FIRST
Annual Meeting 2011
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Fundamental Experiment for Entanglement Communication using Spins
(スピンを介したエンタングルメント通信の基礎実験)

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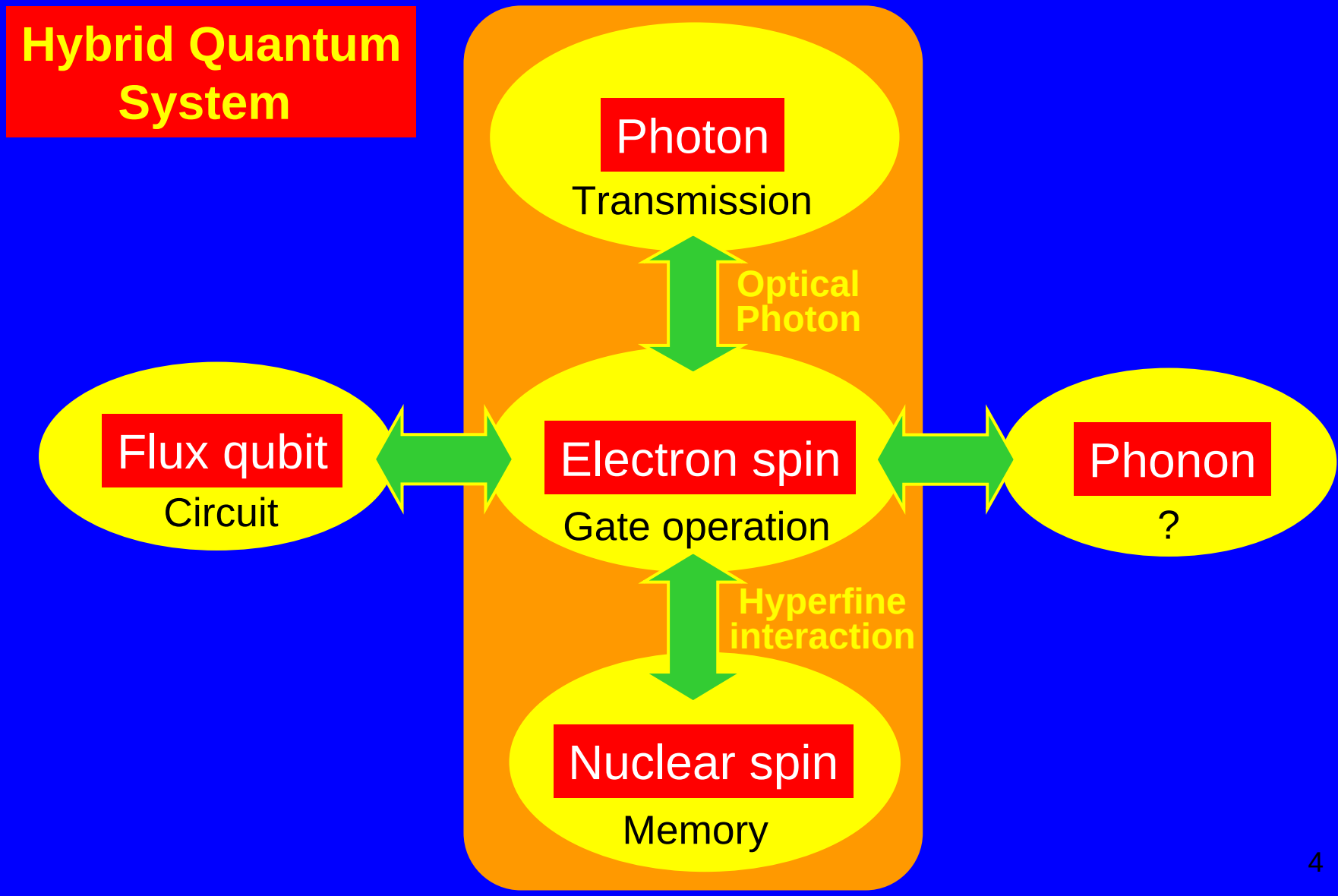
Post-doc position open

Outline

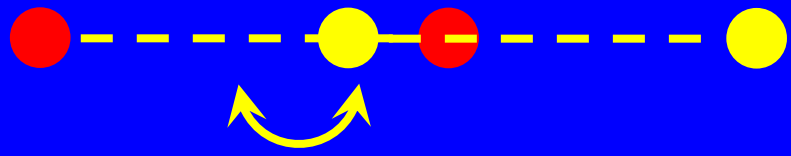
1. Introduction
   - Quantum Media Conversion
   - Quantum Repeater
2. Photon Quantum State Transfer into Diamond
3. Time-bin State Transfer into Semiconductor
4. Summary

Quantum Media Conversion

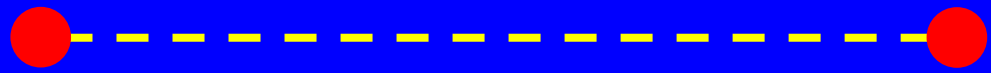


Quantum Repeater

1. Entanglement Generation

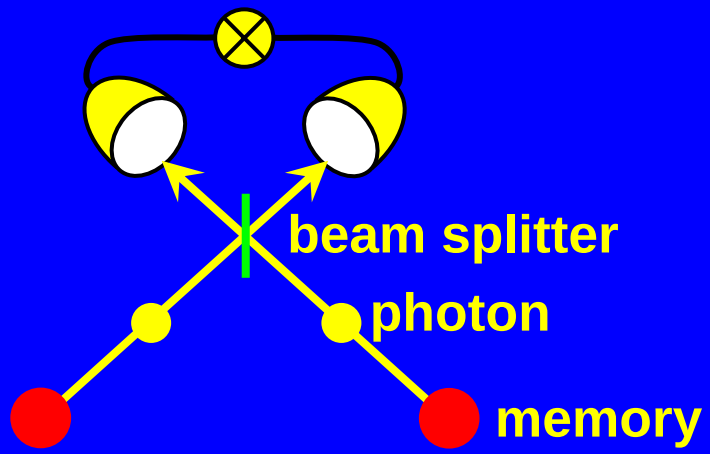


2. Entanglement Swapping

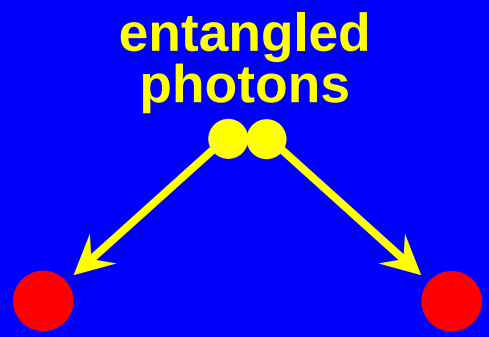


Entanglement Generation

1. Emission

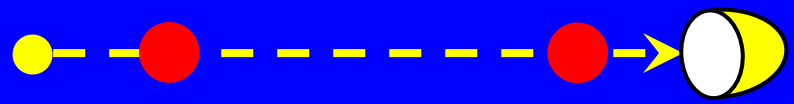


2. Absorption



3. Emission & Absorption

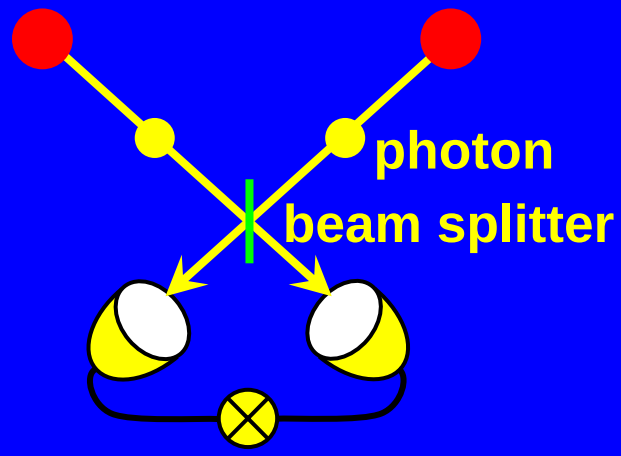
4. Scattering



Entanglement Swapping

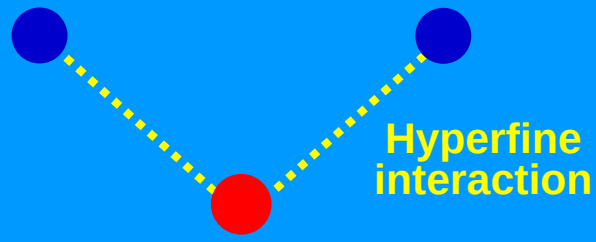
1. Emission

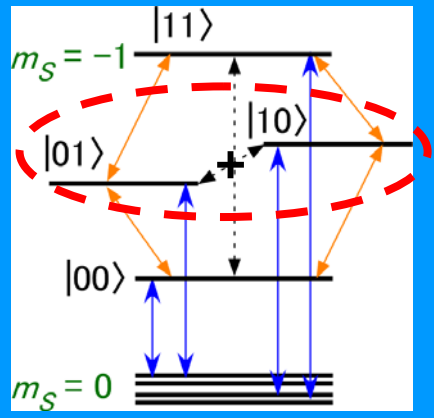
memory A memory B



2. Local operation

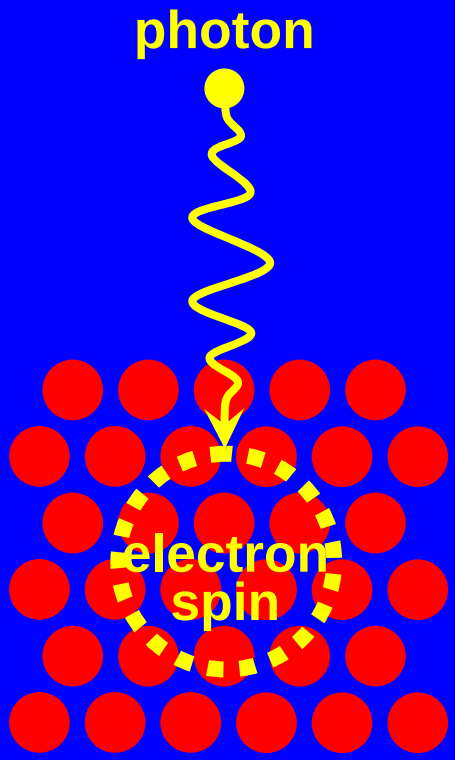
memory A memory B





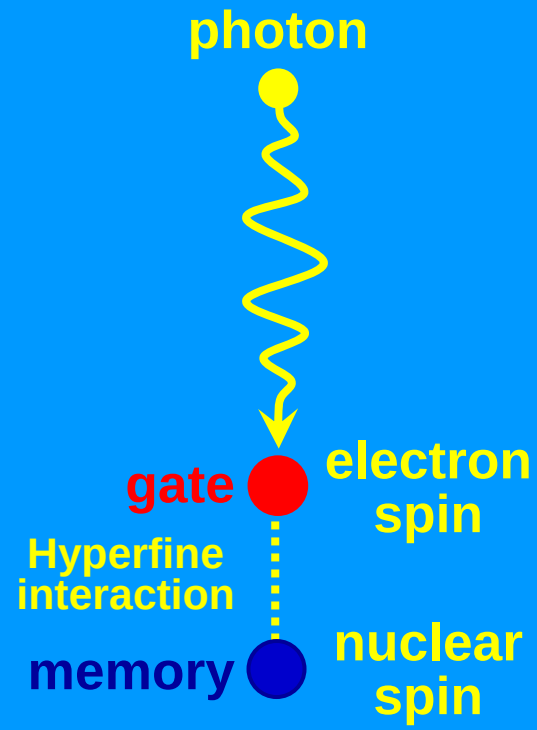
Memory Configuration

1. Ensemble system



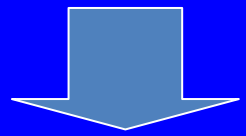
Collective
single excitation
(W state or coherent state)

2. Single particles



Requirements for Memory

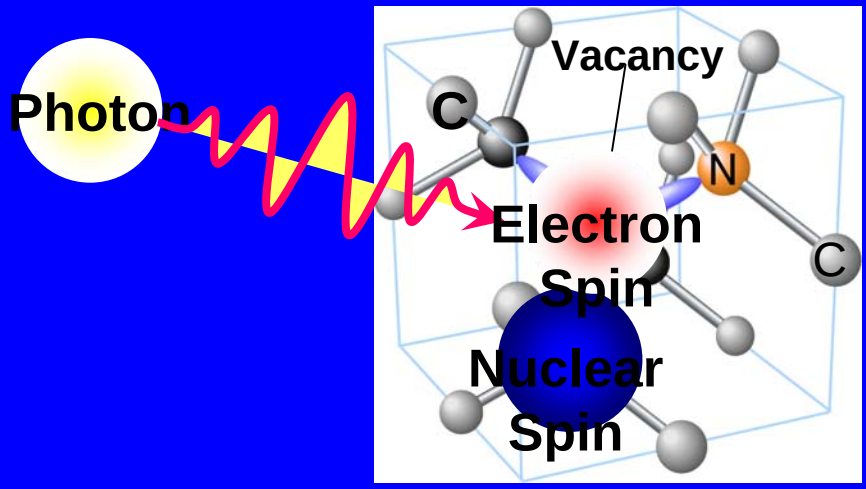
- Initialize
- Write
- Gate operation
- Read out
- Scalability



High fidelity

Long coherence time

Material System for Memory



1. Diamond NV center or other donors
2. Semiconductor quantum dot / donor
3. Nonlinear crystal rare-earth impurity

Outline

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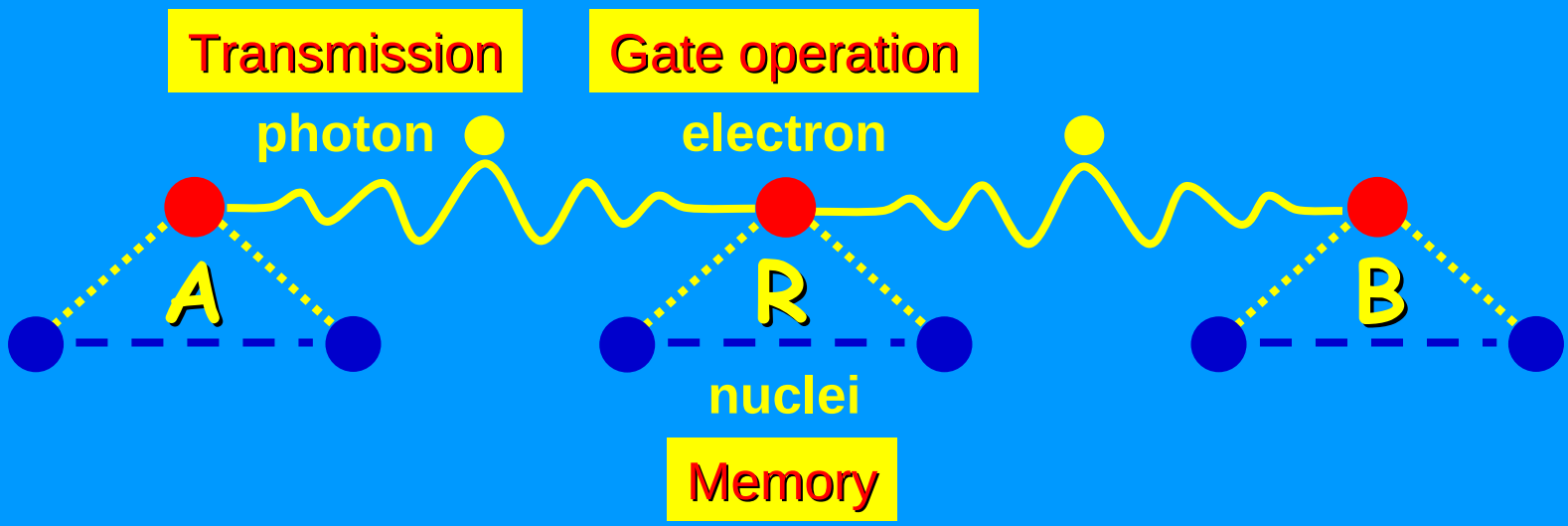
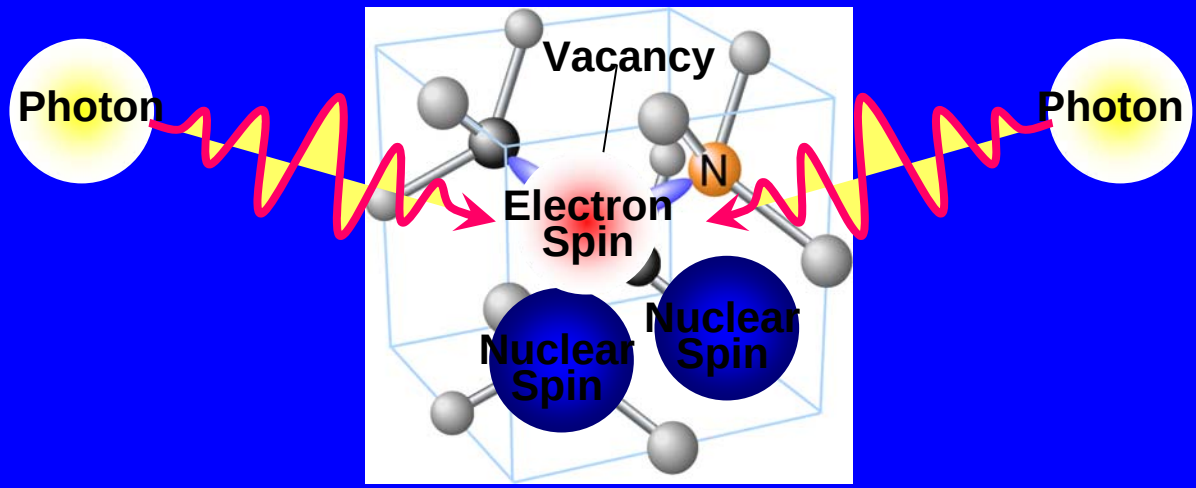
Hybrid Quantum Repeater





Diamond NV center

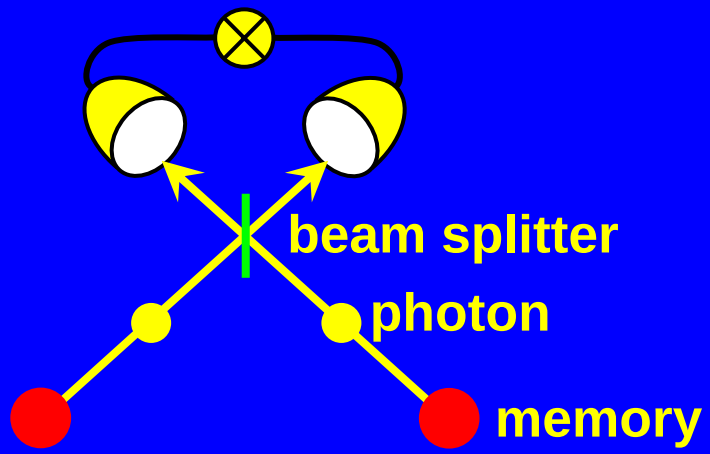
Demonstrated features

- **Long coherence time** (T_2^e > 1 ms & **T_2^n > 1 s** at RT)
- Single electron/nuclear spin manipulation
  → **Gate operation**
- Optical pumping of electron/nuclear spins at RT
  → **Initialization**
- **Entanglement** generation between spins and photons
- Quantum non-demolition measurement of a nuclear spin
  → **Read out**
- Multiple quantum memories on nuclear spins
  → **Scalability**
- **Long coherence** of nuclear spin Bell-stats (T_2 = 5ms at RT)

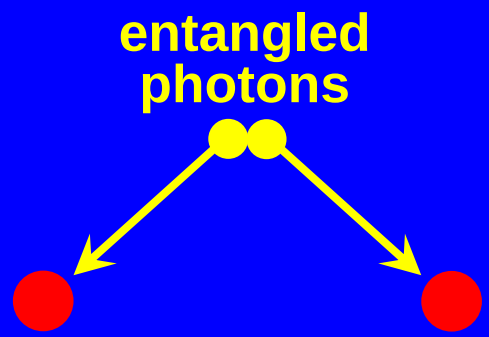
Writing function has not yet been demonstrated

Entanglement Generation

1. Emission



2. Absorption



3. Emission & Absorption

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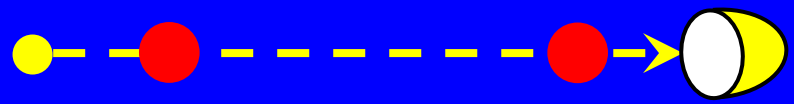
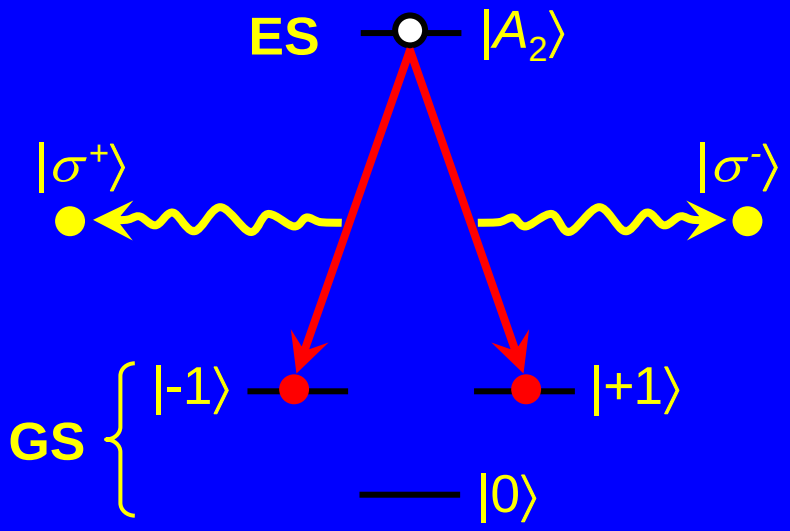
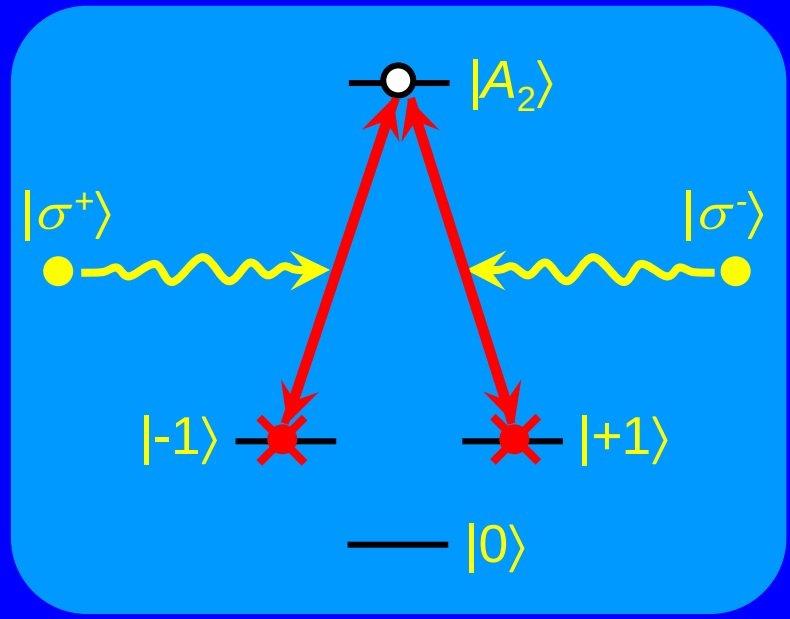


Emission vs. Absorption

1. Emission



2. Absorption



orbit spin

ES

$|A_1\rangle = |E_-\rangle \otimes |+1\rangle - |E_+\rangle \otimes |-1\rangle$

$|A_2\rangle = |E_-\rangle \otimes |+1\rangle + |E_+\rangle \otimes |-1\rangle$

$|E_x\rangle = |X\rangle \otimes |0\rangle$

$|E_y\rangle = |Y\rangle \otimes |0\rangle$

$|E_1\rangle = |E_-\rangle \otimes |-1\rangle - |E_+\rangle \otimes |+1\rangle$

$|E_2\rangle = |E_-\rangle \otimes |-1\rangle + |E_+\rangle \otimes |+1\rangle$

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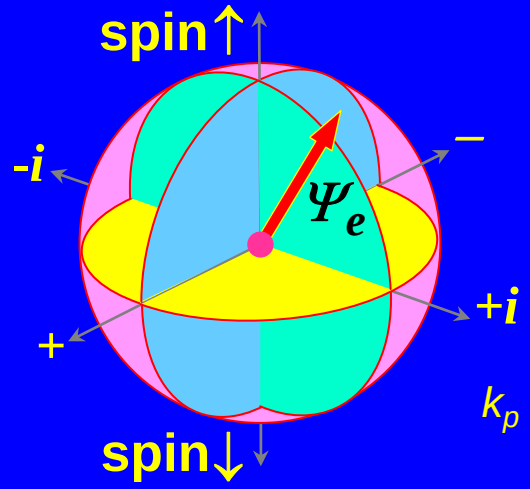
What is Time-bin State?

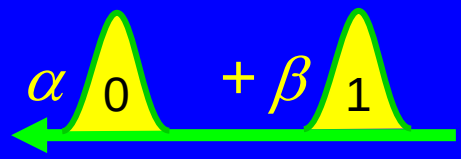
- **Spin** can be a superposition of up/down spin bases.

$$\alpha\left|\uparrow\right\rangle_e + \beta\left|\downarrow\right\rangle_e$$

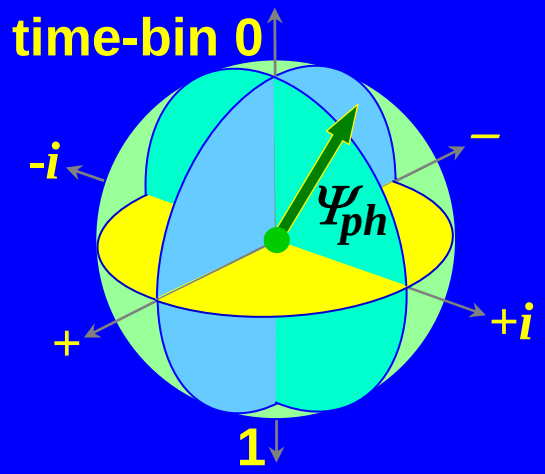


- **Temporal mode** can also be a superposition of two time bases.

$$\alpha\left|0\right\rangle_{ph} + \beta\left|1\right\rangle_{ph}$$

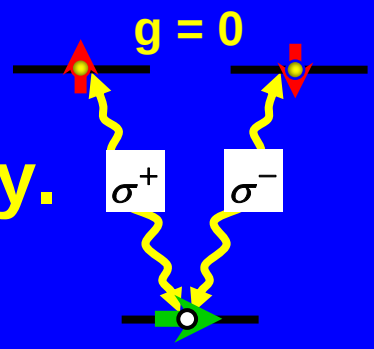


Time-bin state!



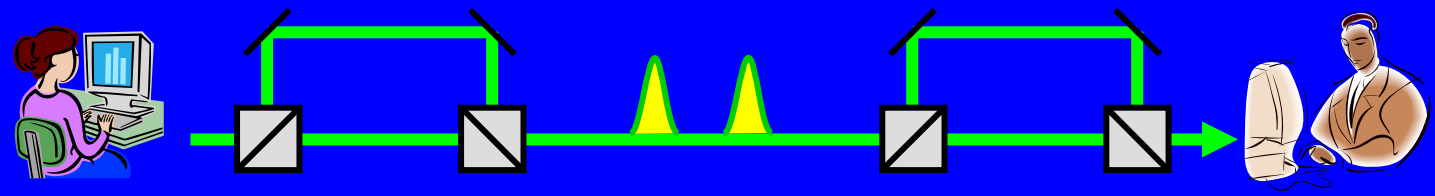
Why Time-bin State?

- Polarization state transfer needs special conditions and spatial symmetry.



PRL 100, 096602 (2008).
Nature 457, 702 (2009).

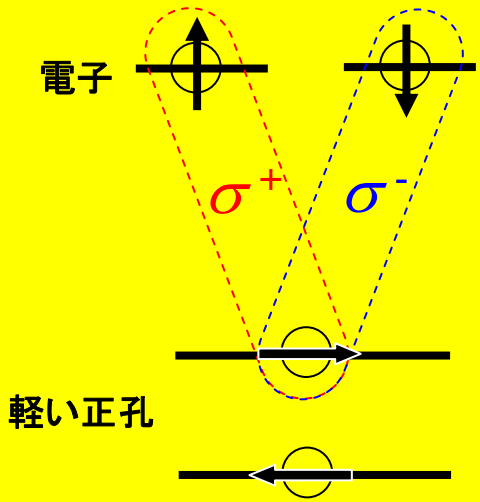
- Time-bin state needs one spatial mode and successful in quantum communications.



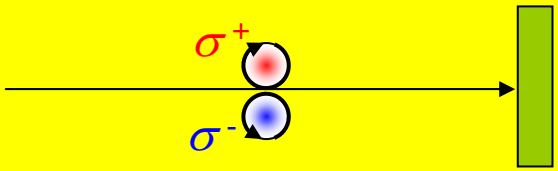
- Direct transfer from time-bin state to spin state should be desirable.

Polarization vs. Time-bin

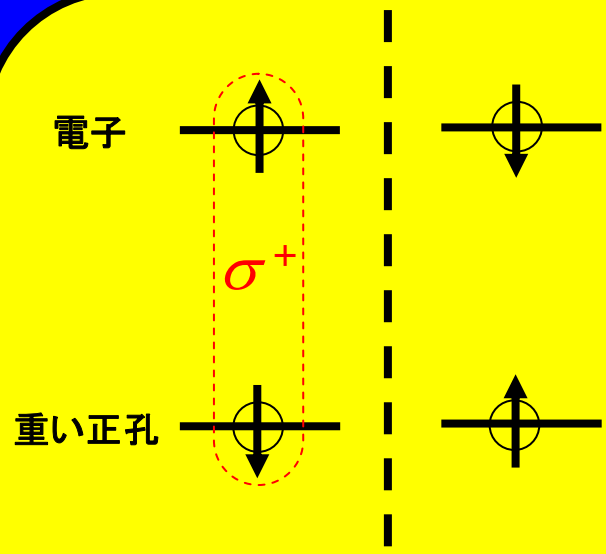
Polarization state transfer



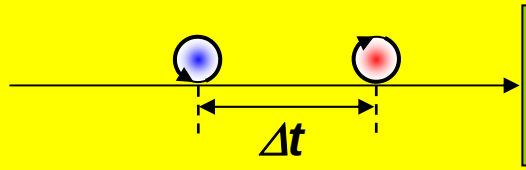
σ^+とσ^-を<u>同時</u>に入射



Time-bin state transfer



同じ偏光を<u>時間差をつけて</u>入射

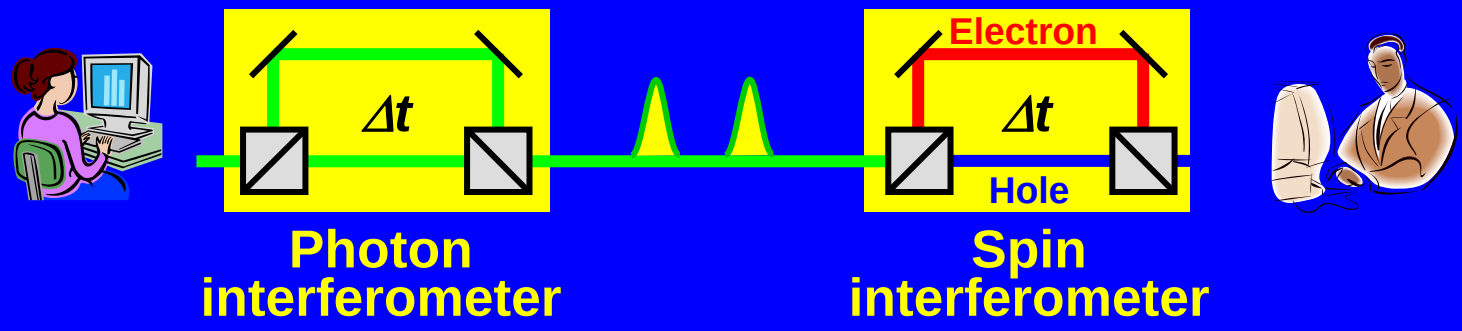


Selection rule

Spin Dynamics

Basic Idea of Time-bin State Transfer

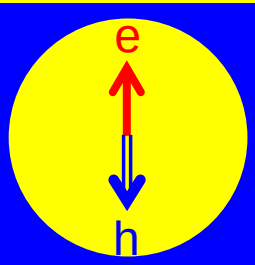
- Tune the time separation to the time difference in spin dynamics between electron and hole.



- Make hole spin indistinguishable to erase which-pass information on hole spin.

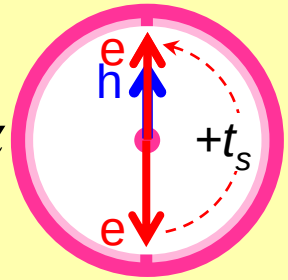
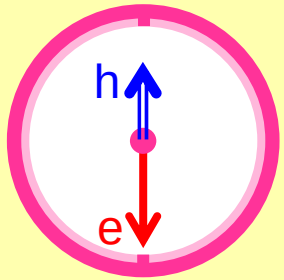
Principle of Time-bin State Transfer

Electron-precession case



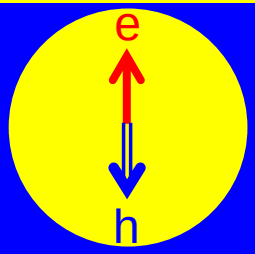
Electron-precession case (HH)

time-bin 0 σ^+ time-bin 1 σ^+

$$\Psi_{ex} = \alpha$$  $$+\beta$$ 

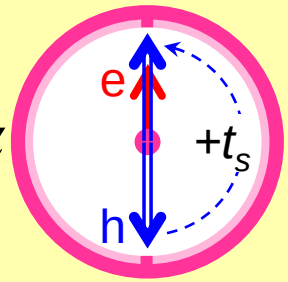
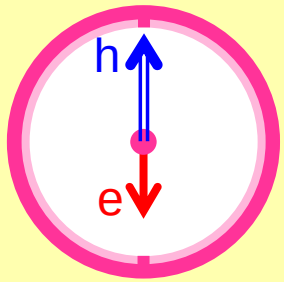
$$\alpha\,|0\rangle_{ph} + \beta\,|1\rangle_{ph} \rightarrow (\alpha\,|\uparrow\rangle_e + \beta\,|\downarrow\rangle_e) \otimes |\Uparrow\rangle_h$$

Hole-precession case



Hole-precession case (LH)

time-bin 0 σ^+ time-bin 1 σ^-

$$\Psi_{ex} = \alpha$$  $$+\beta$$ 

Necessary Conditions

$$t_{ex} > t_s > t_{ph}$$

Exciton coherence | Time separation | Light pulse width

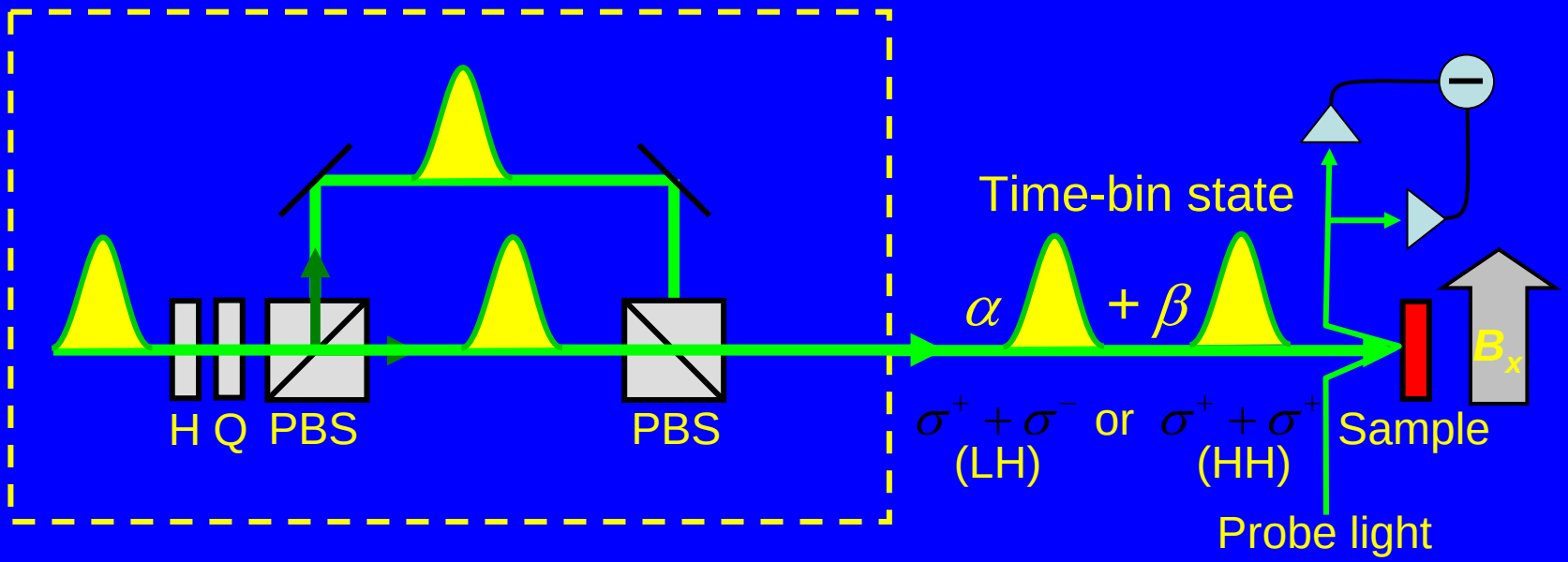
$$\Delta E_{ex} < \Delta E_z < \Delta E_{ph}$$

Exciton bandwidth | Zeeman energy | Photon bandwidth

Proof-of-Principle Experiment

Preparation of time-bin coherent light pulse

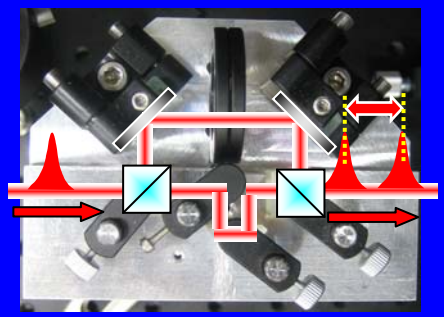
Kerr rotation meas.

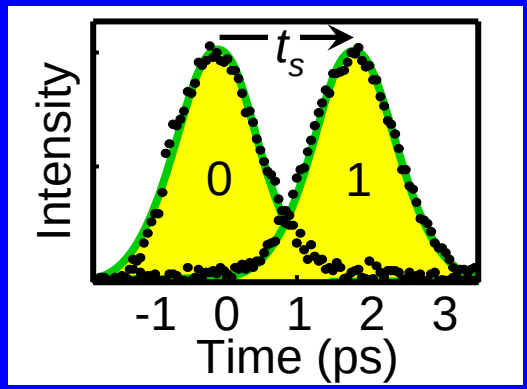


PBS: Polarization beam splitter

H: Half-wave plate

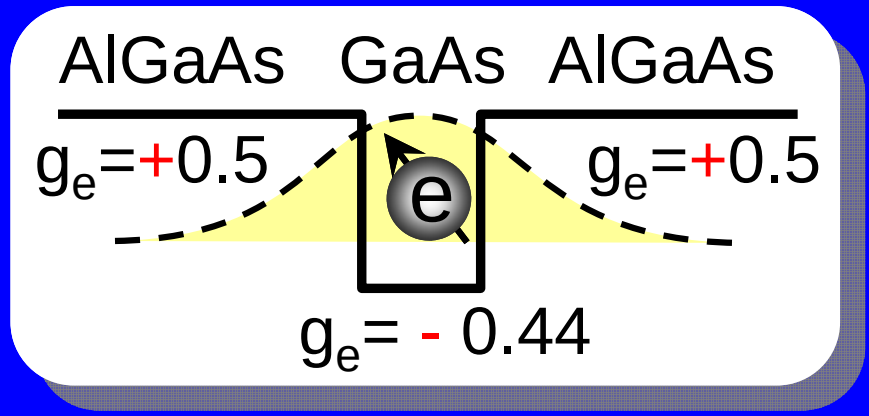
Q: Quarter-wave plate

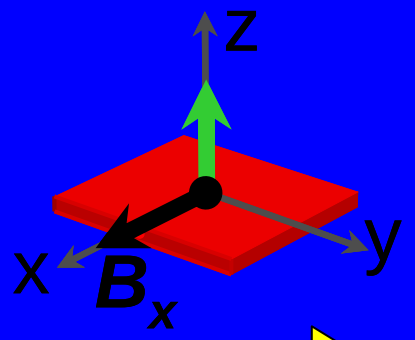




Sample Structure

Non-dope Single quantum well 20 nm



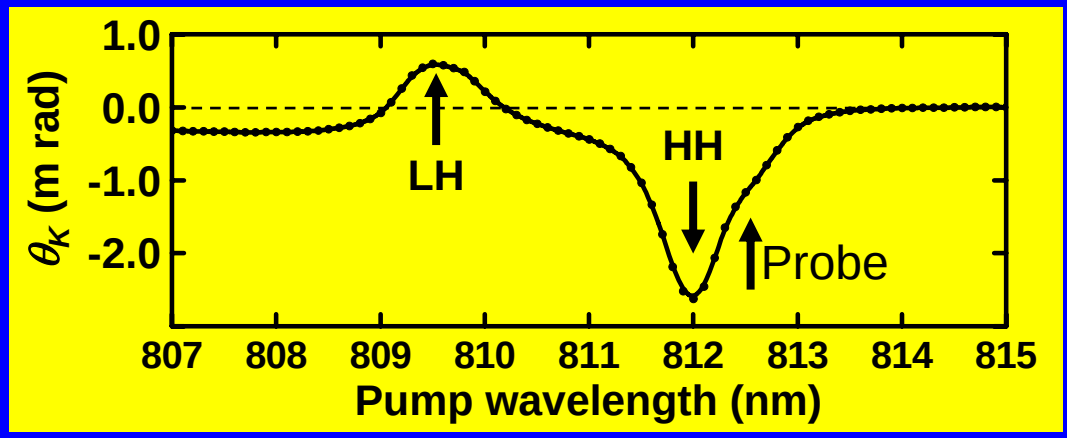


B_x=7T

Inplain B Field

g-factors

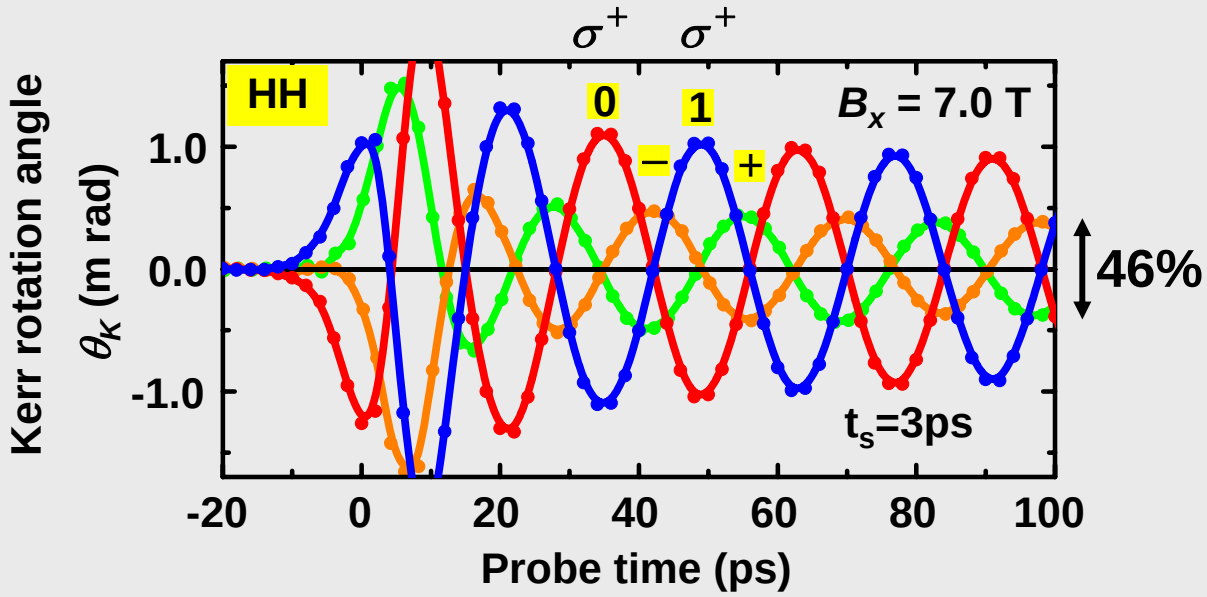
- **Electron 0.37**
- **Light hole 2.0** ➡ **Hole-precession case**
- **Heavy hole ~0** ➡ **Electron-precession case**



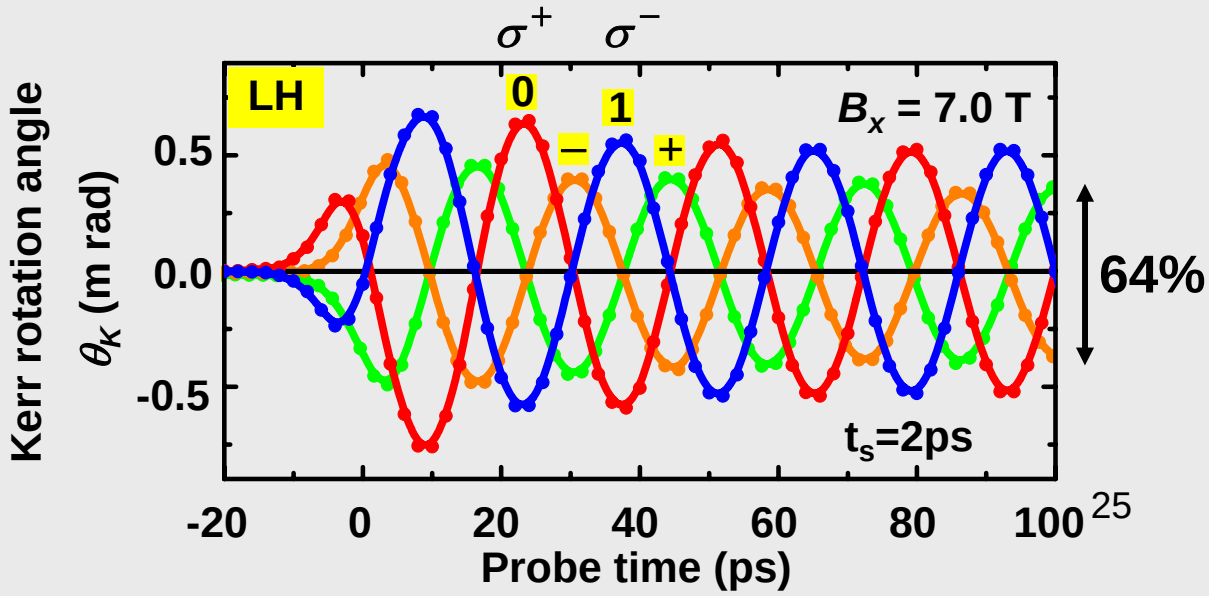
T=6K

Experimental results

Electron-precession case (Heavy-hole exciton)

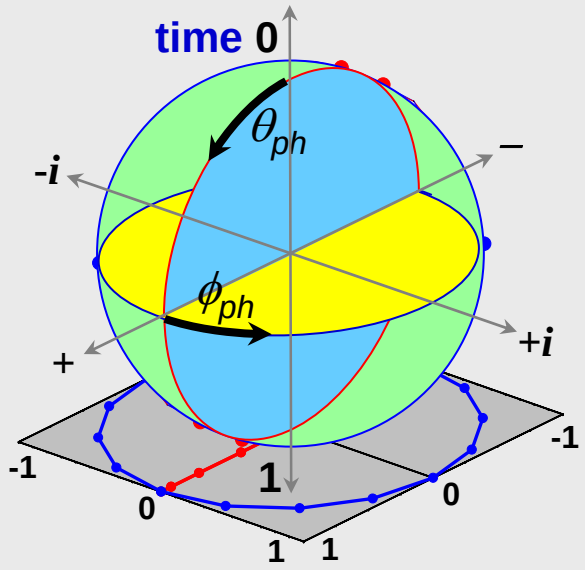


Hole-precession case (Light-hole exciton)

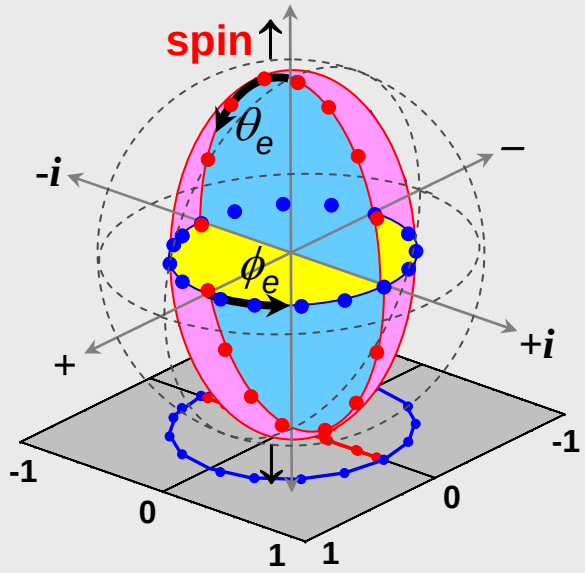


Fidelity of Transfer

Light Time-bin



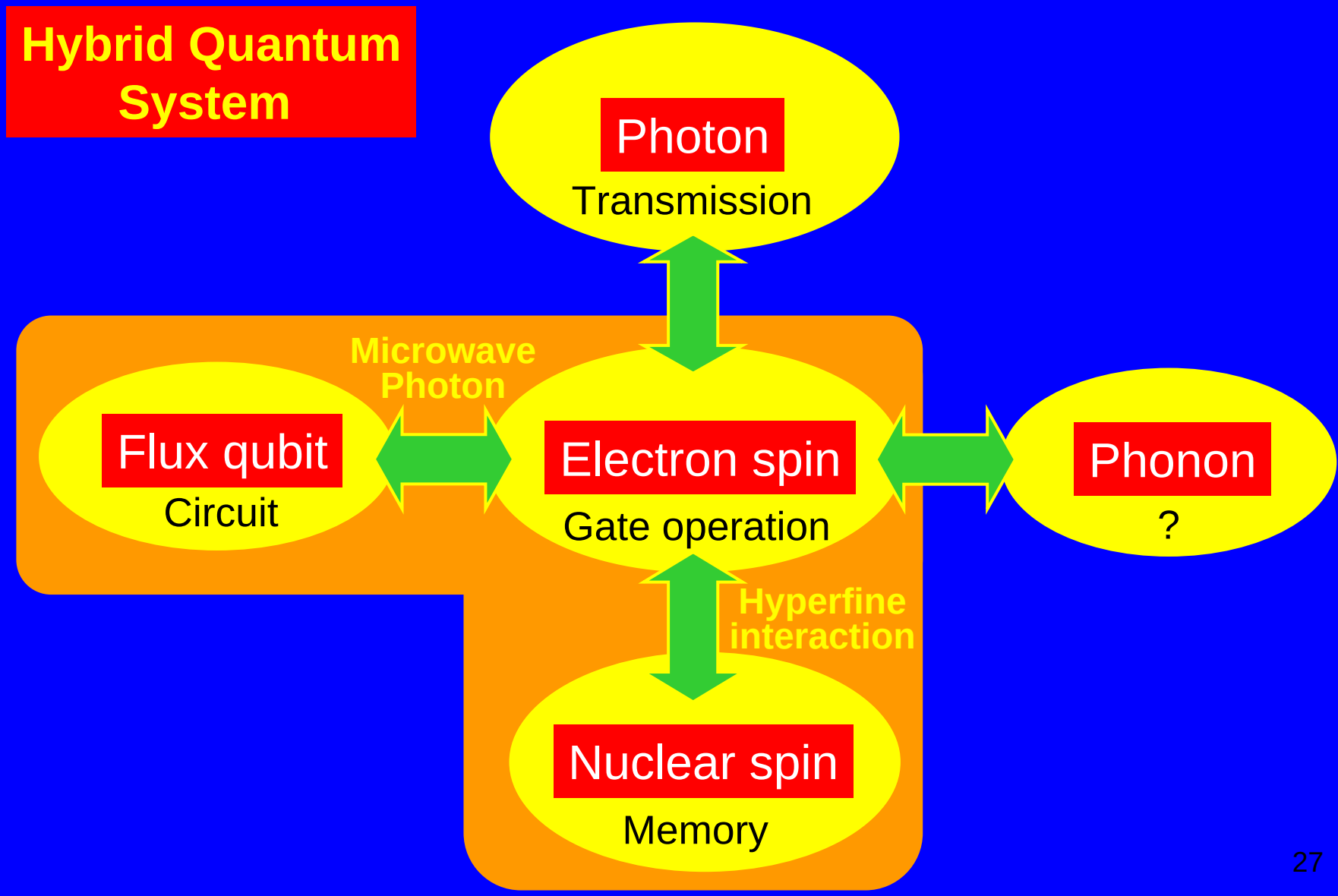
Electron Spin



Transfer Fidelity (average)
89% (Hole-precession case)
58 % (Electron-precession case)

$\pi/2$ phase shift
due to π-rotation of hole
(Geometric phase)

Quantum Media Conversion



Summary

- Quantum media conversion is need for building hybrid quantum systems.
- NV in diamond is promising as a gate and memory.
- Photon state transfer into nuclear spin needs to be done.
- Time-bin state transfer to electron spin state has been demonstrated.
- Time-bin scheme is applicable to e spin, h spin, n spin, NV spin to store optical or microwave photon state.

Post-doc position open