The 4th Yamada Symposium on Advanced Photons and Science Evolution, 2010(APSE 2010)
JICA Osaka, 14-18 June 2010 (Presented on 14 June 2010)

Quantum Nature of Photons and Optical Information

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Osaka G-COE
DYCE Optical Science of Dynamically Correlated Electrons
Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)

Photons

- Mass-less : moves with velocity c
  → OK for transmission but NG for memories

- Strong or very weak interaction with matters
  ↓ Low-loss transmission possible
  - Nearly ideal "first-kind measurement" possible

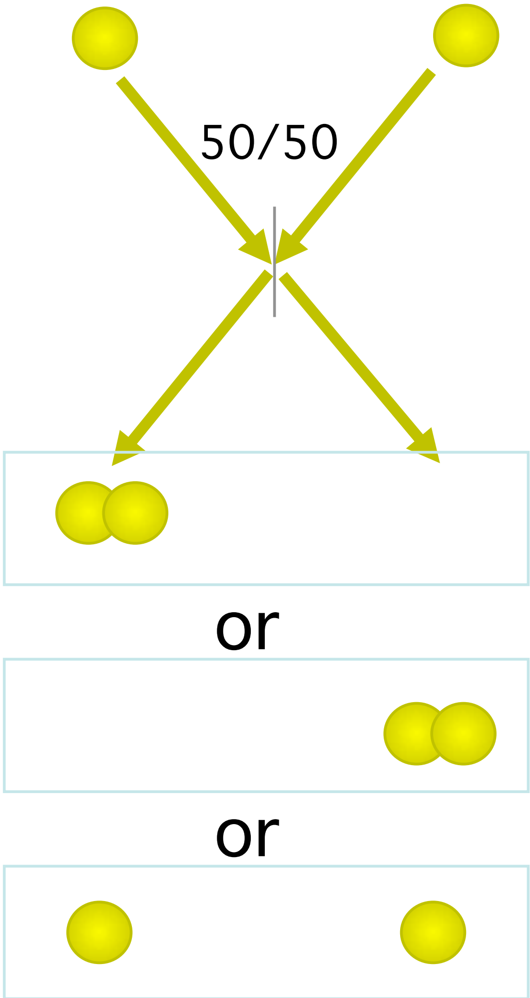
- No direct interaction between photons
  - Linear interaction is strong with the help of matters
  - Nonlinear interaction is weak → a few of those available

- Bosons → ・Large amplitude possible → wave like
  → ・Multi-particle interference

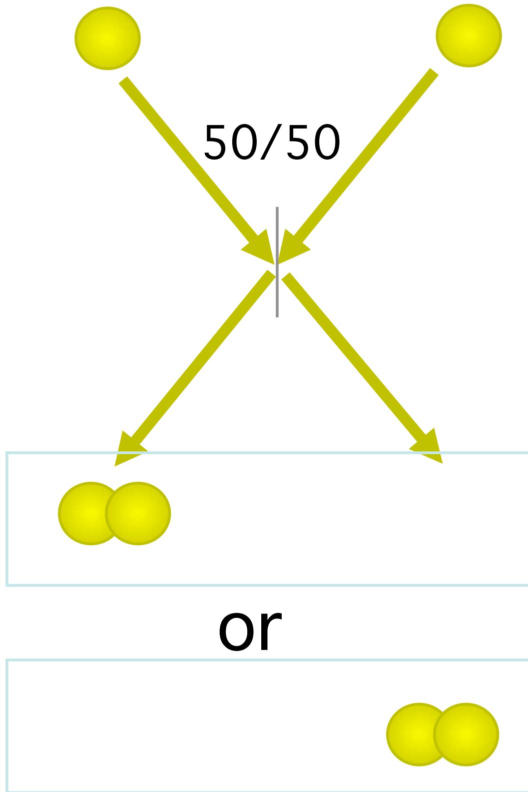
- Feedback oscillation possible (lasers)
  → Easy to prepare in a well-controlled mode

- Spin 1 particles → Polarization (well controlled)

Two-photon interference



truth is・・・



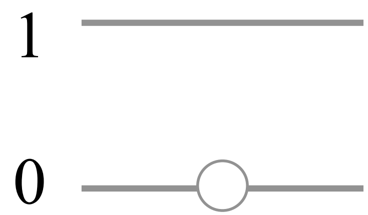
Hong-Ou-Mandel

Bits and Qubits

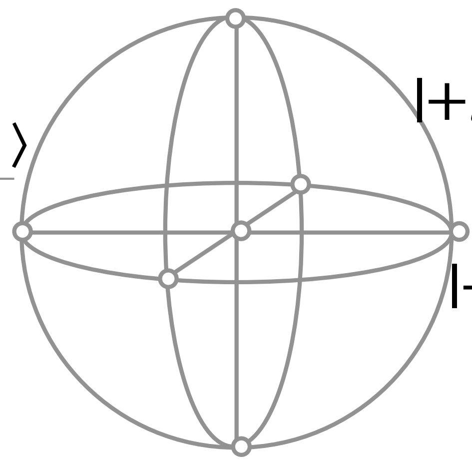
Bit : a system that takes state 0 or 1

A bistability device can be used.

Example : switch, memory



Qubit : a system that takes not only 0 and 1, but also $\alpha 0 + \beta 1$
where, $|\alpha|^2 + |\beta|^2 = 1$



$|+i\rangle \equiv \frac{|0\rangle + i|1\rangle}{\sqrt{2}}$

$|-\rangle \equiv \frac{|0\rangle - |1\rangle}{\sqrt{2}}$

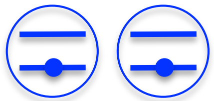
$|+\rangle \equiv \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

$|-i\rangle \equiv \frac{|0\rangle - i|1\rangle}{\sqrt{2}}$

Physical systems : photons, atoms, spins, quantum dots, molecules, etc.

Physical object		Qubit variable	Control of qubits	
Photon		Polarization Path Photon number Phase	Linear optics Nonlinear optics	
Matter	Single atom ion spin SCs Elementary excitations	 charge flux	π pulse $\pi/2$ pulse Qubit interaction	optical pulse
	Ensemble of atoms etc.		Single photon External field, etc.	

Entanglement among n -partite, m –level systems

2-partite 2-level systems $\rightarrow$ Bell states $= |00\rangle + |11\rangle$, etc. 

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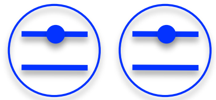
2-partite 2-level systems $\rightarrow$ Bell states $= |00\rangle + |11\rangle$, etc. 

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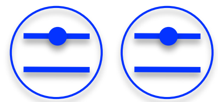

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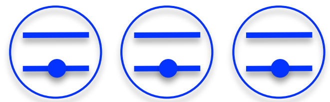

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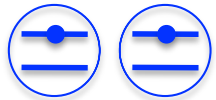

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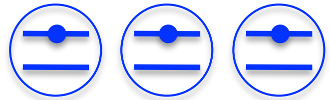

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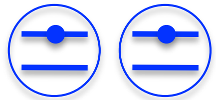

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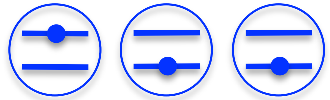

$$W = |100\rangle + |010\rangle + |001\rangle$$

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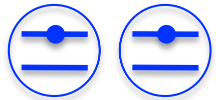

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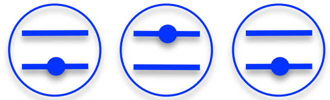

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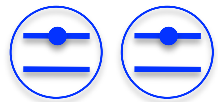

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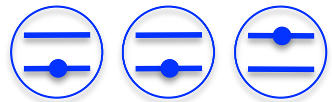

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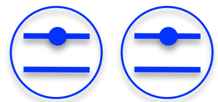

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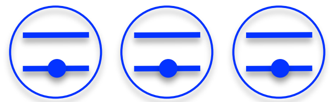

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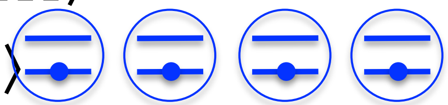

$$C_4 = |0000\rangle + |0011\rangle + |1100\rangle - |1111\rangle$$

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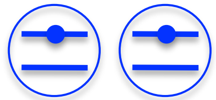

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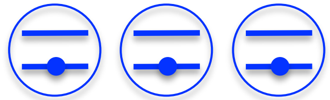

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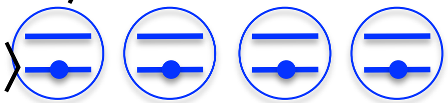

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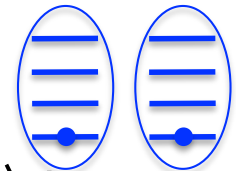

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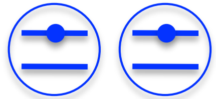

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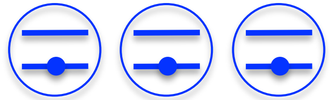

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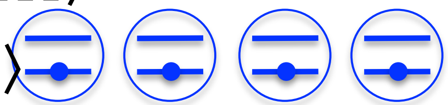

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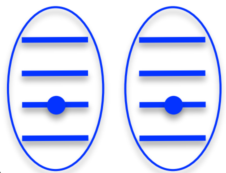

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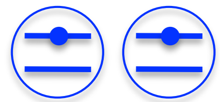
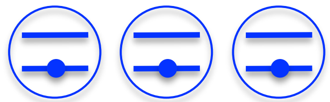
2-partite 2-level systems $\rightarrow$ Bell states $= |00\rangle + |11\rangle$, etc. 

3-partite 2-level systems $\rightarrow$ GHZ $= |000\rangle + |111\rangle$ 

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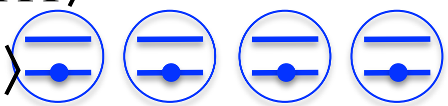

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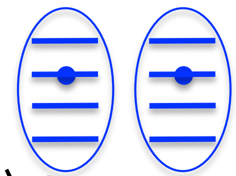

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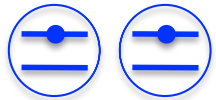

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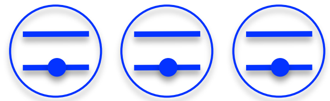

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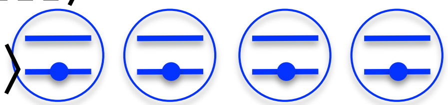

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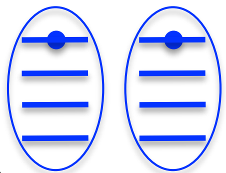

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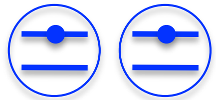

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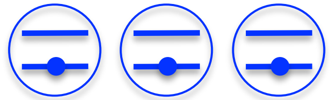

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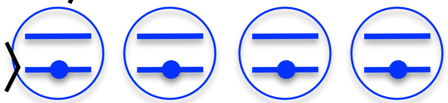

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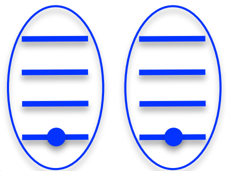

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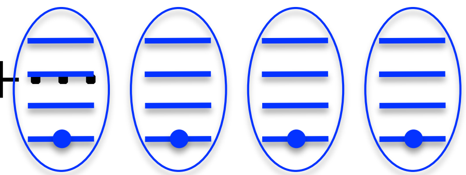

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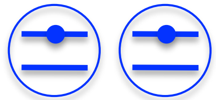

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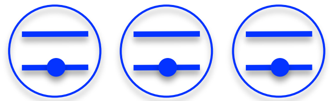

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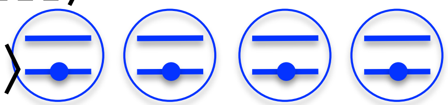

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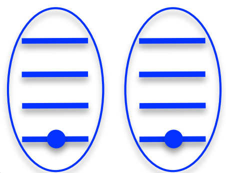

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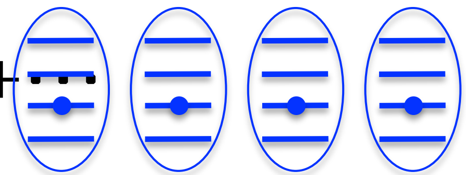

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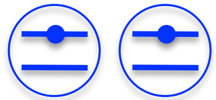

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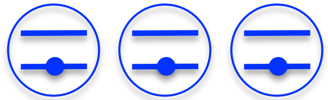

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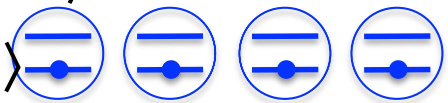

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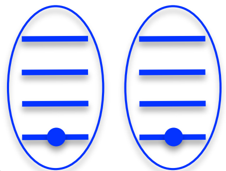

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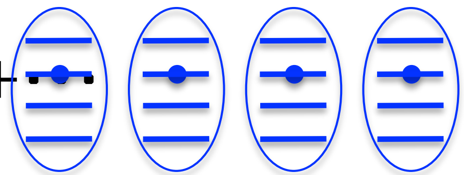

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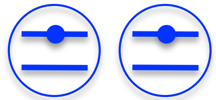
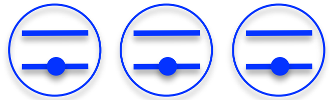


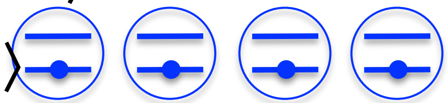
3-partite 2-level systems $\rightarrow$ GHZ $= |000\rangle + |111\rangle$



$\mathrm{W} = |100\rangle + |010\rangle + |001\rangle$

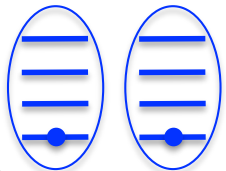
More than 4-partite 2-level systems $\rightarrow$ GHZ$= |0000\rangle + |1111\rangle$

$\mathrm{W} = |1000\rangle + |0100\rangle + |0010\rangle + |0001\rangle$



$\mathrm{C}_4 = |0000\rangle + |0011\rangle + |1100\rangle - |1111\rangle$

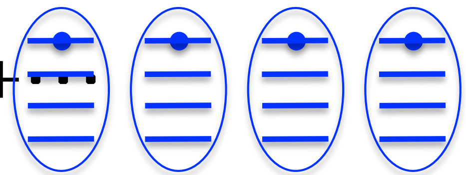
etc.$\cdots$



2-partite multi-level systems $\rightarrow$ MES $= |00\rangle + |11\rangle + |22\rangle + |33\rangle + \cdots$

etc.$\cdots$

n-partite m–level systems $\rightarrow$ $|0000\rangle + |1111\rangle + |2222\rangle + \cdots$



etc.$\cdots$

Entanglement among n-partite, 2-level systems

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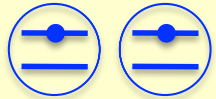

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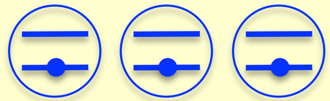

$$W = |100\rangle + |010\rangle + |001\rangle$$

More than 4-partite 2-level systems $\rightarrow$ GHZ$= |0000\rangle + |1111\rangle$

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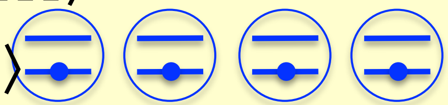

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etc.$\cdots$

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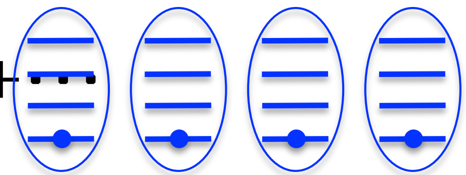

etc.$\cdots$

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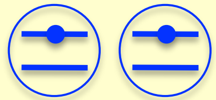

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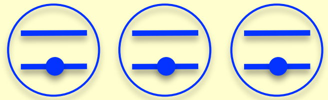
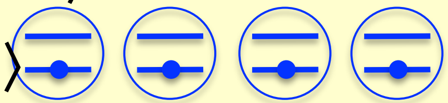


$W = |100\rangle + |010\rangle + |001\rangle$

More than 4-partite 2-level systems → GHZ$= |0000\rangle + |1111\rangle$

$W = |1000\rangle + |0100\rangle + |0010\rangle + |0001\rangle$



$C_4 = |0000\rangle + |0011\rangle + |1100\rangle - |1111\rangle$

etc.···

- difficult to produce (when n is large) → a possible direction
- difficult to protect from environmental decoherence →a possible direction
- how to use? ex1) cluster-state one-way quantum computation

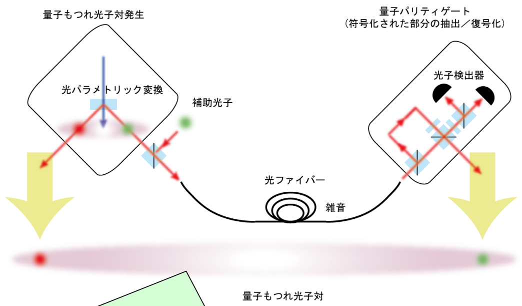
  ex2) When the meters are entangled → Joint weak measurement

  → “anomalous weak value”

Our recent activities

Theory and experiments

Protection of entanglement using DFS (decoherence-free subspace)



Nature (2003), PRL (2005)
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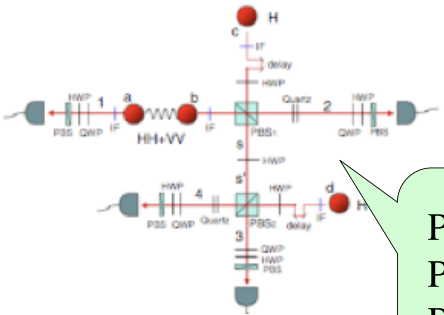
Cluster-state one-way Quantum computing



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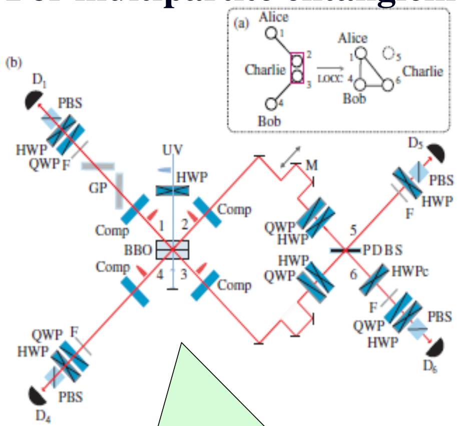

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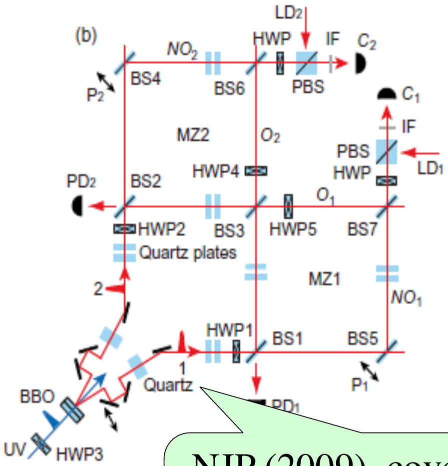

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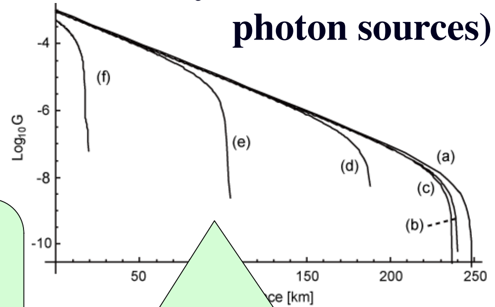

PRL(2007), PRA(2009)

PRA (2010)
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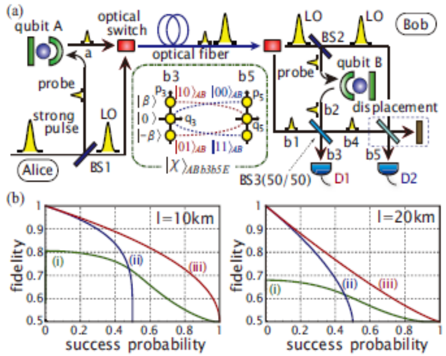
Optimal design for quantum repeaters



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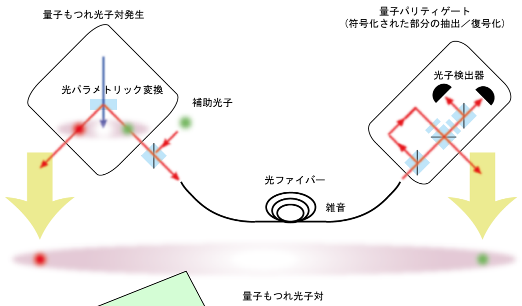

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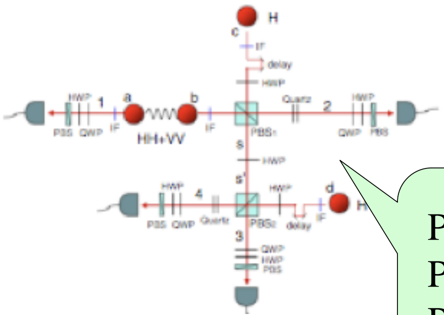

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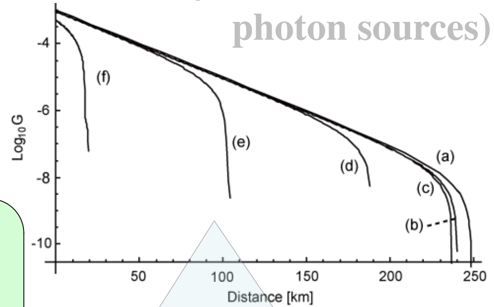

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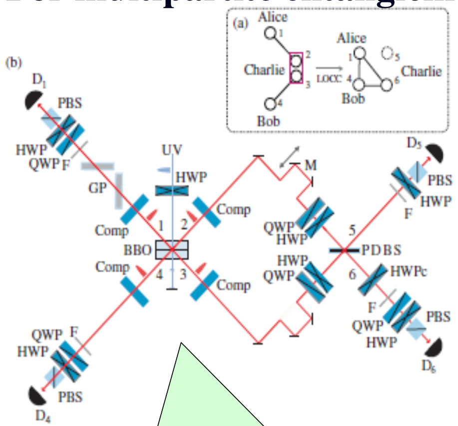

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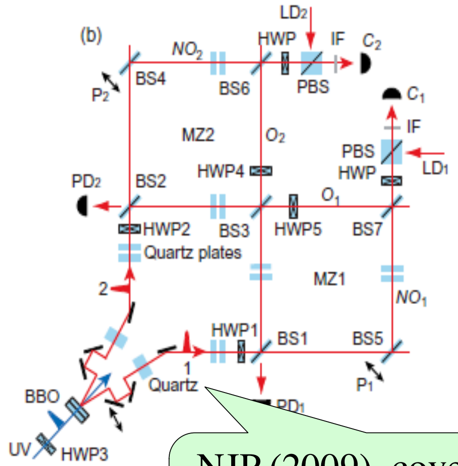

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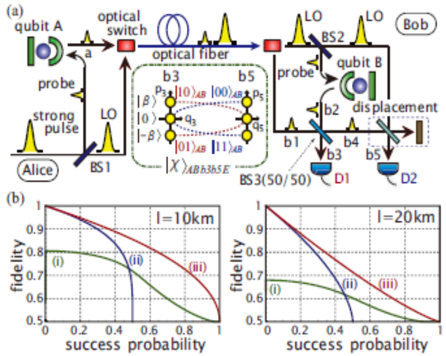
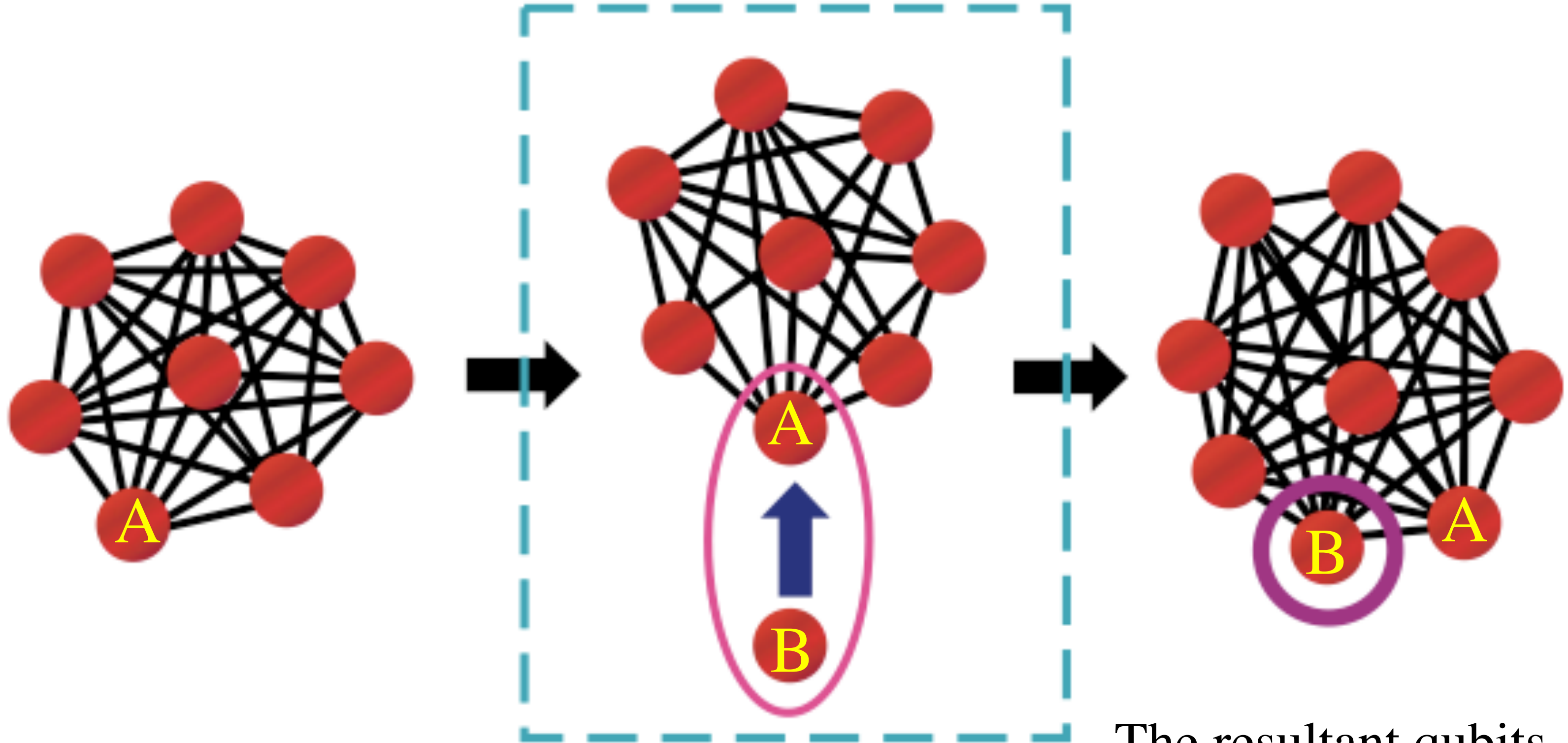


An expansion gate

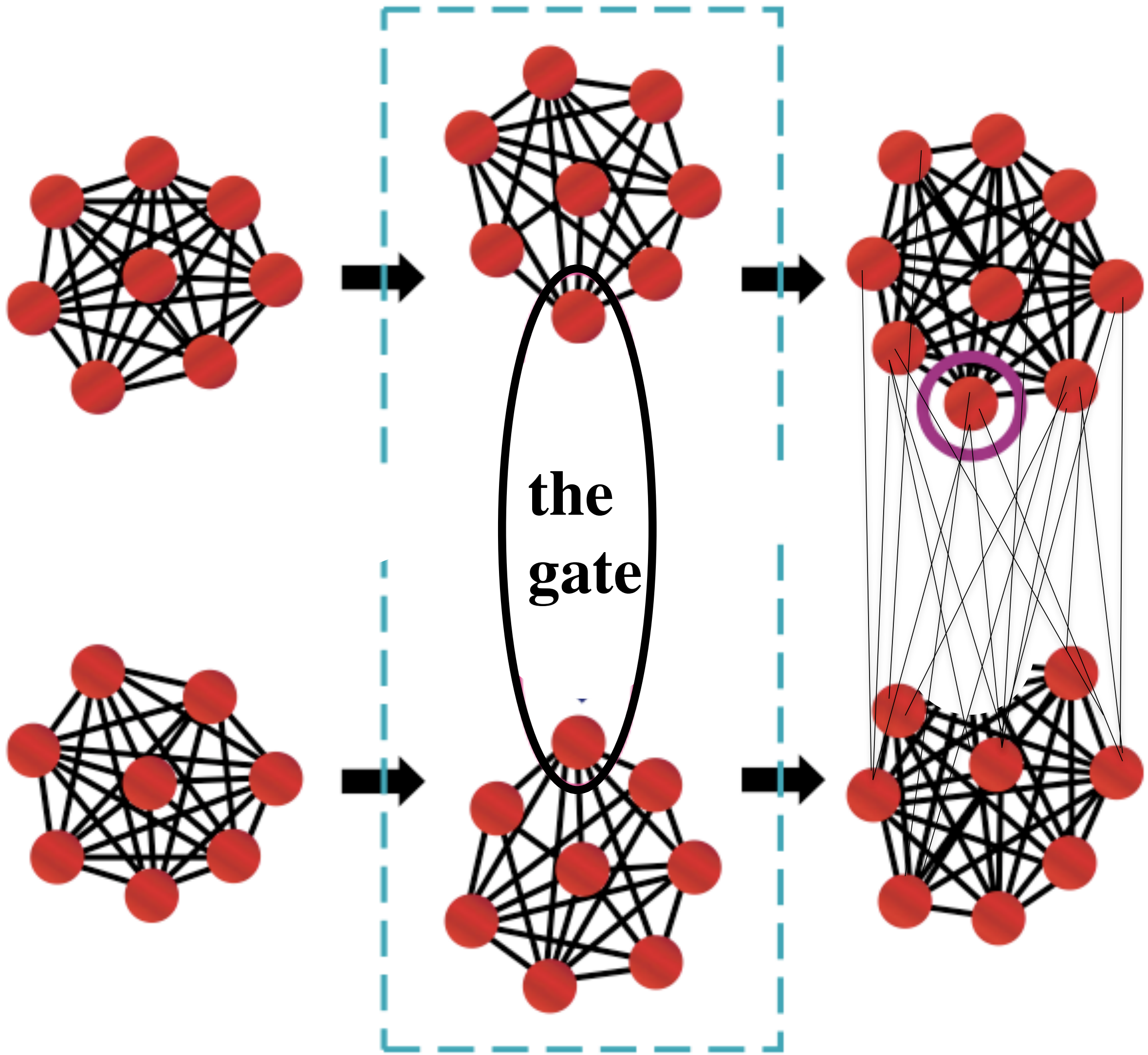


Given n-partite entanglement

Pick up one qubit A from the n qubits and react it with your qubit B using the gate.

The resultant qubits are now the desired n+1 –partite entangled state.

A fusion gate



Question: can do you it deterministically by only accessing one qubit?

Answer: "Yes" for GHZ and cluster states, but "No" for W states.

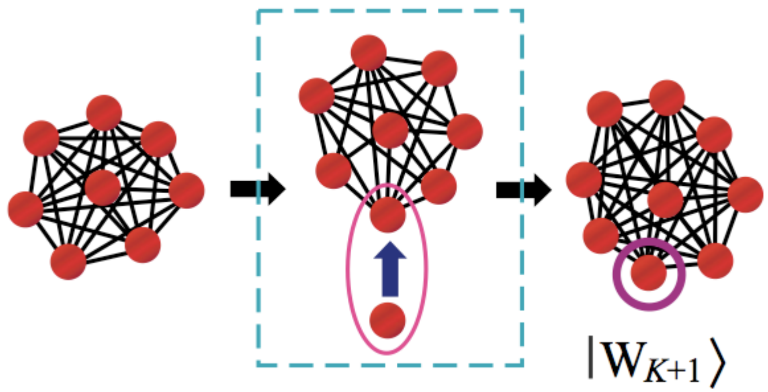
Related work: "persistency of entanglement in W-states" Koashi+Buzek+N.I. (2001 PRA)

Question: is it possible to do it *probabilistically* for W states?

Answer: Yes! Even using linear optics + photon counting.

(→ papers [1][2][3] in the next viewgraph)

An expansion gate



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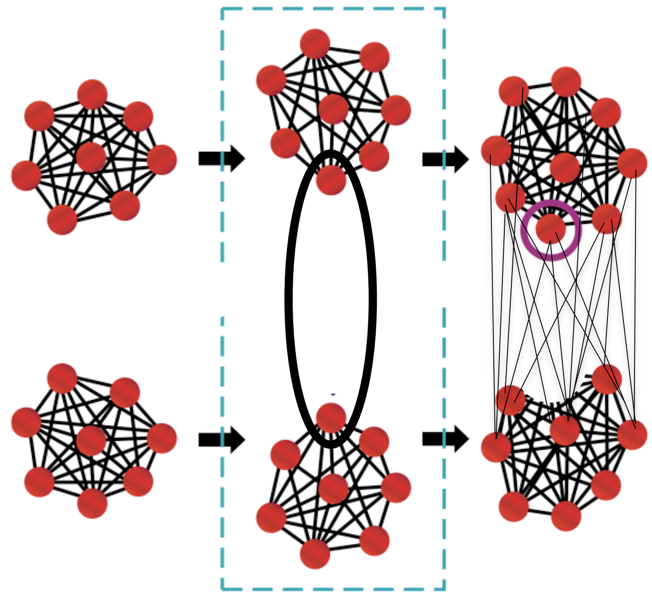

T. Tashima, S. K. Ozdemir, M. Koashi, T. Yamamoto, N.I. etc.

[1] Theoretical proposal of a simple expansion gate
for "$n \rightarrow n$+2" W states
PRA77, 030302(R) (2008).

[2] Theoretical proposal of a simple expansion gate
for "$n \rightarrow n$+1" W states
New J. Phys. 11, 023024 (2009).

[3] Proposal of a simple fusion gate for W states
and experimental verification of the gate by
W2+W2 $\rightarrow$ W3 + 1 photon detection
Phys. Rev. Lett. 102, 130502 (2009).

Our recent activities

Theory and experiments

Theory

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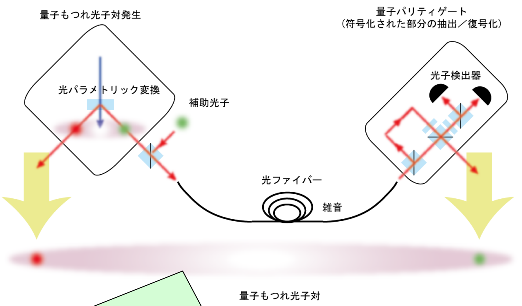

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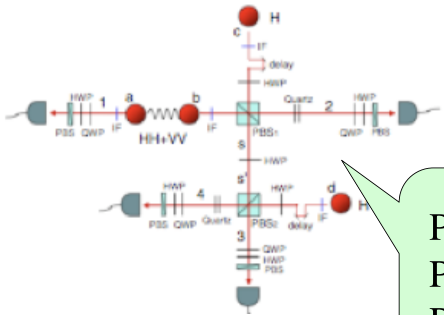

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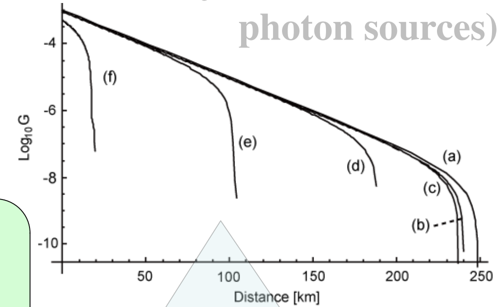

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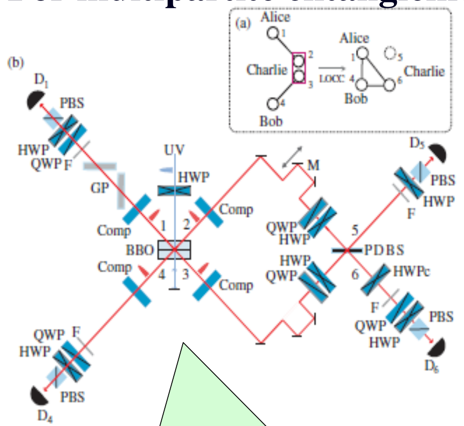

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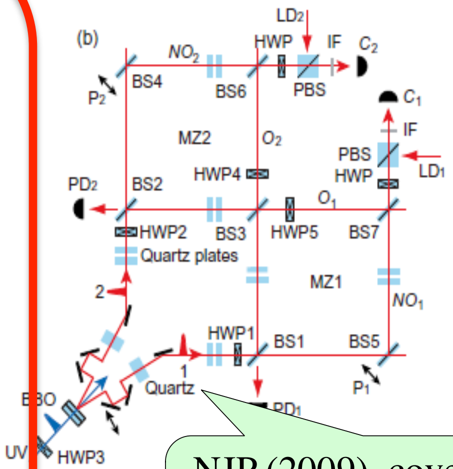

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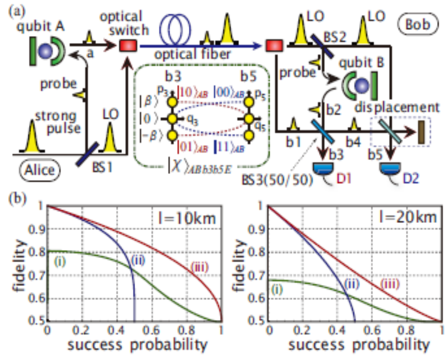

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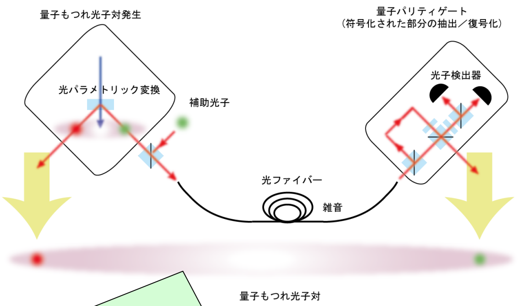

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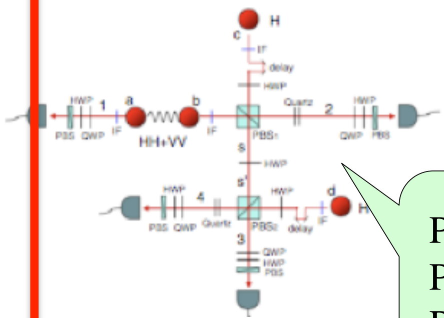

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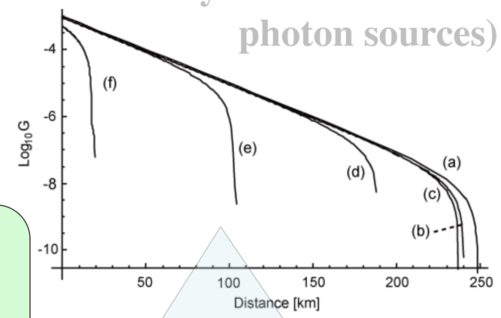

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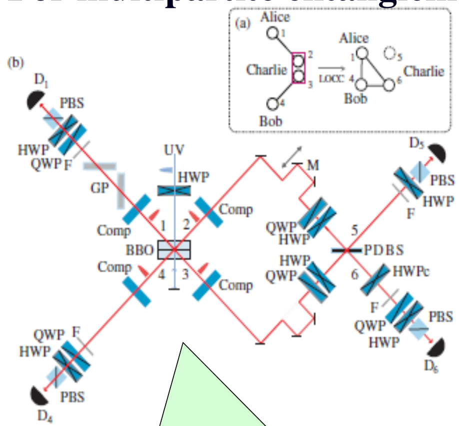

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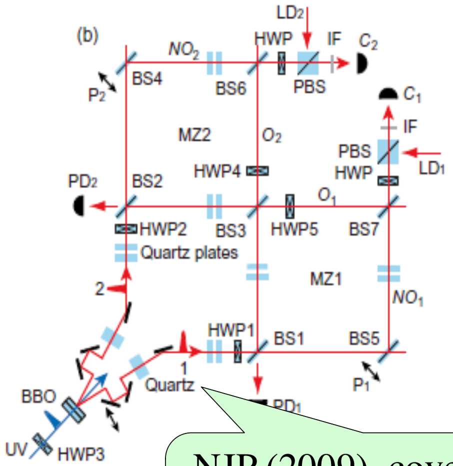

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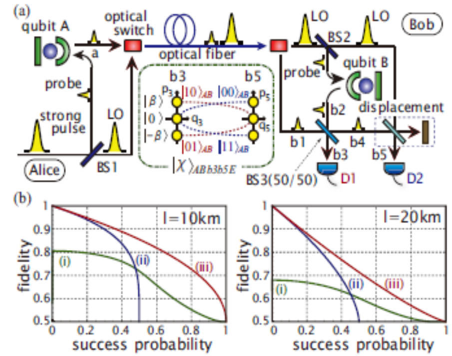


Errors in a qubit

Polarization of a photon:

H, V, 45degree

↑ ↑ ↑

0 1 superposition

Errors: bit/phase/both・・・Pauli matrices

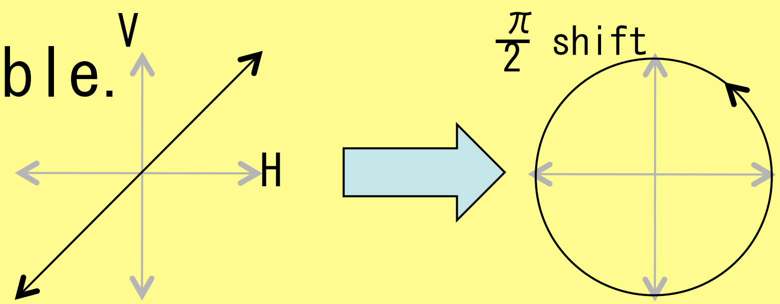
General error correction: Q error correcting codes

(1) needs 5 (or more) physical qubits for 1 logical qubit.

(2) assumes at most 1 error until next correction time.

In an optical fiber, phase error is important.

Phase change between two polarization uncontrollable.

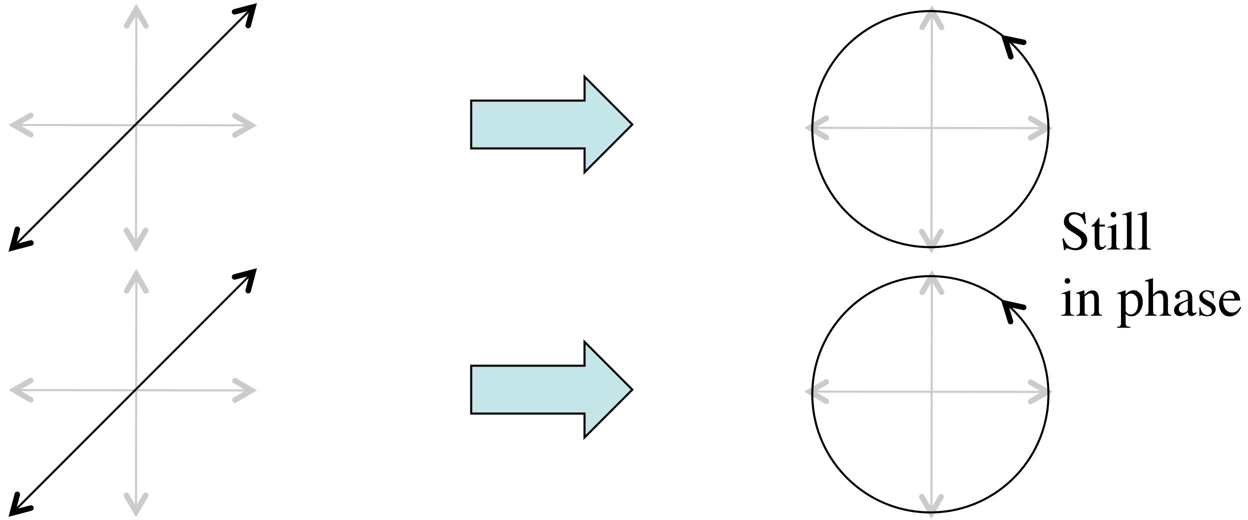


Use of two qubits for 1 logical qubit

case１ : in phase

qubit A

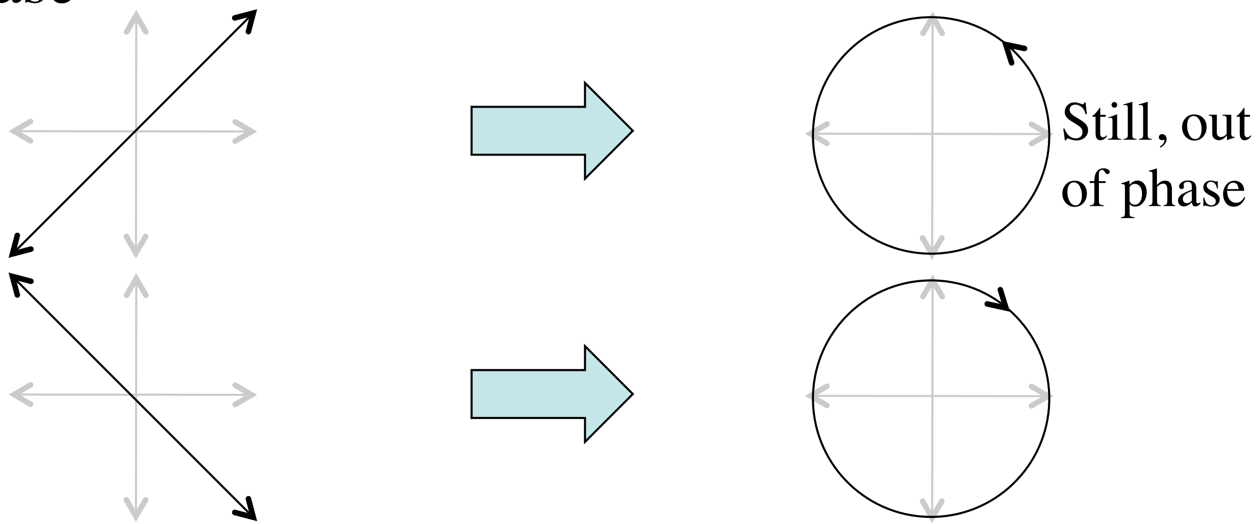
qubit B



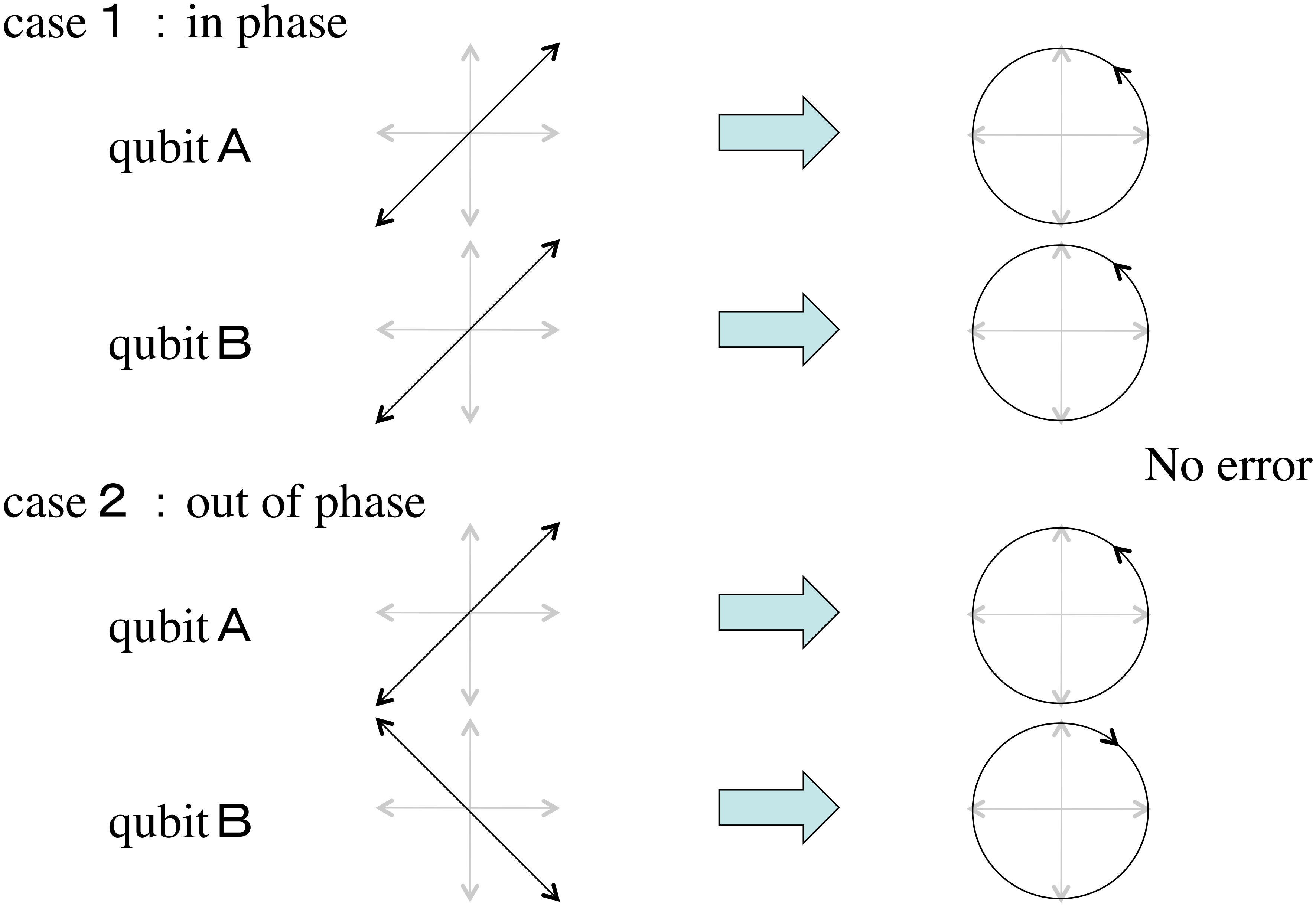
case２ : out of phase

qubit A

qubit B



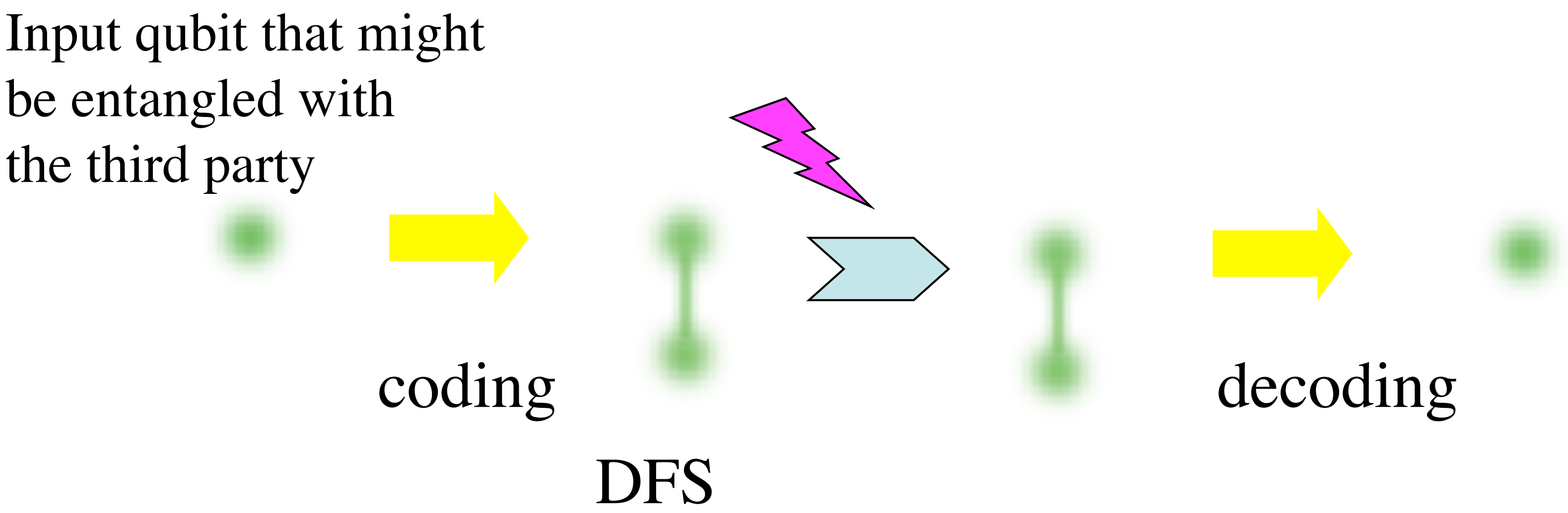
Redifine “in phase” as “0” and “out of phase” as “1”



It is easy if we can prepare the two physical qubits from the beginning.

The input logical qubit is given as a physical qubit.

We need to encode it into the DFS of two qubits without observing.



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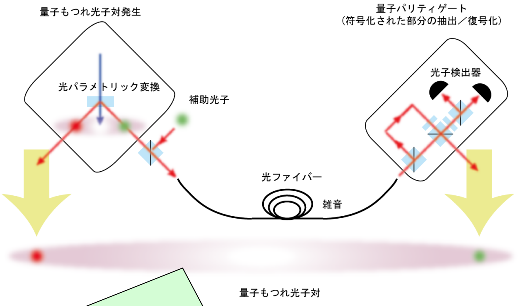

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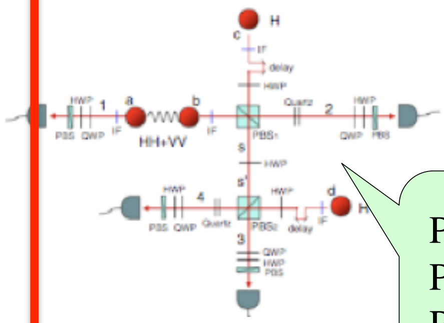

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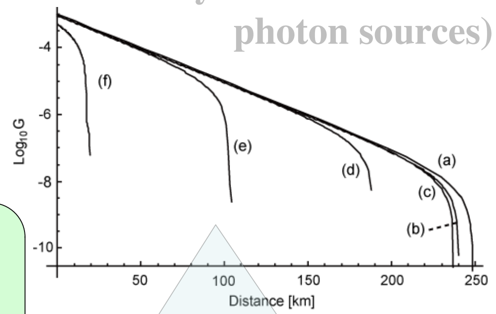

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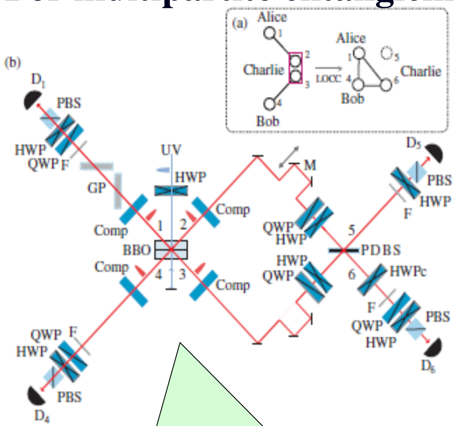

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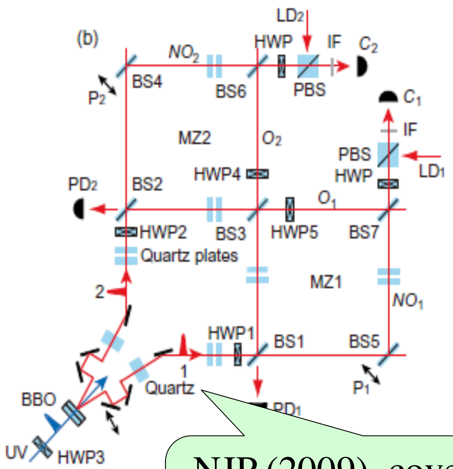

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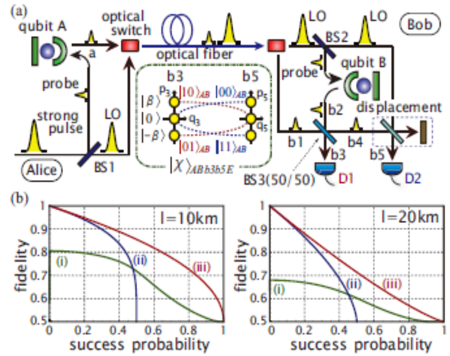

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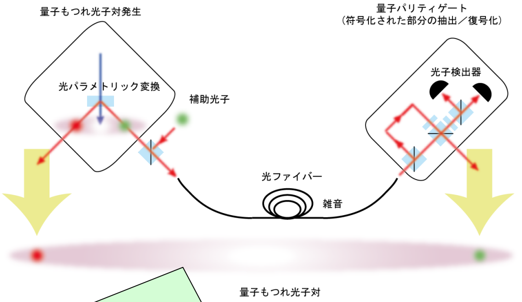

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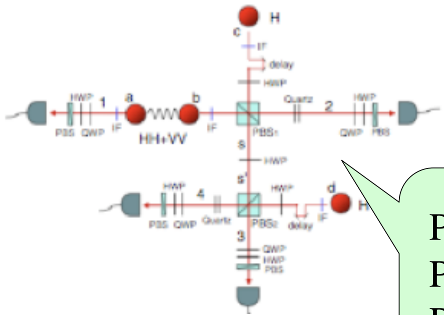

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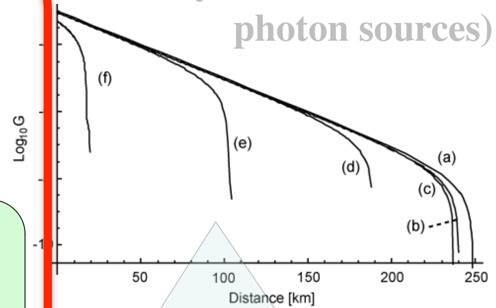

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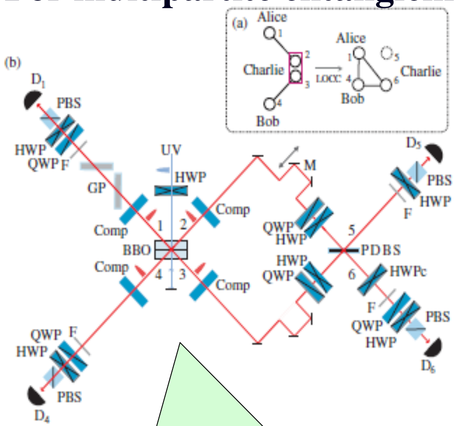
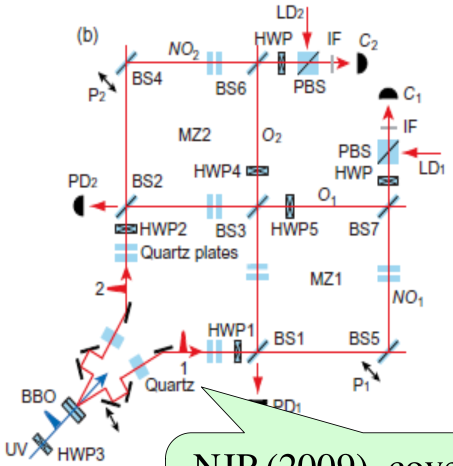


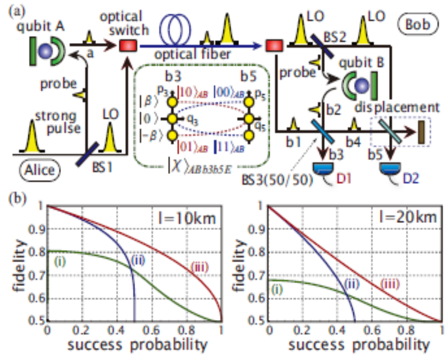
PRL (2009), PRA (2009)
NJP (2009), PRA (2008)

Experimental verification for Aharonov's anomalous weak value



NJP (2009), covered by
The Economist
Wall Street Journal

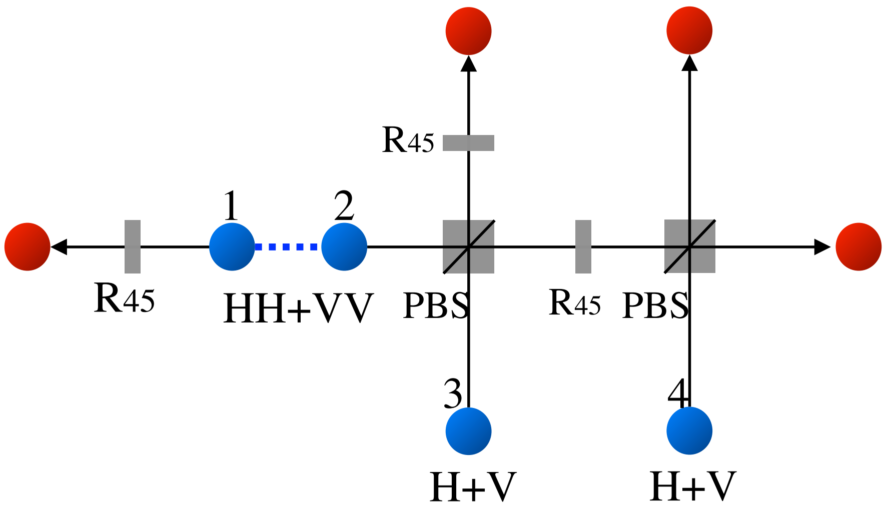
Optimal design for quantum repeaters



4-photon cluster state generation

Simple generation scheme for $|C_4\rangle$

Tokunaga *et al* PRA71, 030301R(2005)



- No need of interferometer stabilization
- High success probability: 1/4 (1/9 before)

Tokunaga *et al* PRL100, 210501 (2008).

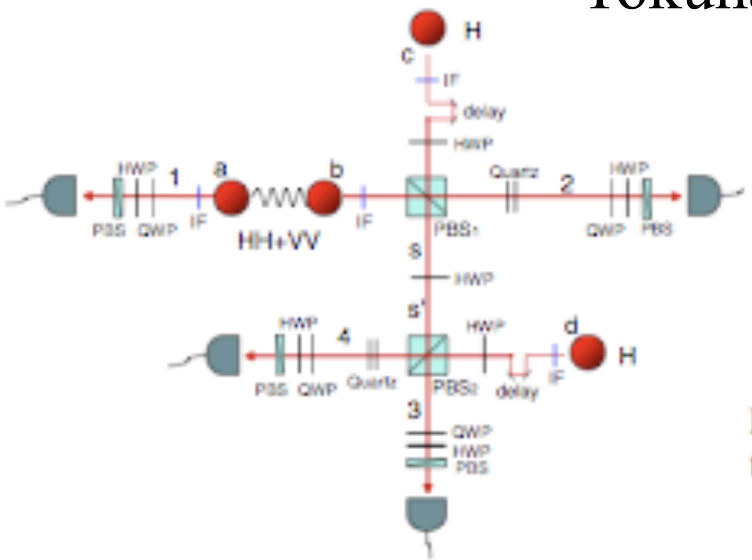


FIG. 1 (color online). Experimental setup for preparing $|C_4\rangle$.

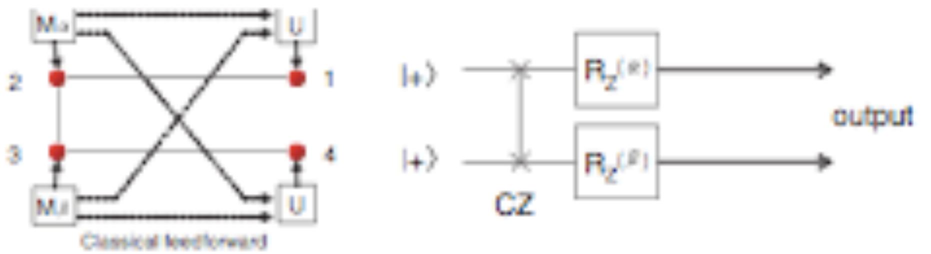


FIG. 4 (color online). Physical implementation and the quantum circuit of a two-qubit gate.

TABLE I. Output state fidelities of two-qubit gates.

α	β	Output state	Fidelity
0	0	$\|\phi_1\rangle = \|H\rangle\|+\rangle + \|V\rangle\|-\rangle$	0.831 ± 0.033
0	$\pi/2$	$\|\phi_2\rangle = \|H\rangle\|R\rangle + \|V\rangle\|L\rangle$	0.847 ± 0.036
0	π	$\|\phi_3\rangle = \|H\rangle\|-\rangle + \|V\rangle\|+\rangle$	0.924 ± 0.025
0	$-\pi/2$	$\|\phi_4\rangle = \|H\rangle\|L\rangle + \|V\rangle\|R\rangle$	0.899 ± 0.028
π	0	$\|\phi_5\rangle = \|H\rangle\|+\rangle - \|V\rangle\|-\rangle$	0.912 ± 0.028
π	$\pi/2$	$\|\phi_6\rangle = \|H\rangle\|R\rangle - \|V\rangle\|L\rangle$	0.913 ± 0.028
π	π	$\|\phi_7\rangle = \|H\rangle\|-\rangle - \|V\rangle\|+\rangle$	0.925 ± 0.024
π	$-\pi/2$	$\|\phi_8\rangle = \|H\rangle\|L\rangle - \|V\rangle\|R\rangle$	0.910 ± 0.027

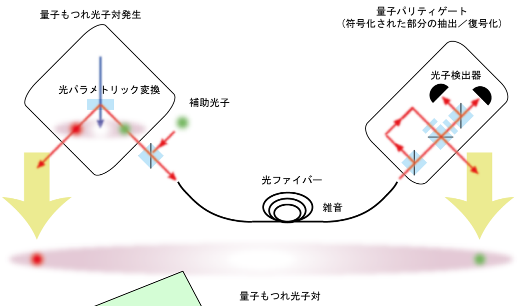
Fidelity（experiment）
=0.895±0.010
>0.854（classical limit）

First to exceed the
classical limit

Our recent activities

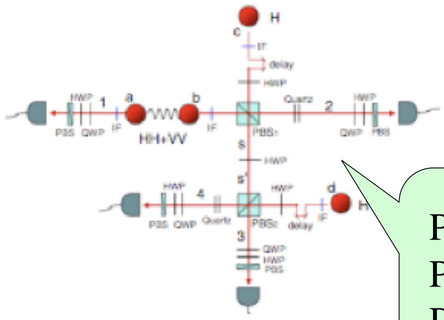
Theory and experiments

Protection of entanglement using DFS (decoherence-free subspace)



Nature (2003), PRL (2005)
NJP (2007), Nature Photonics (2008)

Cluster-state one-way Quantum computing



PRL (2008)
PRA (2006)
PRA (2005)

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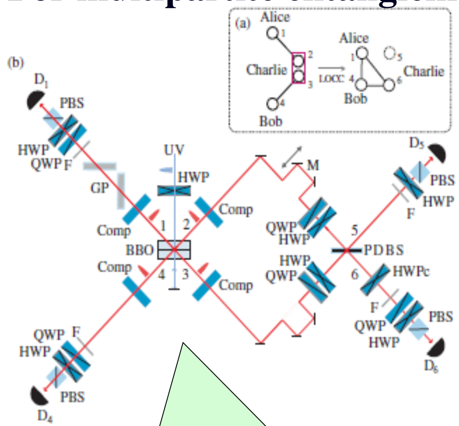

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NJP (2009), PRA (2008)

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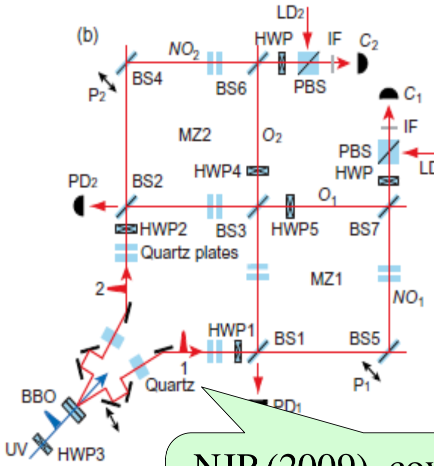
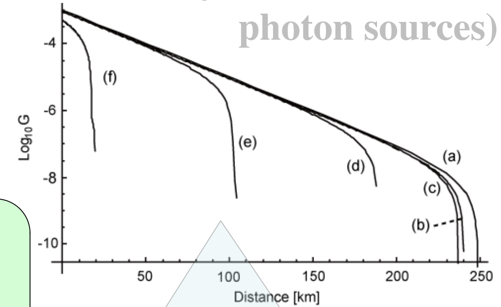


NJP (2009), covered by
The Economist
Wall Street Journal

Theory

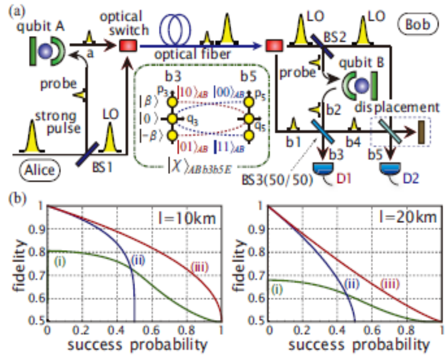
QKD security proof: general theory and for non-ideal photon sources)



PRL(2007), PRA(2009)

PRA (2010)
PRA (2009)

Optimal design for quantum repeaters



Weak measurement・・・

You can tune the strength of a measurement by changing either the magnitude of interaction gt or the state of the meter. (for example, αgt for J-C, and $\alpha\chi^{(3)}L$ for Kerr QND)

When the measurement becomes weaker, the backaction becomes smaller, and the measurement error goes larger.

Thus *a single* weak measurement has no meaning, but if repeated measurements are allowed, the average of an observable can be obtained as precisely as you want (still, without causing back-action).

Therefore, the average of an observable inside an interferometer can be measured without affecting the interference.

Weak value・・・

When you fix (select) the initial state and the final state, the output of a weak measurement *on the way between the initial and final states* is called weak value.

An interesting thing occurs when the selected initial and final states are non-orthogonal. The value can be outside of the spectrum of the physical quantity.

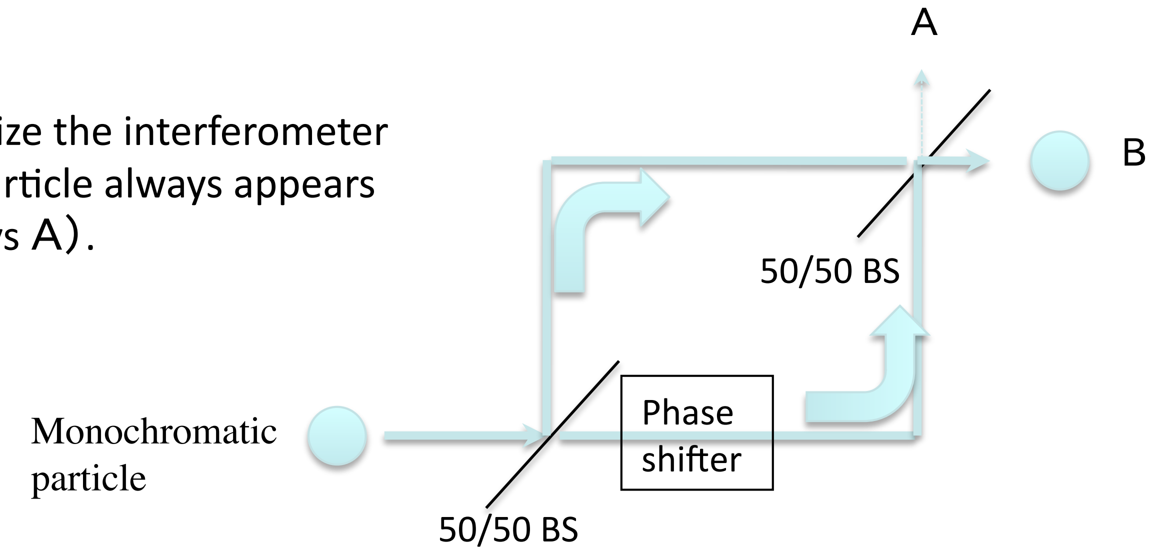
Especially, in Hardy's paradox, Aharonov predicted that prob(A)=1 and prob(B) =1 and still prob(A∩B)=0 !!!

We experimentally demonstrated that Aharonob's prediction is correct. The experiment became possible by

- photon-version of Hardy's paradox, and
- joint weak measurement by means of entangled meters.

Mach-Zehnder interferometer

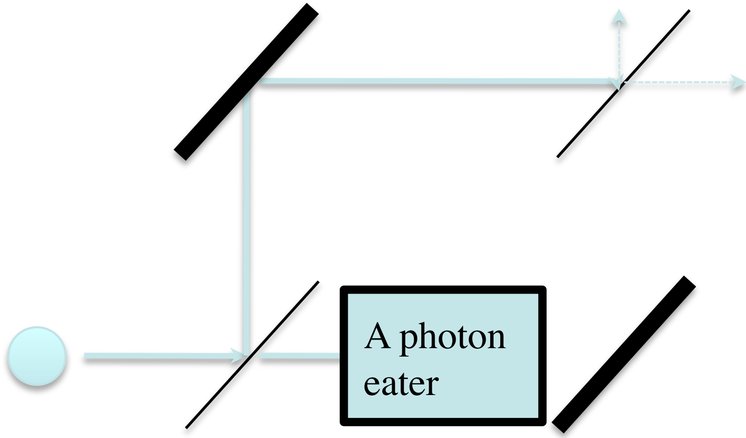
You can stabilize the interferometer
So that the particle always appears
In B (or always A).



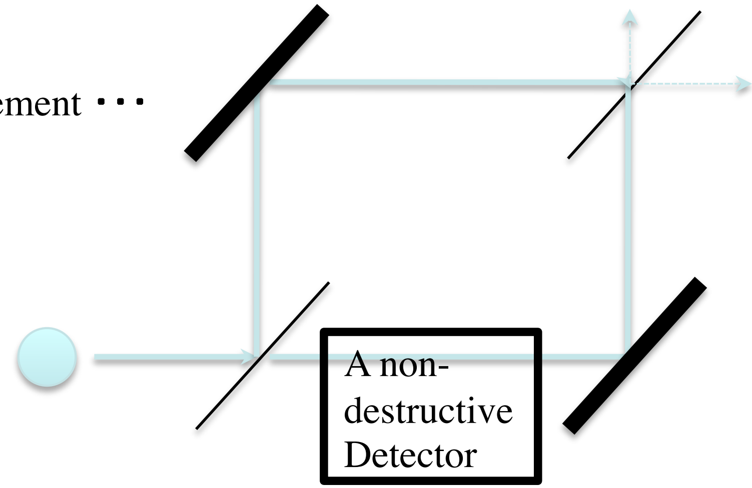
In this situation, you cannot say anything about “which path?”.

Any attempt to look inside destroys interference

regardless whether it is a destructive measurement ・・・

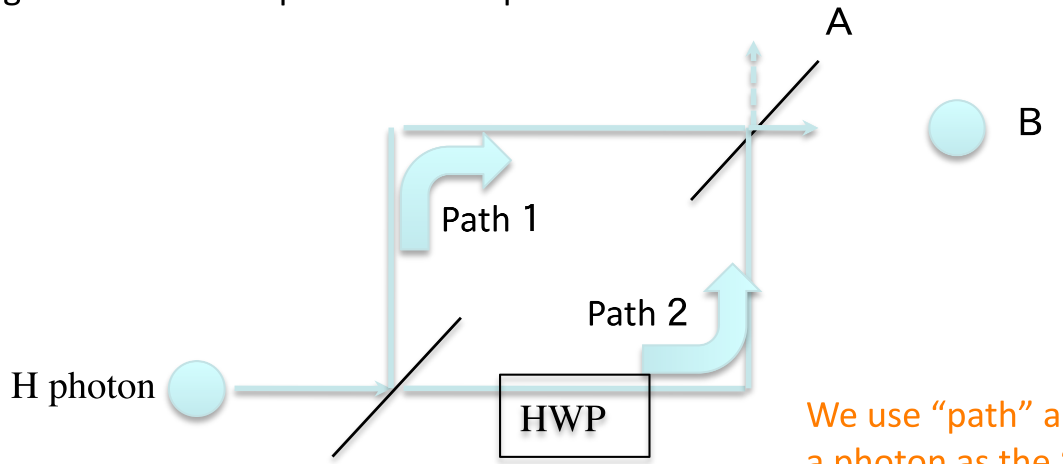


or, a non-destructive measurement ・・・



Polarization rotator can change "path qubit" into "polarization qubit."

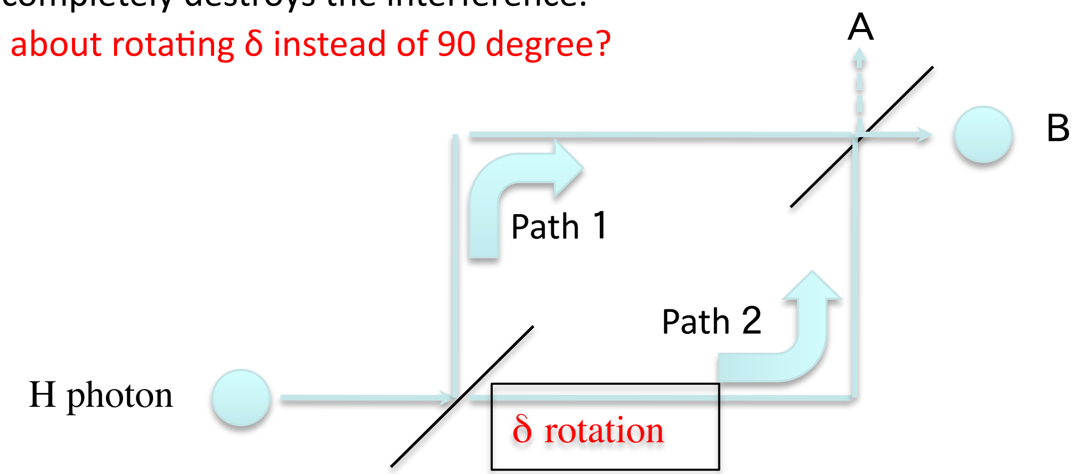
A HWP can change the incident H photon into V photon.



We use "path" and "polarization" of a photon as the "meter" and "system" qubits.

This completely destroys the interference.

How about rotating δ instead of 90 degree?



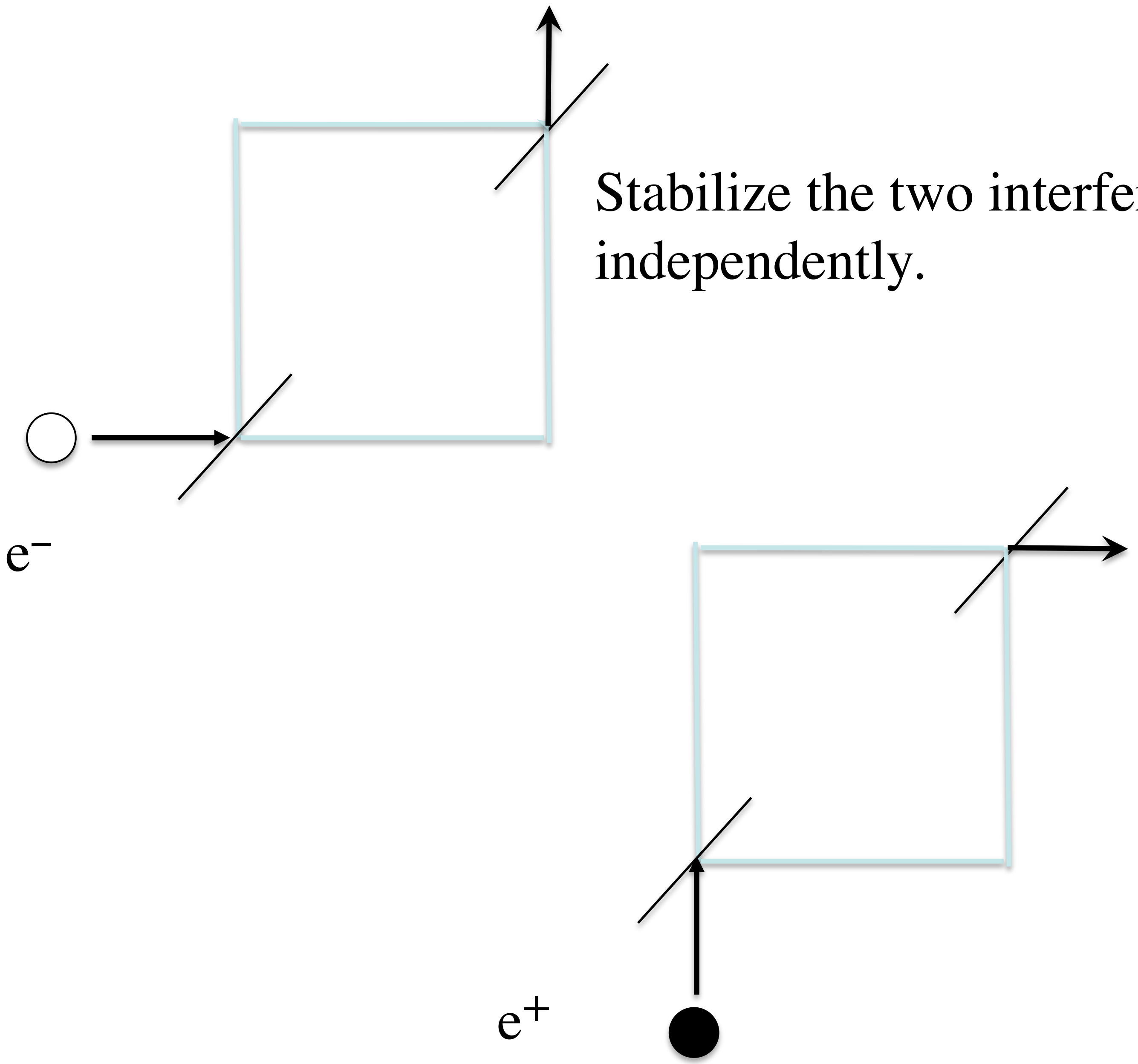
This almost does not destroys the interference, but the path distinguishability is also poor.

Repeating the measurement → weak measurement

In this simple MZ interferometer, the answer is normal: $p = 1/2$ each.

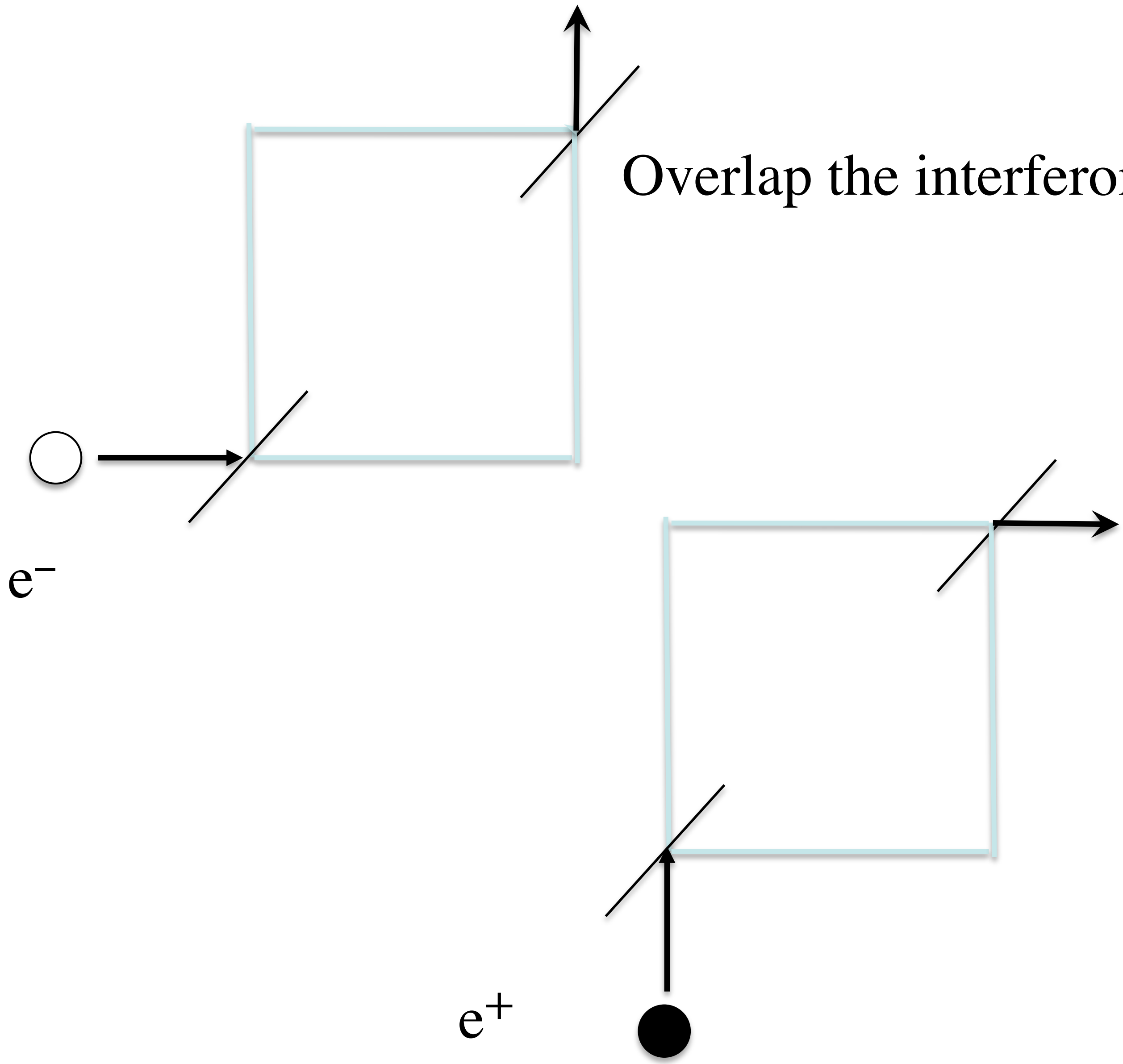
Hardy paradox

Stabilize the two interferometers independently.

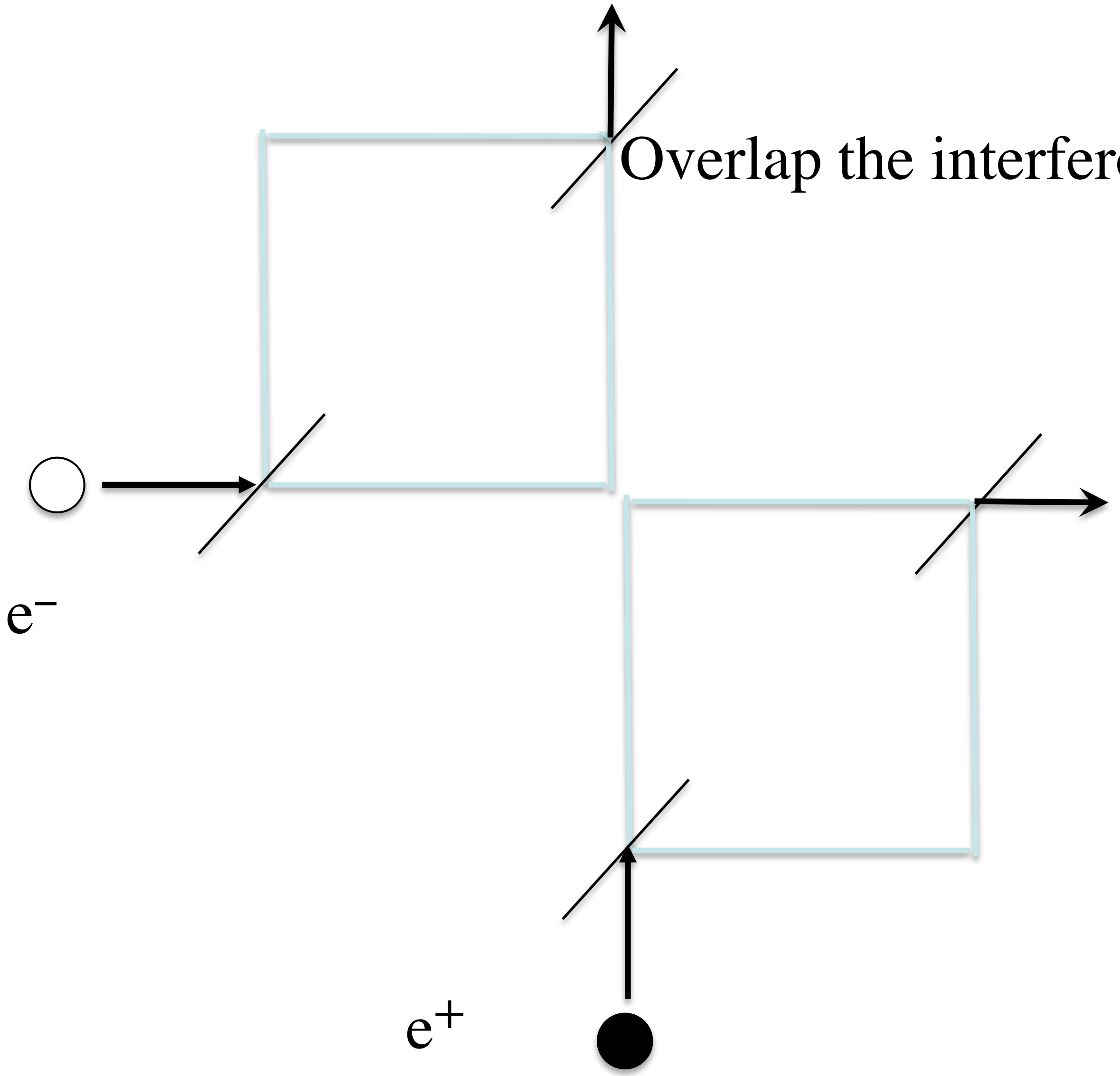


Hardy paradox

Overlap the interferometers.

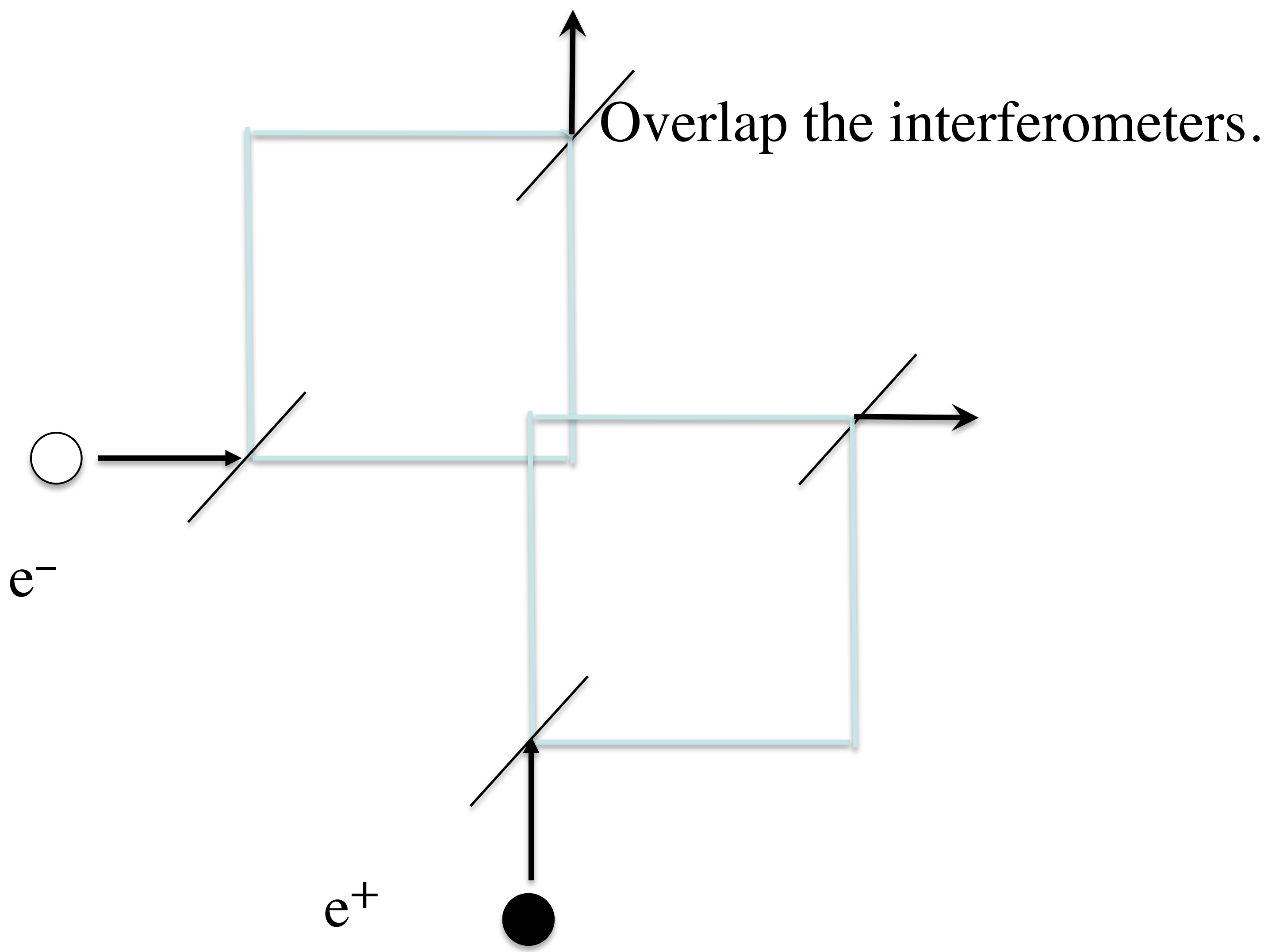


Hardy paradox

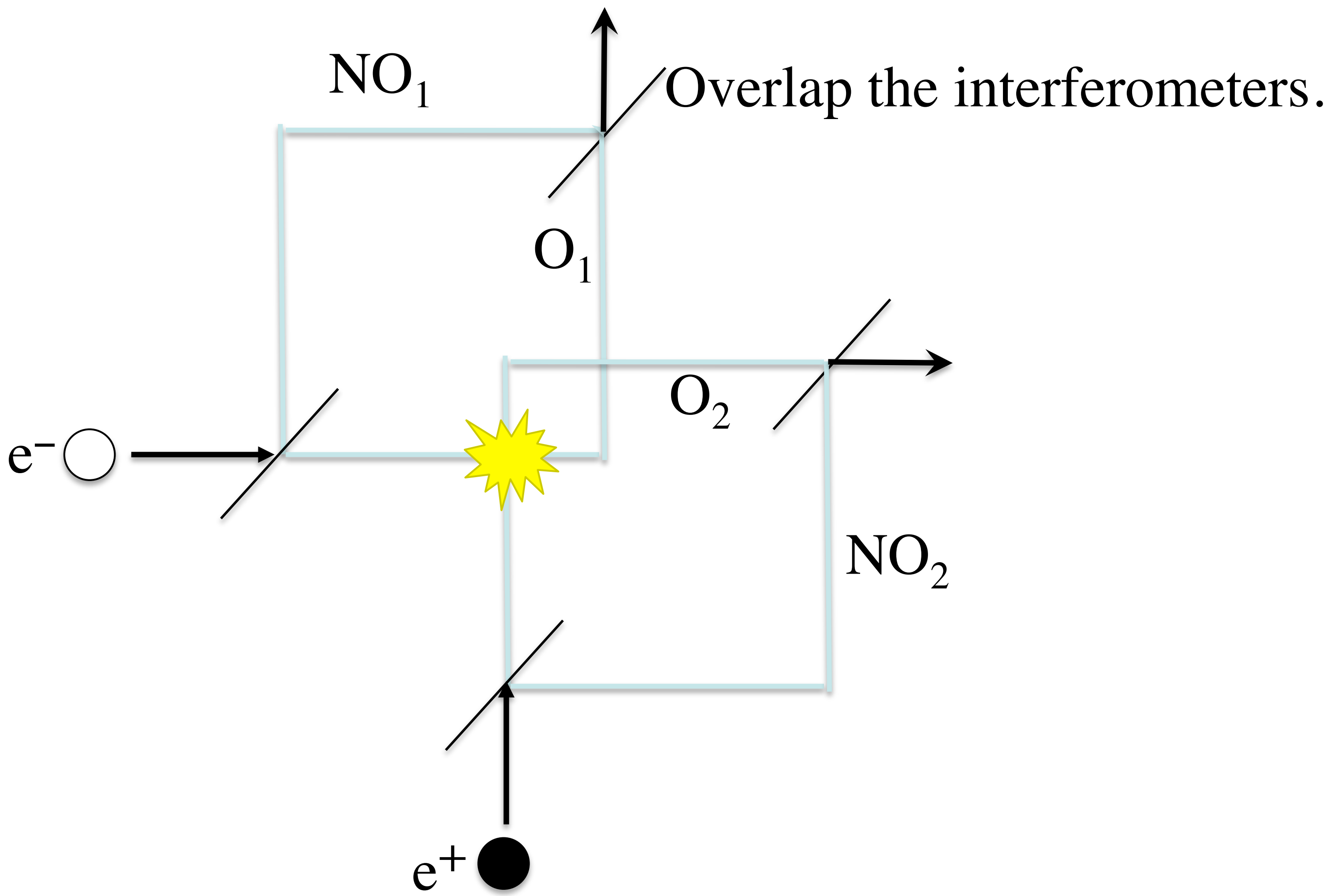


Overlap the interferometers.

Hardy paradox



Hardy paradox



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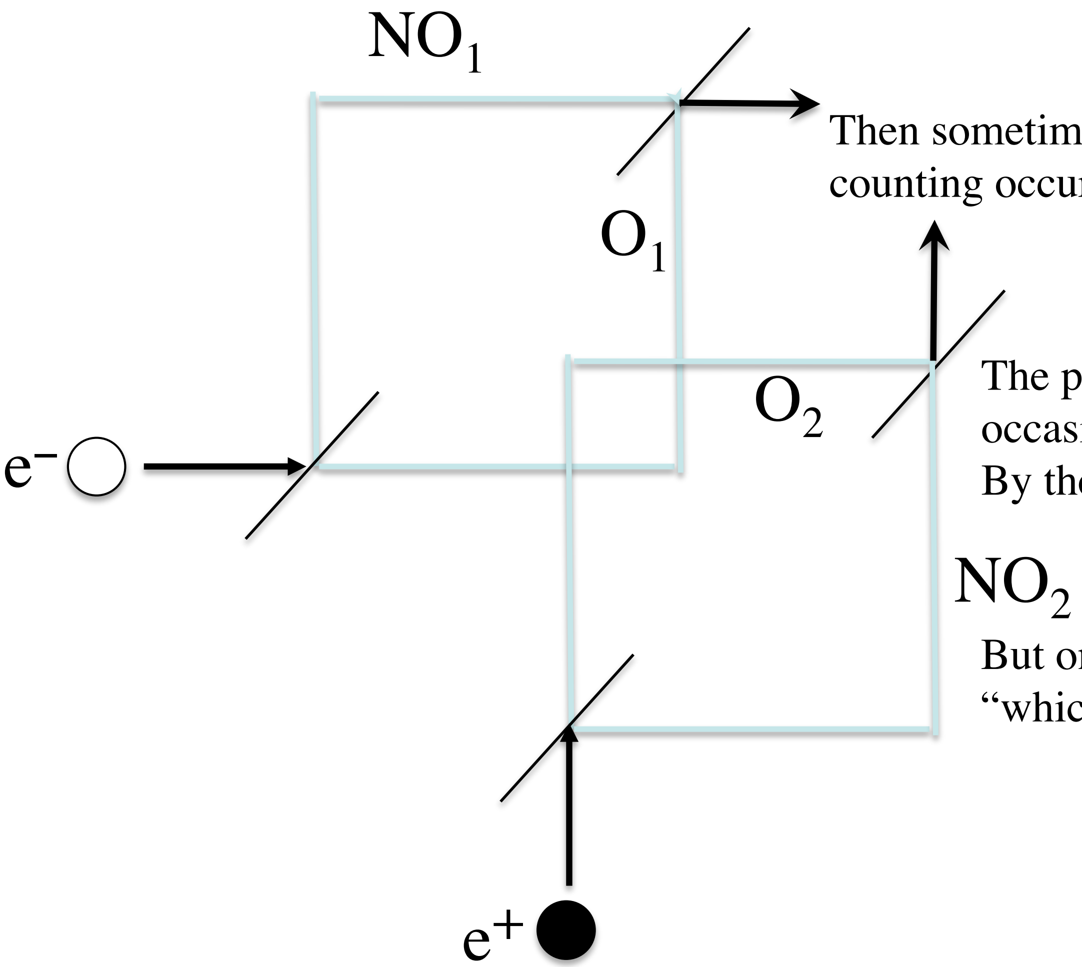
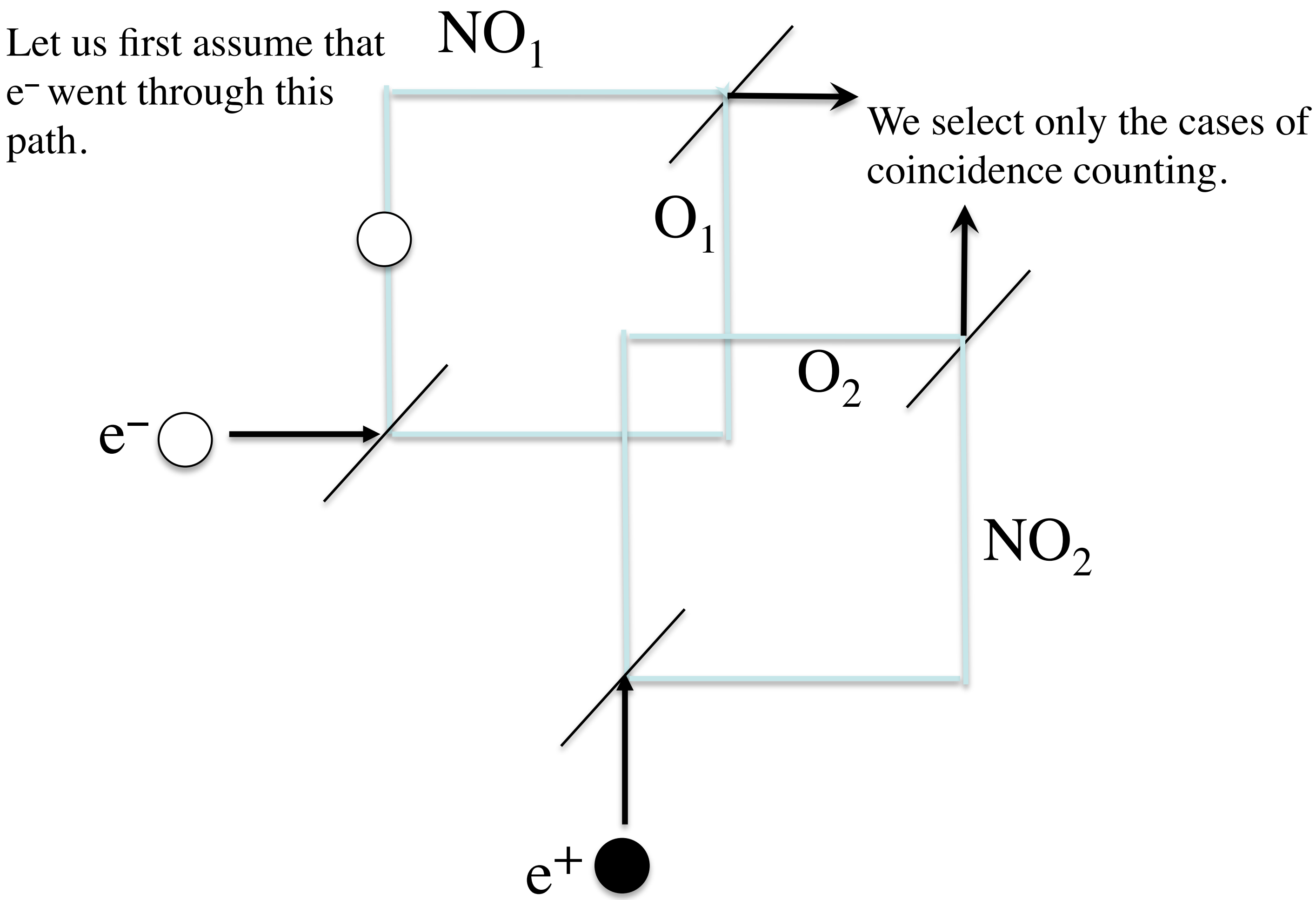


Then sometimes coincidence counting occurs here!

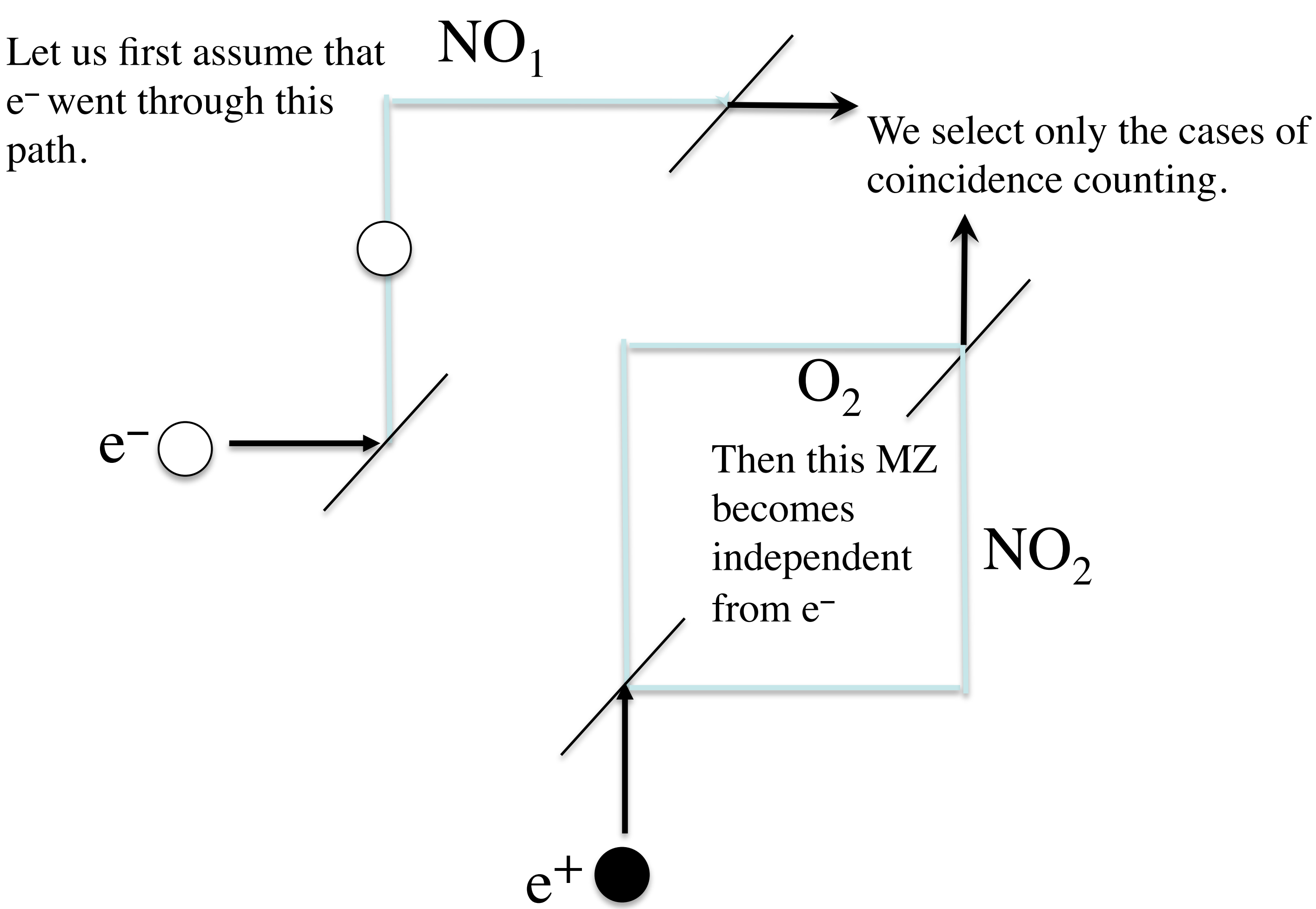
The probability for such occasion can be culculated By the ordinary QM.

But once you start to ask "which path?"・・・

Hardy paradox



Hardy paradox



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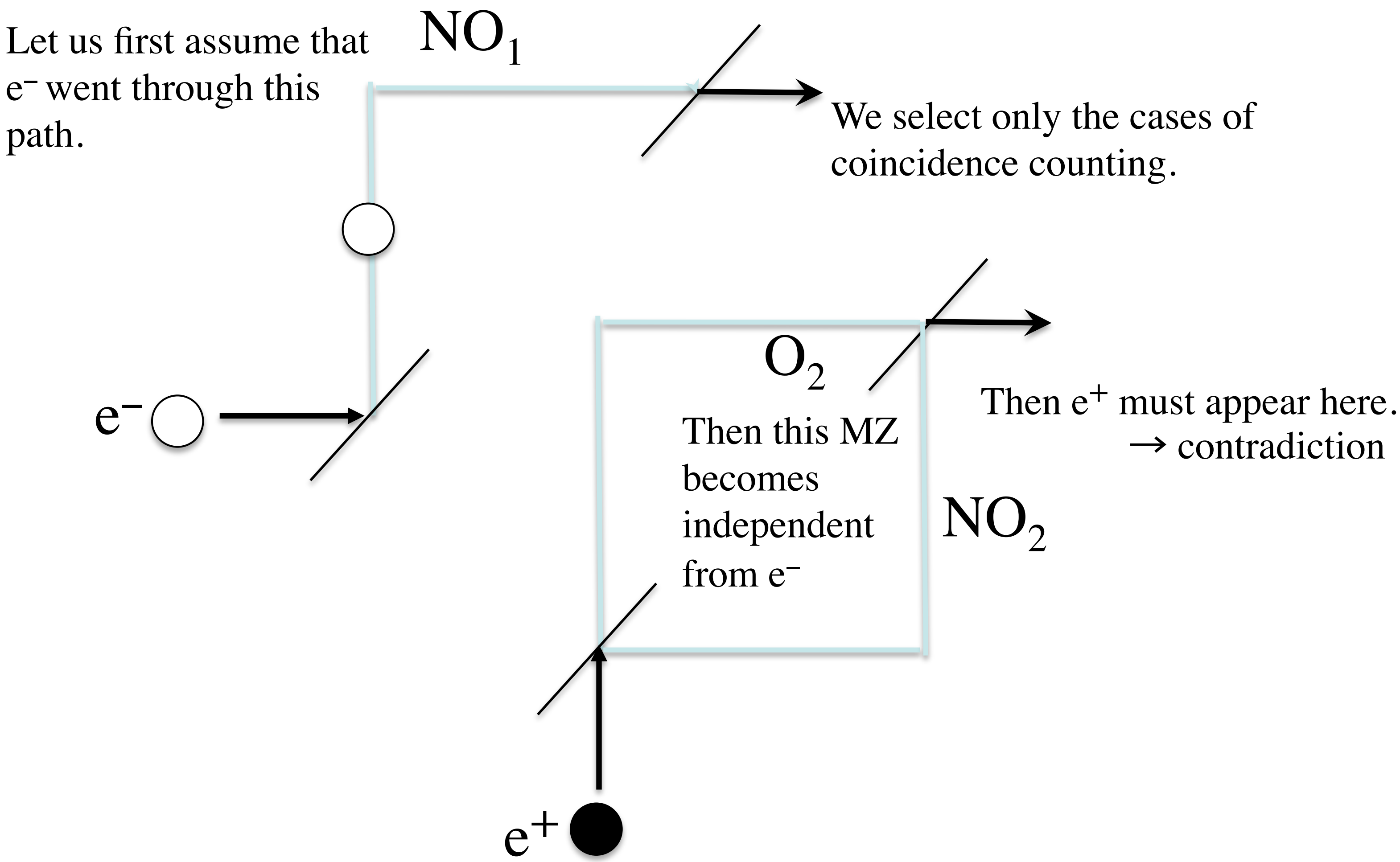

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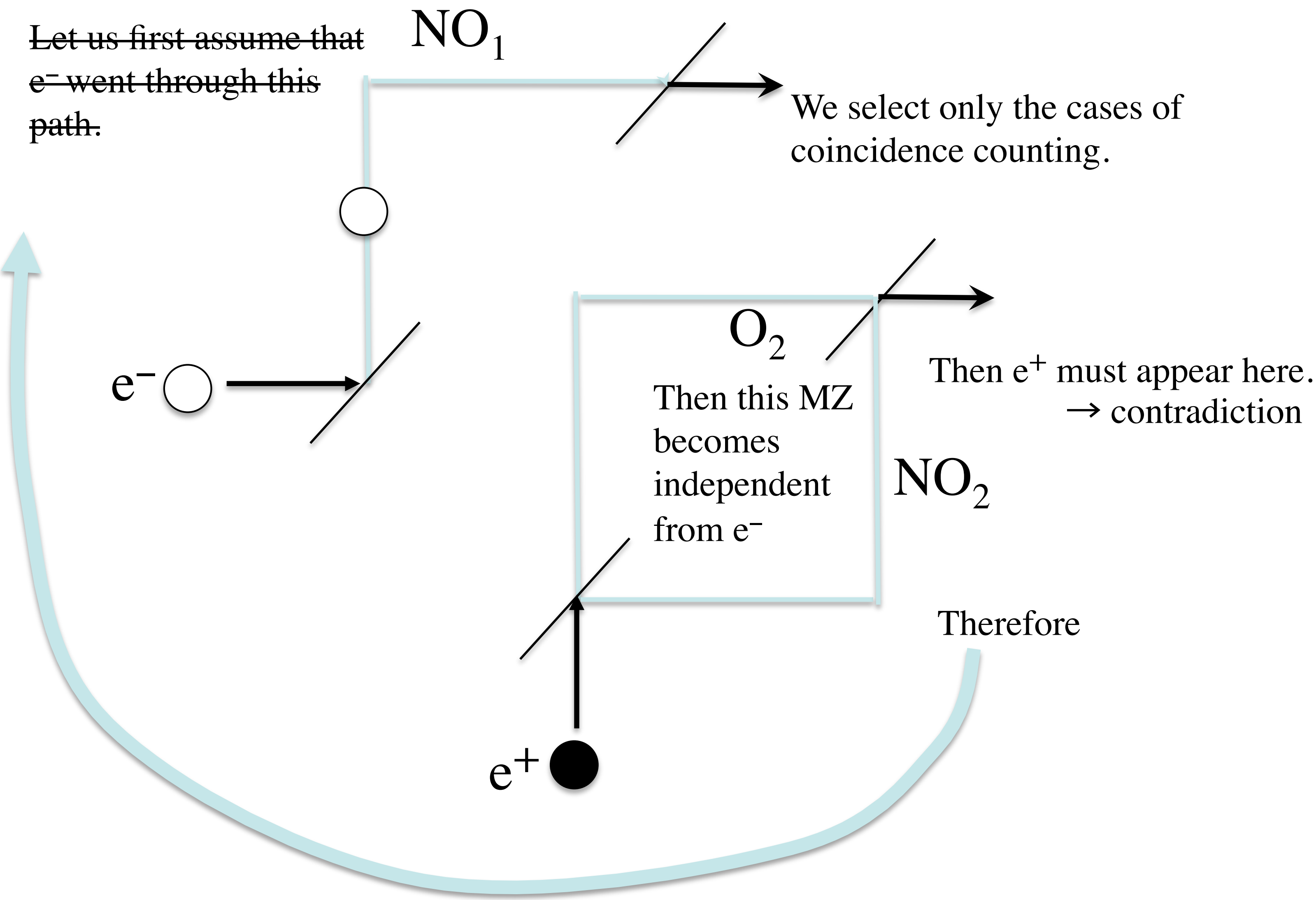

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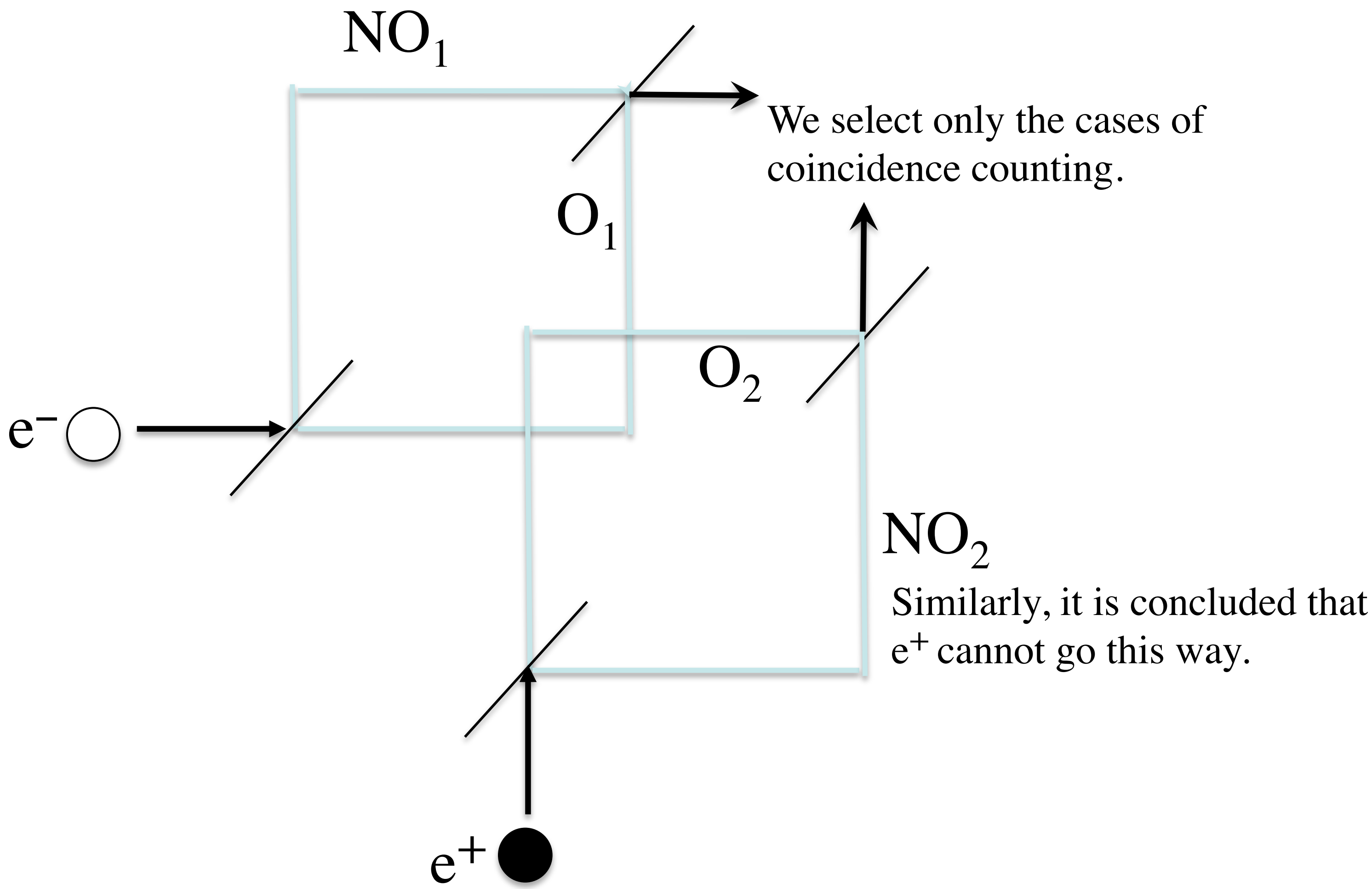

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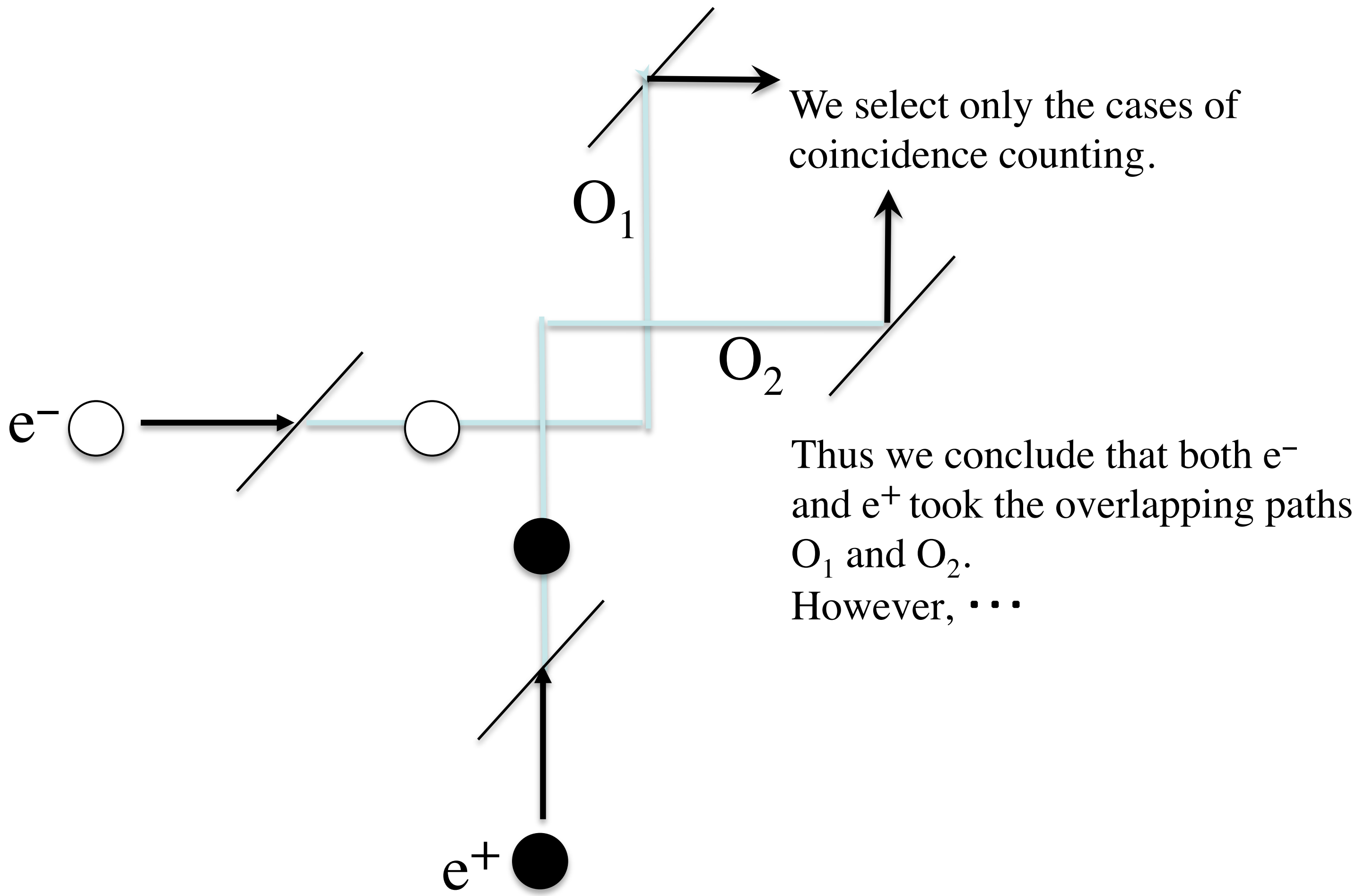

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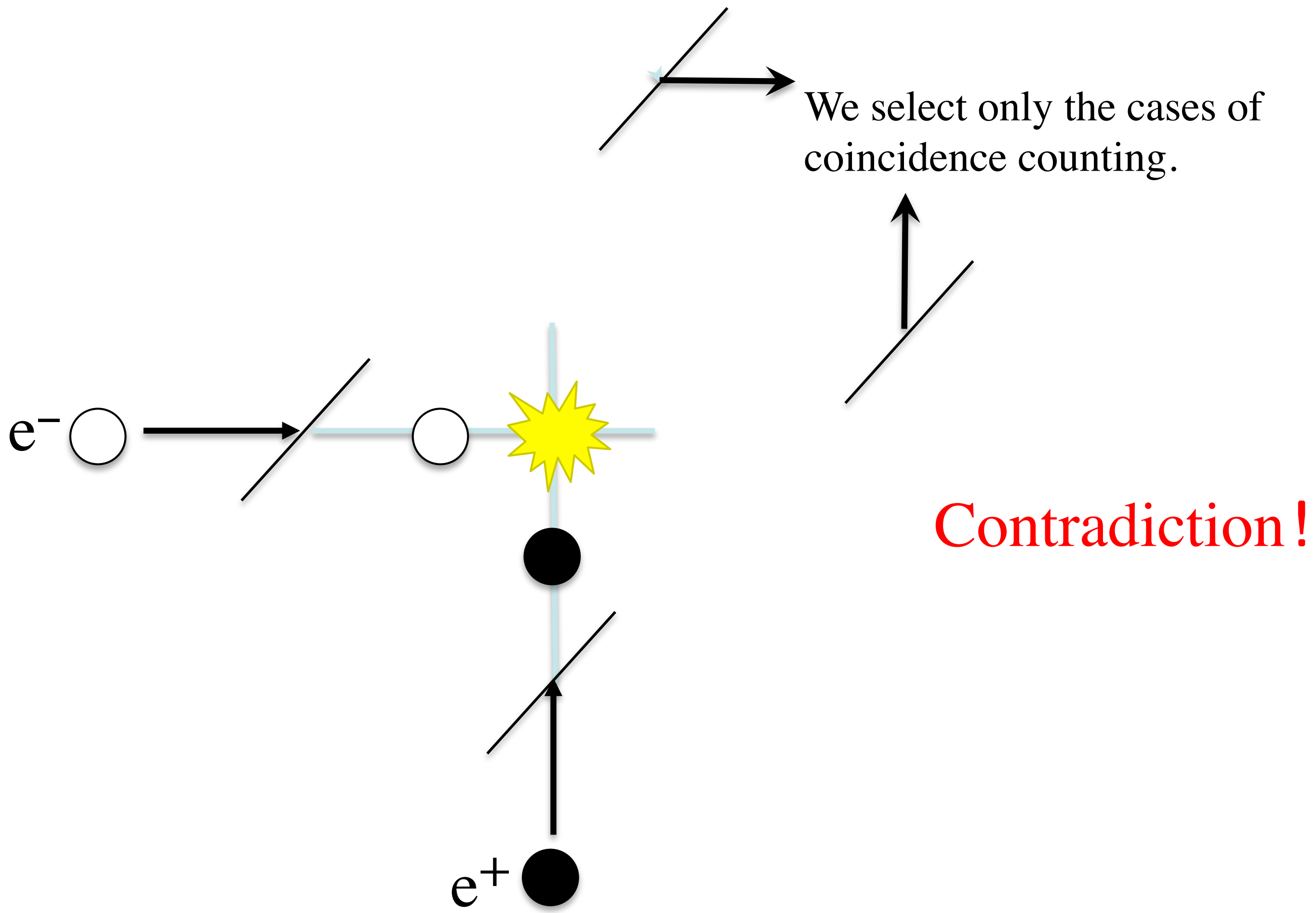
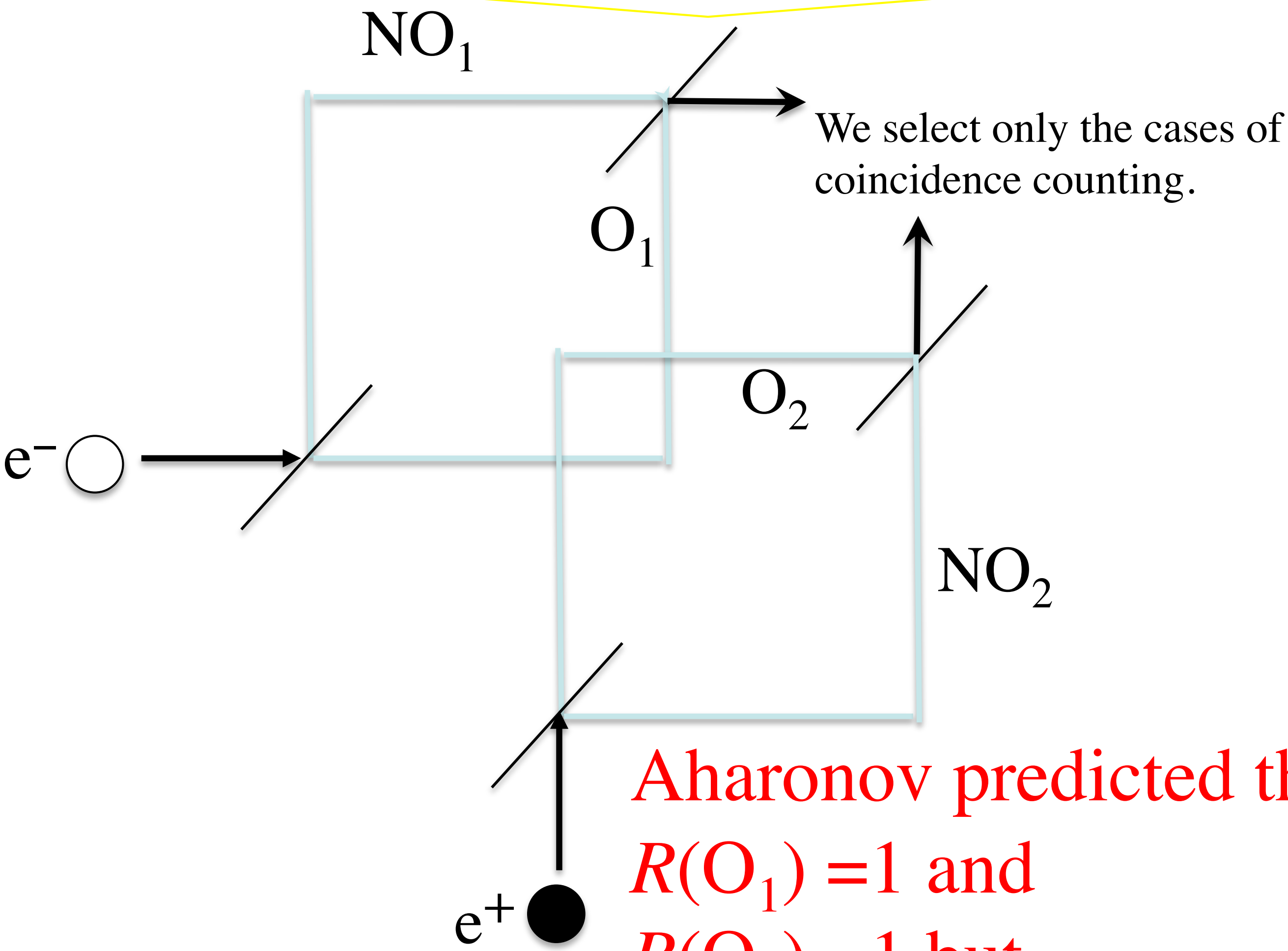


Hardy paradox

I told you. You should not ask "which path?"
Be satisfied with getting the transition probabiity.

No, we can make "weak measurement"!



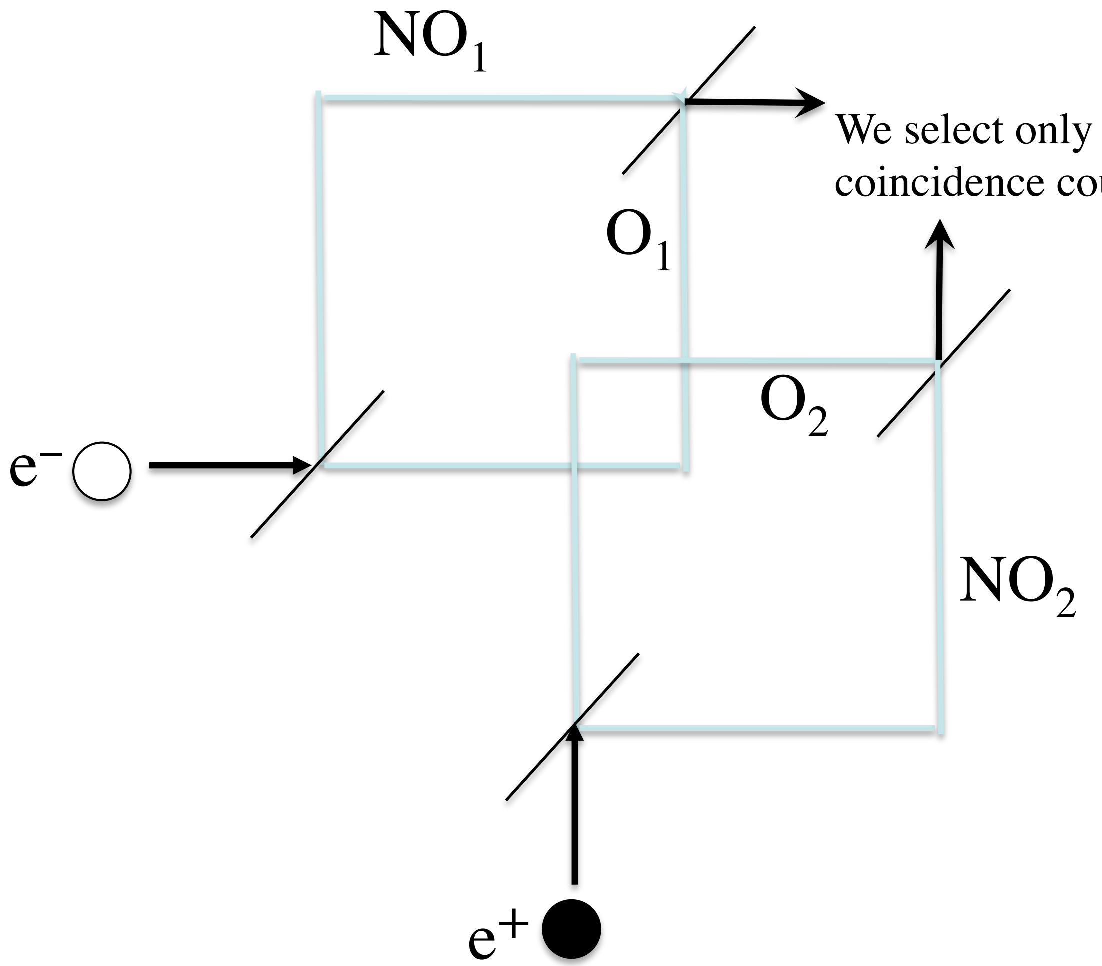
Aharonov predicted that

$R(O_1) = 1$ and

$R(O_2) = 1$ but

$R(O_1 \text{ and } O_2) = 0$

Hardy paradox



We select only the cases of coincidence counting.

In other words,

$R(\mathrm{O}_1 \text{ and } \mathrm{NO}_2) = 1$ and

$R(\mathrm{NO}_1 \text{ and } \mathrm{O}_2) = 1$ and

$R(\mathrm{O}_1 \text{ and } \mathrm{O}_2) = 0$ and

$R(\mathrm{NO}_1 \text{ and } \mathrm{NO}_2) = -1$

$R(\mathrm{O}_1) = R\,(\mathrm{O}_1 \text{ and } \mathrm{O}_2) + R\,(\mathrm{O}_1 \text{ and } \mathrm{NO}_2) = 1$

$R(\mathrm{O}_2) = R\,(\mathrm{O}_1 \text{ and } \mathrm{O}_2) + R\,(\mathrm{NO}_1 \text{ and } \mathrm{O}_2) = 1$

$R(\mathrm{NO}_1) = R\,(\mathrm{NO}_1 \text{ and } \mathrm{O}_2) + R\,(\mathrm{NO}_1 \text{ and } \mathrm{NO}_2) = 0$

$R(\mathrm{NO}_2) = R\,(\mathrm{O}_1 \text{ and } \mathrm{NO}_2) + R\,(\mathrm{NO}_1 \text{ and } \mathrm{NO}_2) = 0$

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Science & Technology

Physics and philosophy

I'm not looking, honest!

Mar 5th 2009
From *The Economist* print edition

The good news is reality exists. The bad is it's even stranger than people thought

"HOW wonderful that we have met with a paradox. Nov making progress." So said Niels Bohr, one of the found Since its birth in the 1920s, physicists and philosophers bizarre consequences that his theory has for reality, in truth that it is impossible to know everything about the whether it really exists at all when it is not being obser physicists, working independently, have demonstrated when unobserved. When no one is peeking, however, it

In the 1990s a physicist called Lucien Hardy proposed a makes nonsense of the famous interaction between ma when a particle meets its antiparticle, the pair always a burst of energy. Dr Hardy's scheme left open the possi when their interaction is not observed a particle and an with one another and survive. Of course, since the inte unseen, no one should ever notice this happening, whic known as Hardy's paradox.

MAY 5, 2009

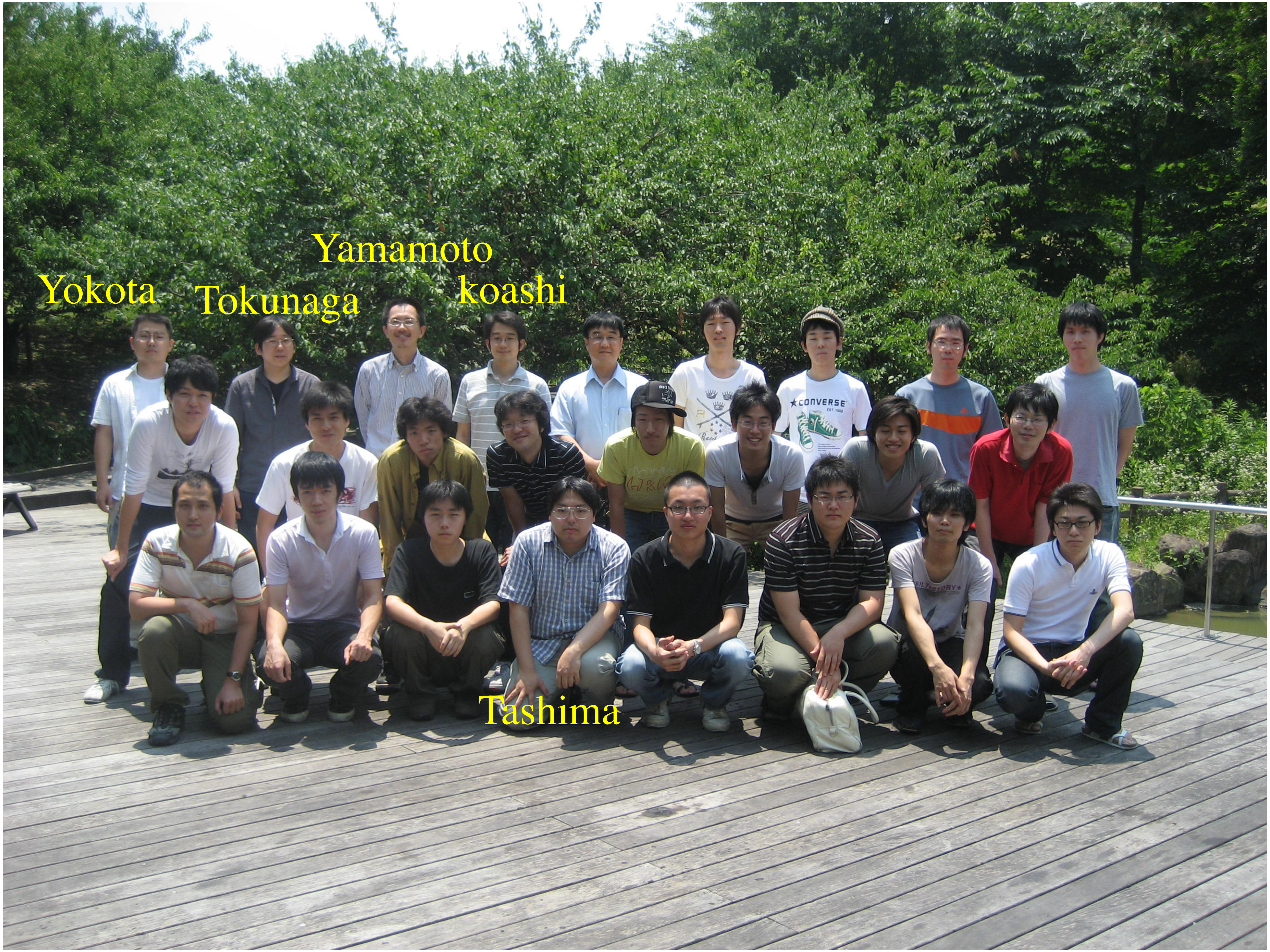
Science, Spirituality, and Some Mismatched Socks

Researchers Turn Up Evidence of 'Spooky' Quantum Behavior and Put It to Work in Encryption and Philosophy

By GAUTAM NAIK

One of quantum physics' crazier notions is that two particles seem to communicate with each other instantly, even when they're billions of miles apart. Albert Einstein, arguing that nothing travels faster than light, dismissed this as impossible "spooky action at a distance."

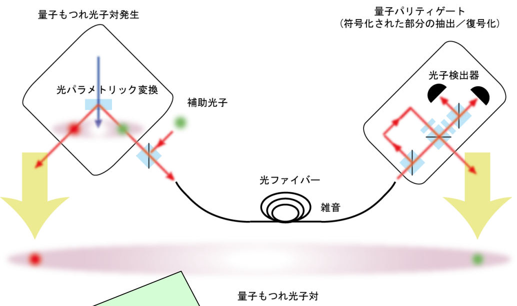
In a striking achievement, scientists from Osaka University have resolved the paradox. They used extremely weak measurements -- the equivalent of a sidelong glance, as it were -- that didn't disturb the photons' state. By doing the experiment multiple times and pooling those weak measurements, they got enough good data to show that the particles didn't annihilate. The conclusion: When the particles weren't observed, they behaved differently.


Yamamoto
Yokota
Tokunaga
koashi
Tashima

Our recent activities

Theory and experiments

Protection of entanglement using DFS (decoherence-free subspace)



Nature (2003), PRL (2005)
NJP (2007), Nature Photonics (2008)

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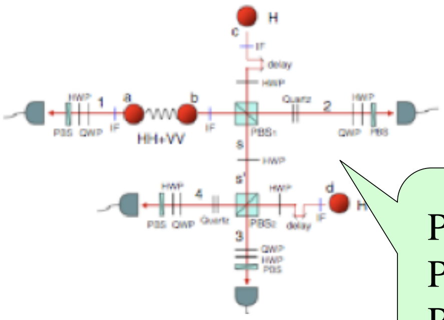

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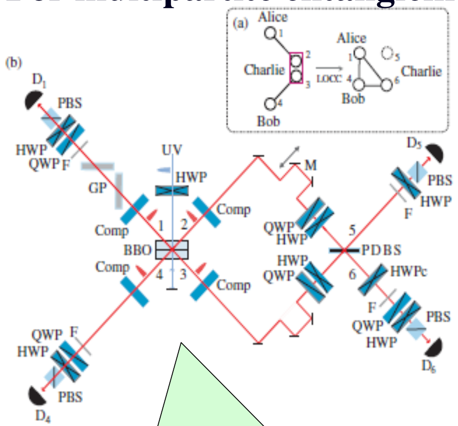

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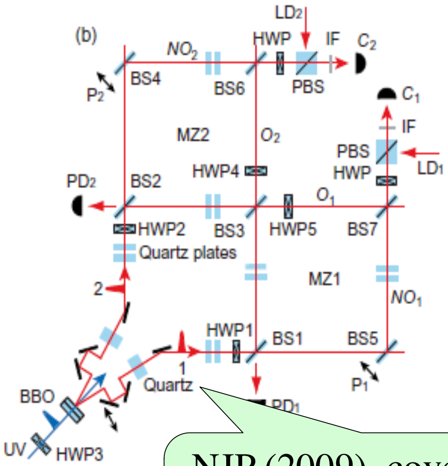

NJP (2009), covered by
The Economist
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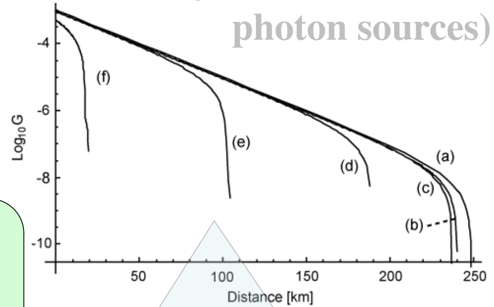
Theory

QKD security proof: general theory and for non-ideal photon sources)



PRL(2007), PRA(2009)

PRA (2010)
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