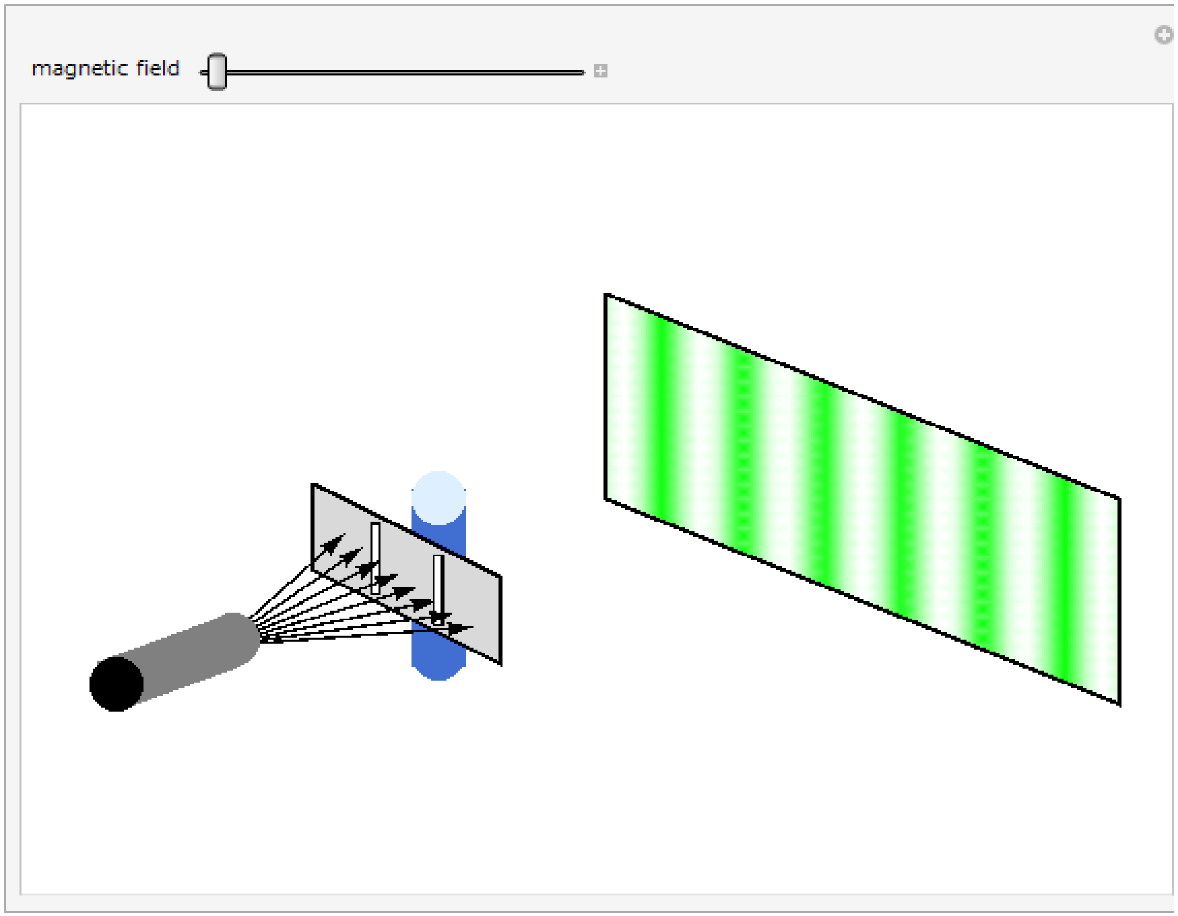
Three-particles Aharonov-Bohm effect



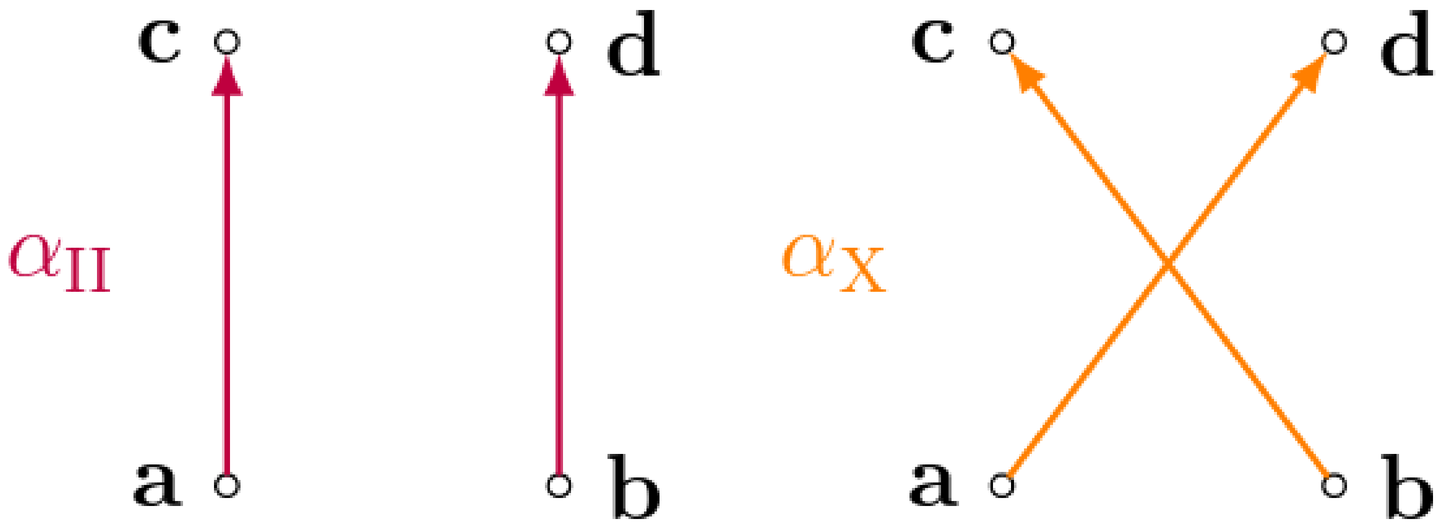
Yutaka Shikano

yshikano@cs.tsukuba.ac.jp

筑波大学
University of Tsukuba

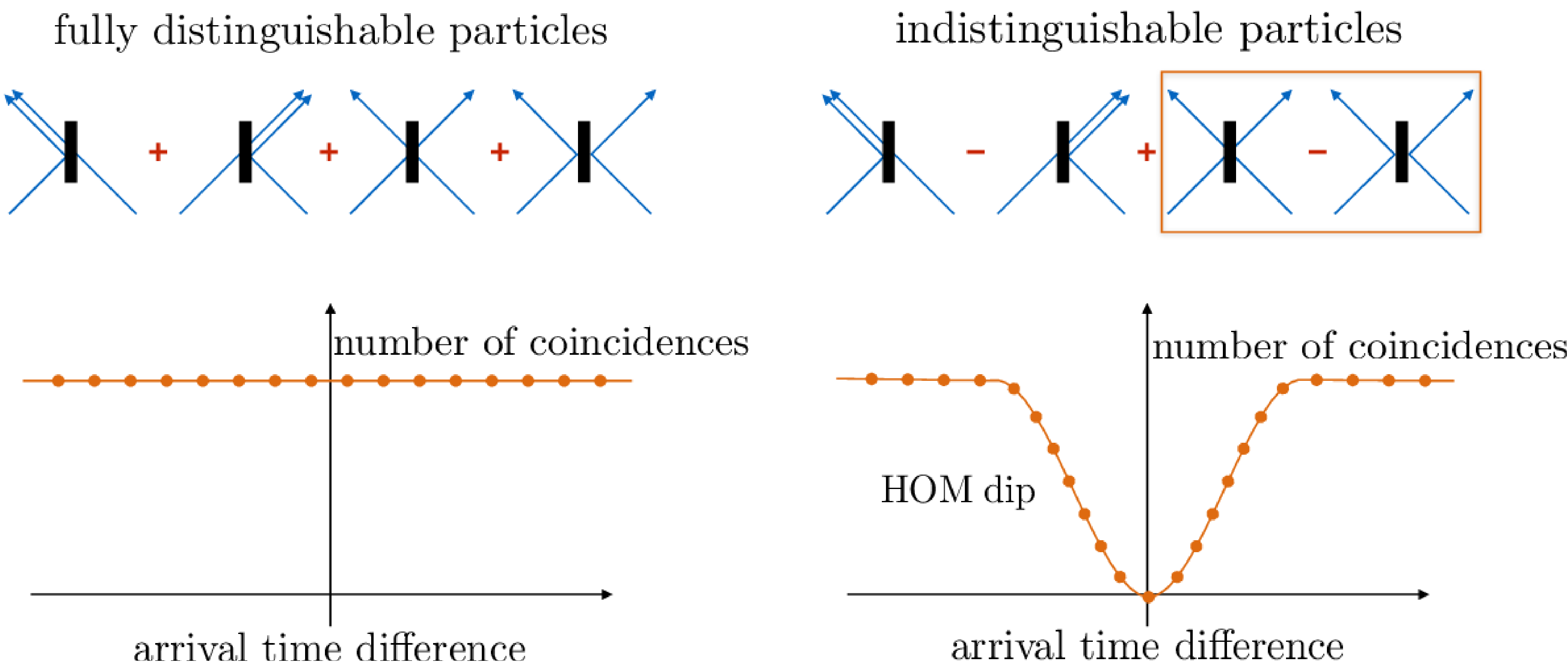
CHAPMAN UNIVERSITY
1861

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



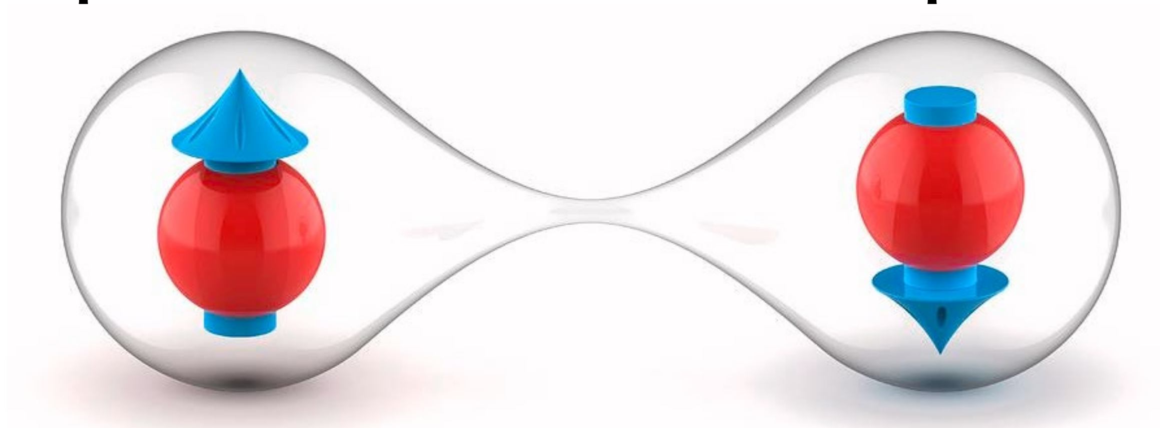
The amplitude depends on the indistinguishability.

Two-photon interference



Photons recognize the indistinguishability?

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.

$$|\psi\rangle_{B,\text{Alice thinks}} = |\uparrow\rangle_B \text{ or } |\downarrow\rangle_B$$

2. When Bob evaluate his own state,

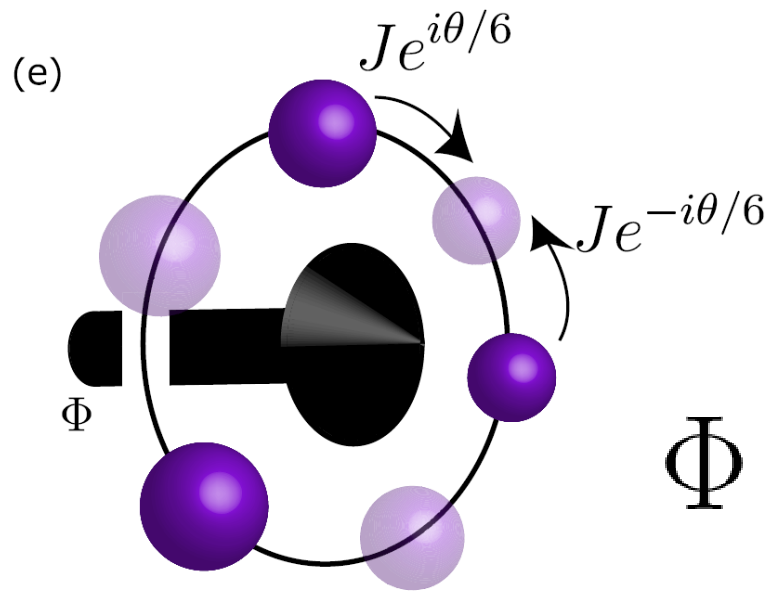
$$\rho_{B,\text{Bob thinks}} = \frac{1}{2}\left(|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow|\right)$$

Today's main question

Is there the information-dependent indistinguishability setup?

Aharonov-Bohm effect interference

Three **indistinguishable** charged particles



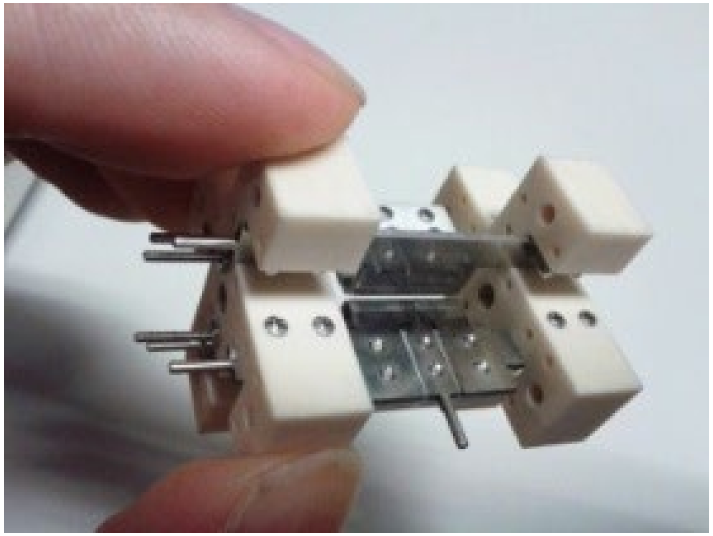
$$\theta = \boxed{3\times}\, 2\pi\Phi/\phi_0$$

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

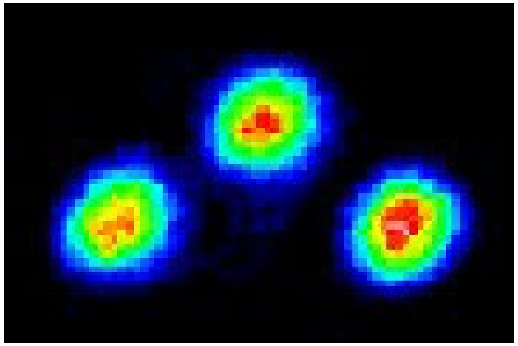
Transition probability with AB effect

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

Experimental feasibility: Ion-trap experiment w/ Paul trap



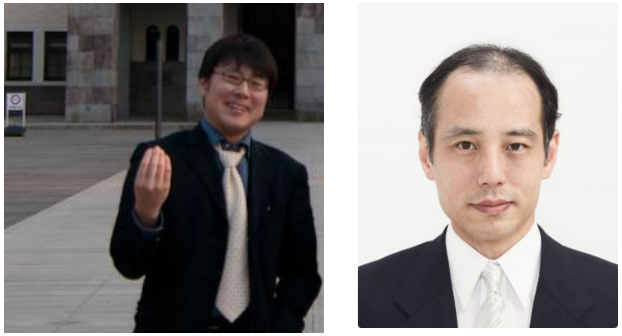
$$U = \sum_i \sum_{k=x,y,z} \frac{1}{2} m\omega_k^2 u_{k,i}^2 + \sum_{i,j} \frac{e^2}{4\pi\epsilon_0} r_{i,j}^{-1}$$



$^{40}Ca^+$

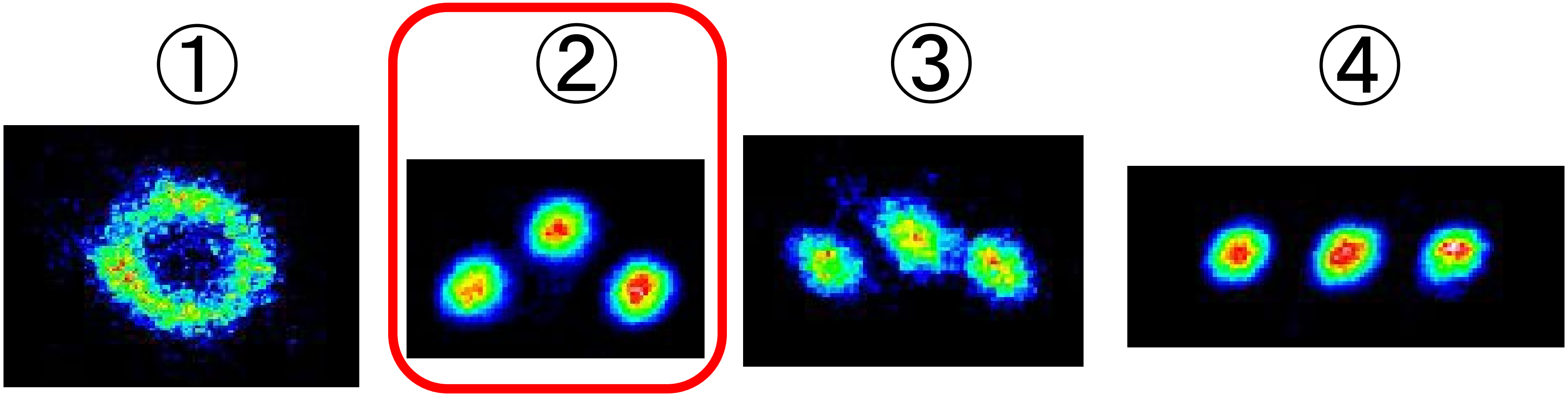
The collective motion of ions can be cooled down into the motional ground state.

Atsushi Noguchi moved to The University of Tokyo.

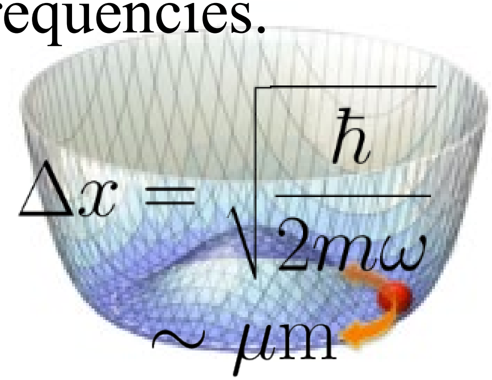


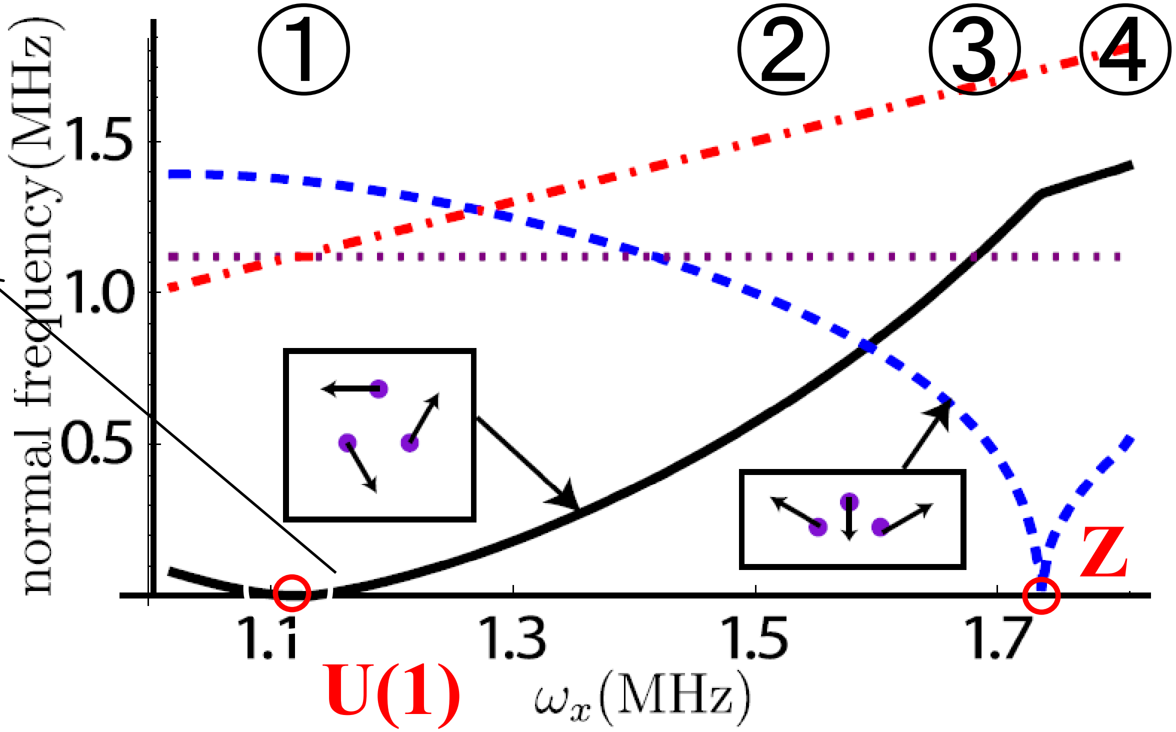
大阪大学
OSAKA UNIVERSITY

Collective motion (=phonon) frequency

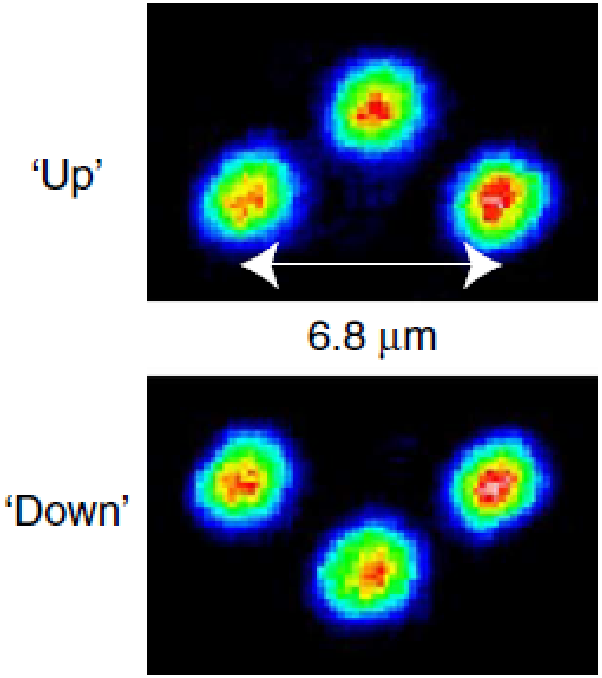


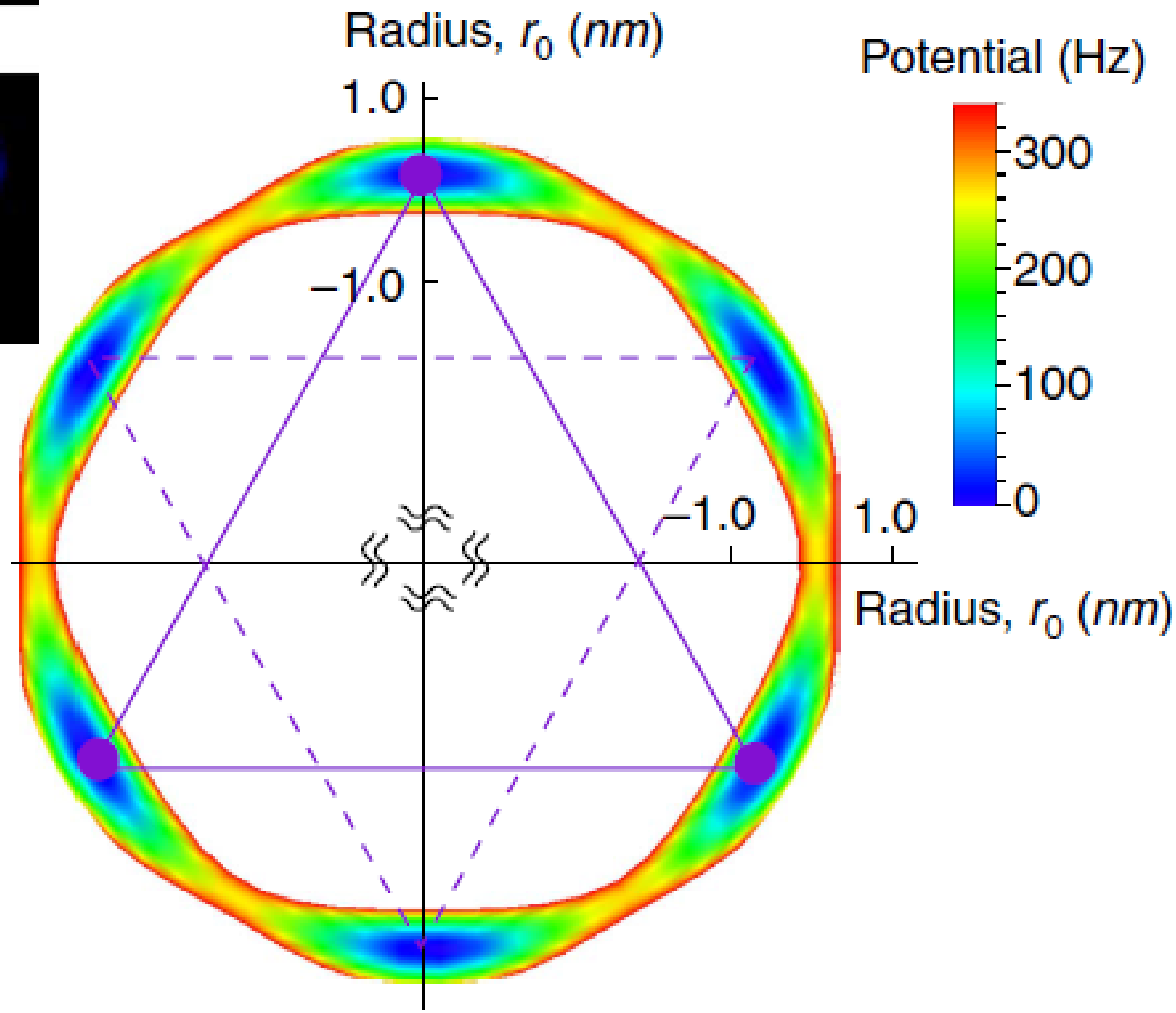
The wave functions of the ground states spread with the small normal mode frequencies.



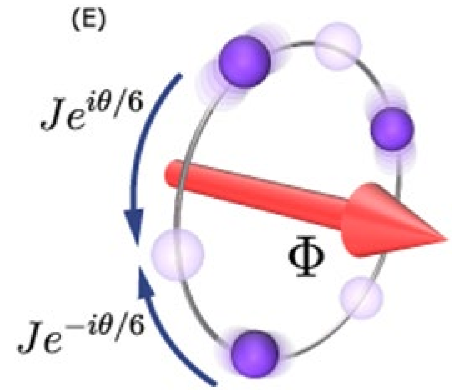


Potential of 3 ions

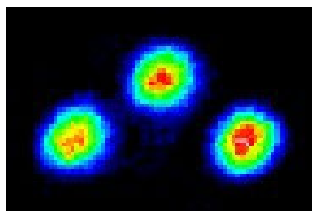




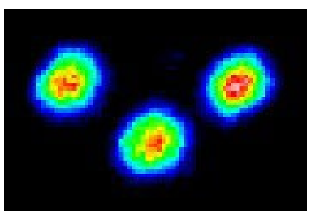
Quantum tunneling rotor as an interferometer



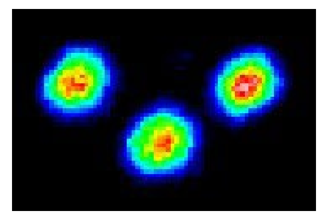
Two directional rotations cannot be distinguished.



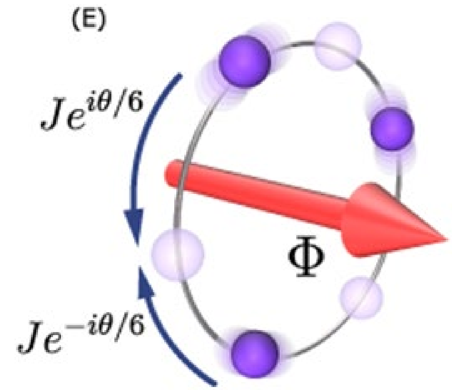
Anti-clockwise



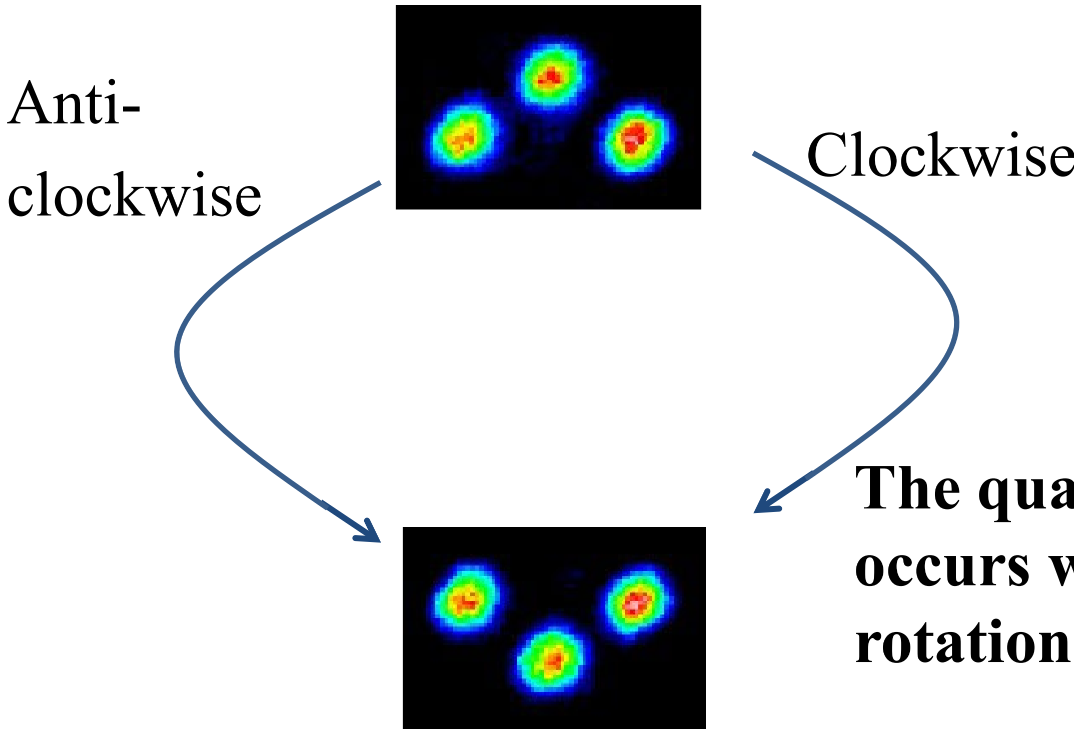
Clockwise



Quantum tunneling rotor as an interferometer



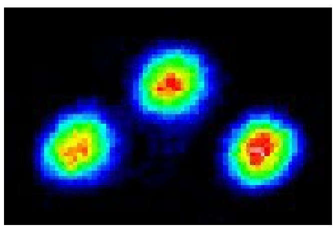
Two directional rotations cannot be distinguished.



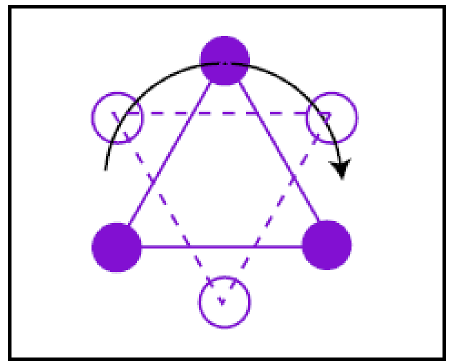
The quantum interference occurs with two directional rotations.

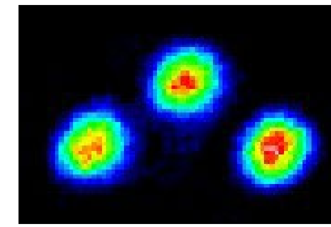
Experimental Procedures

For laser cooling

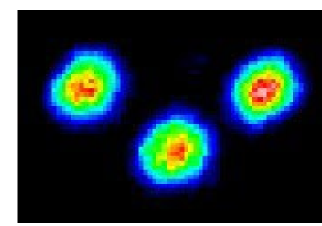


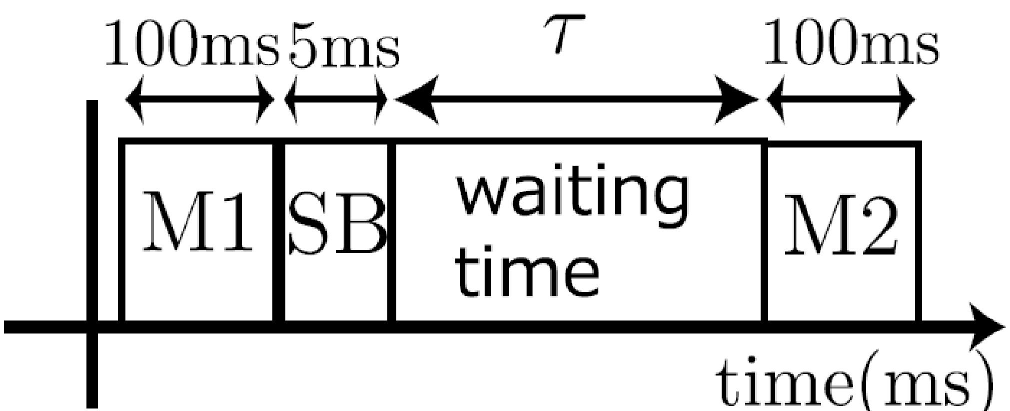
Quantum tunneling

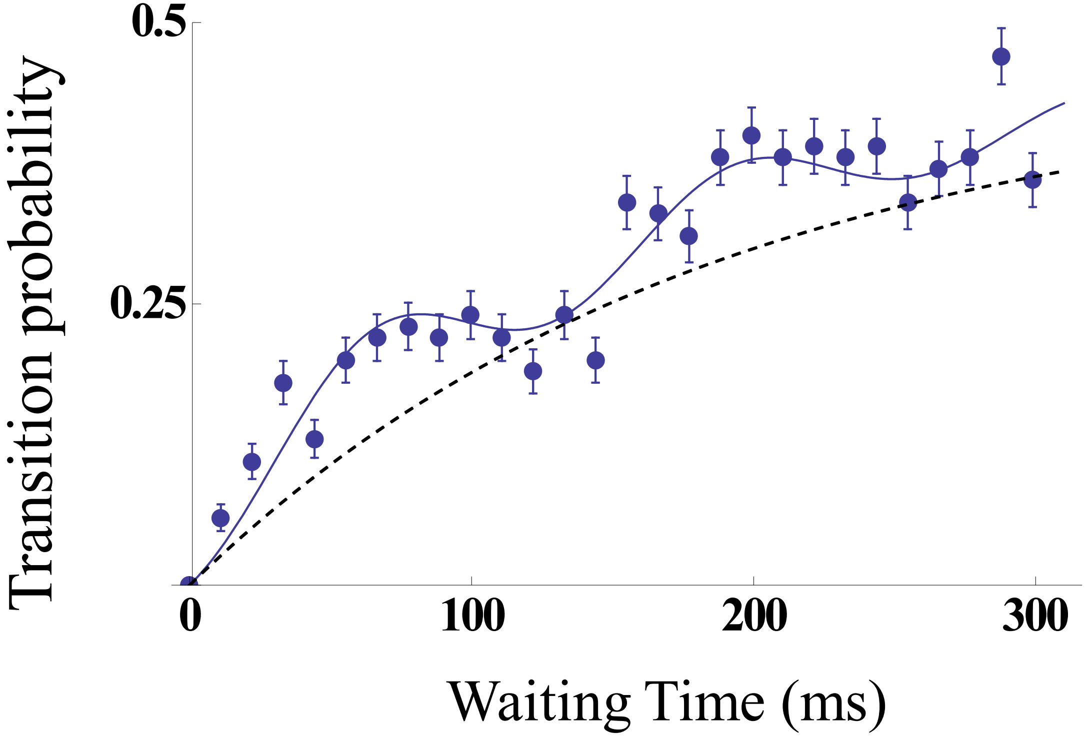




+







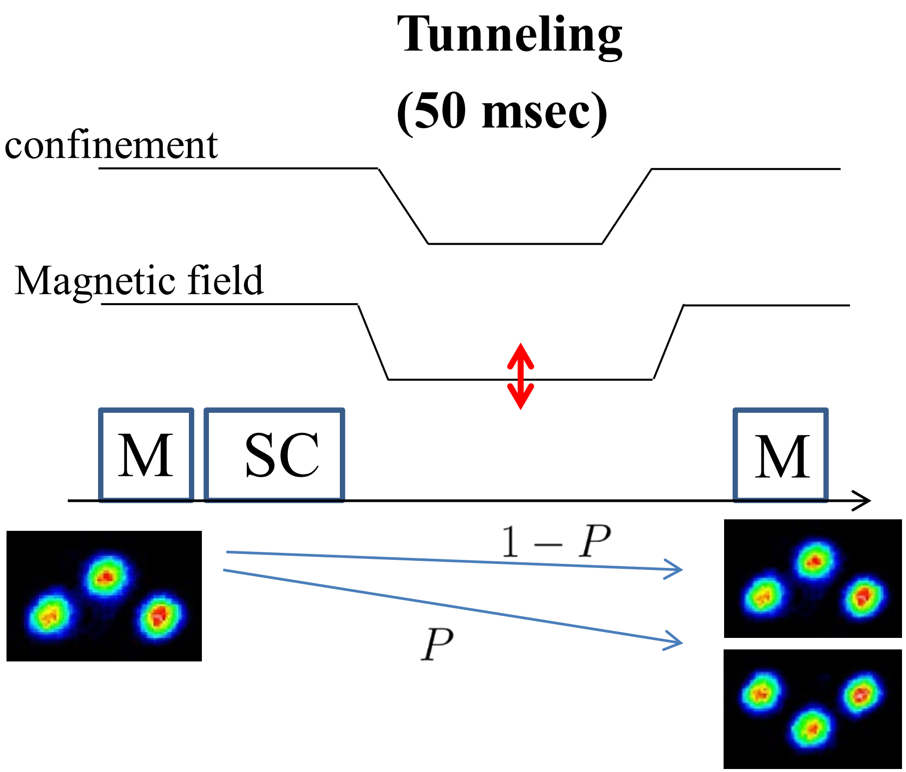
$$f(p_0, \nu, \tau_0, v) = p_0 \times \left(\frac{1 - e^{-(t/T_2)^2}\cos(2\pi\nu t)}{2}\right) + (1 - p_0) \times \frac{1 - e^{-vt}}{2}$$

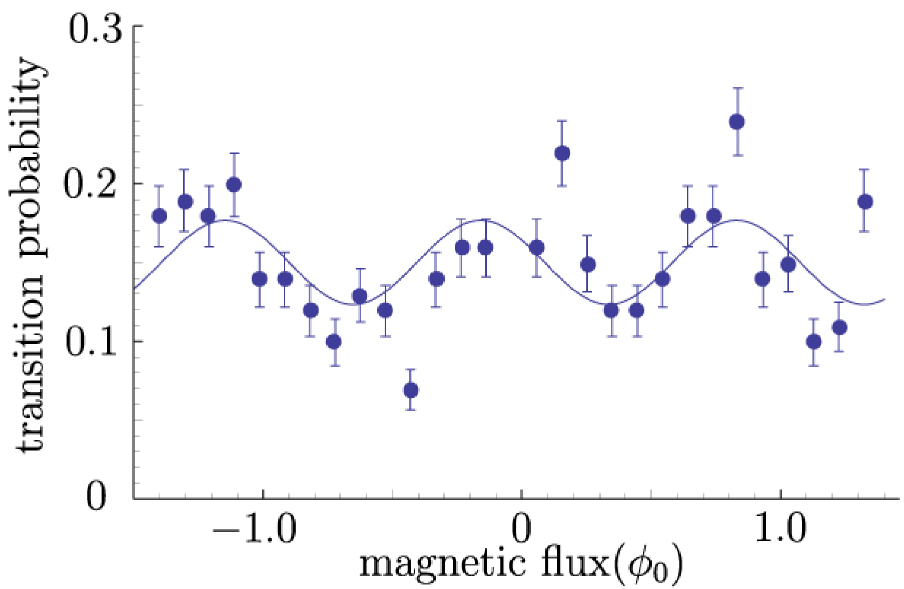
Coherent Tunneling Part — Heating

p_0	ν	T_2	v
0.10 ± 0.02	$7.6 \pm 0.3\text{Hz}$	$300 \pm 200\text{ms}$	$5.4 \pm 0.3\text{s}^{-1}$.

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

Experimental demonstration: AB effect interference

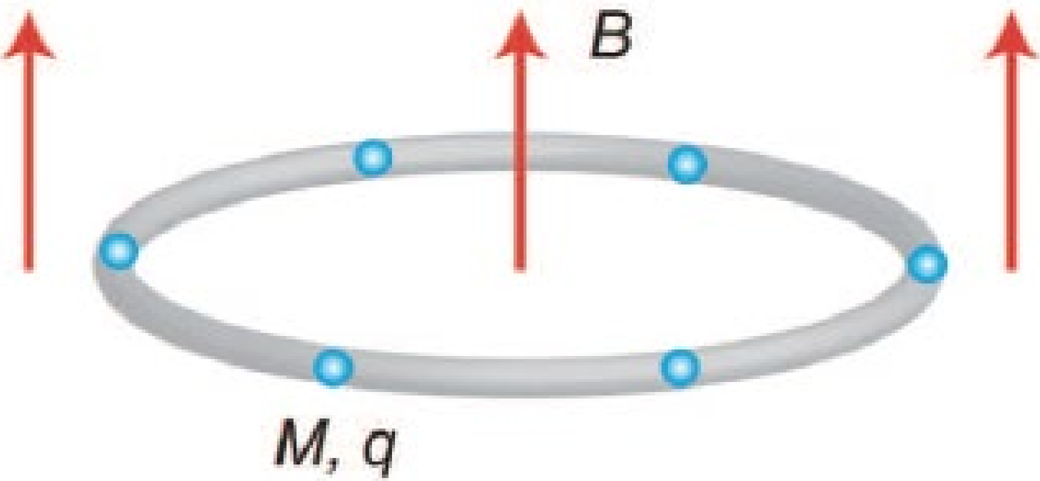




A. Noguchi, YS, K. Toyoda, and S. Urabe, Nat. Comm. **5**, 3868 (2014).
First demonstration on AB effect w/ quantum tunneling

AB effect phase shift can lead to the change of transition probability.

Is this the time crystal?
= spontaneous symmetry breaking in time



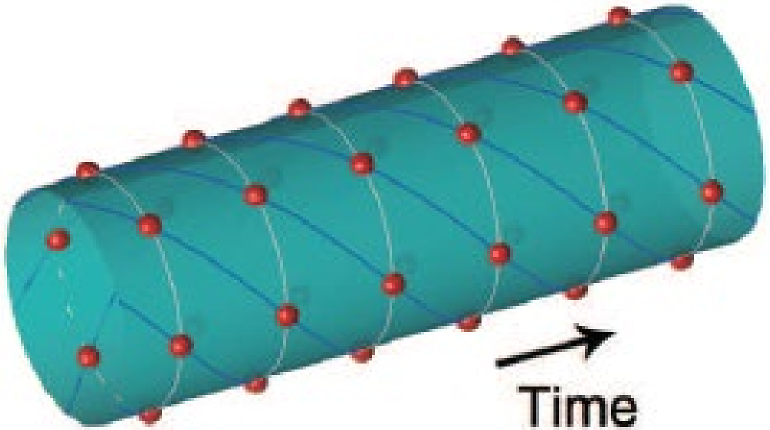
F. Wilczek,
PRL **109**, 160401 (2012)
T. Li et al.,
PRL **109**, 163001 (2012)

$$H = \frac{2\hbar^2}{Md^2}\Big[\big(-i\frac{\partial}{\partial q_1} - \sqrt{N}\alpha\big)^2 + \sum_{j=2}^{N}\big(-\frac{\partial^2}{\partial q_j^2} + \eta^2\omega_j^2 q_j^2\big)\Big]$$

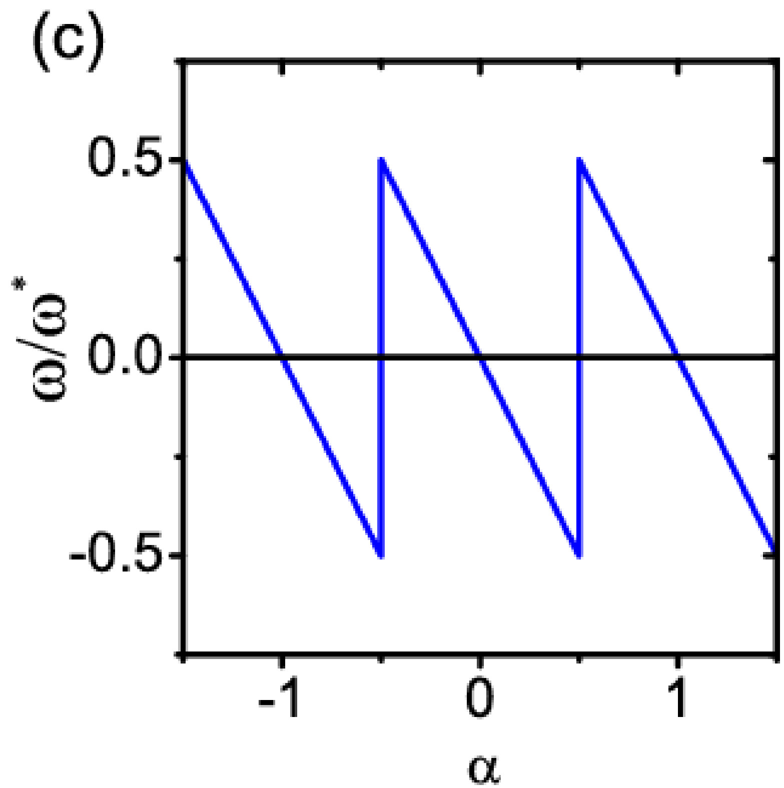
$$E_{n_1} = E^*(n_1-\alpha)^2 = \frac{2N\hbar^2}{Md^2}(n_1-\alpha)^2,$$

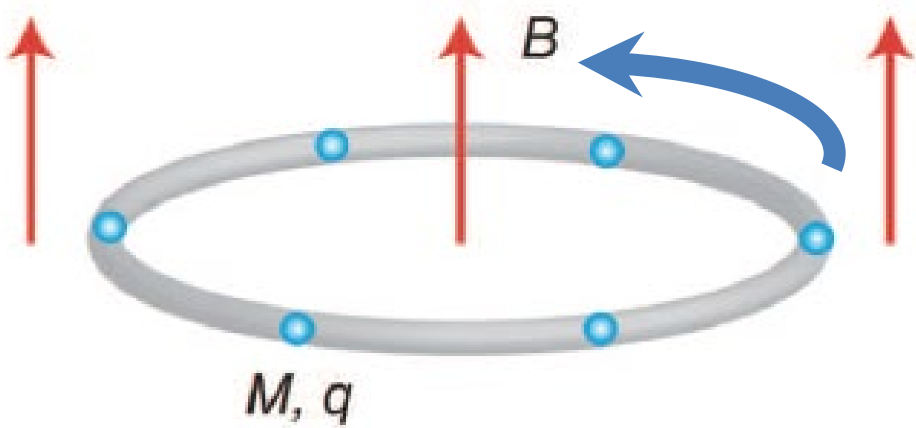
$$\omega_{n_1} = \omega^*(n_1-\alpha) = \frac{4\hbar}{Md^2}(n_1-\alpha),$$

Spontaneous symmetry breaking in time?
= creation of unidirectional rotation



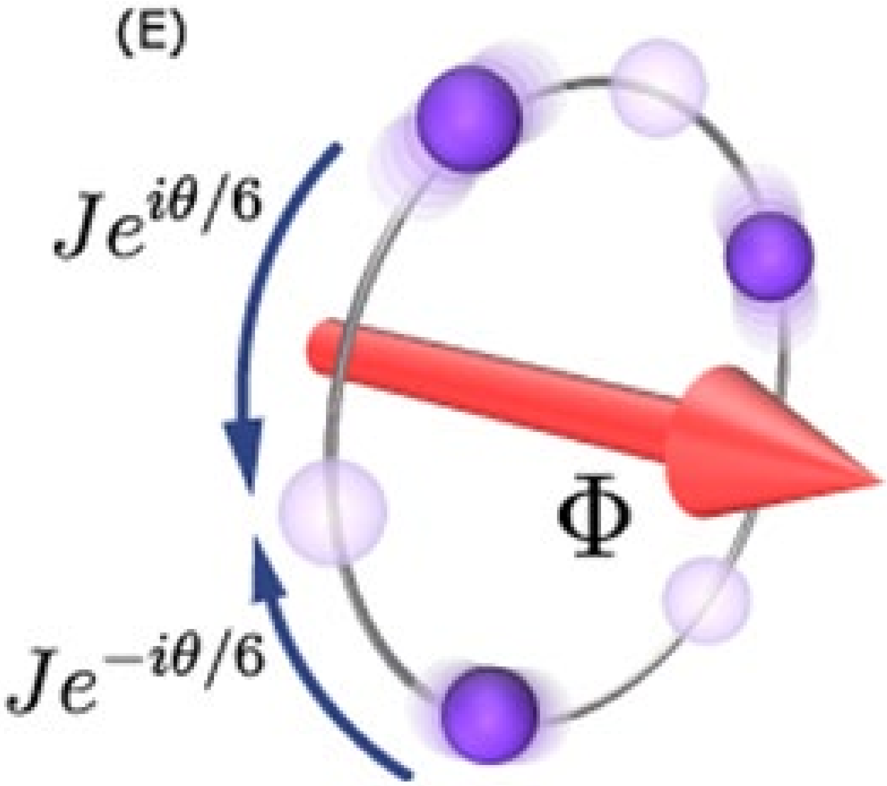
In principle,
we cannot observe this theory.





This theory seems to contradict our observed interreference?

How to detect the rotational direction?



Identical particles cannot be distinguished.

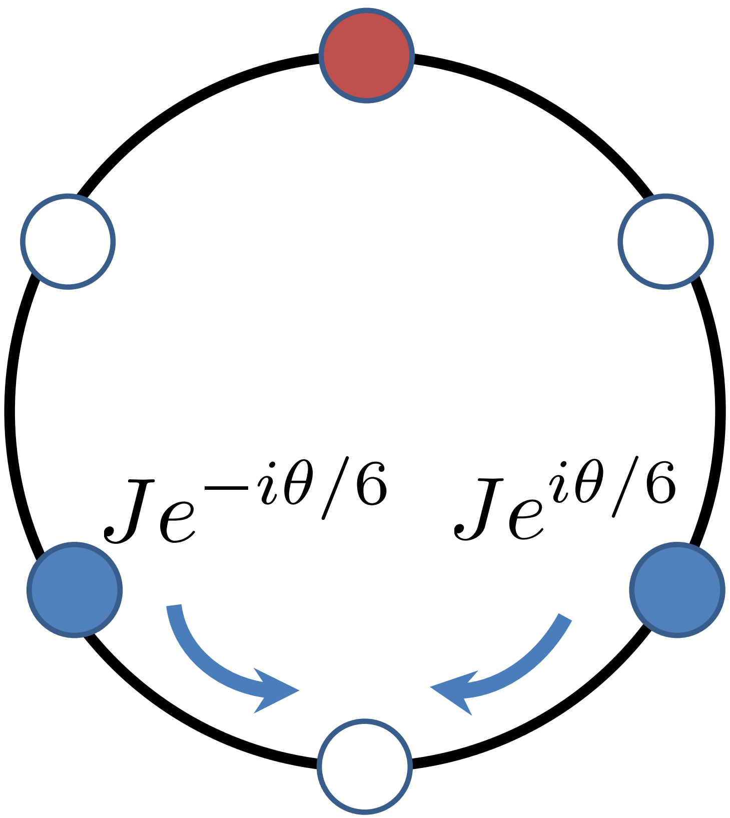
Feasibility:

local spin flipping / isotope control

Returning the question

Information-dependent indistinguishability setup?

Situation 1: one label & triangle obs.



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

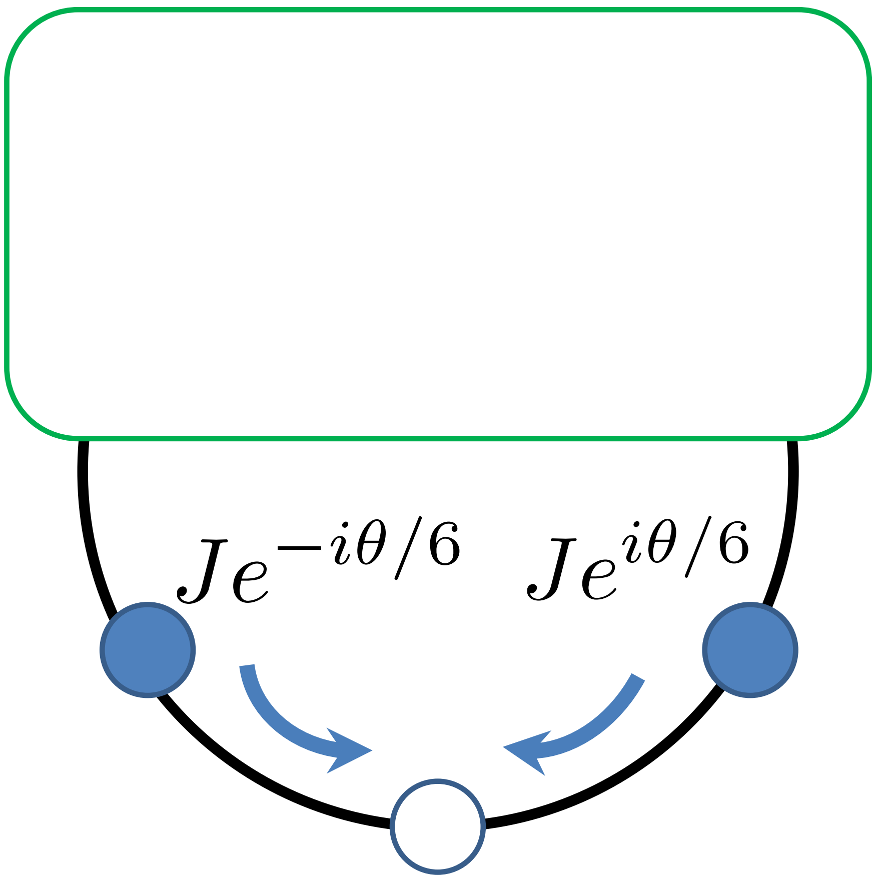
Label effect

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

$$P \propto |\cos\theta/6|^2$$

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

Situation 2: one label & local obs.



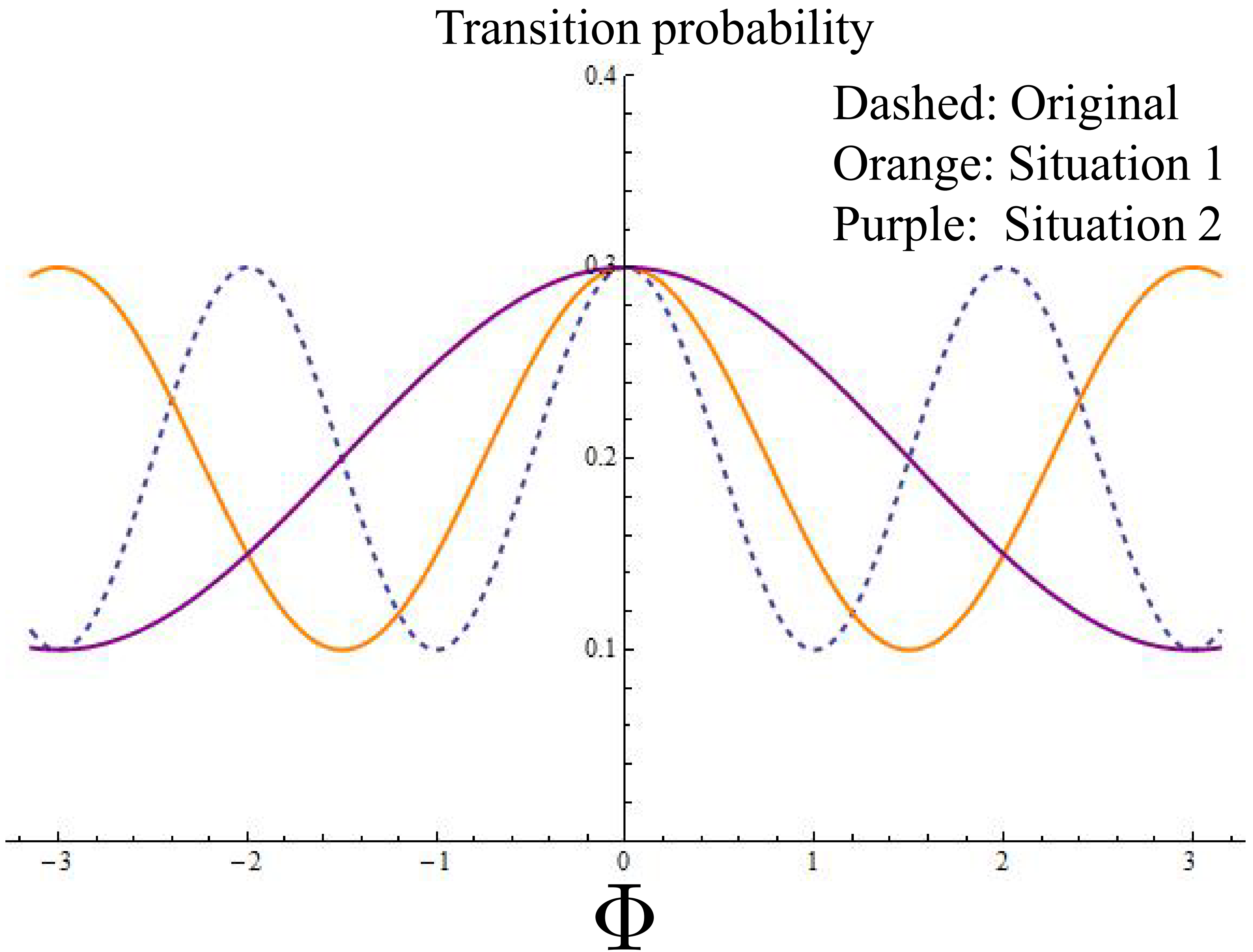
$$\theta = 3 \times 2\pi\Phi/\phi_0$$

Identical particle

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

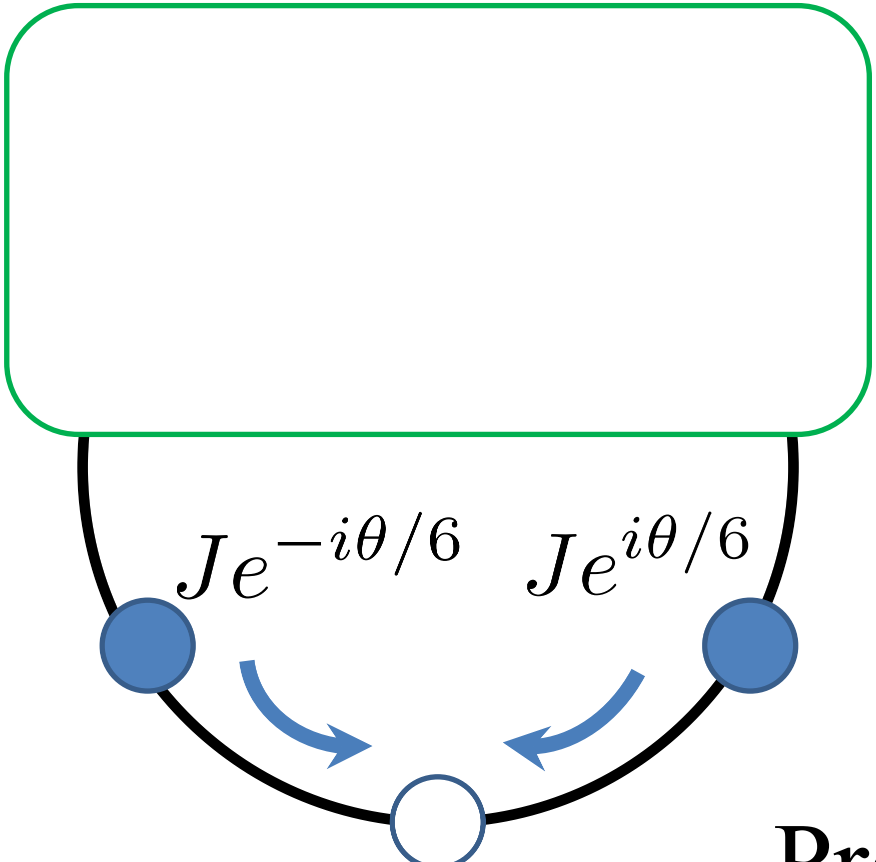
$$P \propto |\cos\theta/6|^2$$

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



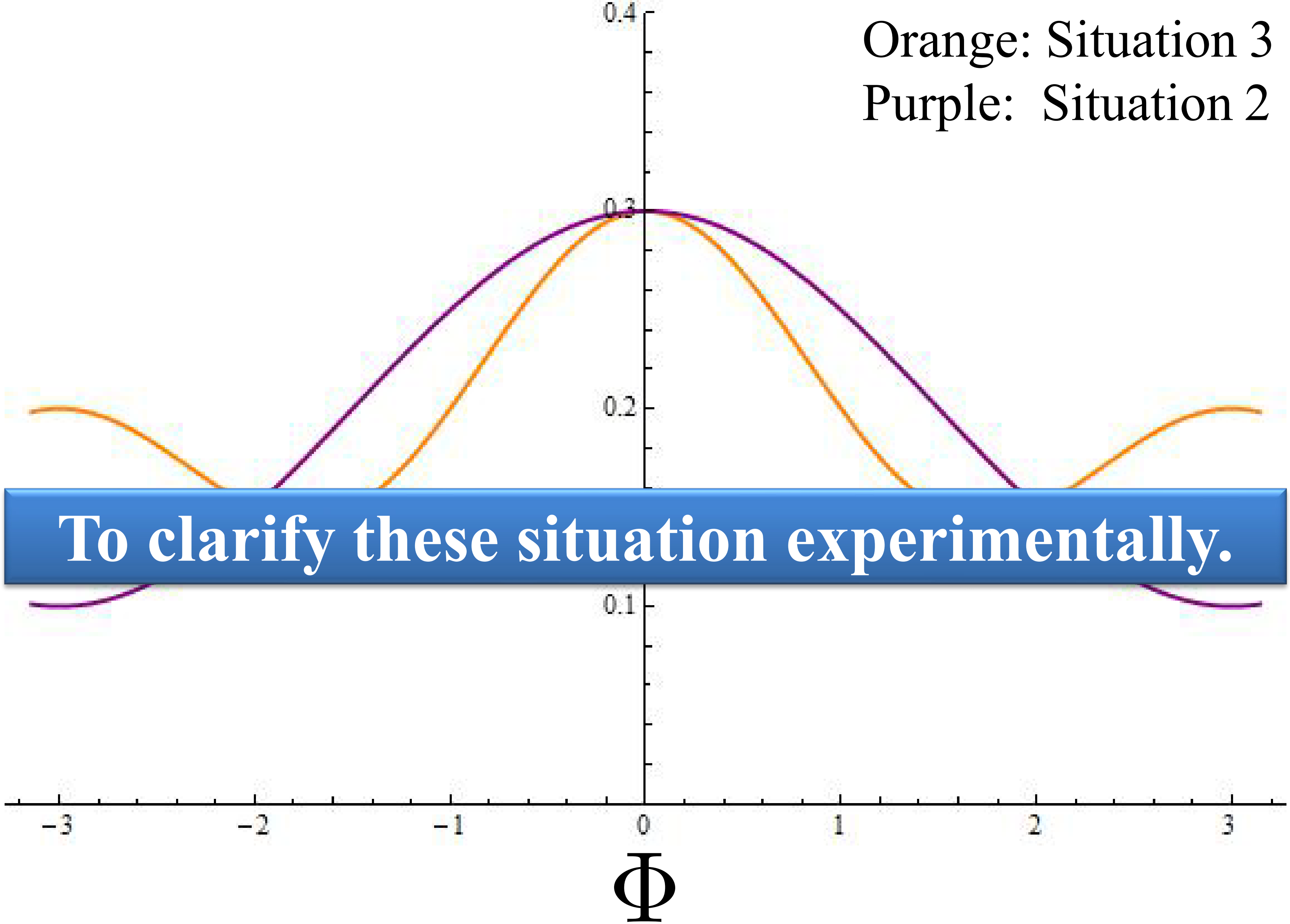
Transition probability
Dashed: Original
Orange: Situation 1
Purple: Situation 2
0.4
0.3
0.2
0.1
−3
−2
−1
0
1
2
3
Φ

Situation 3: one label & local obs. w/ observer dependent description



Probabilistic mixture
Situation 1 + Situation 2

Transition probability



Conclusion and Outlooks

- We propose the information-dependent indistinguishability experimental setup by the Aharonov-Bohm interference with ion trap.
- The discussion on no apparent observation of the time crystal is needed.
  - Under discussion w/ David Wineland
- On the isotope control, the experimental feasibility of the Wigner crystal should be discussed.
- How to affect many-body physics?