Quantum Information Processing Based on Quantum-dots in Optical Double-sided Microcavities

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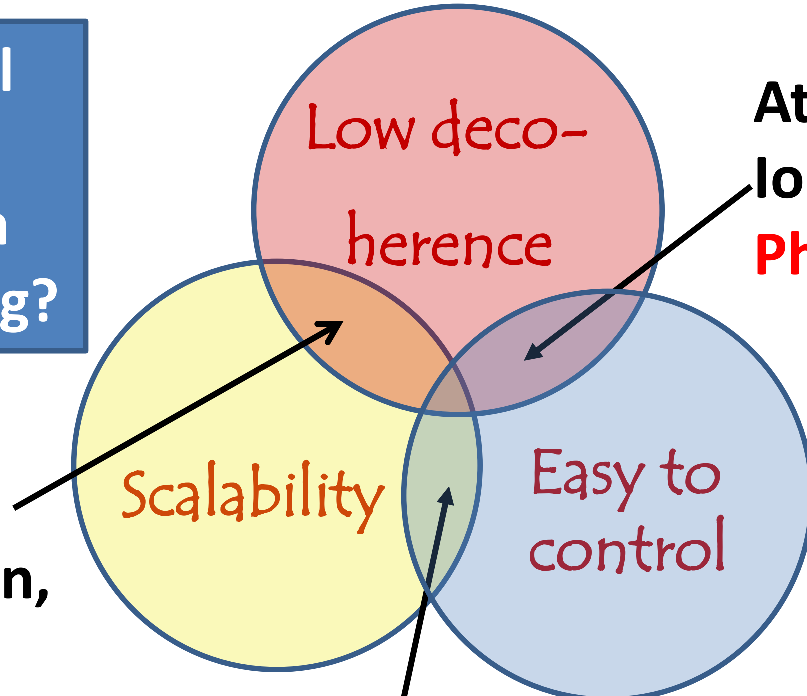
Background

What kinds of physical systems can meet the demands for quantum information processing?



Atoms, Trapped Ions, N-V center, Photons, etc.

Quantum Dots, Quantum wells, Solid nuclear spin, etc.

Superconducting Josephson Junction

The Di Vincenzo criteria for quantum computer:

- ✓ Well-defined qubits;
- ✓ Efficient Initialization and Measurement;
- ✓ Universal Logic and Long Coherence Time;

The photon-spin hybrid system

- Flying qubit - photon
  - Single photon sources
    - ✓ Electrically /optically driven
    - ✓ Indistinguishable
    - ✓ Cavity-QED enhanced
  - Entangled photon-pair sources
- Static qubit - electron spin
  - long coherence time: ms~s
  - Operating temperature: 100 mK (quantum dot)
    room temp. (NV center)
  - scalable, compatible with semiconductor technology

Challenges in the photon-spin hybrid system

1. In the direct transmission of the information(photon) , raw rate decreases exponentially with distance.

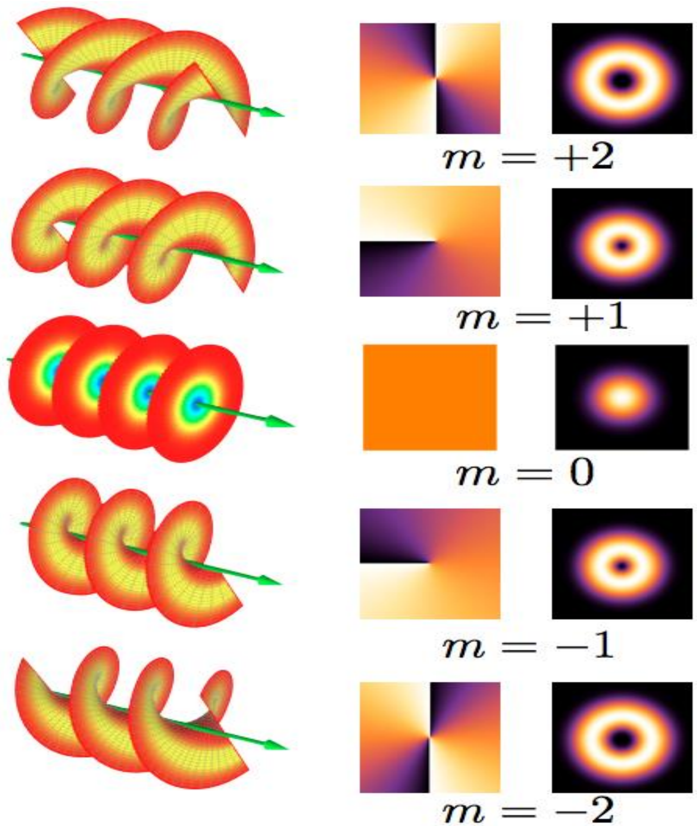
- ✓increase the number of photons (e.g.redundant quantum parity codes)
- ✓multiple degrees of freedom(multi-DOFs) encoding

Advantages achieved for multi-DOF QIP :

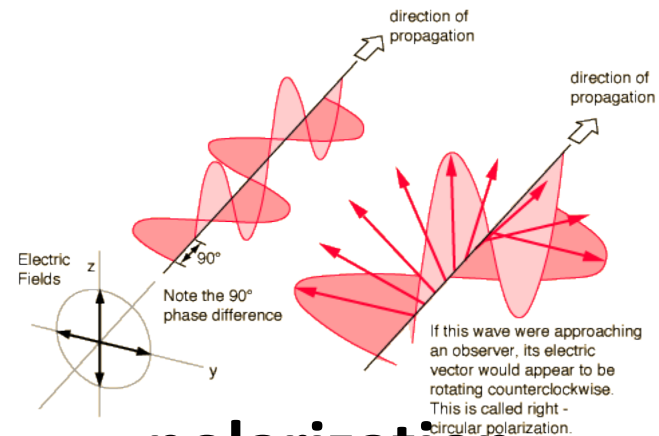
- ✓ **increase the channel capacity via superdense coding;**
- ✓ **significantly reduce physical qubits required in distributed quantum computing ;**
- ✓ **simplify the implementation of quantum logic gates;**
- ✓ **complete deterministic entanglement purification , error rejection with a time DOF;**
- ✓ **assist complete Bell-state analysis…**

Multiple degrees of freedom (DOFs) of photon systems

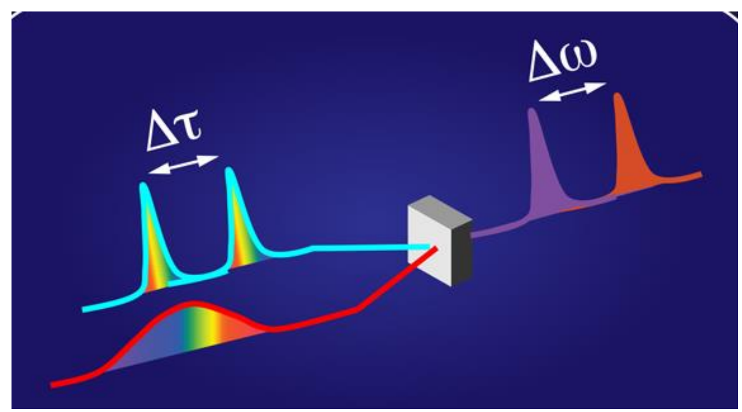
polarization, orbital angular momentum , discrete path , spatial position , time-bin , frequency, and global spatial symmetry…



orbital angular momentum



polarization



time-bin & frequency

Challenges in the multi-DOFs photon-spin hybrid system：

When the two-DOF-encoding photons interact with the spin qubits,

- 1.will two photonic DOFs affect each other ?
- 2.can each photonic DOF interact with the spin *independently* ?
- 3.can two photonic DOFs be *simultaneously* interacting with one spin ?
- 4.can two DOFs be simultaneously controlled by a single spin？

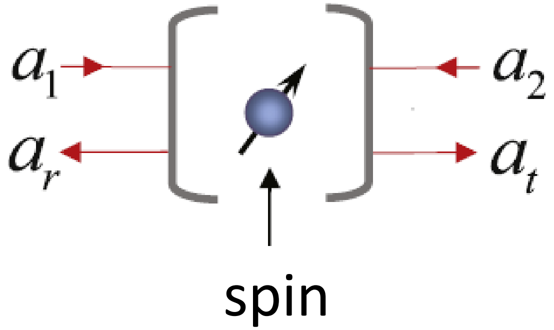
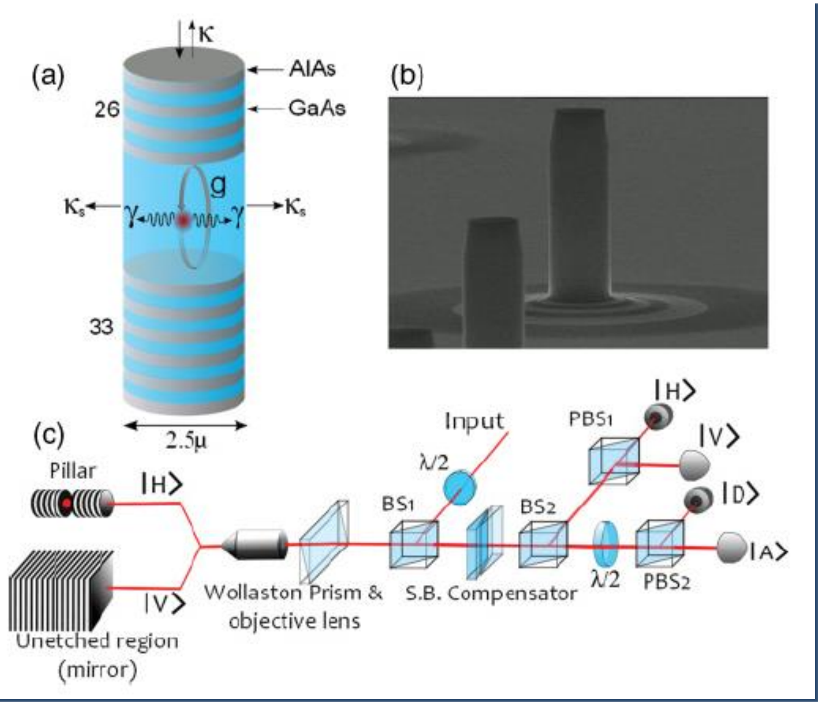
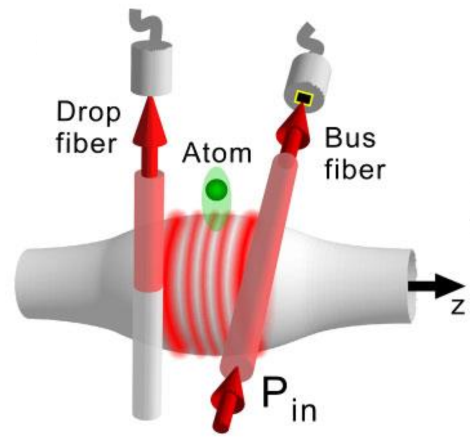


Fig.The double-sided cavity-spin coupled system.

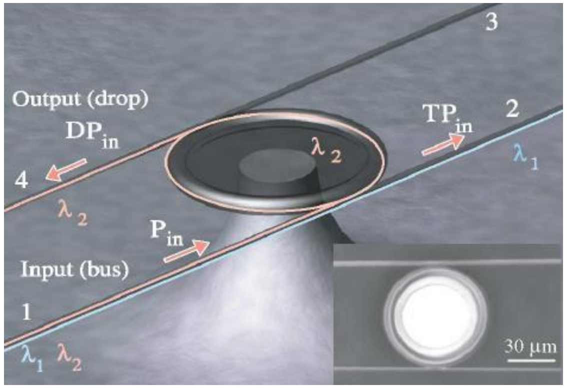
The experimental realization for double-sided cavity



(pillar) Phys. Rev. A 84, 011803(R) (2011)



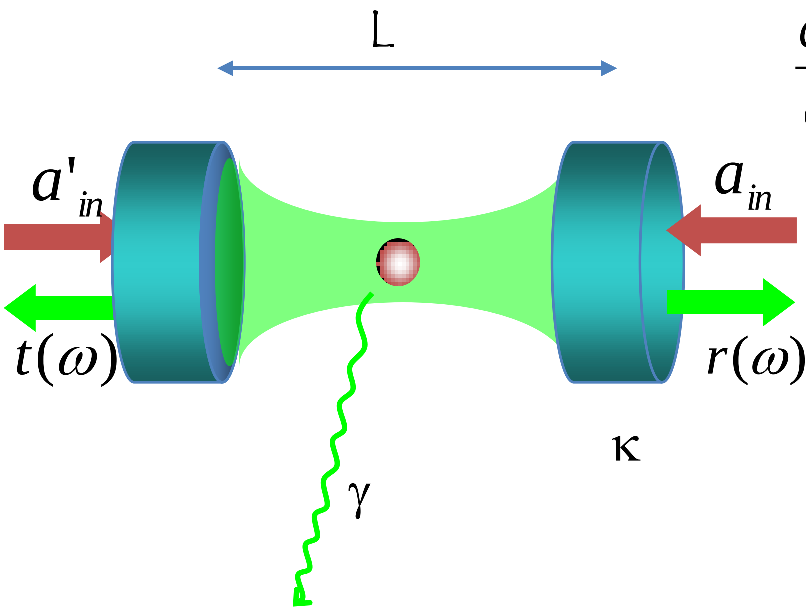
(bottle)Phys.Rev.Lett.111.193601(2013)



(toroid)Phys.Rev.Lett.92.253905(2004)

In the double sided cavity, the photon's **polarization DOF** **spatial-mode DOF** can be and operated simultaneously.

The input-output theory of Jaynes-Cummings model



$$\frac{d\hat{a}}{dt} = -[i(\omega_c - \omega) + \kappa + \frac{\kappa_s}{2}]\hat{a} - g\sigma_- - \sqrt{\kappa}\hat{a}_{in} - \sqrt{\kappa}\hat{a}'_{in} + \hat{H}$$

$$\frac{d\sigma_-}{dt} = -[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}]\sigma_- - g\sigma_z\hat{a} + \hat{G}$$

$$a_{out}(t) = a_{in}(t) + \sqrt{\kappa}a(t)$$

- coupled system:

$$r(\omega) = \frac{[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}][i(\omega_C - \omega) + \frac{\kappa_s}{2}] + g^2}{[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}][i(\omega_C - \omega) + \kappa + \frac{\kappa_s}{2}] + g^2},$$

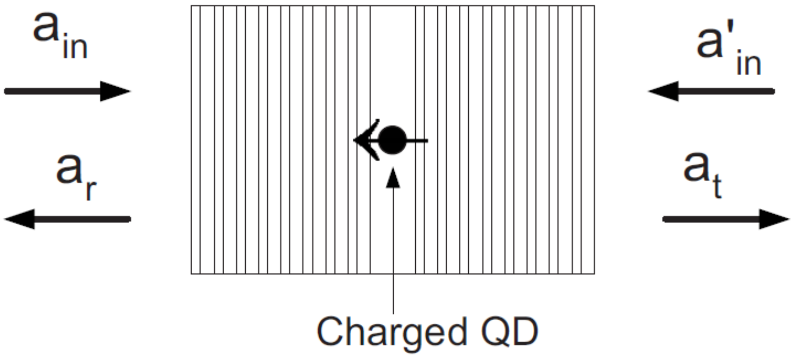
$$t(\omega) = \frac{-\kappa[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}]}{[i(\omega_{X^-} - \omega) + \frac{\gamma}{2}][i(\omega_C - \omega) + \kappa + \frac{\kappa_s}{2}] + g^2}$$

uncoupled system:

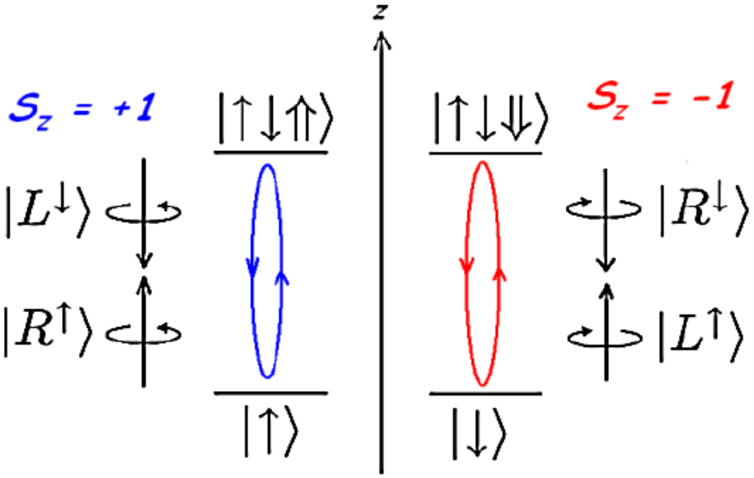
$$r_0(\omega) = \frac{i(\omega_0 - \omega) + \frac{\kappa_s}{2}}{i(\omega_0 - \omega) + \frac{\kappa_s}{2} + \kappa}$$

$$t_0(\omega) = \frac{-\kappa}{i(\omega_0 - \omega) + \frac{\kappa_s}{2} + \kappa}.$$

Quantum dot coupled with microcavity



C. Hu, Phys. Rev. B 80, 205326 (2009)



C. Bonato, Phys. Rev. Lett. 104, 160503 (2010)

$$|R^{\uparrow},\uparrow\rangle \rightarrow |L^{\downarrow},\uparrow\rangle, \qquad |L^{\uparrow},\uparrow\rangle \rightarrow -|L^{\uparrow},\uparrow\rangle,$$

$$|R^{\downarrow},\uparrow\rangle \rightarrow -|R^{\downarrow},\uparrow\rangle, \qquad |L^{\downarrow},\uparrow\rangle \rightarrow |R^{\uparrow},\uparrow\rangle,$$

$$|R^{\uparrow},\downarrow\rangle \rightarrow -|R^{\uparrow},\downarrow\rangle, \qquad |L^{\uparrow},\downarrow\rangle \rightarrow |R^{\downarrow},\downarrow\rangle,$$

$$|R^{\downarrow},\downarrow\rangle \rightarrow |L^{\uparrow},\downarrow\rangle, \qquad |L^{\downarrow},\downarrow\rangle \rightarrow -|L^{\downarrow},\downarrow\rangle.$$

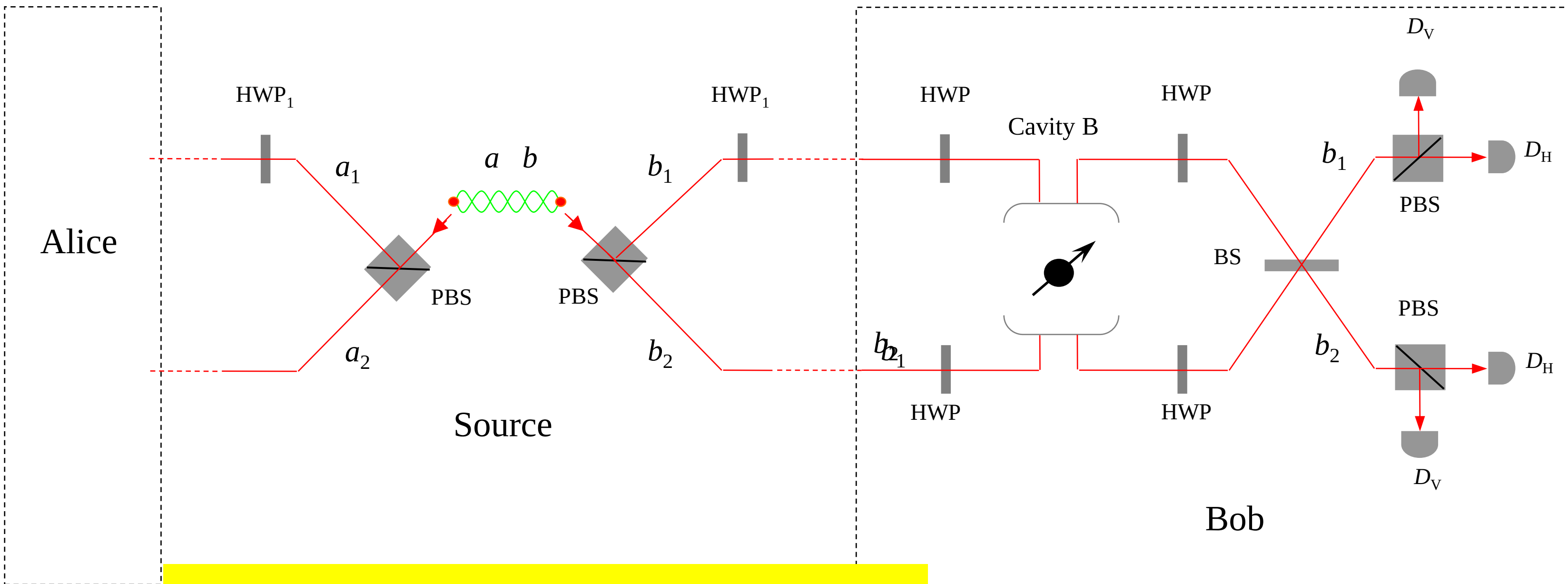
Challenges in the multi-DOFs photon-spin hybrid system

When the two-DOF encoding photon interact with the spin qubit,

1. will two photonic DOFs affect each other ?

- SCHEME1:

Quantum repeater based on spatial entanglement of photons and quantum-dot spins in optical microcavities



PHYSICAL REVIEW A **85, 062311 (2012)**

The source emits an entangled photon pair:

$$|\Psi\rangle_{ab} = \frac{1}{\sqrt{2}}|H\rangle|H\rangle(|a_1\rangle|b_1\rangle + |a_2\rangle|b_2\rangle)$$

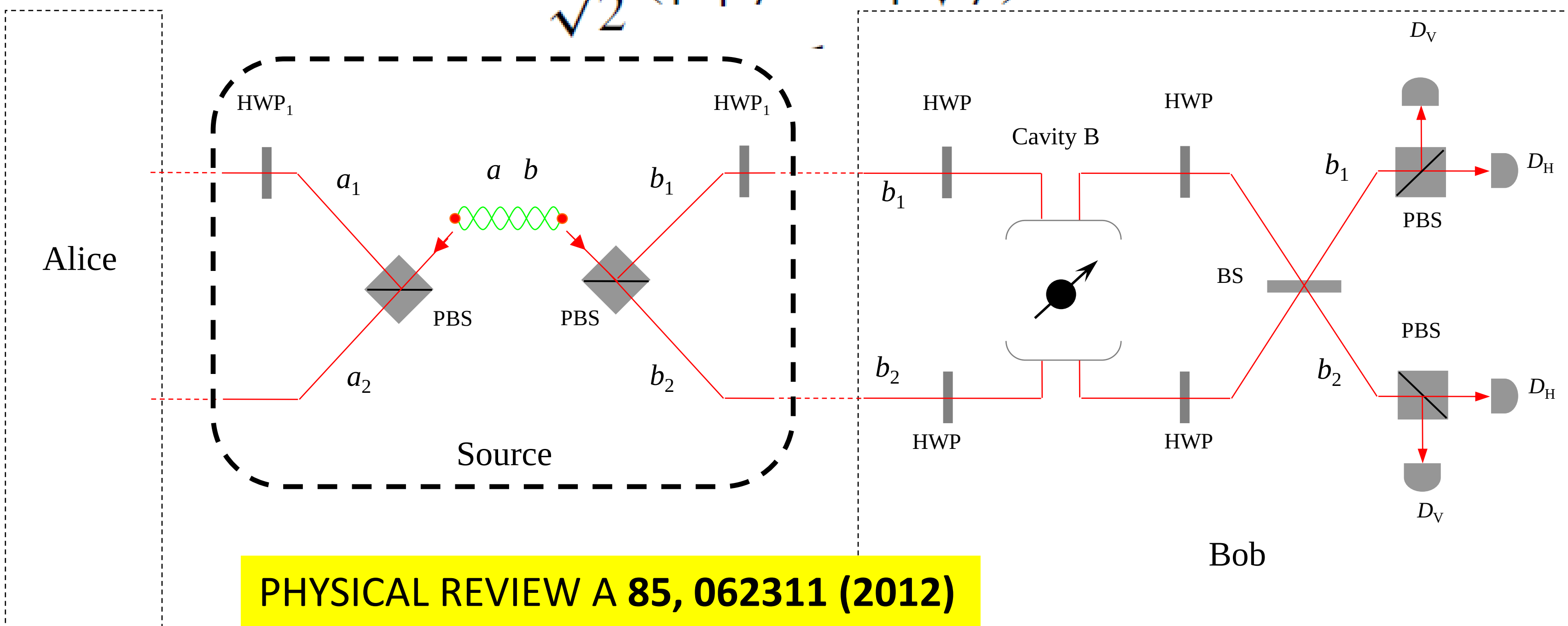
after long transition over a noisy channel:

$$\rho_s = |\phi^+\rangle_s\langle\phi^+|, \quad \rho_p = p_1|HH\rangle\langle HH| + p_2|HV\rangle\langle HV|$$

Nature (London) 423, 417 (2003)

$$+ p_3|VH\rangle\langle VH| + p_4|VV\rangle\langle VV|,$$

The initial spin states: $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$



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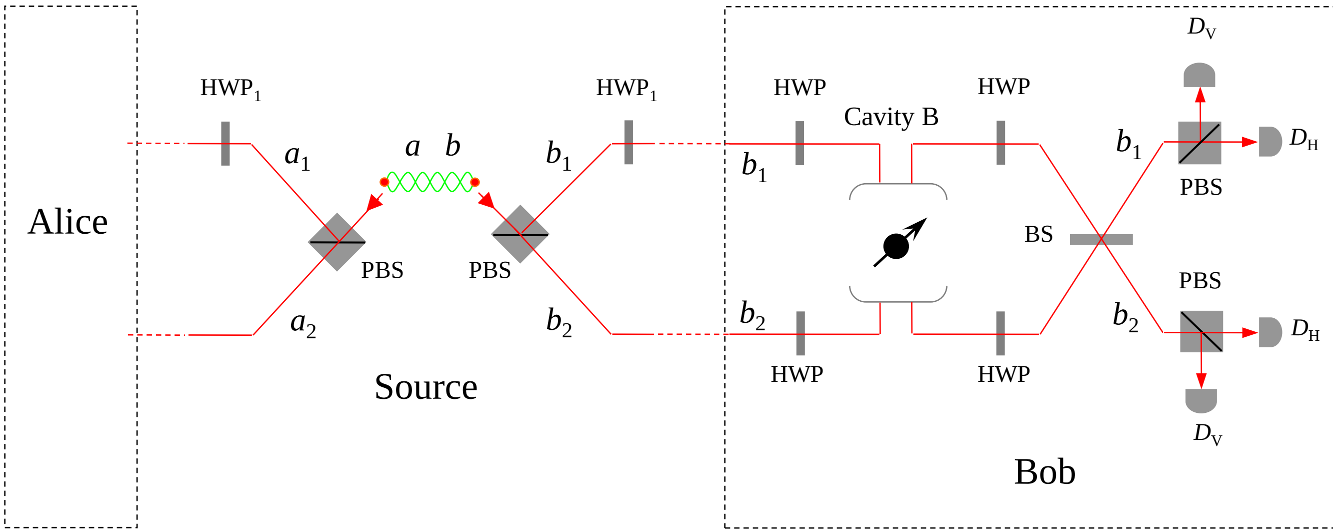

- the unkown mixed polarization state of the photon-pair can NOT affect the entanglement transfer between the spatial DOF of the photons and spin qubits.

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$$\frac{1}{2}\{|\phi^+\rangle_{AB}|\phi^+\rangle_p(|a_1b_1\rangle+|a_2b_2\rangle)_{ab}$$
$$-|\phi^-\rangle_{AB}|\phi^+\rangle_p(|a_1b_2\rangle+|a_2b_1\rangle)_{ab}$$
$$-|\psi^+\rangle_{AB}|\psi^+\rangle_p(|a_1b_1\rangle-|a_2b_2\rangle)_{ab}$$
$$-|\psi^-\rangle_{A,B}|\psi^+\rangle_p(|a_1b_2\rangle-|a_2b_1\rangle)_{ab}\}$$

Spin - entanglement

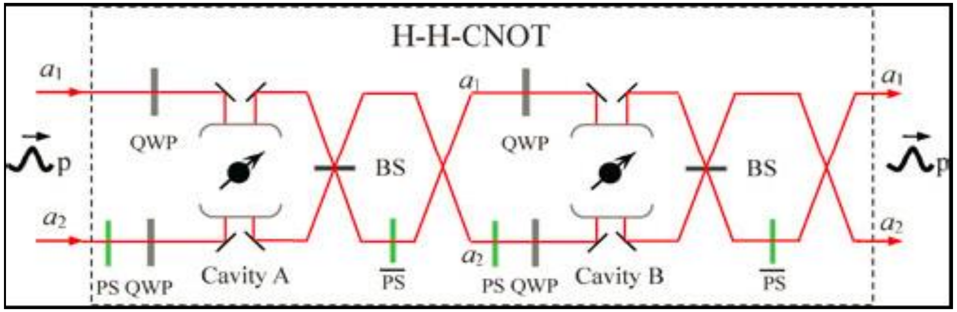
Polarization DOF Spatial-mode DOF

Challenges in the multi-DOFs photon-spin hybrid system

When the two-DOF encoding photon interact with the spin qubit,

2.can each photonic DOF interact with the spin independently ?

- SCHEME2: The hybrid hyper-CNOT gate



The initial photonic states: $(\alpha|R\rangle + \beta|L\rangle)_p(\gamma|a_1\rangle + \xi|a_2\rangle)_s$

The initial spin-states: $(\alpha'|\uparrow\rangle + \beta'|\downarrow\rangle)_A \otimes (\gamma'|\uparrow\rangle + \xi'|\downarrow\rangle)_B$

After the hybrid hyper-CNOT gating:

$$= [\alpha'|\uparrow\rangle_A(\gamma|a_1\rangle + \xi|a_2\rangle)_s + \beta'|\downarrow\rangle_A(\gamma|a_2\rangle + \xi|a_1\rangle)_s]$$
$$\otimes [\gamma'|\uparrow\rangle_B(\alpha|R\rangle + \beta|L\rangle)_p + \xi'|\downarrow\rangle_B(\alpha|L\rangle + \beta|R\rangle)_p].$$

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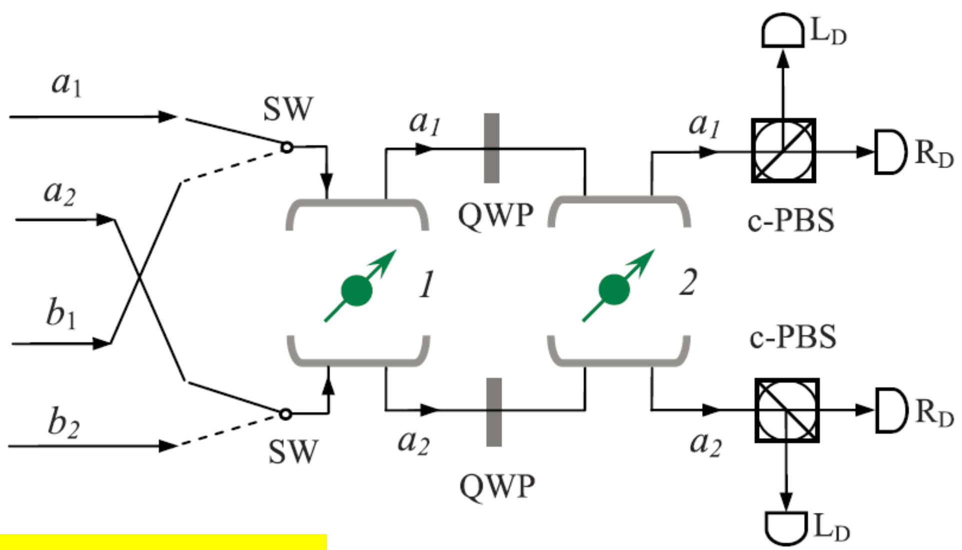
Challenges in the multi-DOFs photon-spin hybrid system

When the two-DOF encoding photons interact with the spin qubits,

3.can two photonic DOFs be simultaneously interacting with one spin ?

- SCHEME3: **Generation and complete analysis of the hyperentangled Bell state for photons**



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Hyper-entangled photon-pair: $|\varphi^{AB}\rangle_{PS} = |\zeta_{AB}\rangle_P \otimes |\eta_{AB}\rangle_S,$

In the polarization DOF:

$$|\phi^{\pm}_{AB}\rangle_P = \frac{1}{\sqrt{2}}(|RR\rangle_{AB} \pm |LL\rangle_{AB}),$$

$$|\psi^{\pm}_{AB}\rangle_P = \frac{1}{\sqrt{2}}(|RL\rangle_{AB} \pm |LR\rangle_{AB}).$$

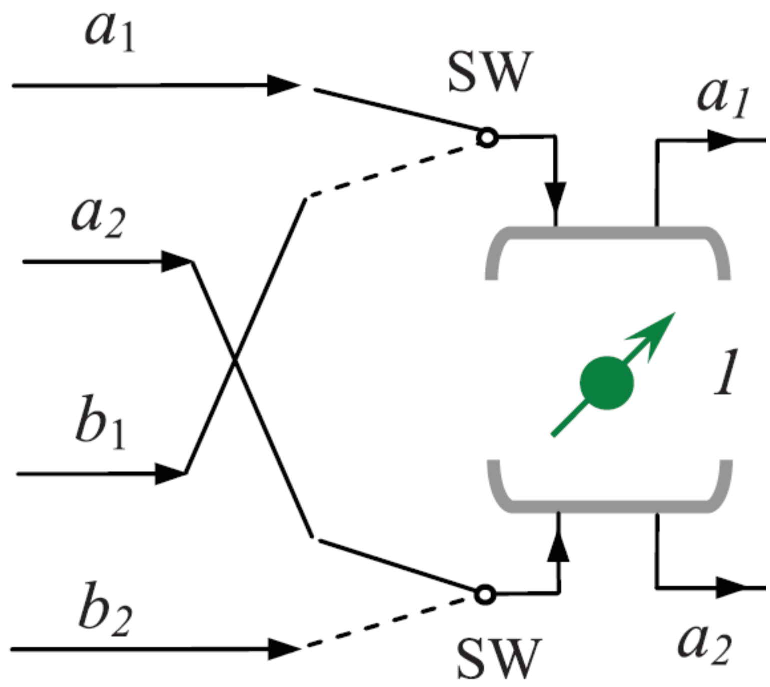
In the spatial-mode DOF:

$$|\phi^{\pm}_{AB}\rangle_S = \frac{1}{\sqrt{2}}(|a_1 b_1\rangle_{AB} \pm |a_2 b_2\rangle_{AB}),$$

$$|\psi^{\pm}_{AB}\rangle_S = \frac{1}{\sqrt{2}}(|a_1 b_2\rangle_{AB} \pm |a_2 b_1\rangle_{AB}),$$

The initial spin-states: $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

When the photons pass through a double-sided cavity, the spin in the cavity records the relationship between the phase information in these two DOFs.

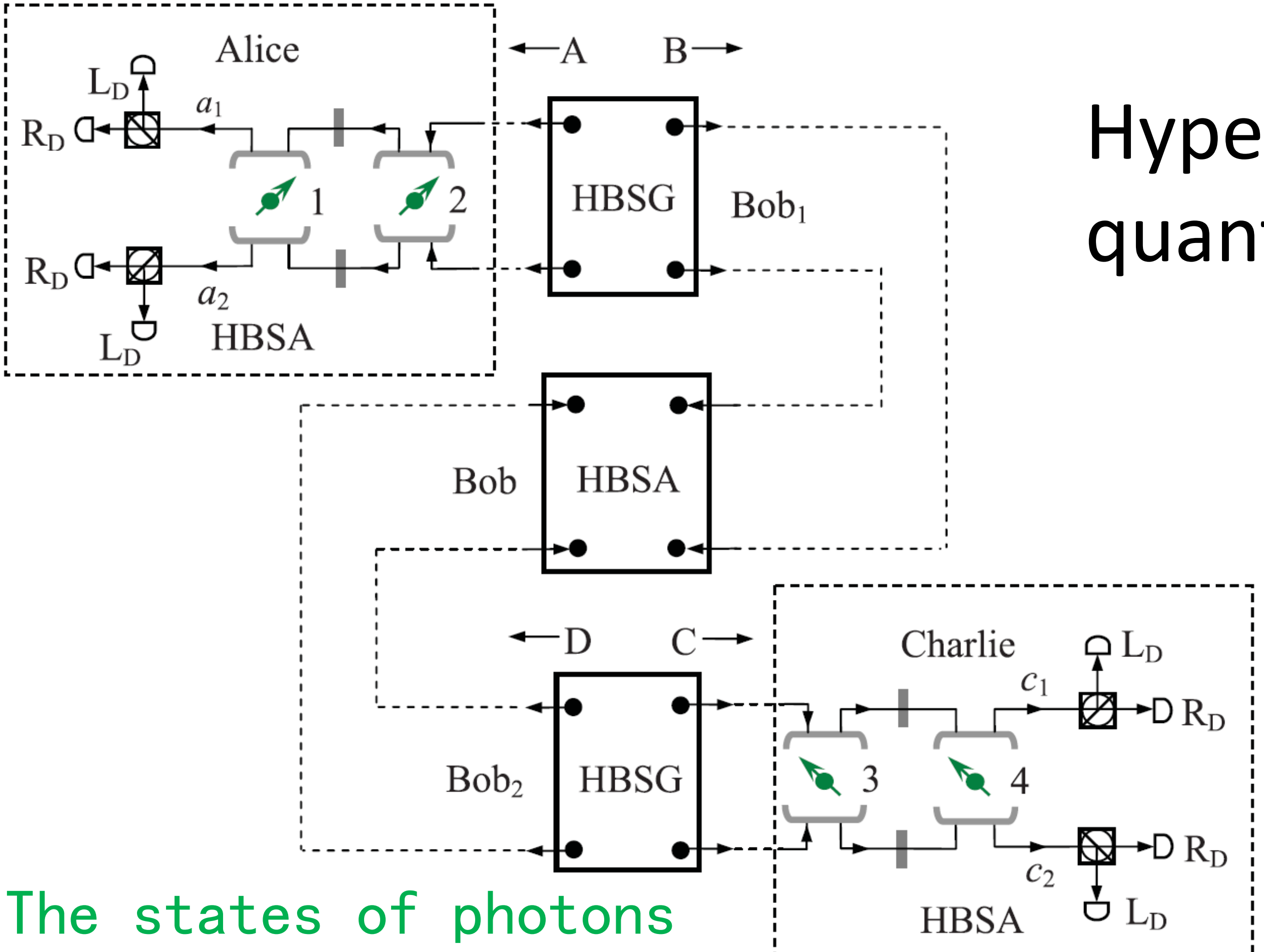


PHYSICAL REVIEW A **86, 042337 (2012)**

If the phase information in the two DOFs are the same,

the spin remains in the state $\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

Otherwise, the state of the spin changes to $\frac{1}{\sqrt{2}}(|\uparrow\rangle - |\downarrow\rangle)$



Hyper-entanglement quantum repeater

The states of photons

$$[|RR\rangle_{AC} + |LL\rangle_{AC}] \otimes [(|a_1c_1\rangle_{AC} + |a_2c_2\rangle_{AC})|\phi^+\rangle_{23}|\phi^+\rangle_{14} + (|a_1c_2\rangle_{AC} - |a_2c_1\rangle_{AC})|\psi^+\rangle_{23}|\psi^-\rangle_{14}] + [|RL\rangle_{AC} + |LR\rangle_{AC}] \otimes [(|a_1c_2\rangle_{AC} + |a_2c_1\rangle_{AC})|\phi^+\rangle_{23}|\psi^+\rangle_{14} - (|a_1c_1\rangle_{AC} - |a_2c_2\rangle_{AC})|\psi^+\rangle_{23}|\phi^-\rangle_{14}],$$

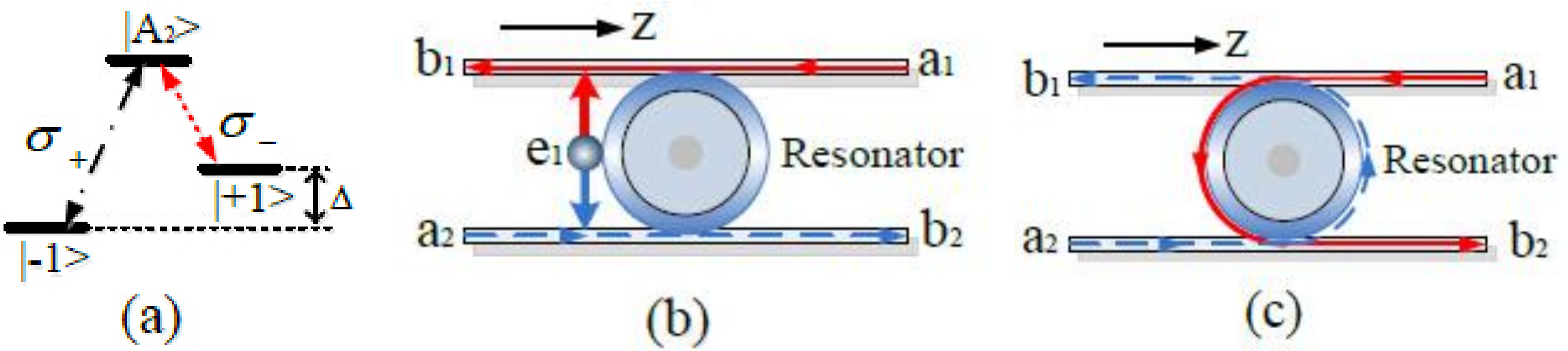
Entangled spin qubits

Challenges in the multi-DOFs photon-spin hybrid system

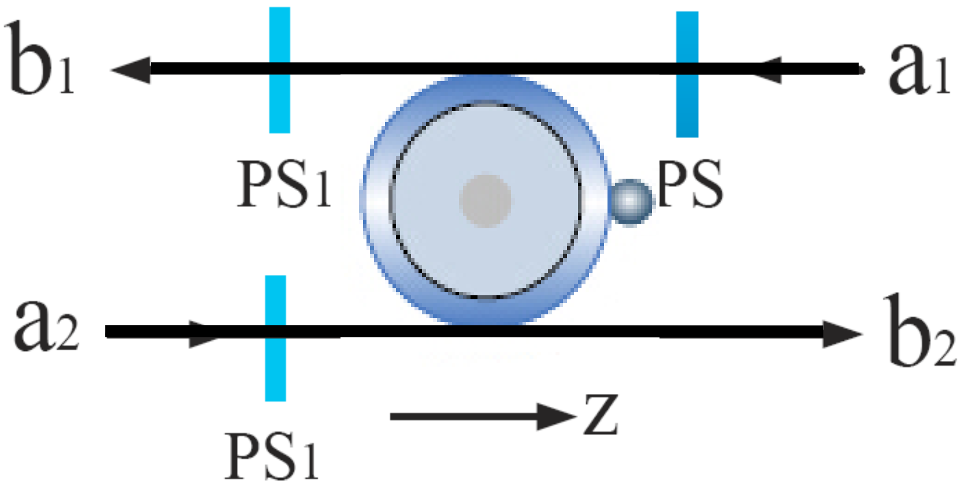
When the two-DOF encoding photons interact with the spin qibits,

4.can two DOFs be simultaneously controlled by a single spin?

- SCHEME4: The hybrid three-qubit Fredkin gate



$$
\begin{aligned}
|La_1,+1\rangle &\rightarrow \ \ |Lb_1,+1\rangle, & |Ra_1,+1\rangle &\rightarrow -|Lb_2,+1\rangle,\\
|La_2,+1\rangle &\rightarrow -|Rb_1,+1\rangle, & |Ra_2,+1\rangle &\rightarrow \ \ |Rb_2,+1\rangle,\\
|La_1,-1\rangle &\rightarrow -|Rb_2,-1\rangle, & |Ra_1,-1\rangle &\rightarrow -|Lb_2,-1\rangle,\\
|La_2,-1\rangle &\rightarrow -|Rb_1,-1\rangle, & |Ra_2,-1\rangle &\rightarrow -|Lb_1,-1\rangle.
\end{aligned}
$$



The initial photonic states: $(\alpha|R\rangle+\beta|L\rangle)_p(\gamma|a_1\rangle+\xi|a_2\rangle)_s$;

The initial spin-states: $(\alpha'|-1\rangle+\beta'|+1\rangle)_{e_1}$

After the hybrid Fredkin gating:

$$\alpha'|-1\rangle_{e_1}(\gamma|b_2\rangle+\xi|b_1\rangle)_s(\alpha|L\rangle+\beta|R\rangle)_p$$

$$+\beta'|+1\rangle_{e_1}(\gamma|L\rangle+\xi|R\rangle)_p(\alpha|b_2\rangle+\beta|b_1\rangle)_s.$$

Submitted to PHYSICAL REVIEW A

Summary

- When the two-DOF encoding photons interact with the spin qubits,
  - ✓1. two photonic DOFs will not affect each other;
  - ✓2. each photonic DOF can interact with the spin independently ;
  - ✓3. two photonic DOFs can simultaneously interact with one spin;
  - ✓4. two DOFs can be controlled simultaneously by a single spin.

Group Members

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Thanks!

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