Ontic- or *epistemic*-distinguishability of identical particles by using Aharonov-Bohm effect

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Three Nobel Laureates
Funded in 1872 (precursor)
Moved to Tsukuba in 1973
筑波大学
University of Tsukuba
University of Tsukuba
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Tsuchiura
土浦市
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かすみがうら市
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Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen.

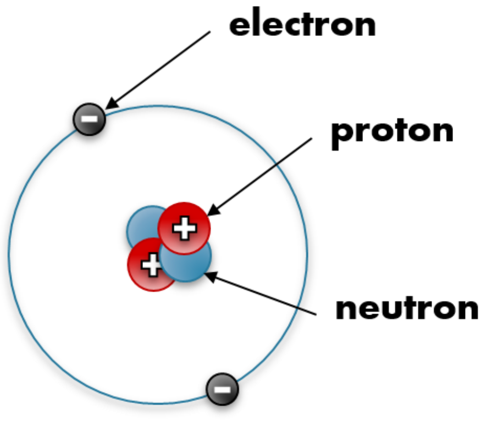
Von **W. Heisenberg** in Göttingen.

(Eingegangen am 29. Juli 1925.)

In der Arbeit soll versucht werden, Grundlagen zu gewinnen für eine quantentheoretische Mechanik, die ausschließlich auf Beziehungen zwischen prinzipiell beobachtbaren Größen basiert ist.

INTERNATIONAL YEAR OF
Quantum Science
and Technology

How did physicists convince the formulation of quantum mechanics?



Helium Atom

Mehrkörperproblem und Resonanz in der Quantenmechanik.

Von **W. Heisenberg** in Kopenhagen.

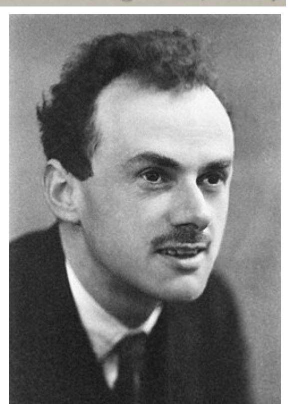
(Eingegangen am 11. Juni 1926.)

Die Arbeit versucht, eine Grundlage für die quantenmechanische Behandlung des Mehrkörperproblems zu geben. Zu diesem Zwecke wird ein für die Quantenmechanik des Mehrkörperproblems charakteristisches Resonanzphänomen ausführlich untersucht und ein Zusammenhang der auf Grund dieser Untersuchung gewonnenen Resultate mit der Einstein-Boseschen Abzählung und dem Paulischen Verbot äquivalenter Bahnen hergestellt.

On the Theory of Quantum Mechanics.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received August 26, 1926.)



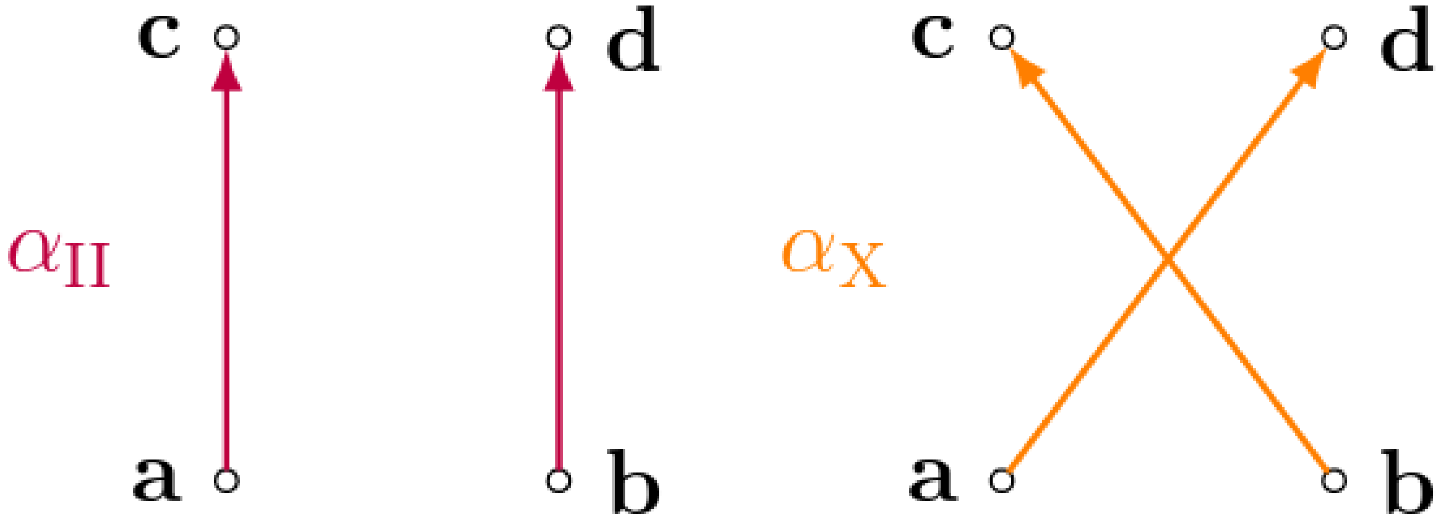
This alternative, though, also leads to difficulties. The symmetry between the two electrons requires that the amplitude associated with the transition $(mn) \rightarrow (m'n')$ of x_1, a co-ordinate of one of the electrons, shall equal the amplitude associated with the transition $(nm) \rightarrow (n'm')$ of x_2, the corresponding co-ordinate of the other electron, *i.e.*,

$$x_1(mn\,;\ m'n') = x_2(nm\,;\ n'm'). \tag{12}$$

If we now count (mn) and (nm) as both defining the same row and column of the matrices, and similarly for $(m'n')$ and $(n'm')$, equation (12) shows that each element of the matrix x_1 equals the corresponding element of the matrix x_2, so that we should have the matrix equation

$$x_1 = x_2.$$

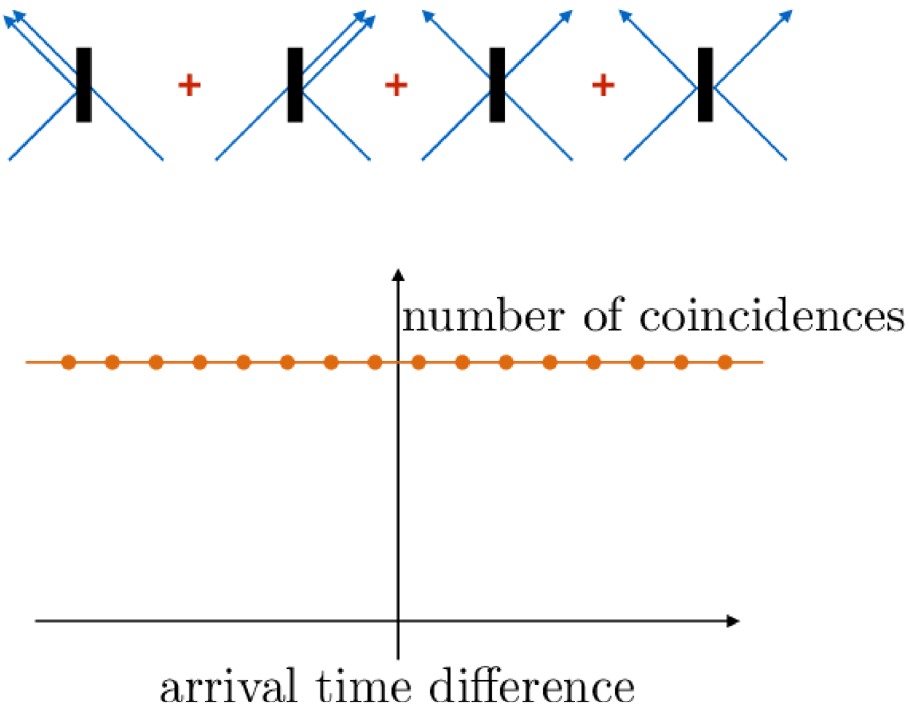
From **one** to **two** in QM



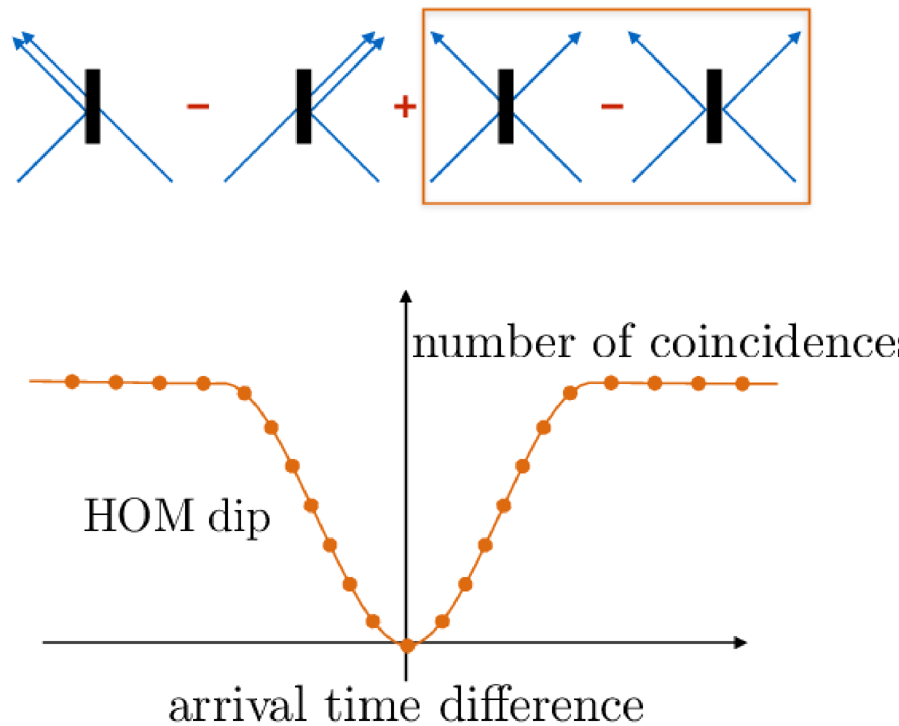
The amplitude depends on the indistinguishability.

Two-photon interference

fully distinguishable particles

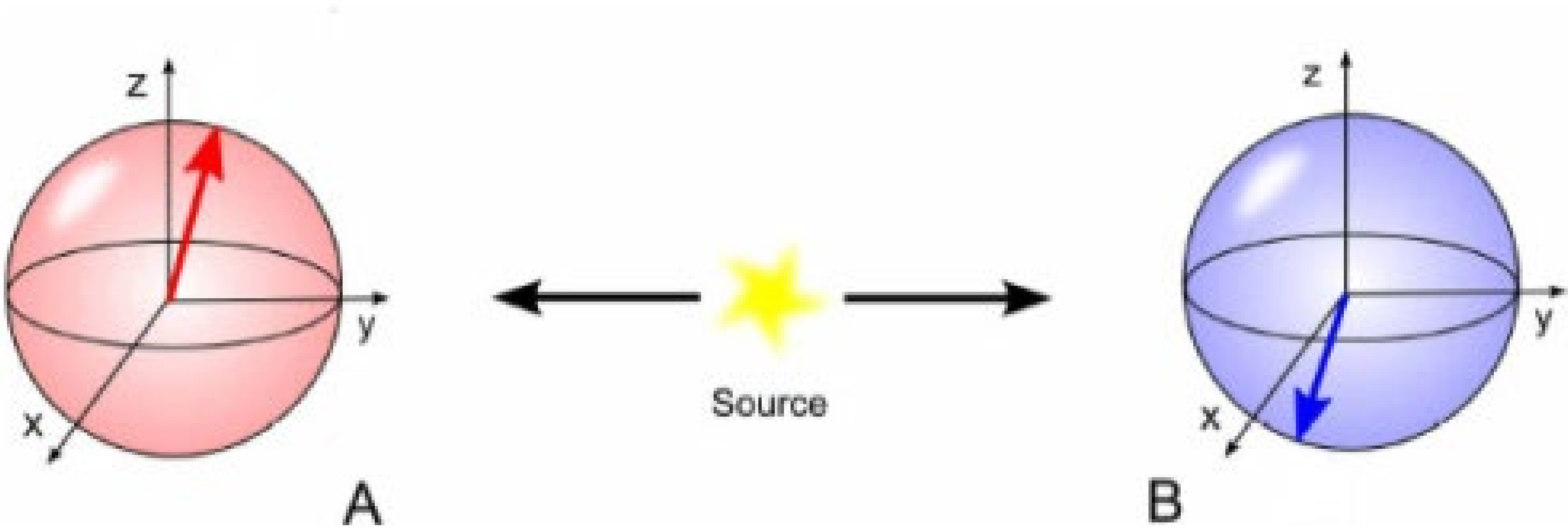


indistinguishable particles



Photons recognize the indistinguishability?

Another two-particle system in QM



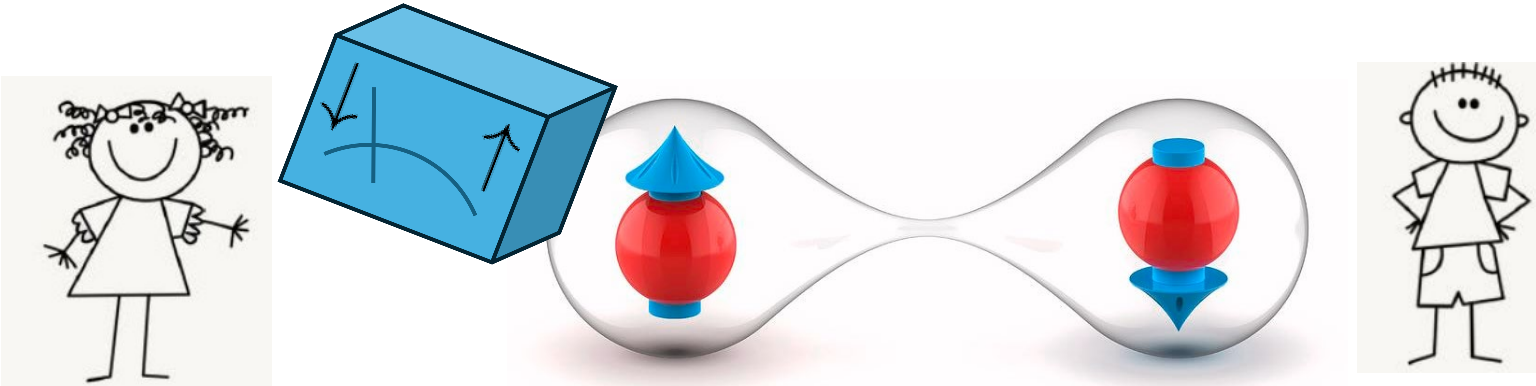
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Information-dependent quantum state description



$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_A |\downarrow\rangle_B + |\downarrow\rangle_A |\uparrow\rangle_B\right)$$

1. When Alice measures the spin, Alice can evaluate Bob's spin state.

2.

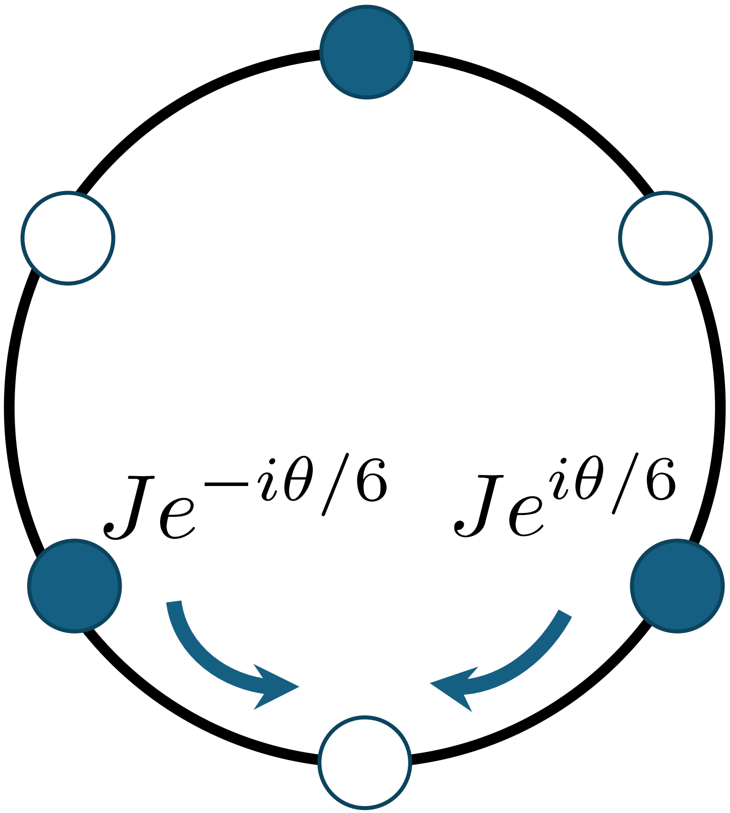
The quantum state does not only depend on the particle but also the measurement-object information.

$$\rho_{B,\text{Bob thinks}} = \frac{1}{2}\left(|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow|\right)$$

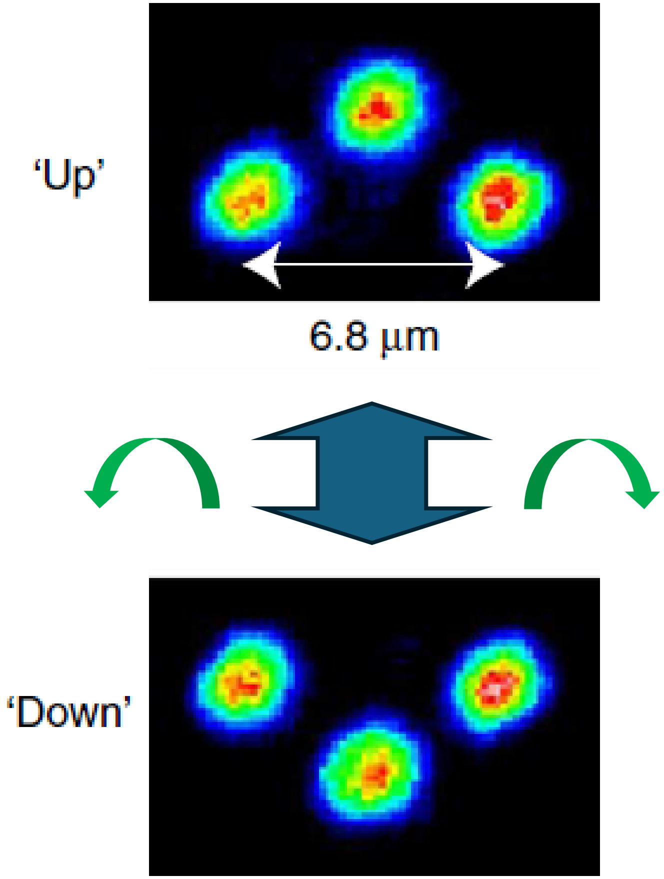
Today's main question

Is there the information-dependent indistinguishability setup?

From two to three in QM: Three **identical** particles with Two configurations

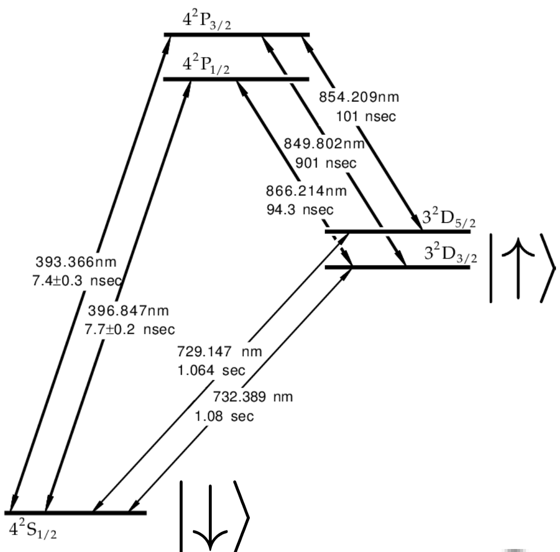


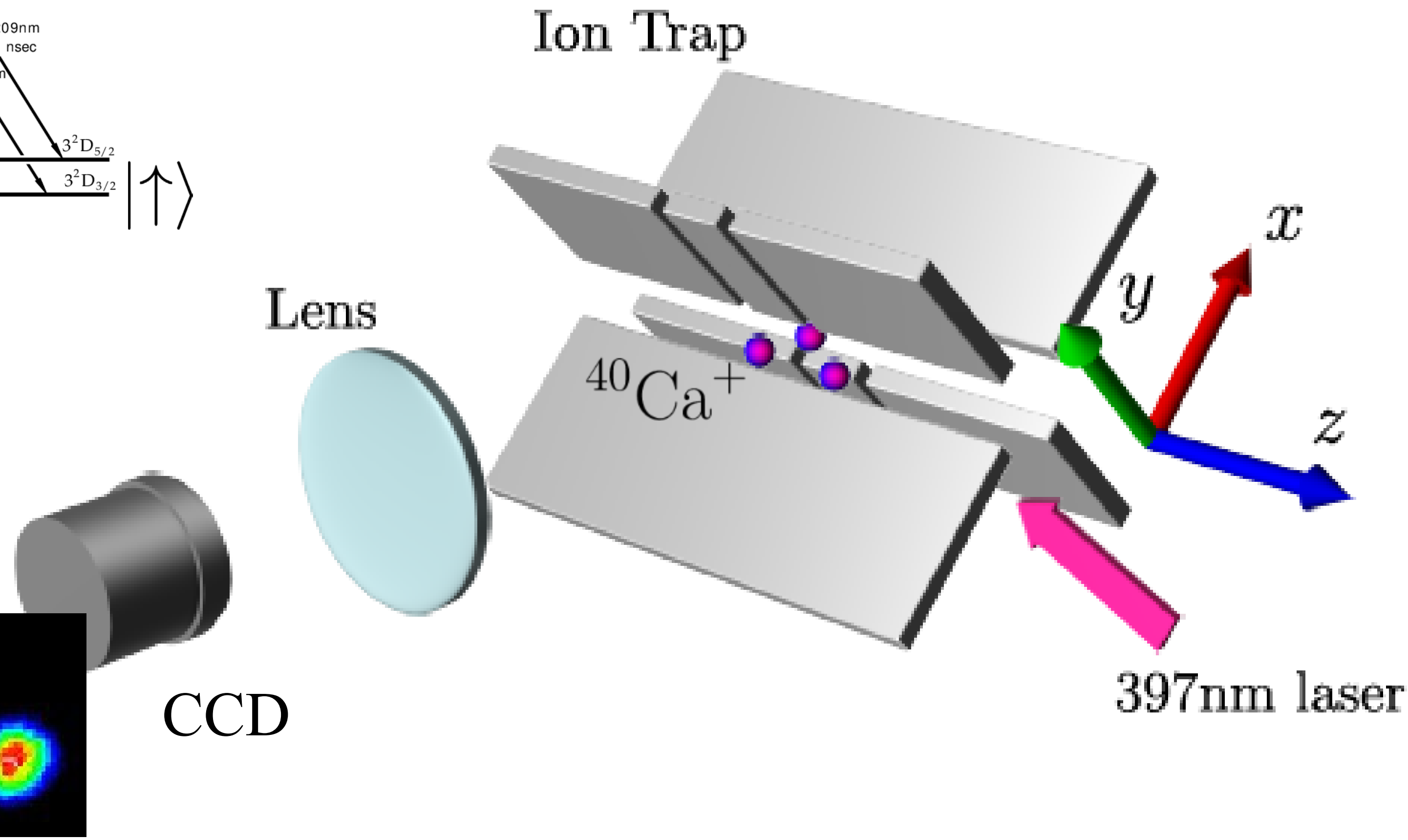
$^{40}Ca^{+}$



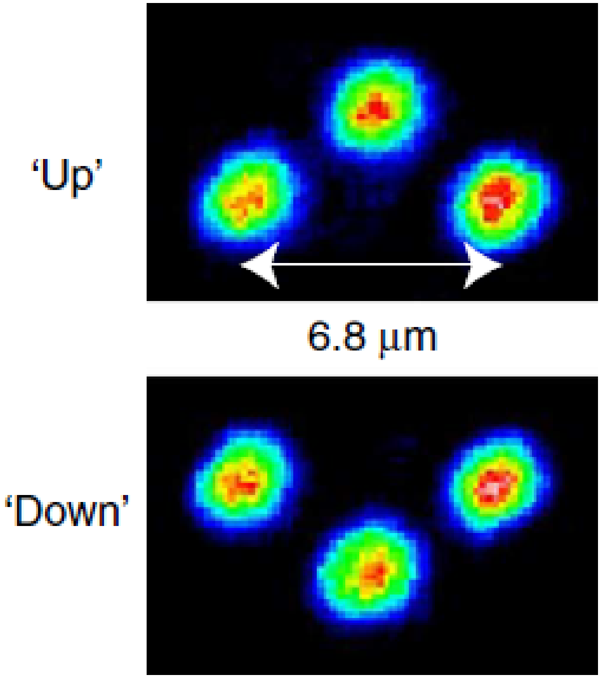
Coherent tunneling hopping

Experimental setup:
Ion trap using the segmented Paul trap

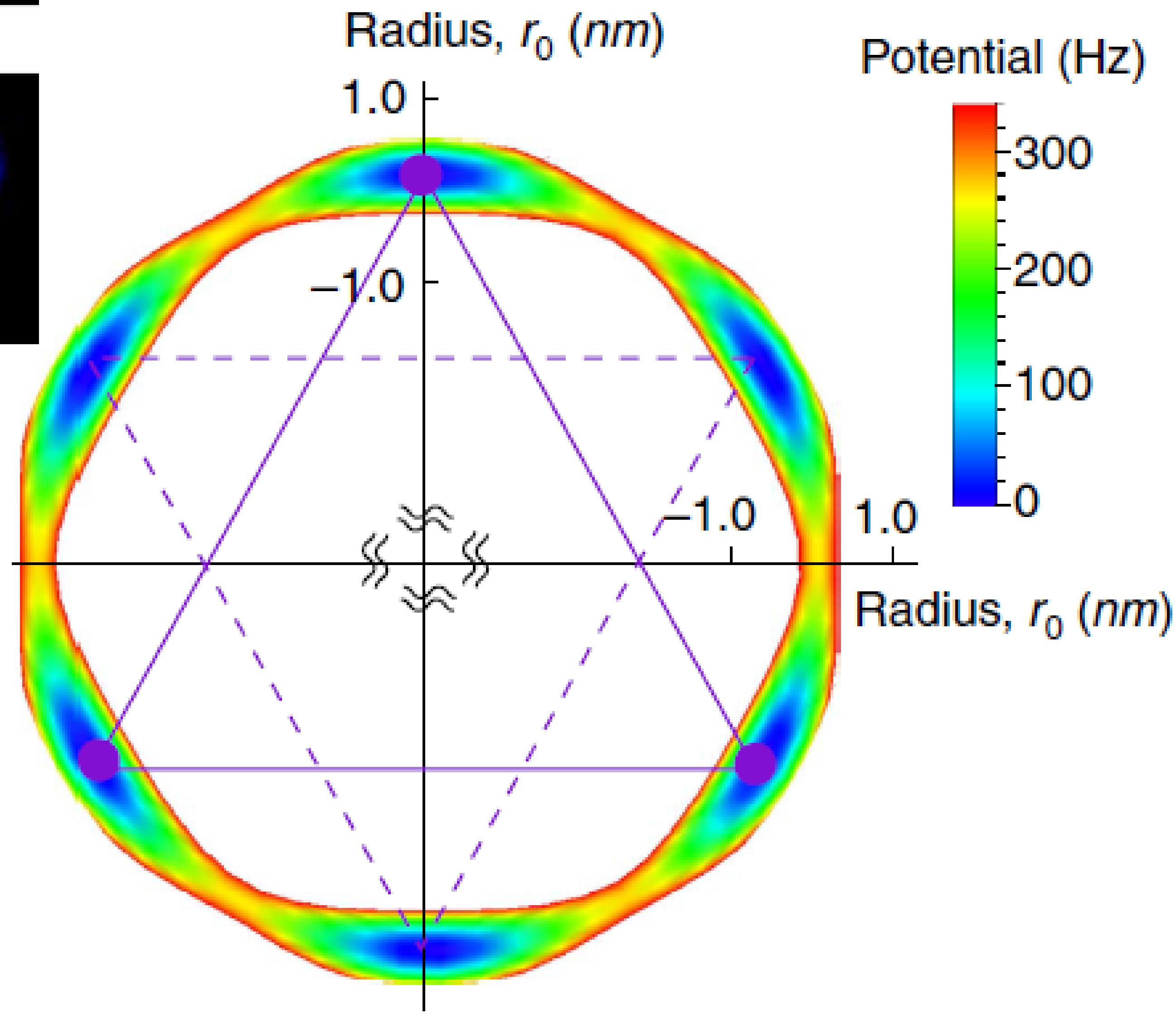




Potential of 3 ions

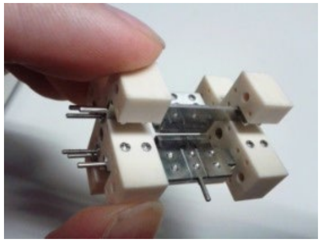


$^{40}Ca^{+}$



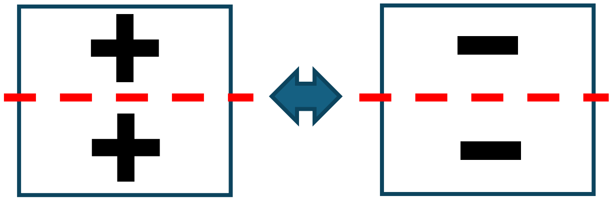
The challenge for 2D crystals in Paul trap

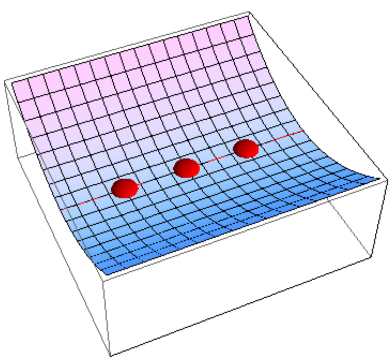
Challenge： never cooled

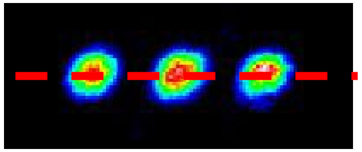


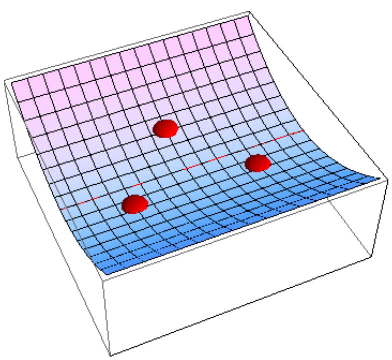
Heating from micro-motion

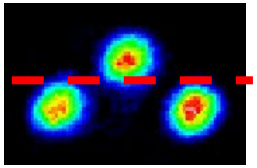
Trapped ions are driven except for the center line of the trap.











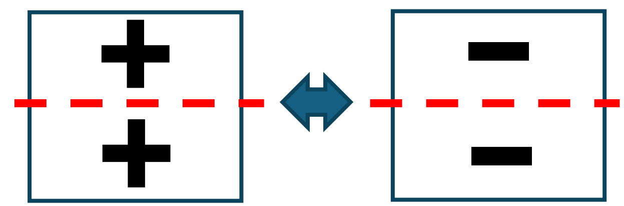
RF zero line

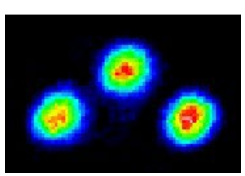
Here, we demonstrate the one of the 2D phonon mode can be cooled to near the ground state.

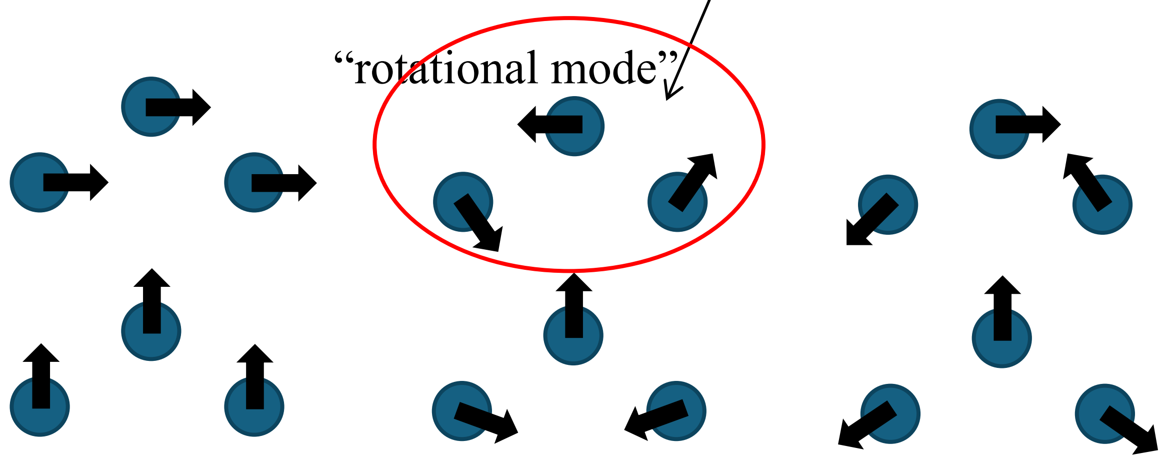
Technical idea:
Collective modes of a 2D crystal

The crystal of N ions has 3N collective mode.

Can the rotational mode be affected by driving force?

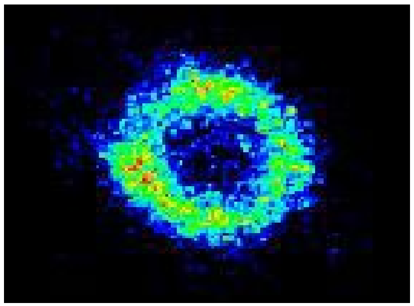


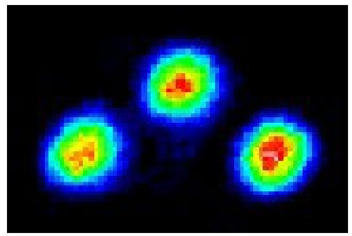


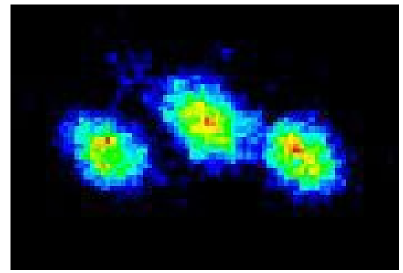


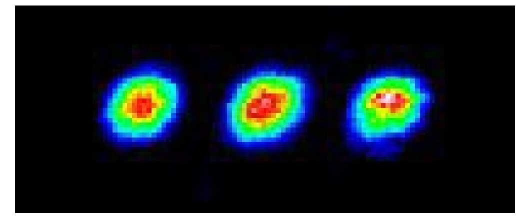
Our configuration
= Quantum Tunneling Rotor

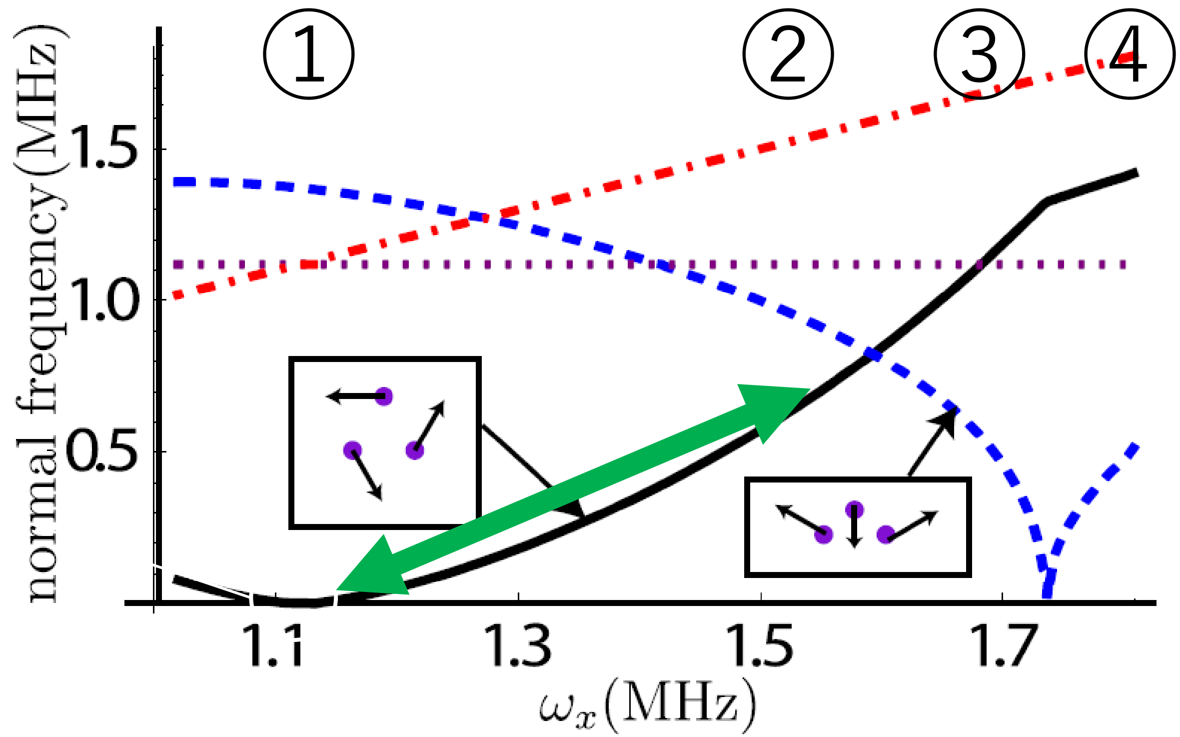
①　②　③　④





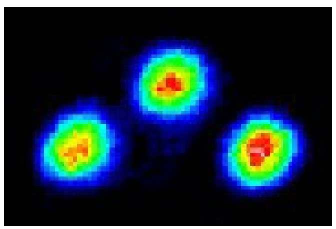




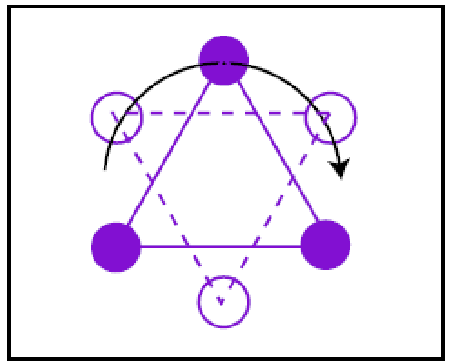


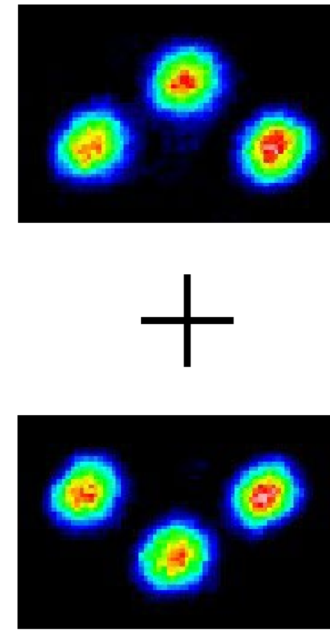
Experimental Procedures

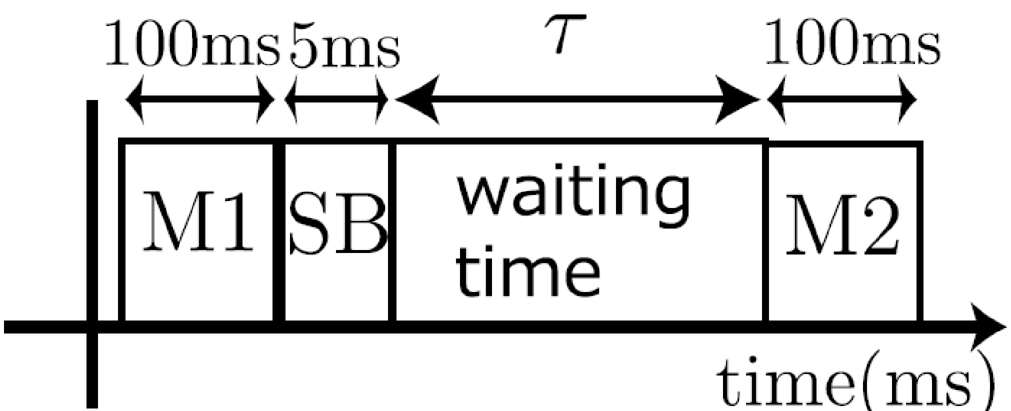
For laser cooling



Quantum tunneling



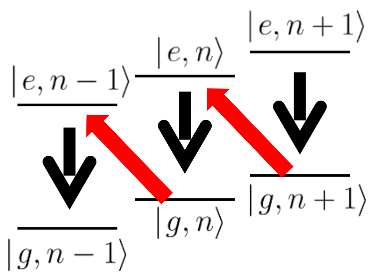


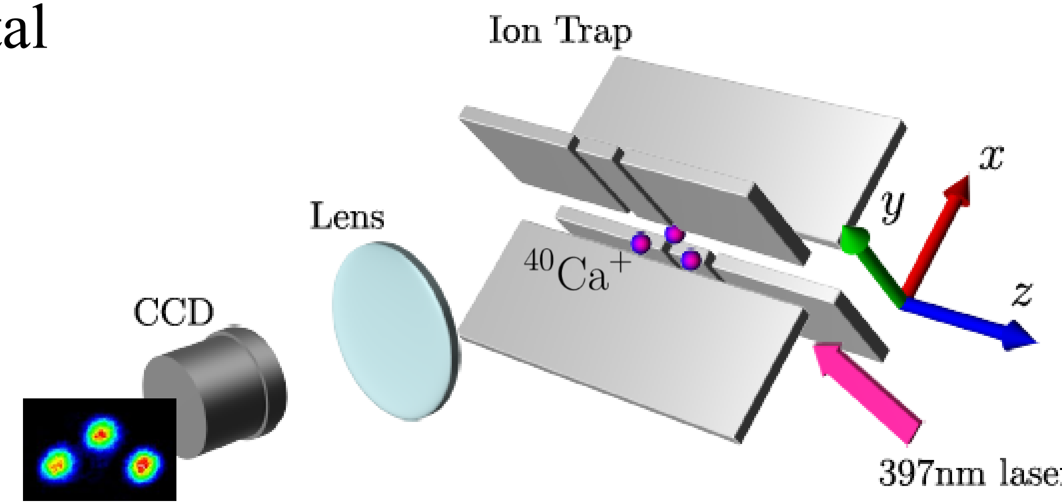


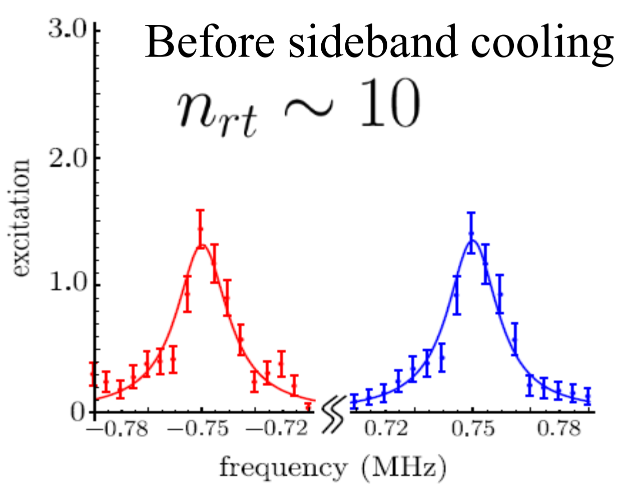
Ground-State Cooling of 2D crystal

Laser cooling of 2D crystal

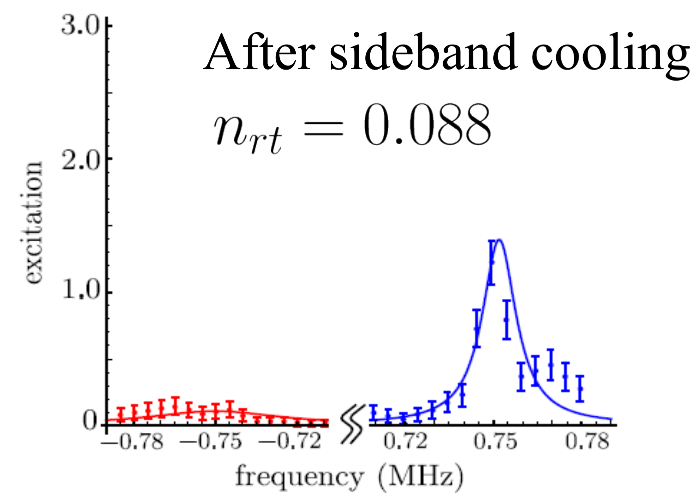
- ○ Doppler cooling
- ○ Sideband cooling





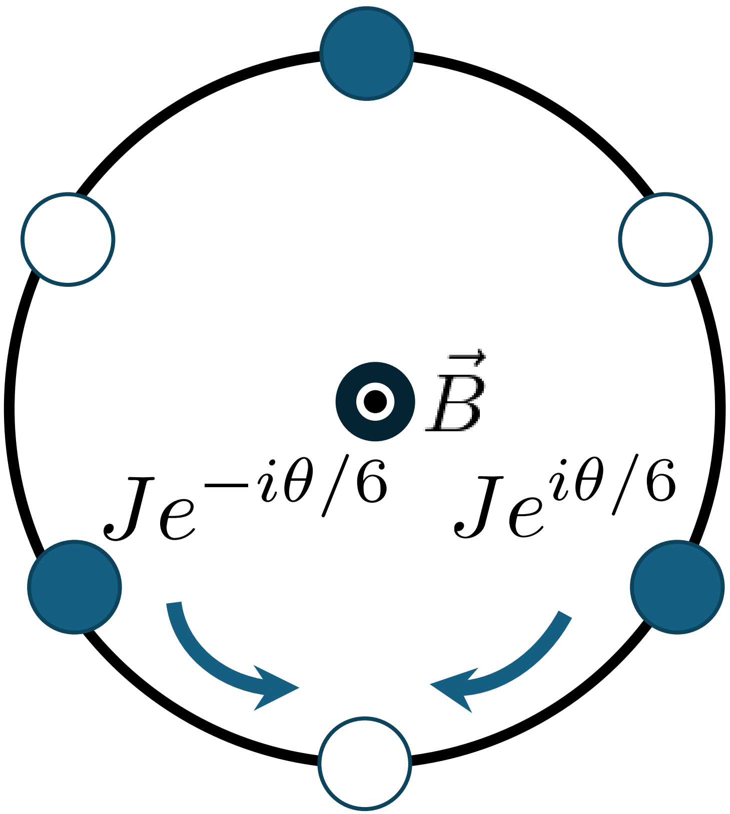


Sideband cooling



Aharonov-Bohm (AB) phase interference

Three **indistinguishable** charged particles



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

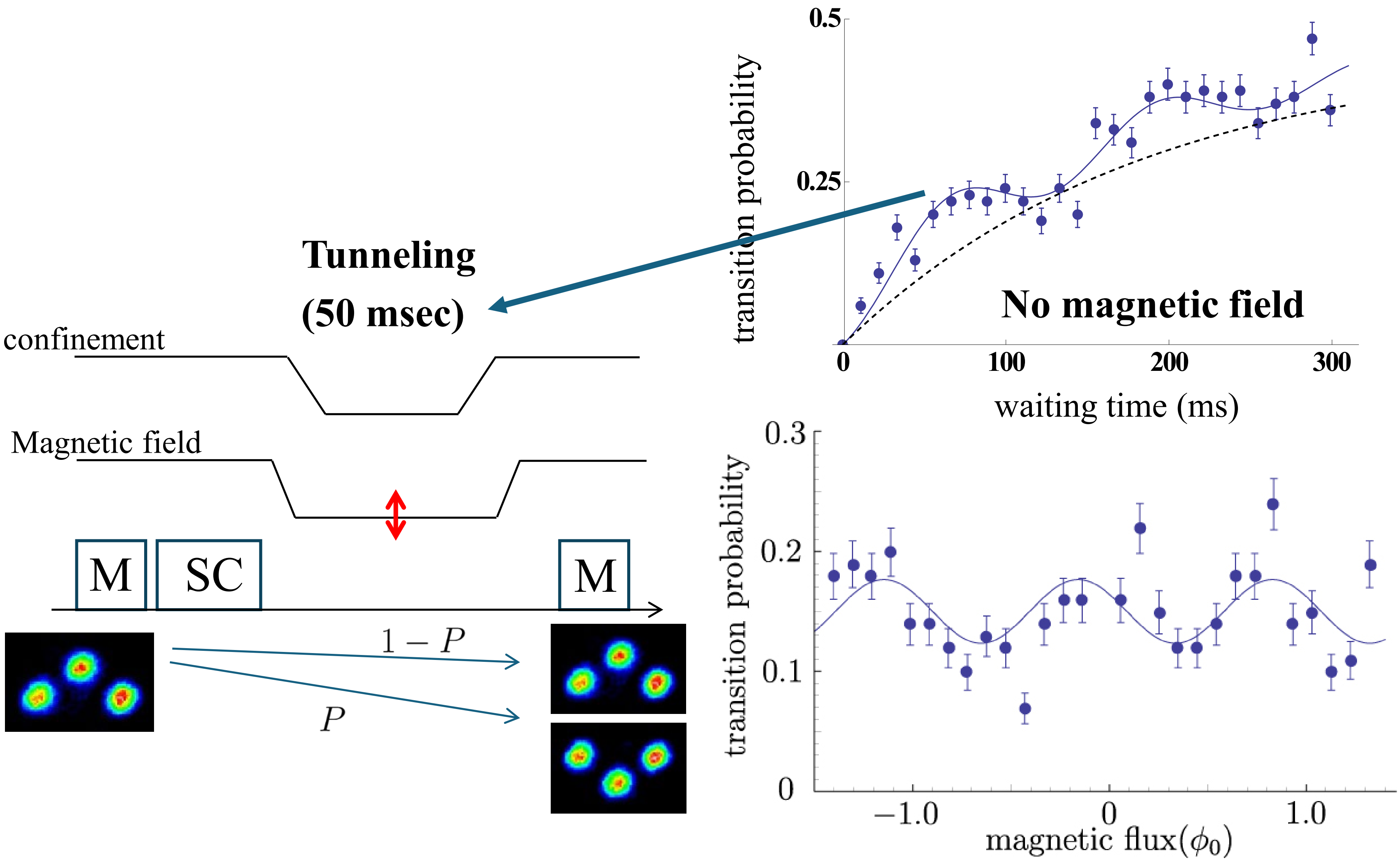
$$\Phi = SB_\perp$$

$$\phi_0 = h/e$$

Transition probability with AB effect

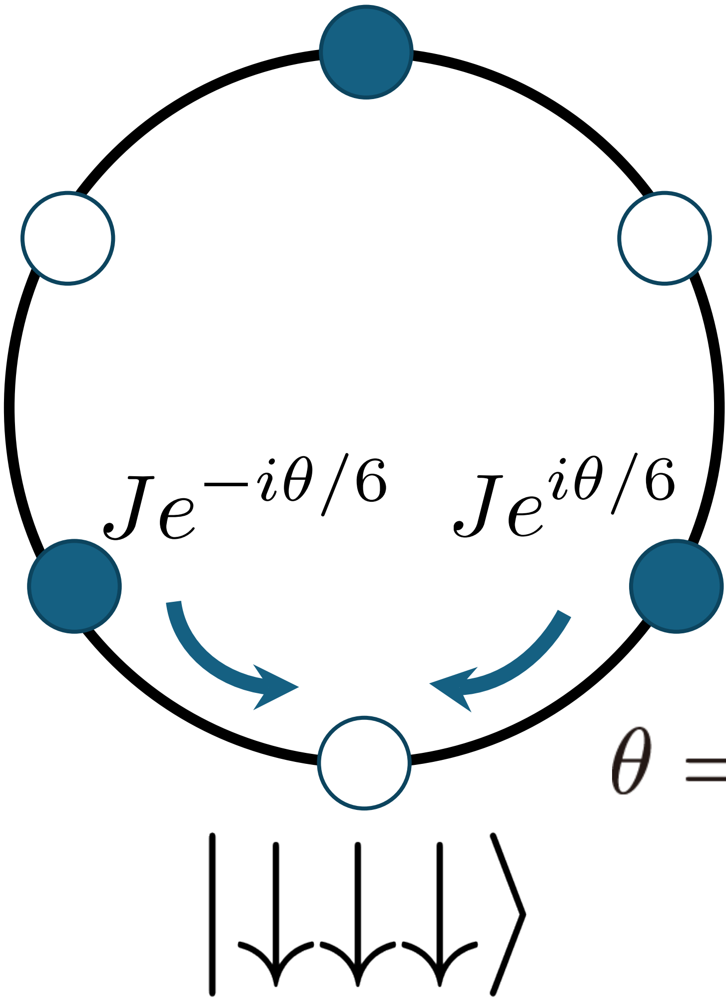
$$P \propto |\cos(\pi\Phi/\phi_0)|^2 = (1 + \cos(2\pi\Phi/\phi_0))/2$$

Experimental demonstration

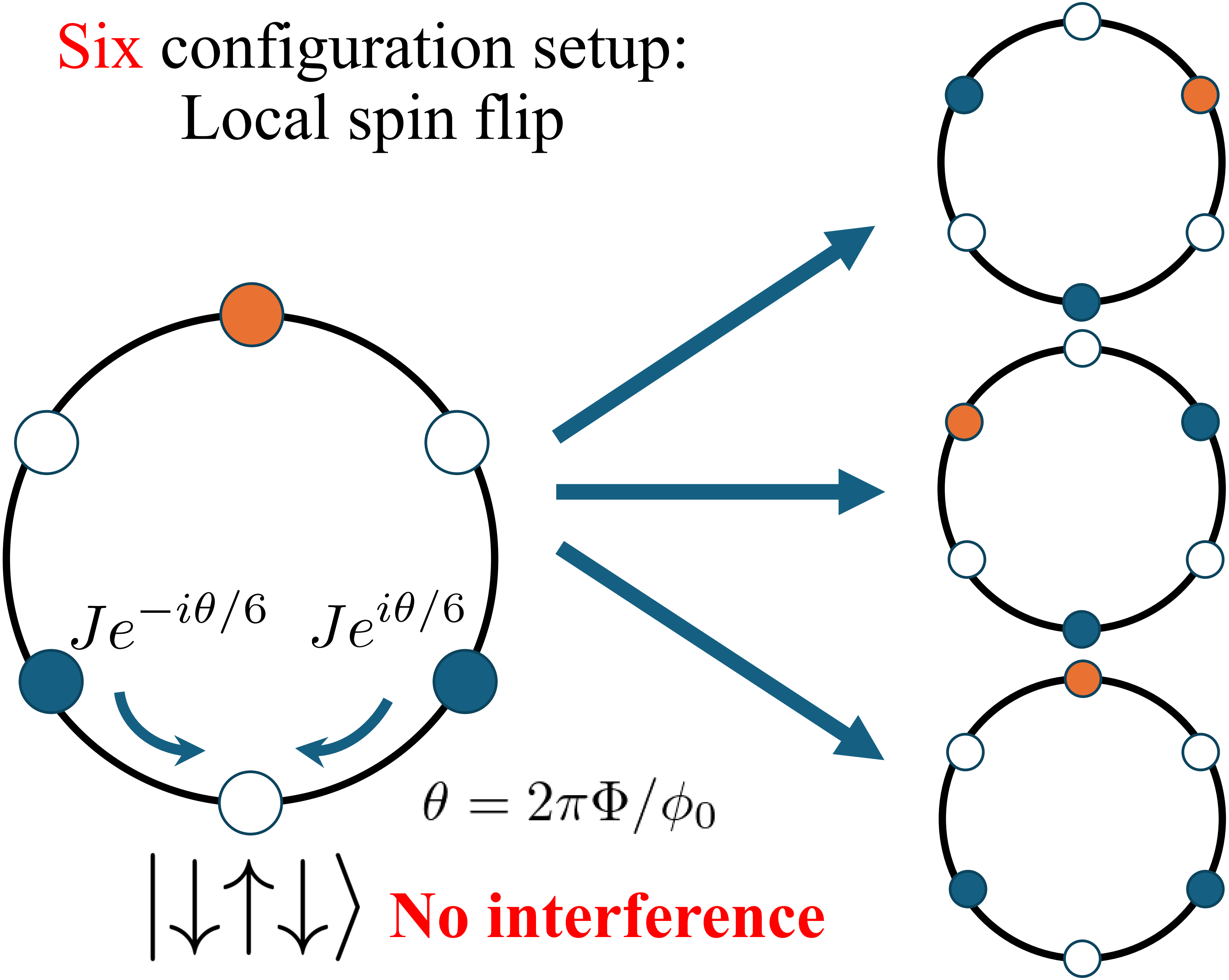


A. Noguchi, YS, K. Toyoda, and S. Urabe, Nat. Comm. **5**, 3868 (2014).

Two configuration setup:

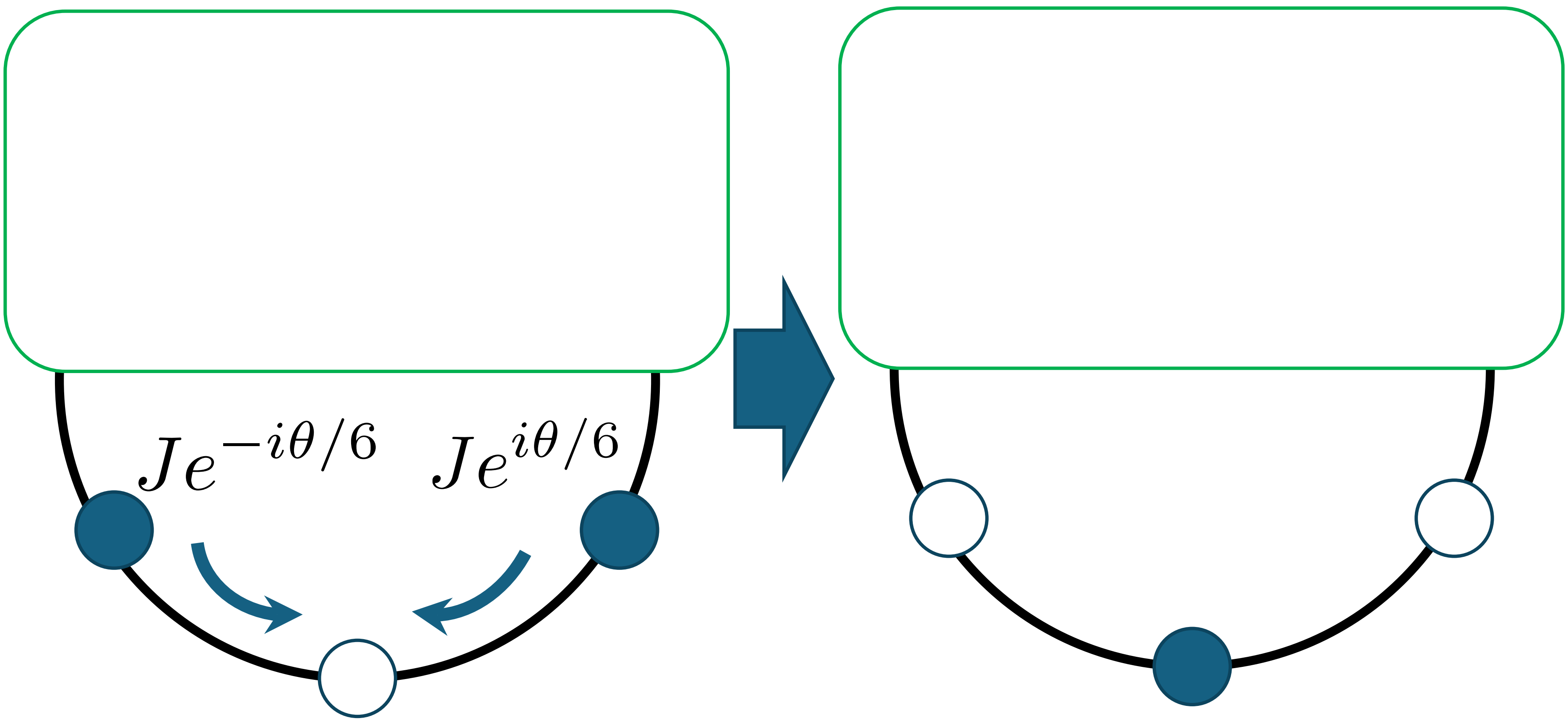


$$\theta = 3 \times 2\pi\Phi/\phi_0$$


Six configuration setup:
Local spin flip
$Je^{-i\theta/6}$
$Je^{i\theta/6}$
$\theta = 2\pi\Phi/\phi_0$
$|\downarrow\uparrow\downarrow\rangle$
No interference

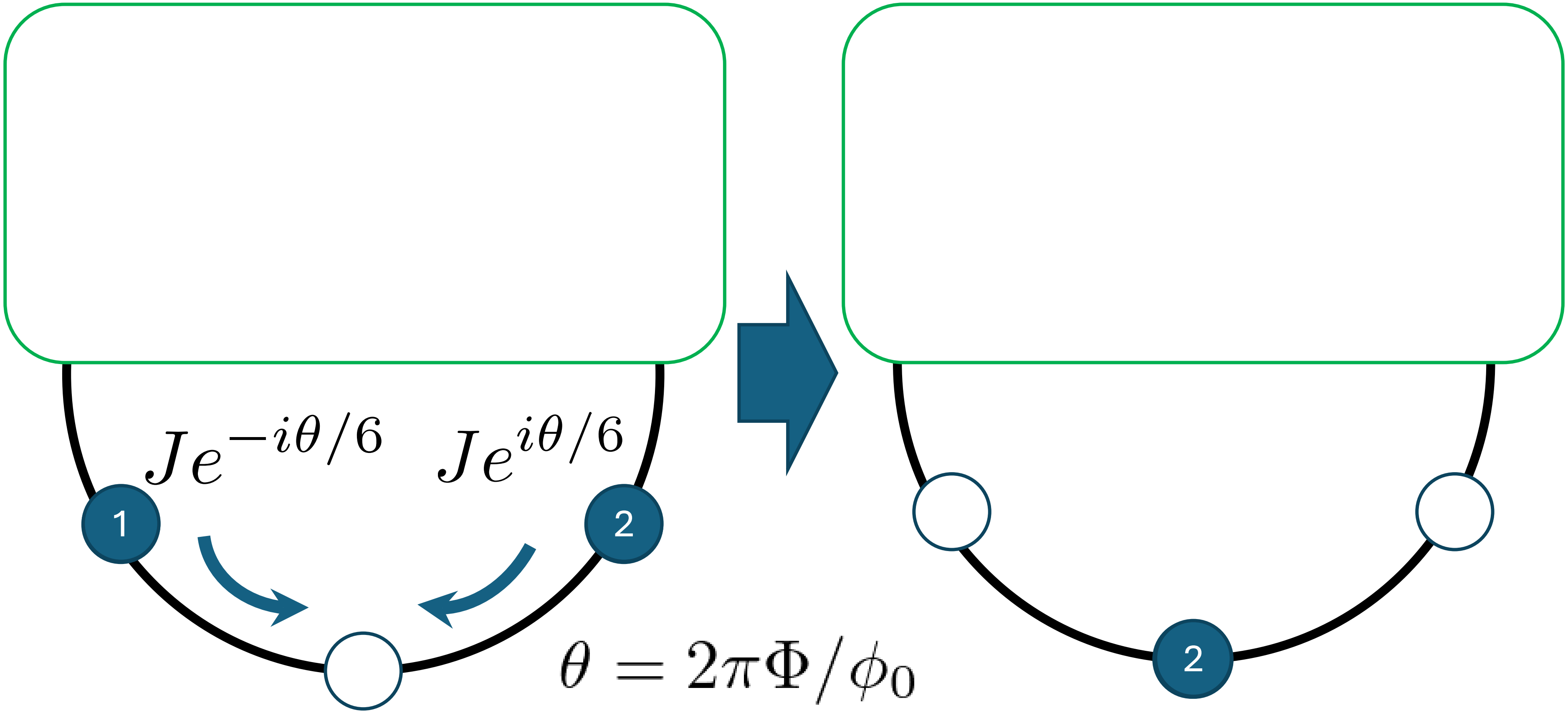
Information-dependent setup

Information-dependent setup: Three charged particles



By changing the magnetic field,
the transition probability is experimentally evaluated.

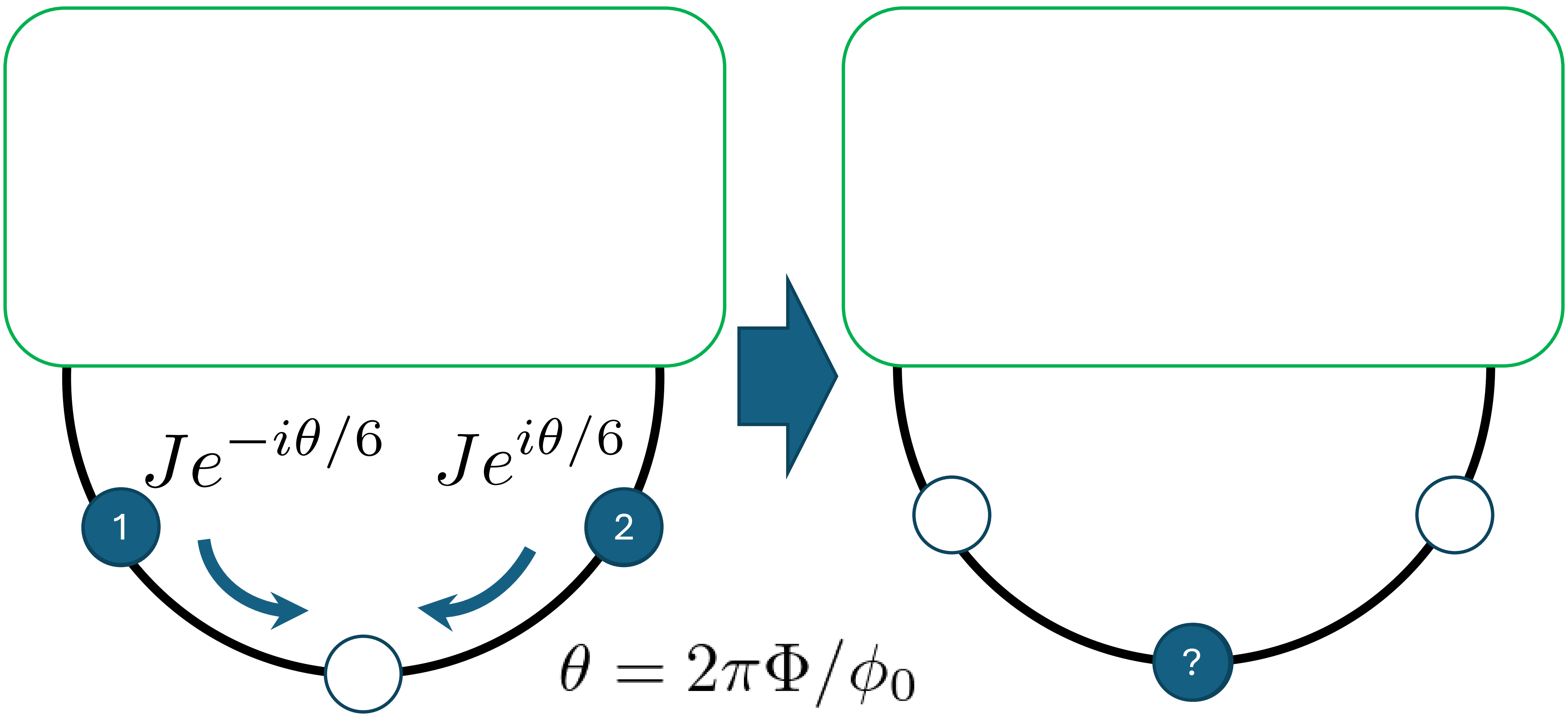
Ontic distinguishability



When the particles themselves recognize the distinguishability, this setting should be labelled to the particle.

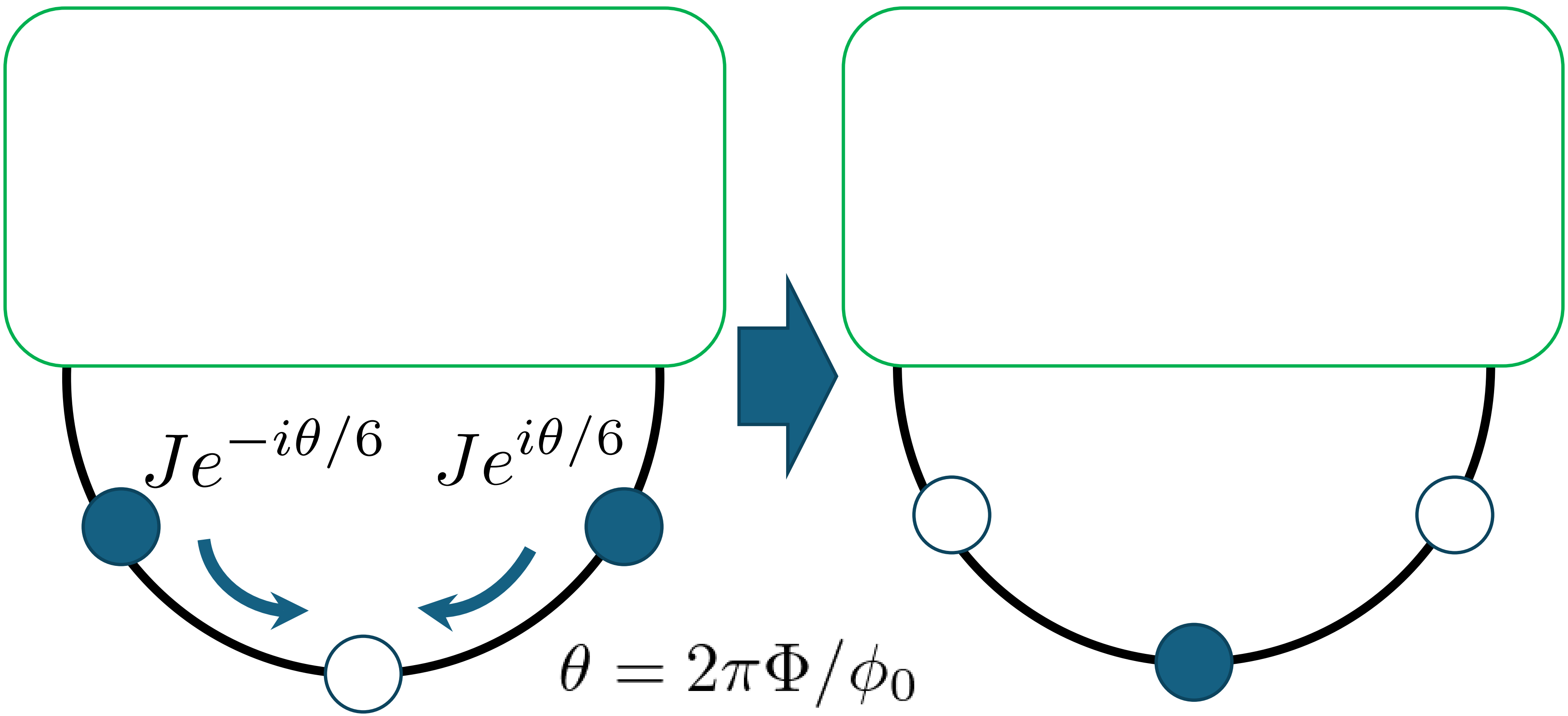
In this setup,
there is **<u>NO</u>** interference.

Epistemic distinguishability



The observers did not know which particles was hopped.
-> The coherence seems to be kept.

Epistemic distinguishability: Coherent hopping case



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

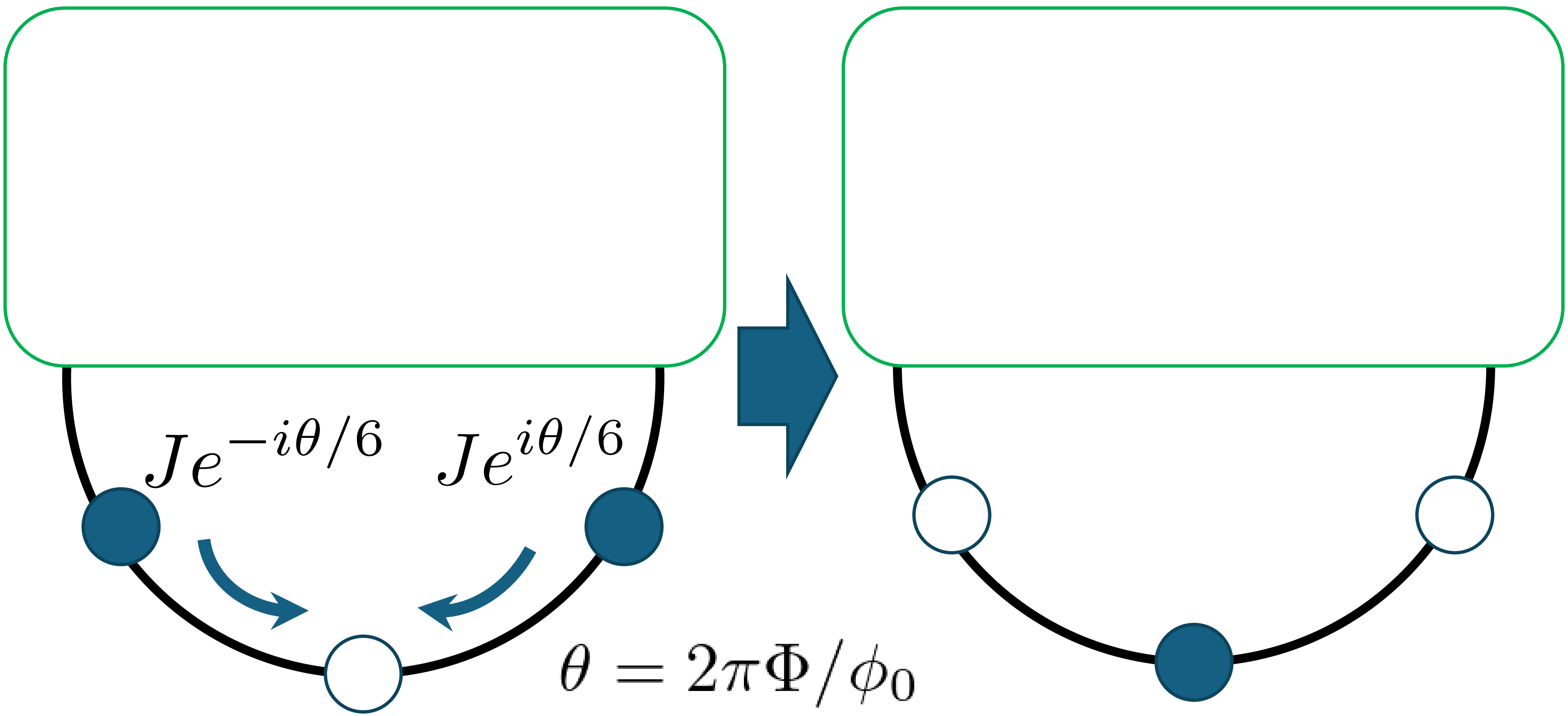
$$\left\| \left(Je^{i\theta/6} + Je^{-i\theta/6} \right) |\psi\rangle \right\|^2 = 2|J|^2 \left(1 + \cos\frac{\theta}{3} \right)$$

$$= 2|J|^2 \left(1 + \cos\frac{2\pi\Phi}{3\phi_0} \right)$$

Interference pattern

In this setup,
there is the AB interference.

Ontic/epistemic distinguishability can experimentally be clarified.



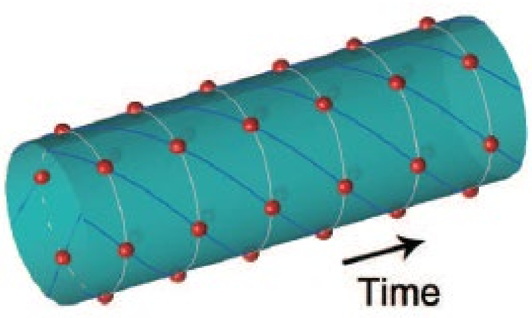
1) Particles (*ontic*) -> NO interference
2) Observers (*epistemic*) -> AB interference

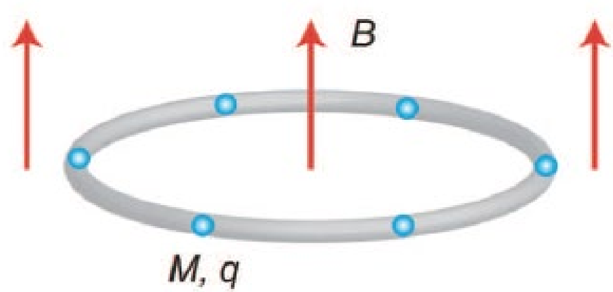
Conclusion and Outlooks

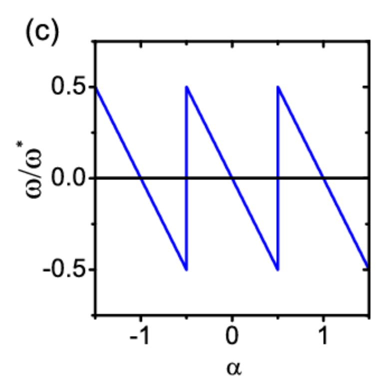
- We propose to clarify the situation whether the distinguishability of the particles is known by particles themselves or the observers.
- This experimental realization is to use the ion trap experiment with the Aharonov-Bohm effect.

YS, in preparation.

- How to affect many-body physics?
- How to understand the time crystal?







Concepts of Quantum and Spacetime

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Fay Dowker (Imperial College London)
Justin Dressel (Chapman University)
Laurent Freidel (Perimeter Institute)
Philipp Höhn (OIST)*
Hidetoshi Katori (University of Tokyo)
Adrian Kent (University of Cambridge)
Akira Matsumura (Kyushu University)
Shunji Matsuura (RIKEN)
Djordje Minic (Virginia Tech)
Takayuki Miyadera (Meiji Gakuin University)
Daniele Oriti (Complutense University of Madrid)
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Deadline for cancelation: February 20, 2026

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