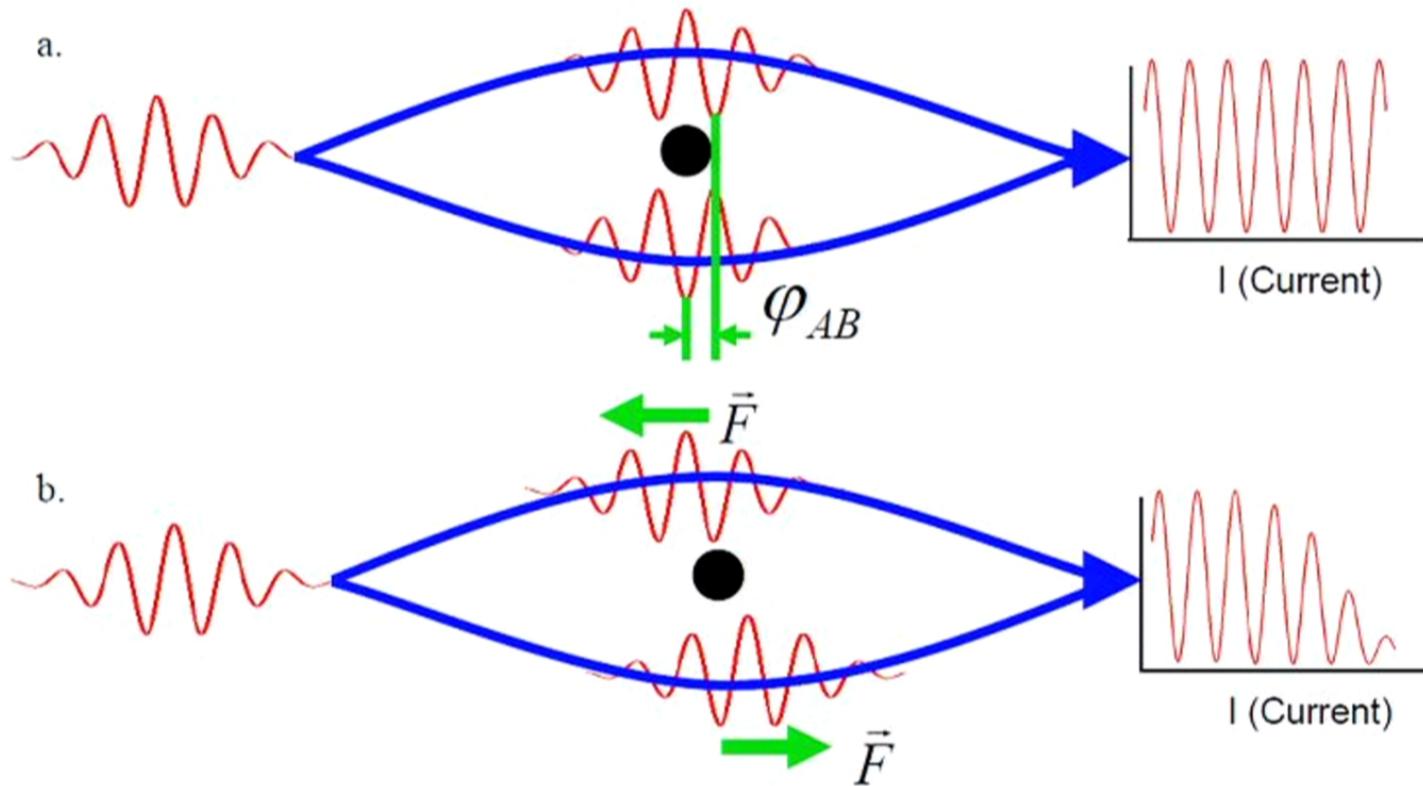
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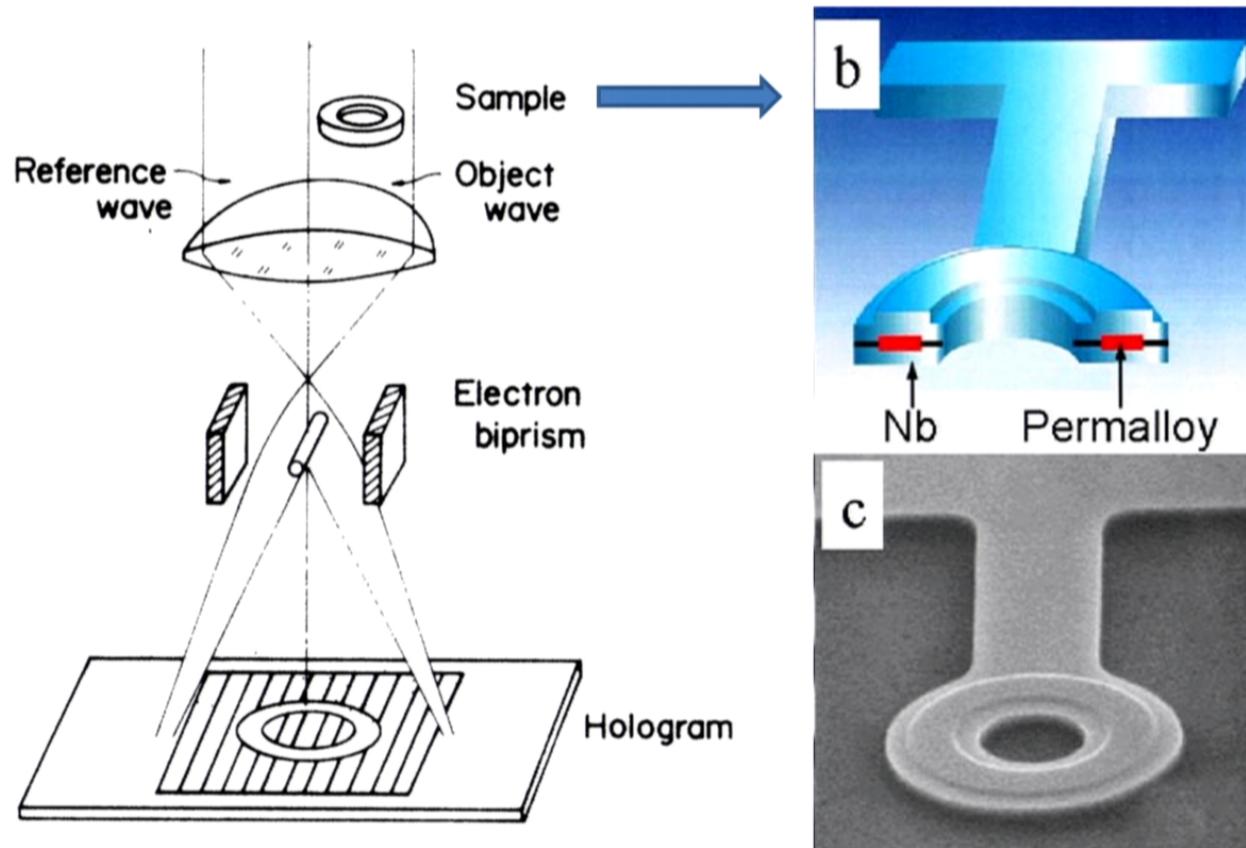
AB effect vs Lorenz force



AB effect vs Lorenz force



Superconducting toroidal magnet



1986 Tonomura et al. experiment



Increasing the magnetic flux

History talked by Yakir
PIRSA:16060082



This phase shift cannot be explained by the
Lorenz force = evidence of AB effect.

Collaborators



Atsushi Noguchi
(Osaka University
-> University of
Tokyo)



Kenji Toyoda
(Osaka University)



Shinji Urabe
(Osaka University)

Experiment was done in Osaka University.



Ion trap

Charged particles are trapped by the electric fields.

With static field : 3D confinement is impossible $\Delta\phi = 0$

$$U = e\phi$$

Ion trap

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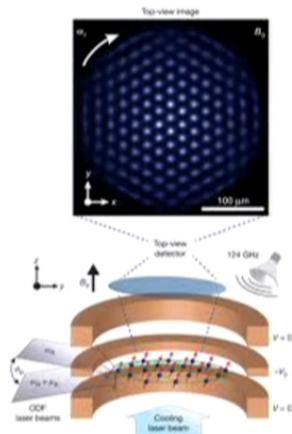
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H. Dehmelt



Static electric field
+ Static magnetic field
Penning Trap



W. Joseph, et. al., Nature, 484, 489 (2012)

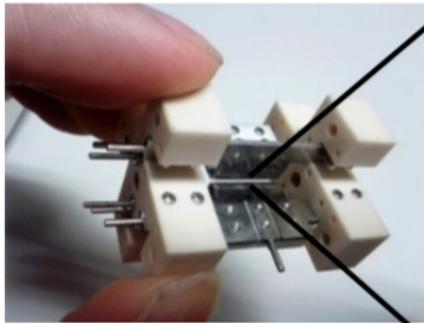
Coulomb crystal

In the linear Paul trap, the potential is expressed as

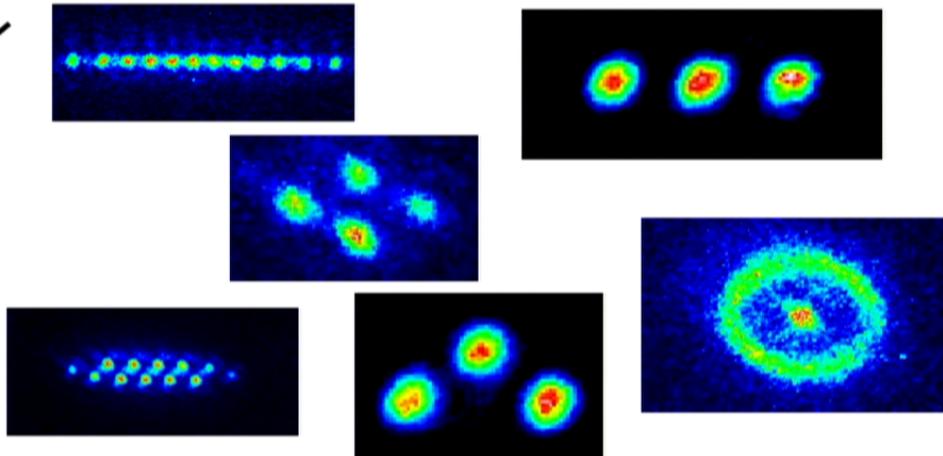
$$U = \sum_i \sum_{k=x,y,z} \frac{1}{2} m \omega_k^2 u_{k,i}^2 + \sum_{i,j} \frac{e^2}{4\pi\epsilon_0} r_{i,j}^{-1}$$

confinement Coulomb interaction

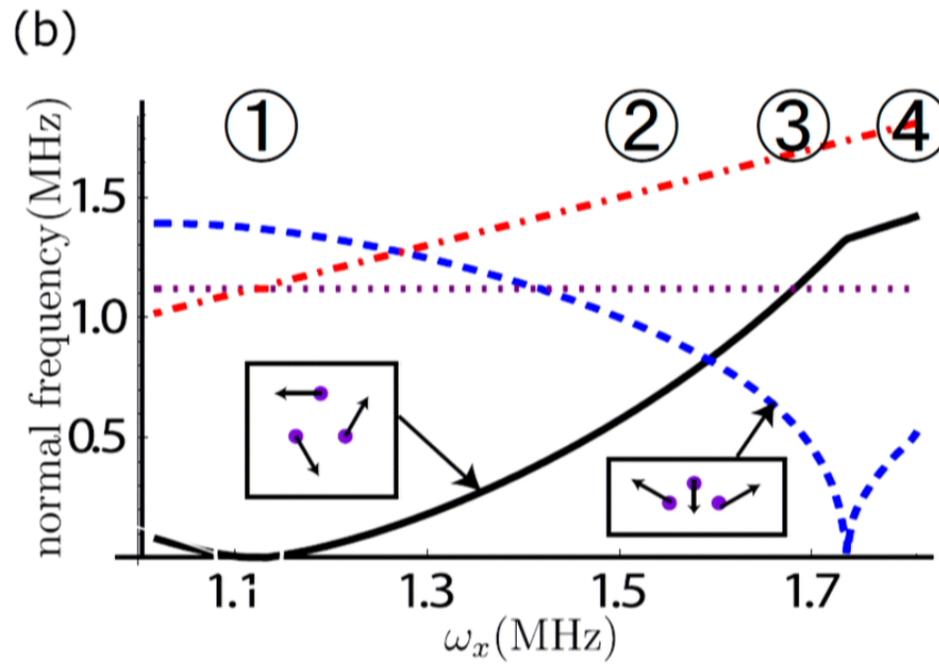
Trapped ions ($^{40}\text{Ca}^+$) are crystalized at low temperature.



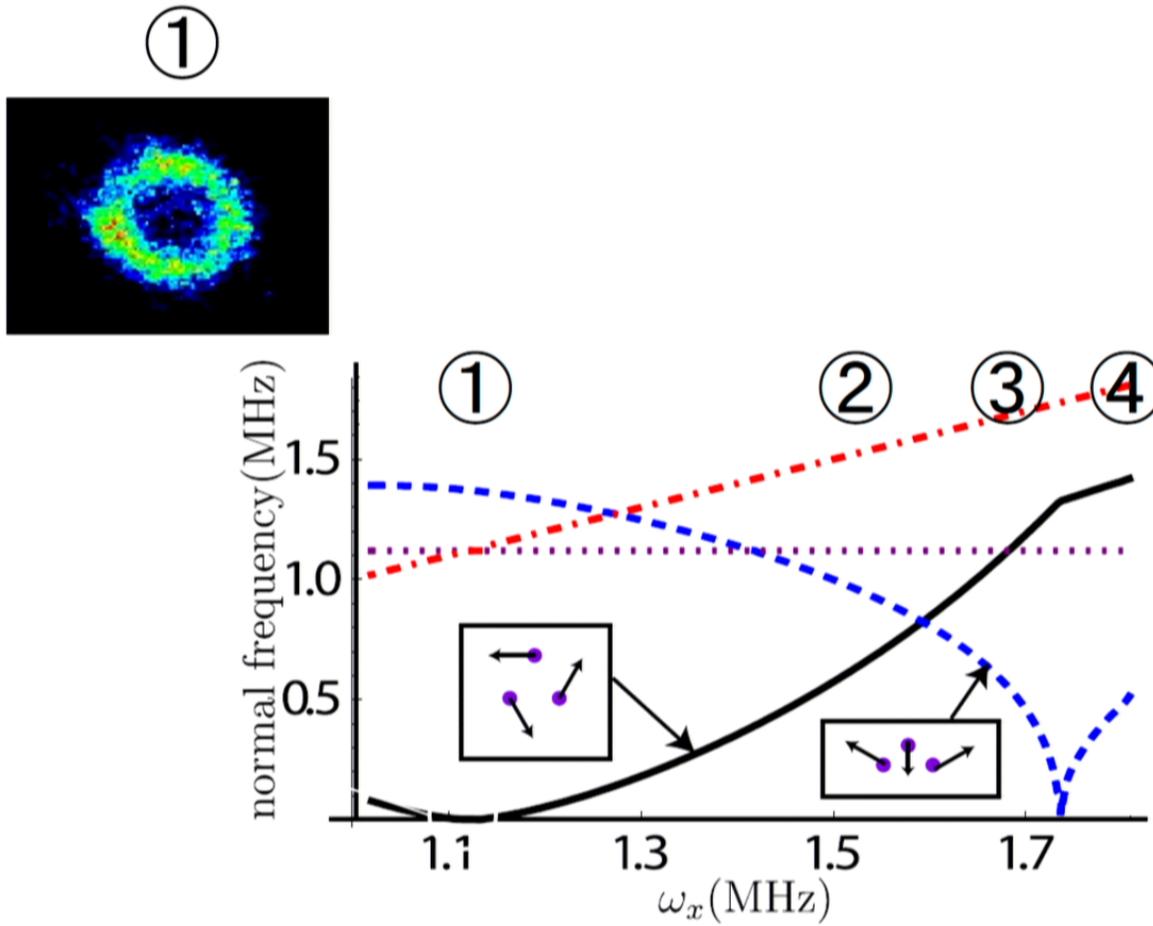
S. Fishman et. al., *PRB* **77**, 064111 (2008).



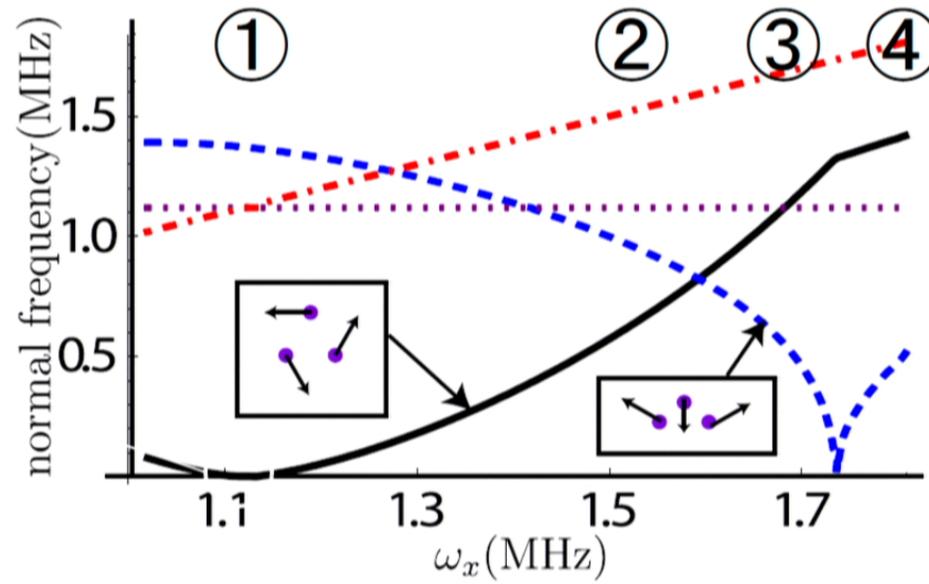
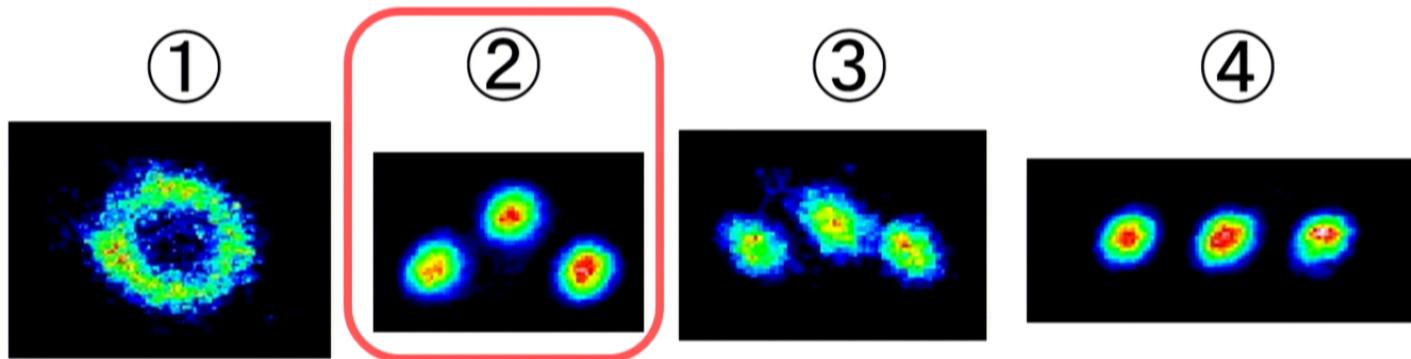
Our configuration



Our configuration

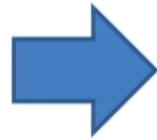
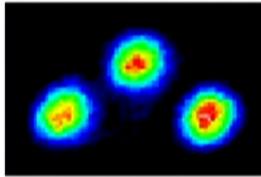


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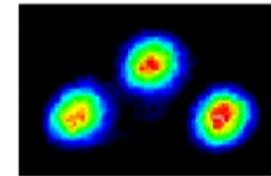
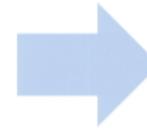
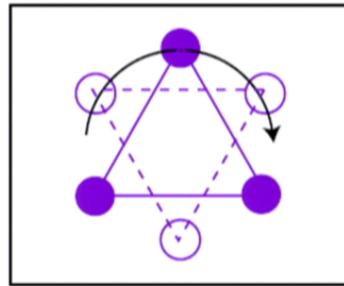


Experimental Procedures

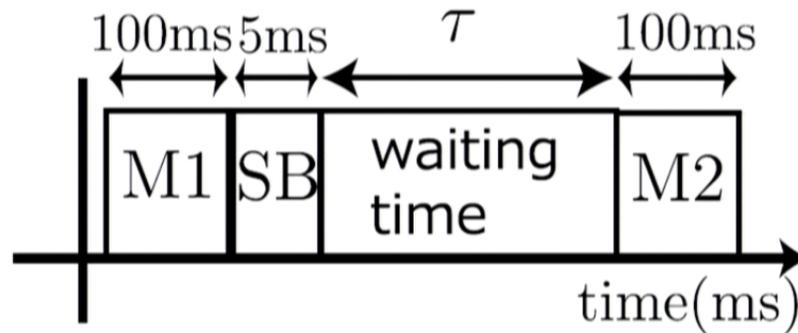
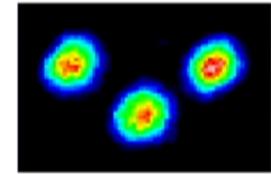
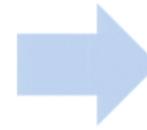
For laser cooling



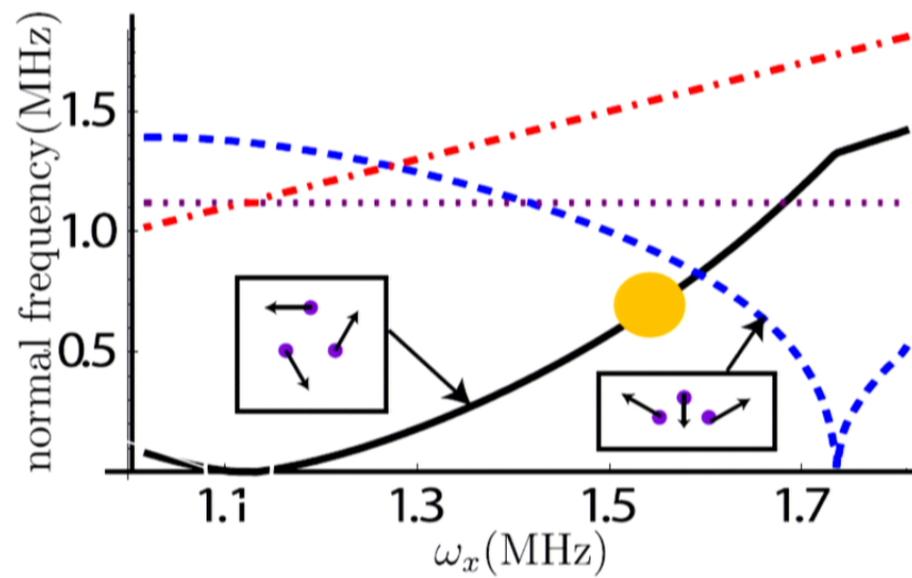
Quantum tunneling



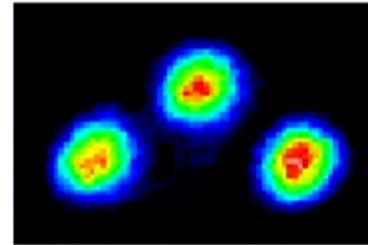
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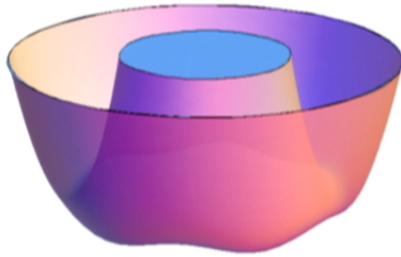


(b)

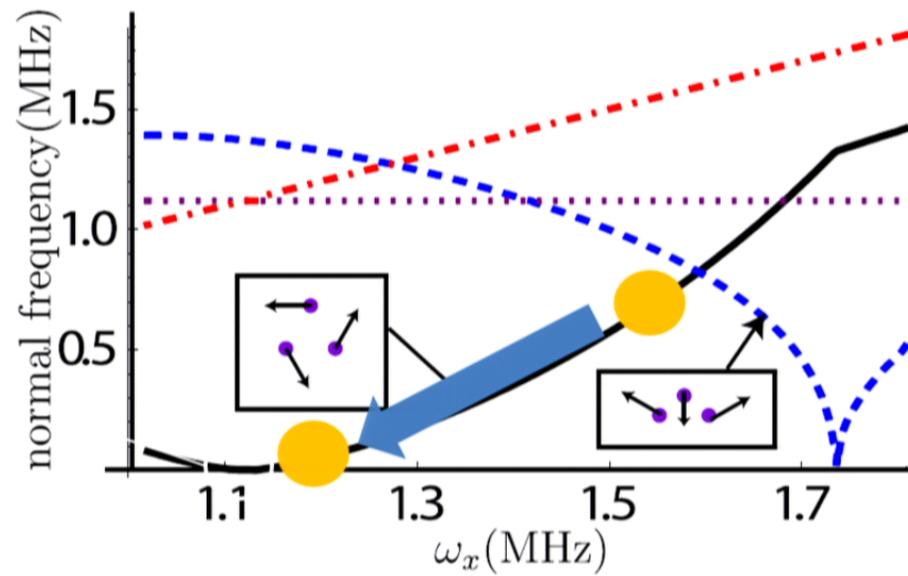
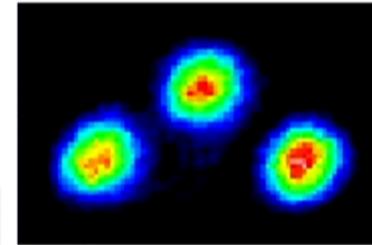


Measurement

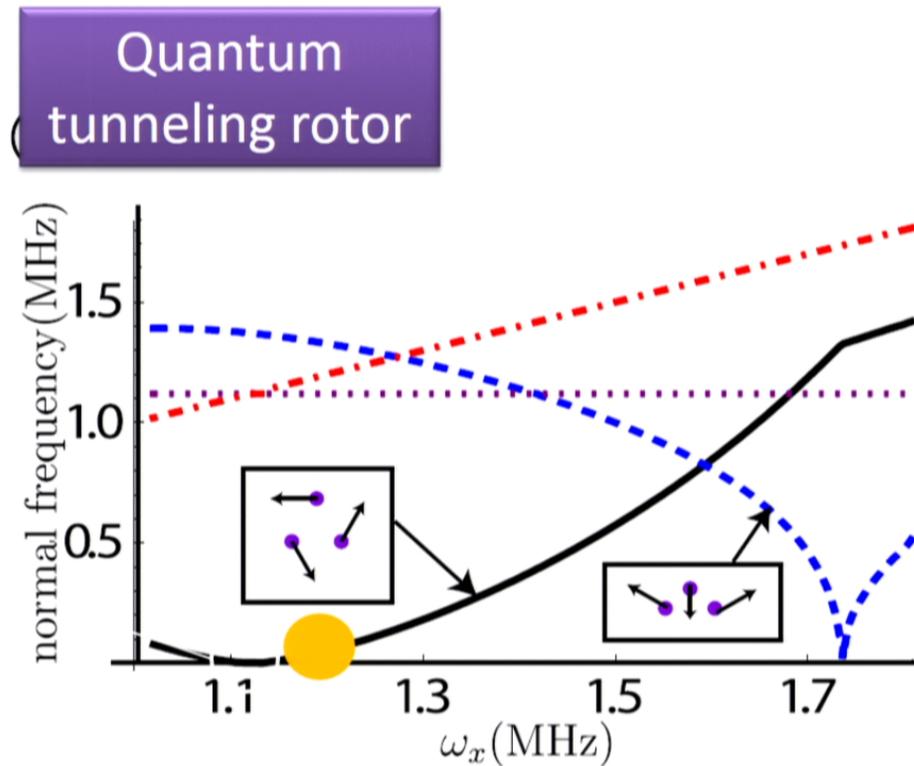


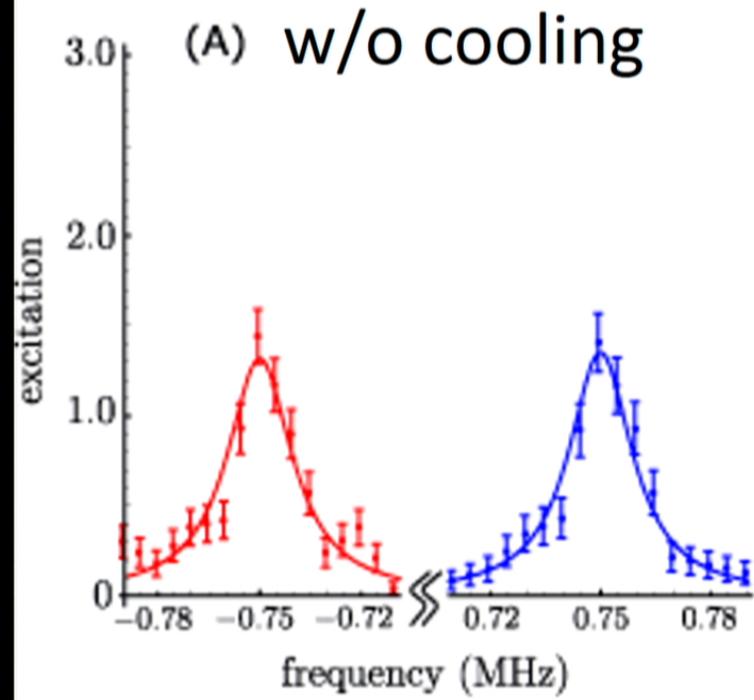


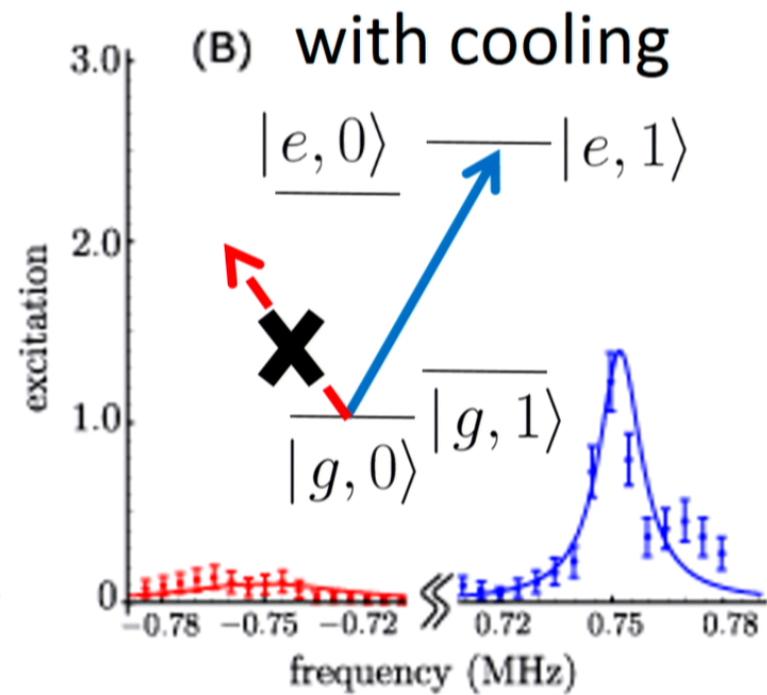
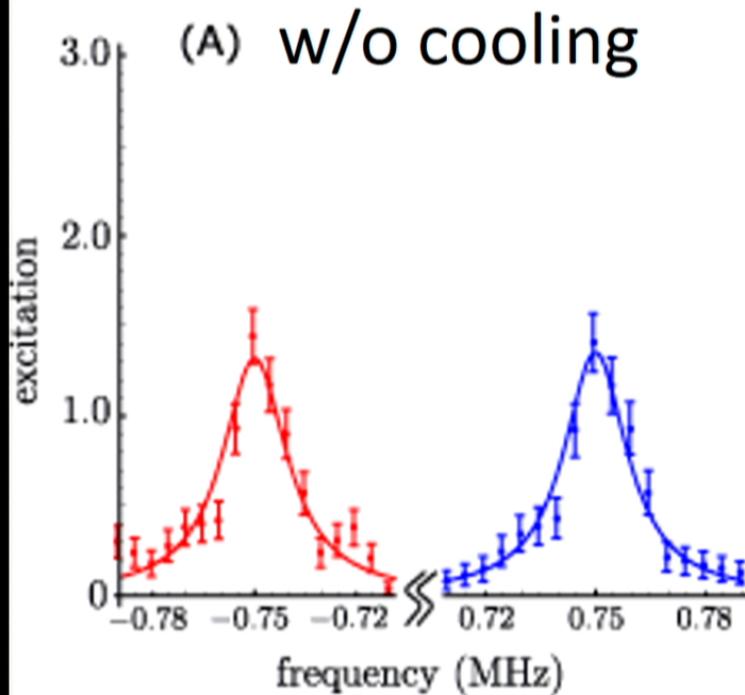
Quantum tunneling rotor Measurement



Our task is to cool down the ground state to the rotational mode.

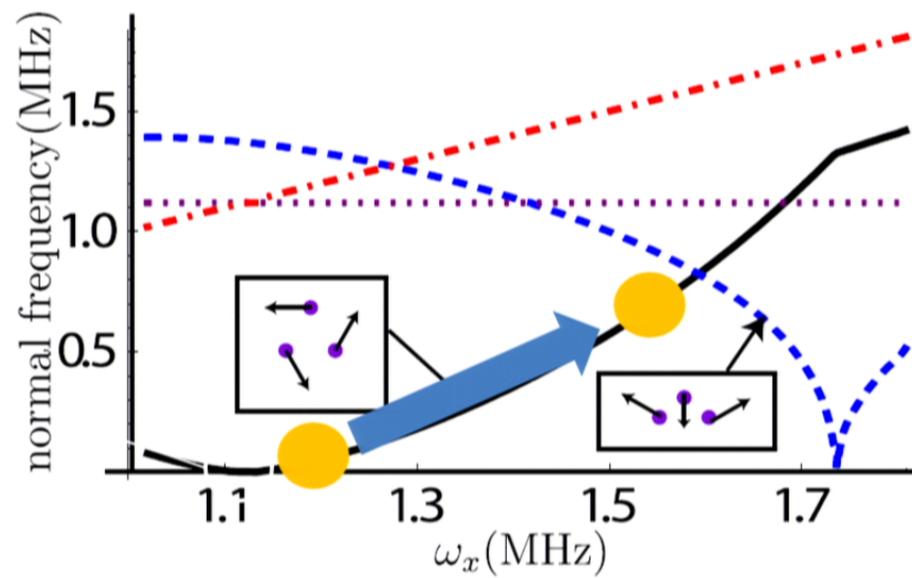
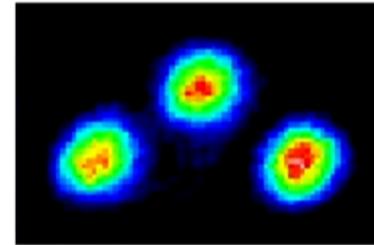






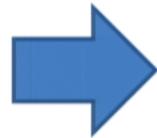
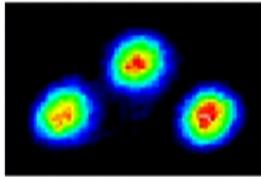
The rotational mode is cooled near its ground state. $n_{rt} = 0.088 \pm 0.007$

Quantum tunneling rotor Measurement

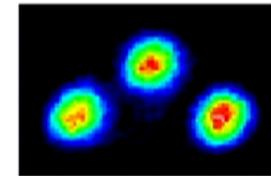
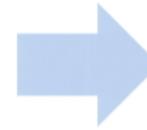
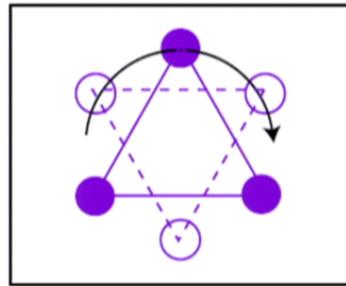


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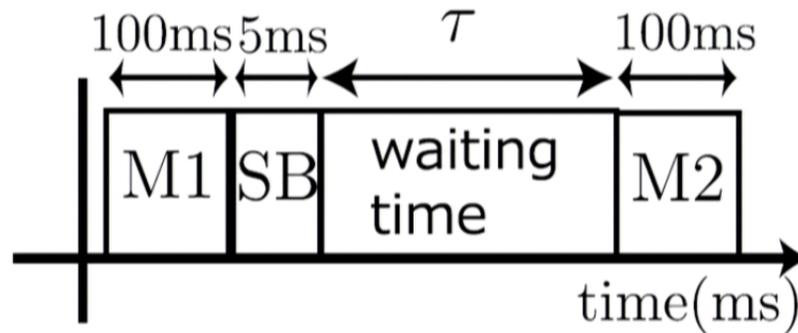
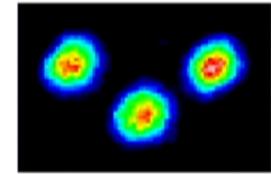
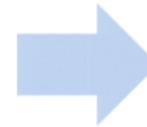
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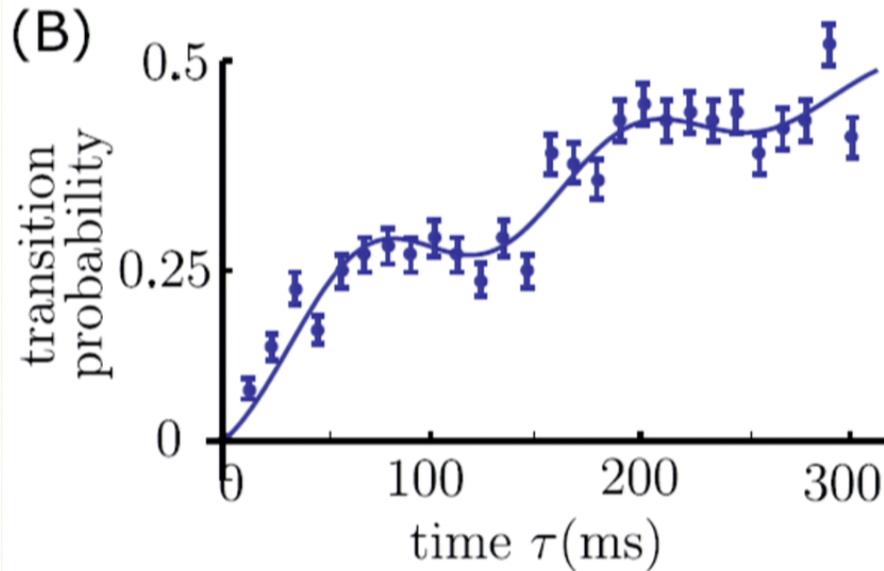


Quantum tunneling



+





$$f(p_0, \nu, \tau_0, v) = p_0 \times \underbrace{\left(\frac{1 - e^{-(t/T_2)^2} \cos(2\pi\nu t)}{2} \right)}_{\text{Coherent Tunneling Part}} + (1 - p_0) \times \underbrace{\frac{1 - e^{-vt}}{2}}_{\text{Heating}}$$

Coherent Tunneling Part

Heating

p_0

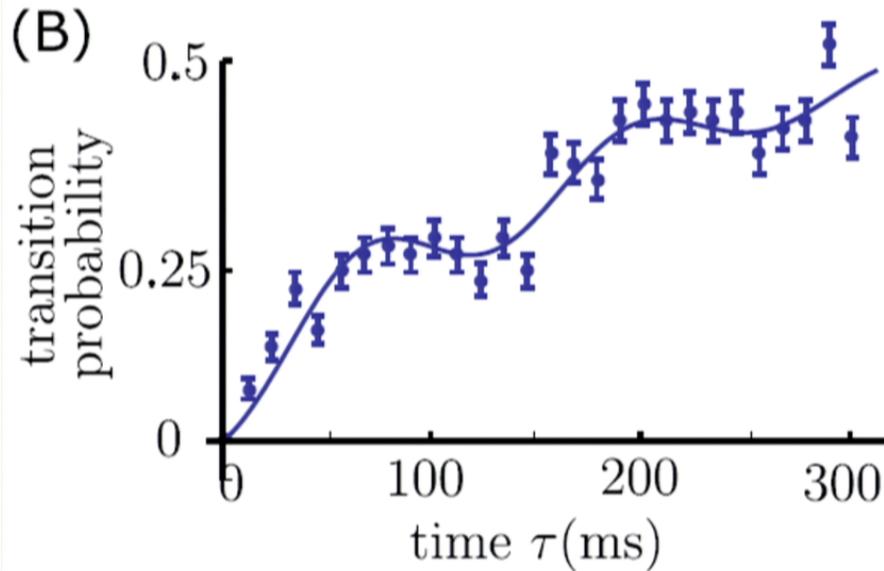
ν

T_2

v

$$0.10 \pm 0.02 \quad 7.6 \pm 0.3\text{Hz} \quad 300 \pm 200\text{ms} \quad 5.4 \pm 0.3\text{s}^{-1}.$$

Around **50 msec**, the averaged tunneling occurred.



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Coherent Tunneling Part

Heating

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ν

T_2

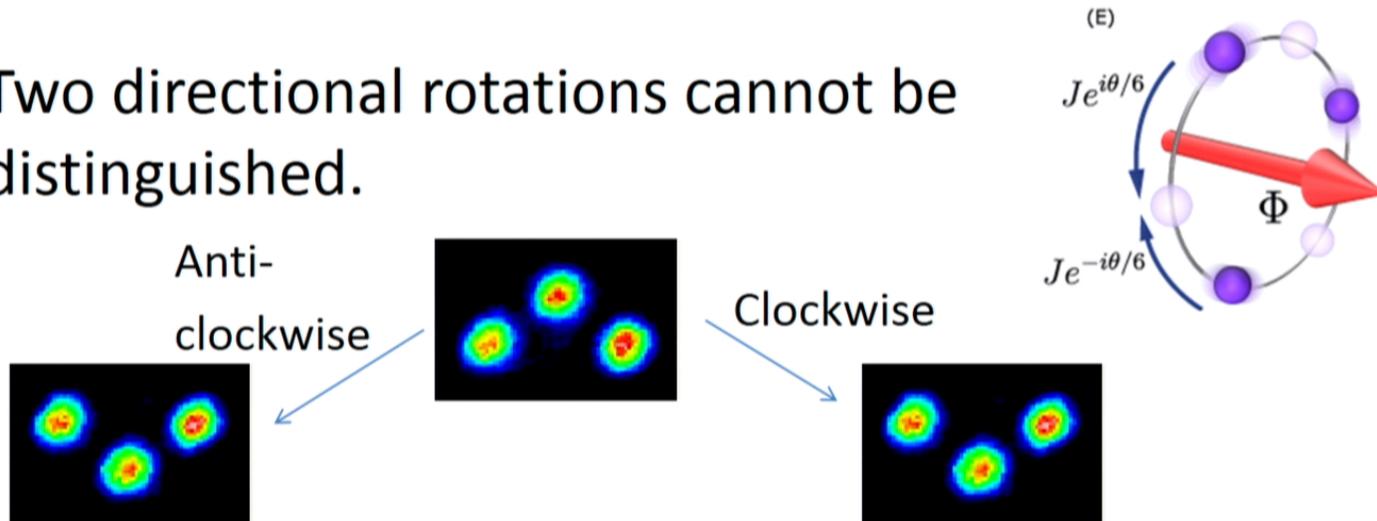
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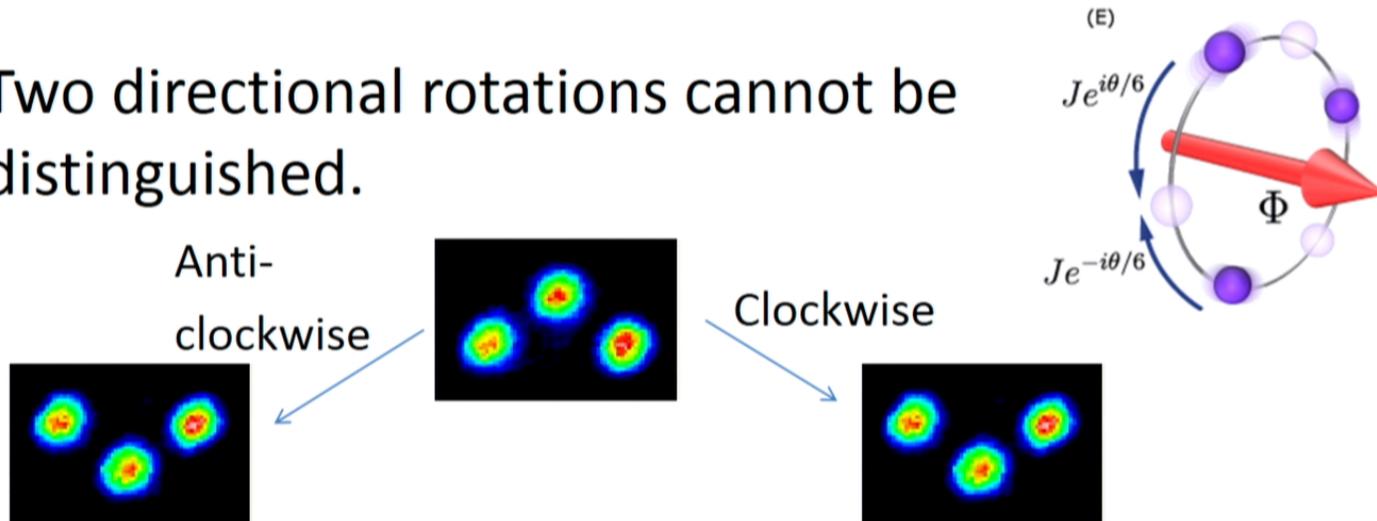
Quantum tunneling rotor as an interferometer

Two directional rotations cannot be distinguished.



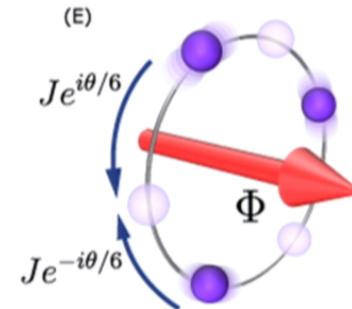
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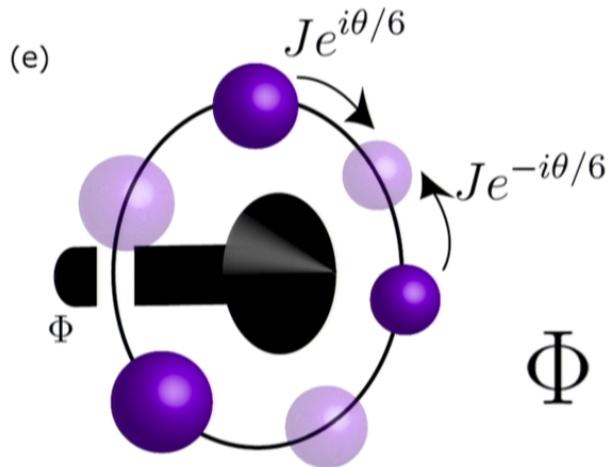


The quantum interference occurs with two directional rotations.

Interference of phonon?

Aharonov-Bohm effect can lead to the phase difference.

Three indistinguishable charged particles



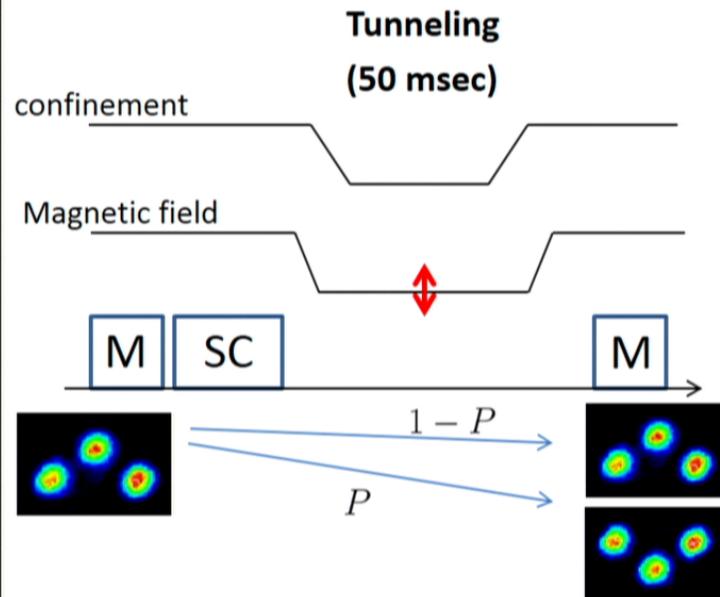
$$\theta = 3 \times 2\pi\Phi / \phi_0$$

$$\Phi = SB_{\perp} \quad \phi_0 = h/e$$

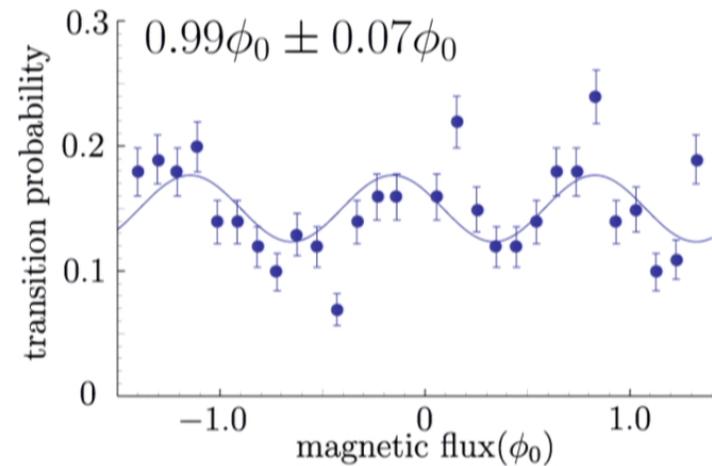
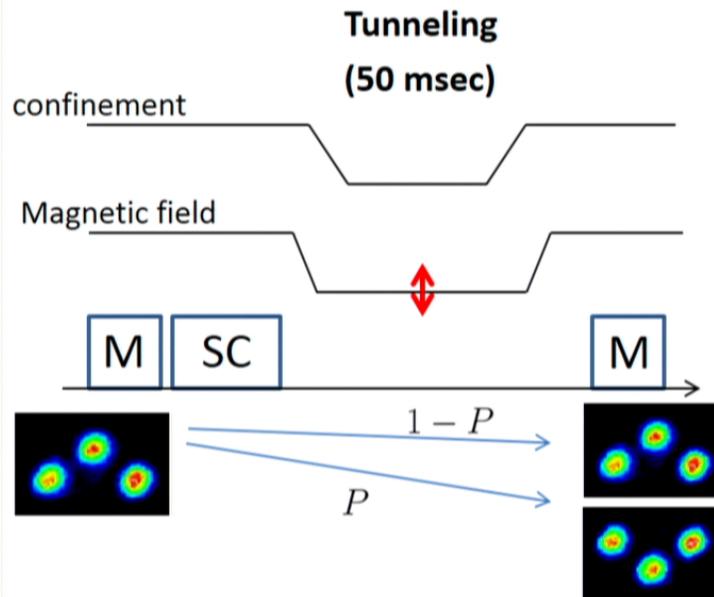
Transition probability with AB effect

$$P \propto | \cos(\pi\Phi / \phi_0) |^2 = (1 + \cos(2\pi\Phi / \phi_0)) / 2$$

Experiment: AB effect of the rotor



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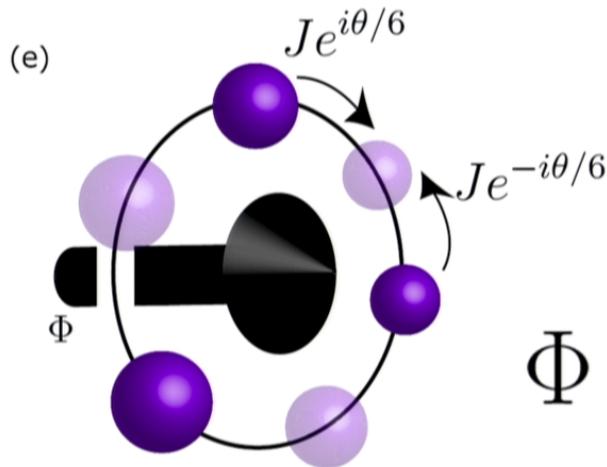


The oscillation whose period is a quantum of the magnetic flux is observed.

Interference of spatially separated phonon

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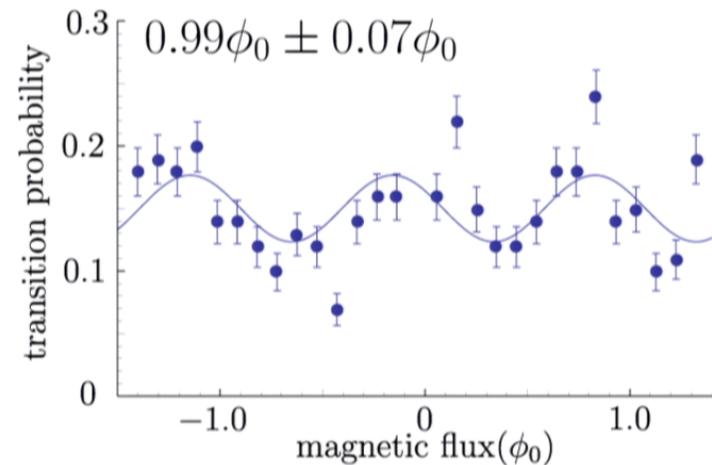
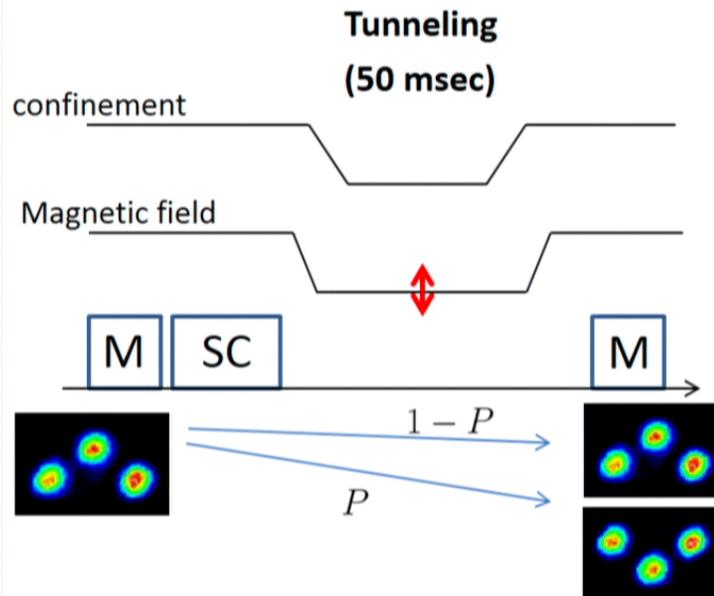
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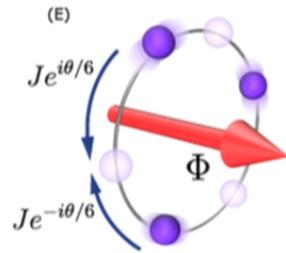
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The oscillation whose period is a quantum of the magnetic flux is observed.

Interference of spatially separated phonon

Magnetic field



Magnetic field is not localized



Ions can be affected by a magnetic field directly.

Z. Phys. A – Atomic Nuclei 328, 1–10 (1987)

Tunnelling of Neutral Spin-1/2 Particles Through Magnetic Fields

A.O. Barut* and M. Božić**
International Centre for Theoretical Physics, Trieste, Italy

Z. Marić
Institute of Physics, Beograd, Yugoslavia

H. Rauch
Atominstut der Österreichischen Universitäten, Wien, Austria

Cf: Aephrim's talk
(Lamor clock and
quantum tunneling time)

From magnetic field :

Zeeman effect

Spins are polarized ✓

$$|\wedge \downarrow \downarrow \downarrow 0\rangle \longrightarrow |\wedge \downarrow \downarrow \downarrow 0\rangle + |\vee \downarrow \downarrow \downarrow 0\rangle$$

Lorenz force

Weak enough ?

$$F = evB \sim 10^{-26} \text{N}$$

$$v = \sqrt{\frac{2|U_0 - E|}{M}} \quad \text{or} \quad v' = Jr_0\pi/3$$

$$r = r_0 \pm \Delta r \quad r_0 = 3.42 \mu\text{m} \quad \Delta r \sim \text{fm}$$



Negligible to consider this effect

How to consider the Lorenz force through the quantum tunneling?

From magnetic field :

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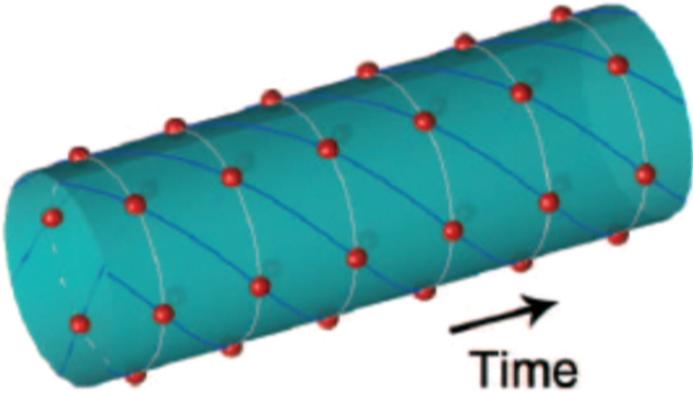
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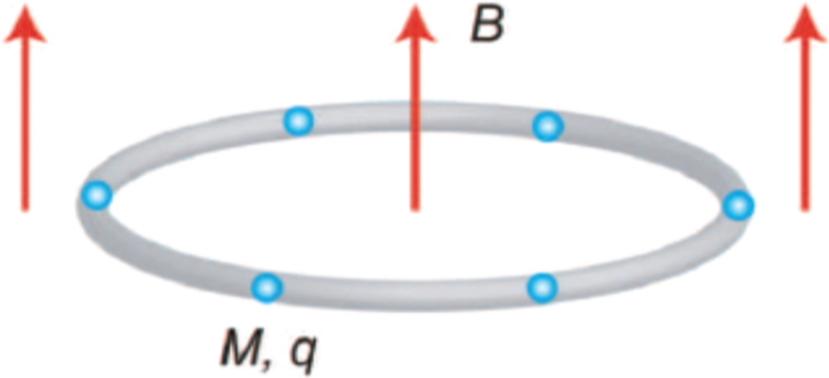
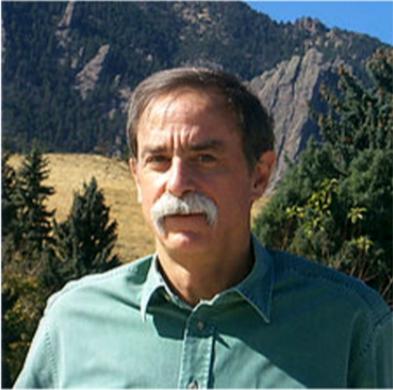
Space-Time Crystal?



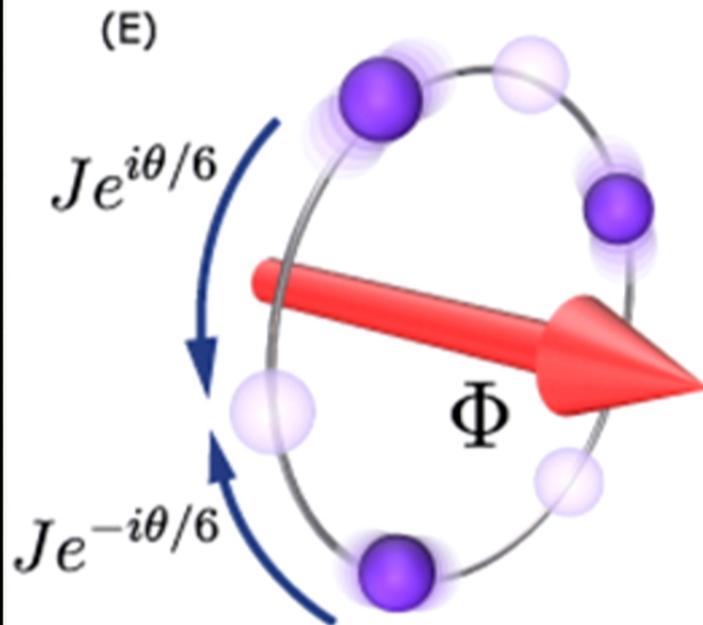
Proposed by



In discussion with



How to detect the rotational direction?



Identical particles cannot be distinguished. We need the label of the ion.

Conclusion

- By linear Paul trap, we demonstrate the quantum tunneling rotor.
- We show the quantum interference of the mechanical motion of our tunneling rotor.

Nature Communications 5, 3868 (2014).