Spin state tomography of a single electron spin in a diamond with a single photon for entanglement swapping

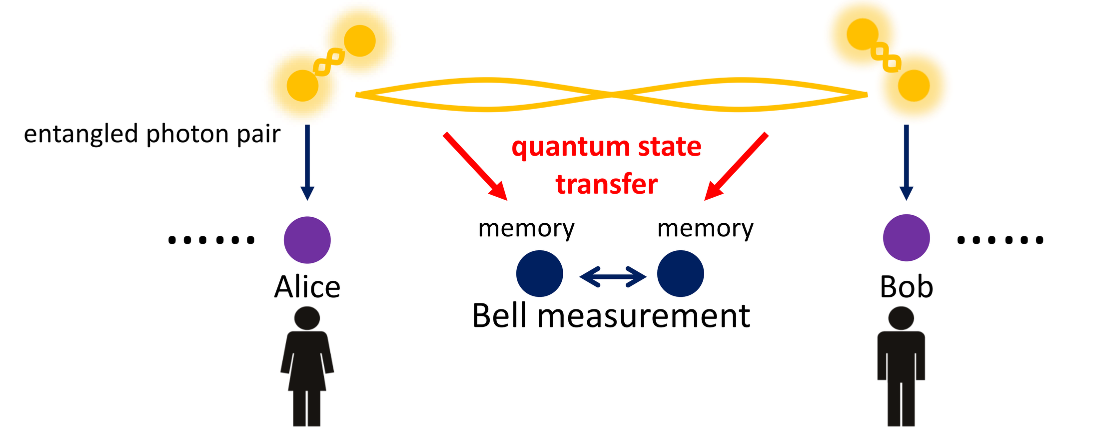
FIRST
NICT
Naeko Niikura, Hideo Kosaka
Yokohama National University

Motivation

We demonstrate optical preparation and readout of electron spin coherence in a single NV center in diamond for quantum repeater.

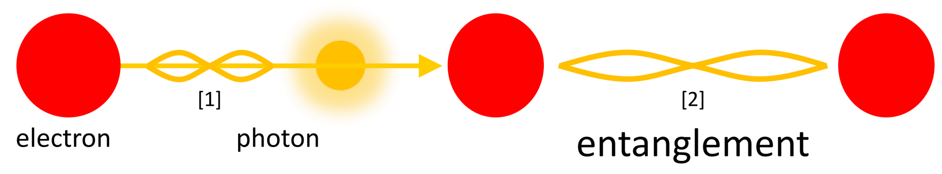
◆Quantum information communication

- Fundamentally secure communications
- Communication distance is : 200km (present)→ >1000km (future)
  - ➢ **A quantum repeater is required**



◆Quantum repeater

●Entanglement swapping

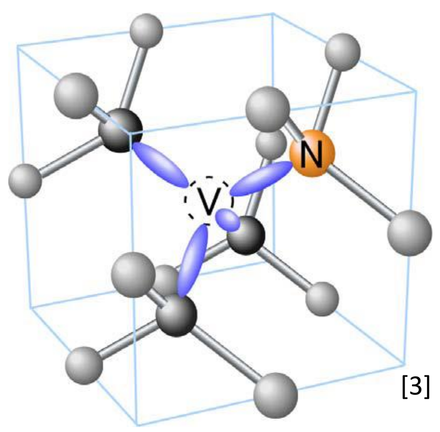


Entanglement detection

Most important function for quantum repeaters

[1] E. Togan et al., Nature 466, 730 (2010)
[2] H. Bernien et al., Nature 497, 86 (2013)

◆NV center in diamond



N : Nitrogen
V : Vacancy

[3] N. Mizuochi et al., Nature Photonics 6, 299 (2012)
[4] G. Balasubramanian et al., Nat. Mater. 8, 383 (2009)
[5] M. V. G. Dutt et al., Science 316, 1312 (2007)
[6] P. C. Maurer et al., Science 336, 1283 (2012)
[7] A. Gruber et al., Science 27, 276 (1997)

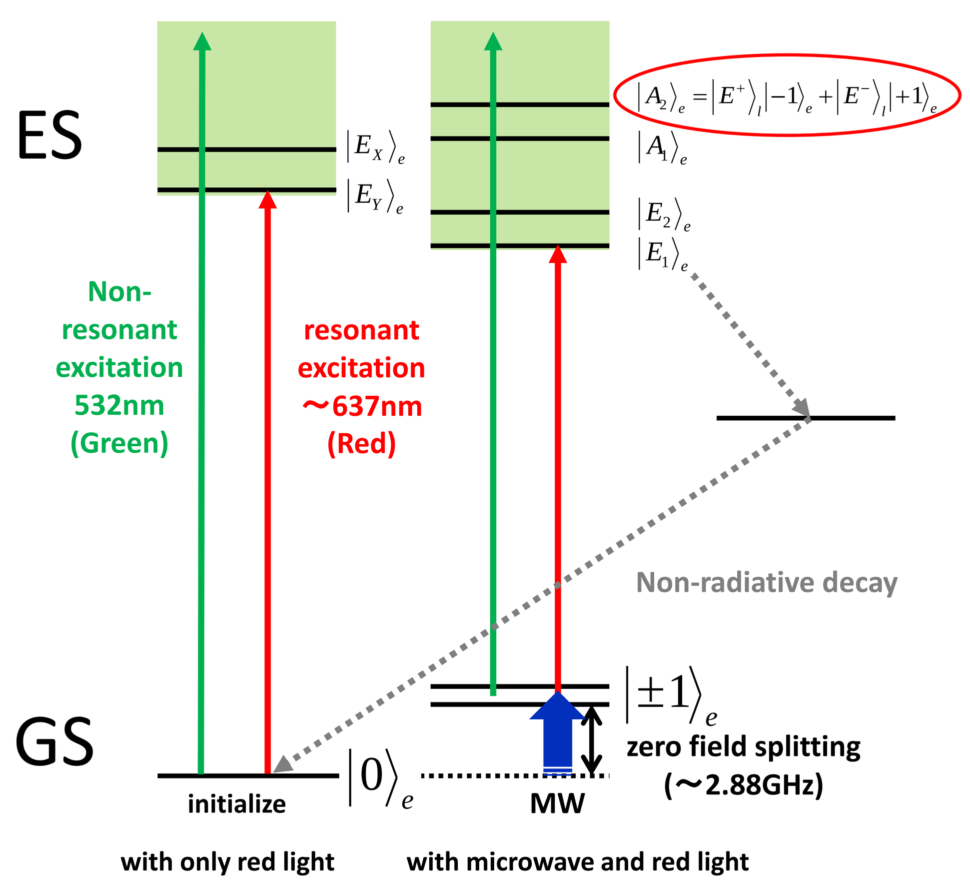
- **Long coherence time (T^2_e>0.6s at 77K, T^2_n>1s at RT)** [4],[5],[6]
- Single electron/nuclear spin manipulation [7]
- Optical Initialization & readout of electron spins [7]

Objectives

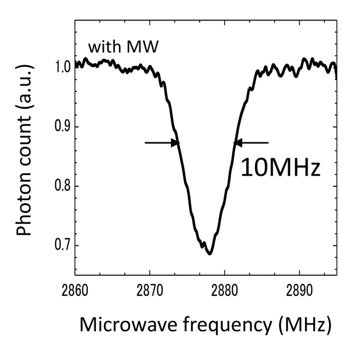
1. **Microwave spin coherence generation**
2. **Optical arbitrary spin state preparation**
   Via coherent population trapping
3. **Photon-spin entanglement detection**
   Via spin-orbit entanglement
4. **Optical spin state tomography**
   Heralded by single photon click
5. **Photon-to-nuclear spin state transfer**
   Via quantum teleportation

Approach

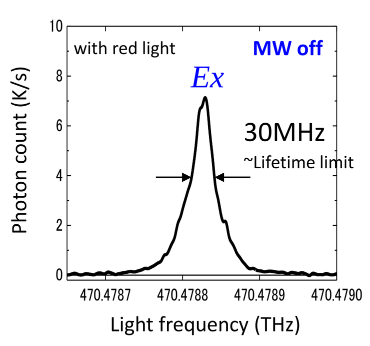
◆Excitation to spin-orbit entangled state



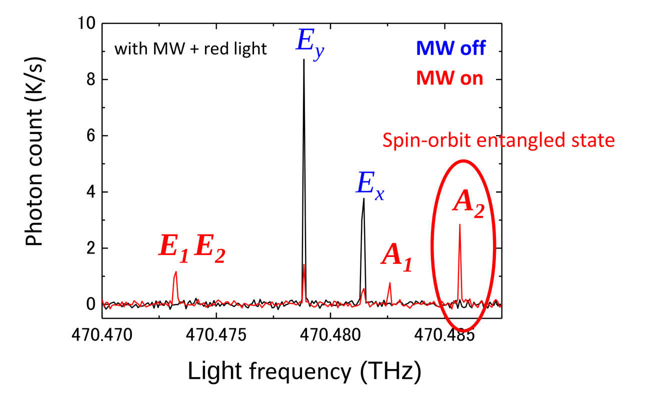
●Microwave resonance



●Optical resonance

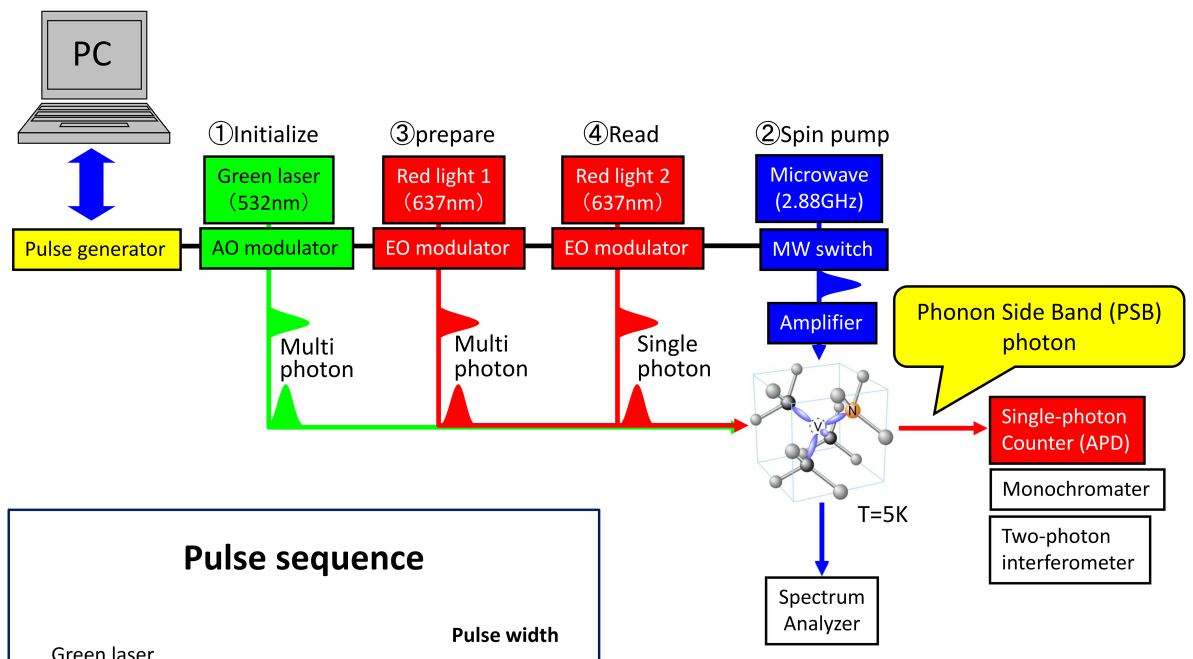


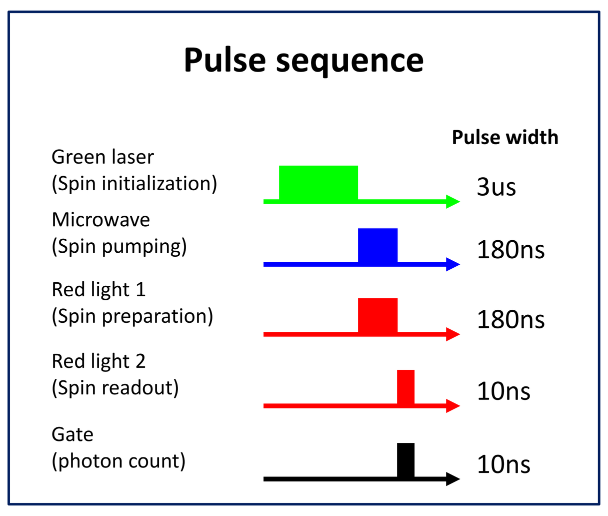
●Magneto-optical double resonance

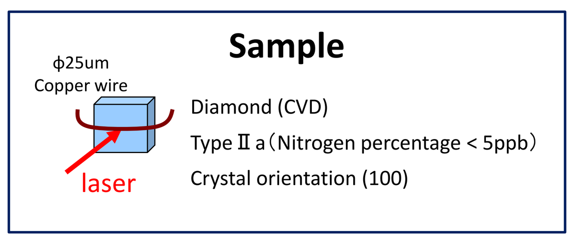


Excitation to $|A_2\rangle$ state, where orbit and spin are entangled, was observed by magneto-optical double resonance.

Experimental setup







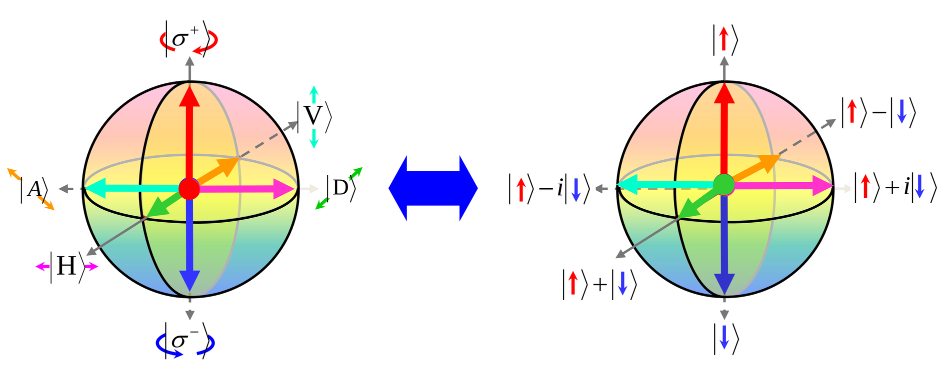
Experimental results

◆Photon-spin correlation

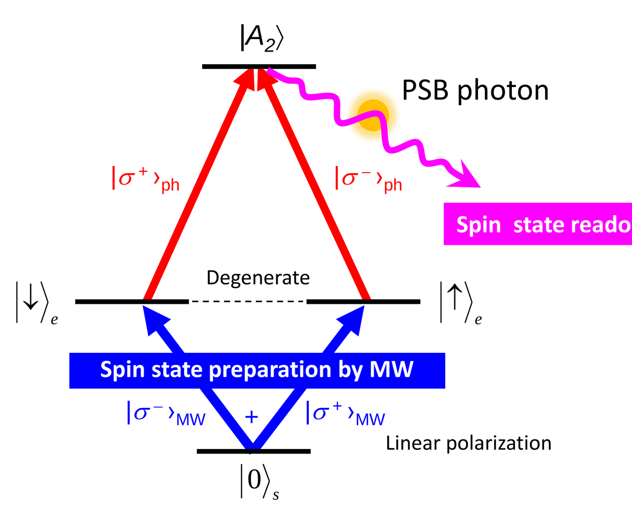
$|A_2\rangle = |\sigma^+\rangle_e|\downarrow\rangle_e + |\sigma^-\rangle_e|\uparrow\rangle_e$

	Prepared spin state	Polarization of writing	Polarization of readout
Z	$\vert\uparrow\rangle$	$\vert\sigma^+\rangle$	$\vert\sigma^-\rangle$
	$\vert\downarrow\rangle$	$\vert\sigma^-\rangle$	$\vert\sigma^+\rangle$
X	$\vert\uparrow\rangle-\vert\downarrow\rangle$	$\vert\sigma^+\rangle+\vert\sigma^-\rangle=\vert H\rangle$	$\vert\sigma^+\rangle-\vert\sigma^-\rangle=\vert V\rangle$
	$\vert\uparrow\rangle+\vert\downarrow\rangle$	$\vert\sigma^+\rangle-\vert\sigma^-\rangle=\vert V\rangle$	$\vert\sigma^+\rangle+\vert\sigma^-\rangle=\vert H\rangle$
Y	$\vert\uparrow\rangle-i\vert\downarrow\rangle$	$\vert\sigma^+\rangle+i\vert\sigma^-\rangle=\vert D\rangle$	$\vert\sigma^+\rangle-i\vert\sigma^-\rangle=\vert A\rangle$
	$\vert\uparrow\rangle+i\vert\downarrow\rangle$	$\vert\sigma^+\rangle-i\vert\sigma^-\rangle=\vert A\rangle$	$\vert\sigma^+\rangle+i\vert\sigma^-\rangle=\vert D\rangle$

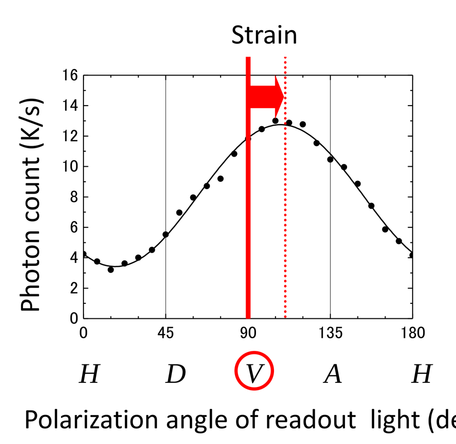
It is possible to read electron spin state prepared by microwave or light by observing the luminescence of PSB photon.



1. Microwave spin coherence generation



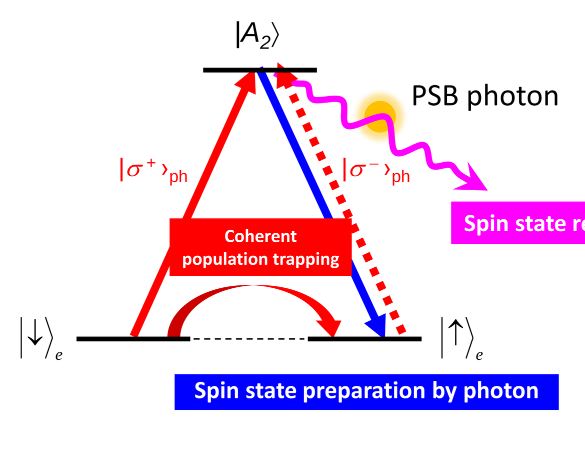
●Spin state readout with light



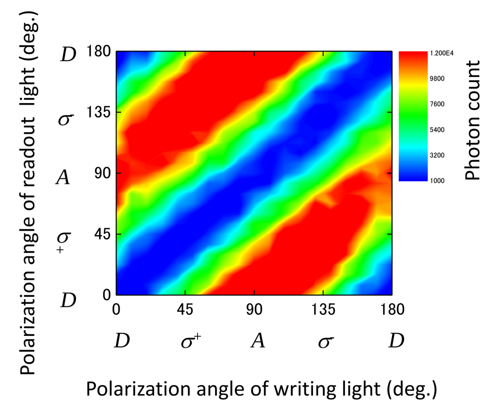
① Coherent spin state preparation by microwave
② Excitation to $|A_2\rangle$ state by light
③ Observing luminescence of PSB photon
→Spin state readout

The luminescence of PSB photon is observed in near V polarization. Therefore, it demonstrated that spin state prepared by MW is $|\uparrow\rangle-|\downarrow\rangle$. (Ref. left table)

2. Optical arbitrary spin state preparation



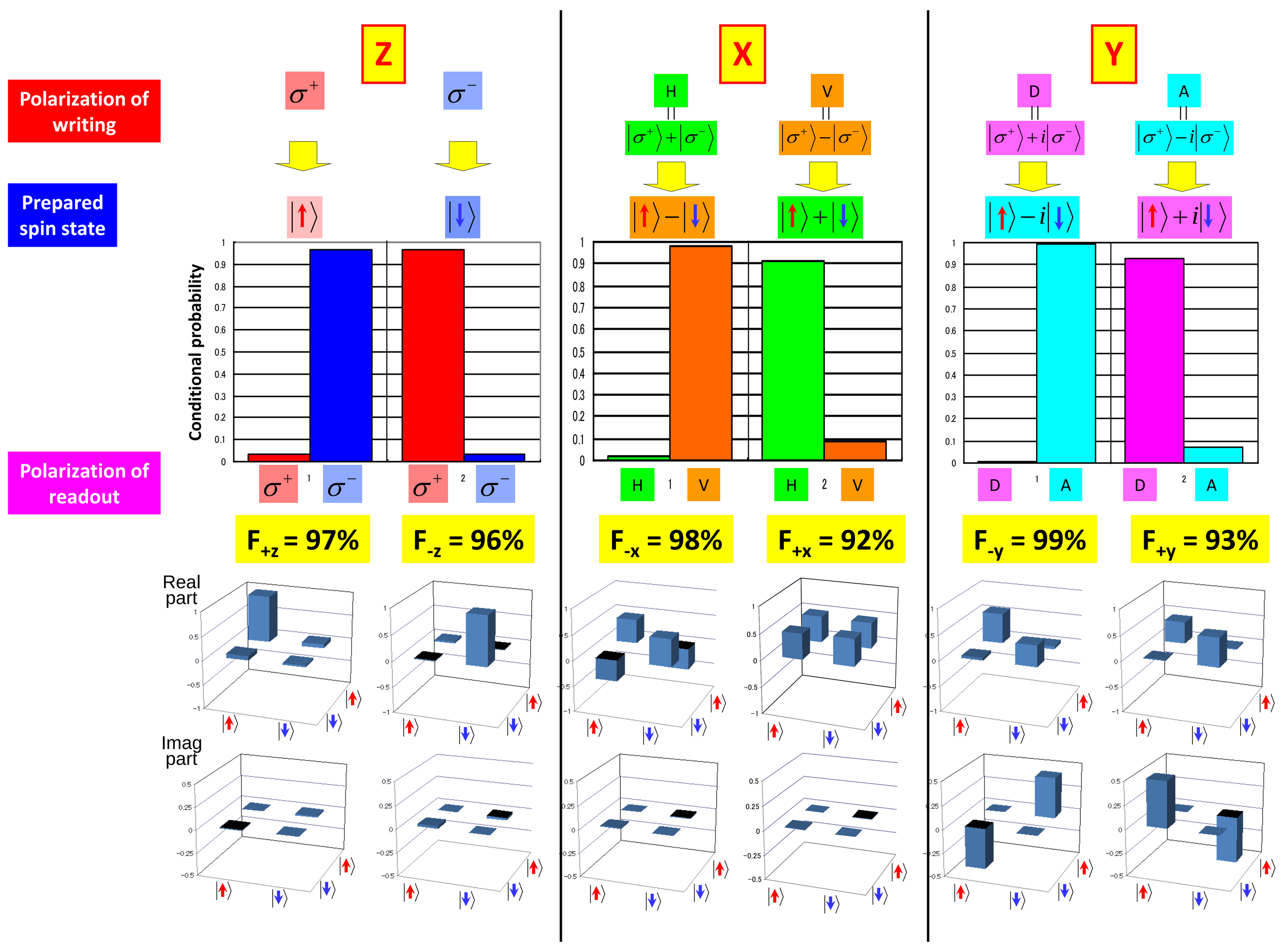
●Spin state writing and readout with light



① Arbitrary spin state preparation by light
② Excitation to $|A_2\rangle$ state by light
③ Observing luminescence of PSB photon
→Spin state readout

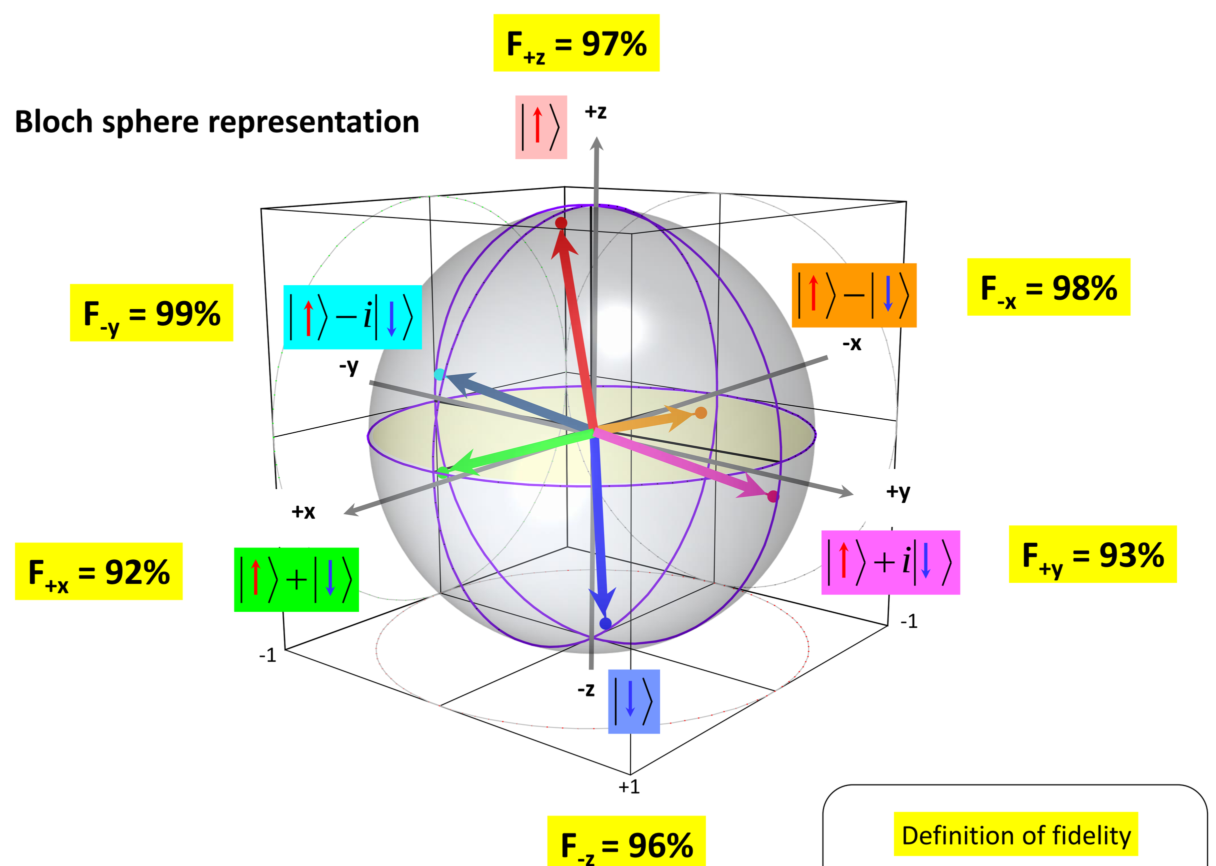
Arbitrary spin state generation and readout by light are demonstrated.

3. Photon-spin entanglement detection



Photon-spin entanglement detection via spin-orbit entanglement is demonstrated with F>92%.

4. Optical spin state tomography

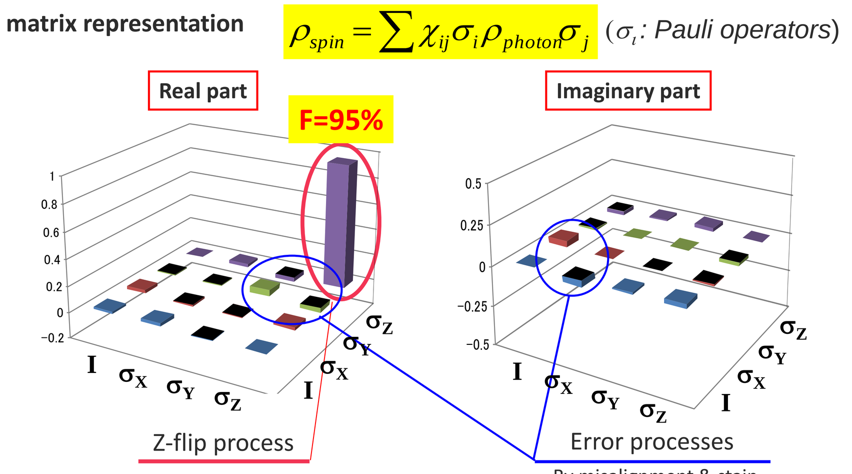


Definition of fidelity

$$F = Tr(\rho_{ideal} \cdot \rho_{meas})$$

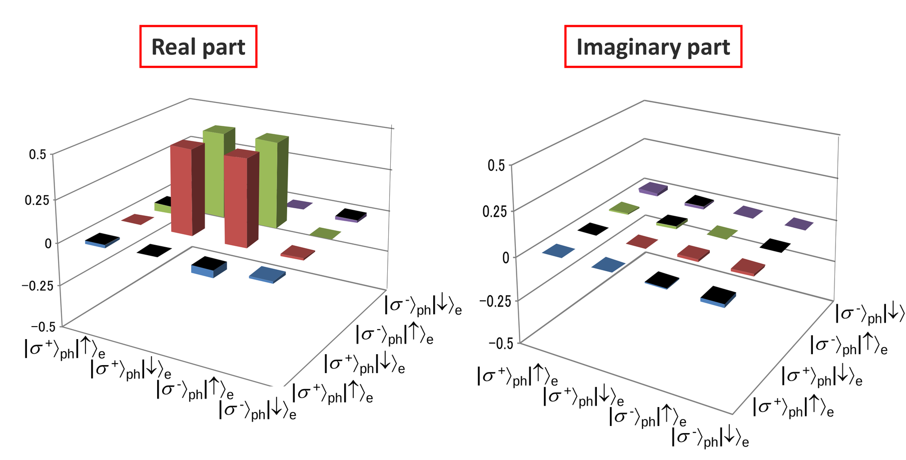
◆Spin preparation process tomography

χ matrix representation $\rho_{spin} = \sum \chi_{ij}\sigma_i \rho_{photon}\sigma_j$ (σ_i: Pauli operators)



$$\chi = \begin{bmatrix} 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&0 \\ 0&0&0&1 \end{bmatrix} : \rho_{spin} = \sigma_z \rho_{photon} \sigma_z$$

◆Spin measurement process tomography



$$\hat{M} = \frac{1}{2}\begin{bmatrix} 0&0&0&0 \\ 0&1&1&0 \\ 0&1&1&0 \\ 0&0&0&0 \end{bmatrix} = |A_2\rangle\langle A_2|$$

Entanglement measurement

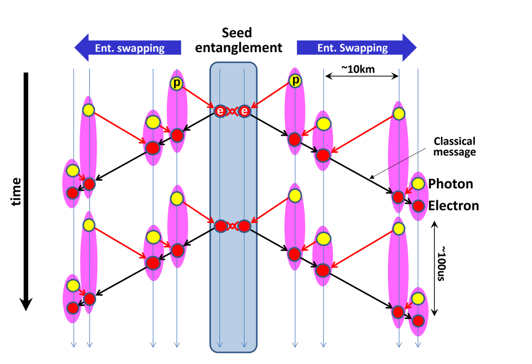
$$Tr(\hat{M} \cdot \hat{\rho}_{photon} \otimes \hat{\rho}_{spin})$$

Conclusions

- ☑ **1. Microwave spin coherence generation**
- ☑ **2. Optical arbitrary spin state preparation**
  Via coherent population trapping
- ☑ **3. Photon-spin entanglement detection**
  Via spin-orbit entanglement (F>90%)
- ☑ **4. Optical spin state tomography**
  Heralded by single photon click

Outlook

1. **Photon-to-nuclear spin state transfer**
   Via quantum teleportation
2. **Demonstration of entanglement swapping**



Acknowledgements

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