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Solid-state quantum communications and quantum computation based on single quantum-dot spin in optical microcavities

Chengyong Hu and John G. Rarity
Electrical & Electronic Engineering, University of Bristol
United Kingdom
chengyong.hu@bristol.ac.uk

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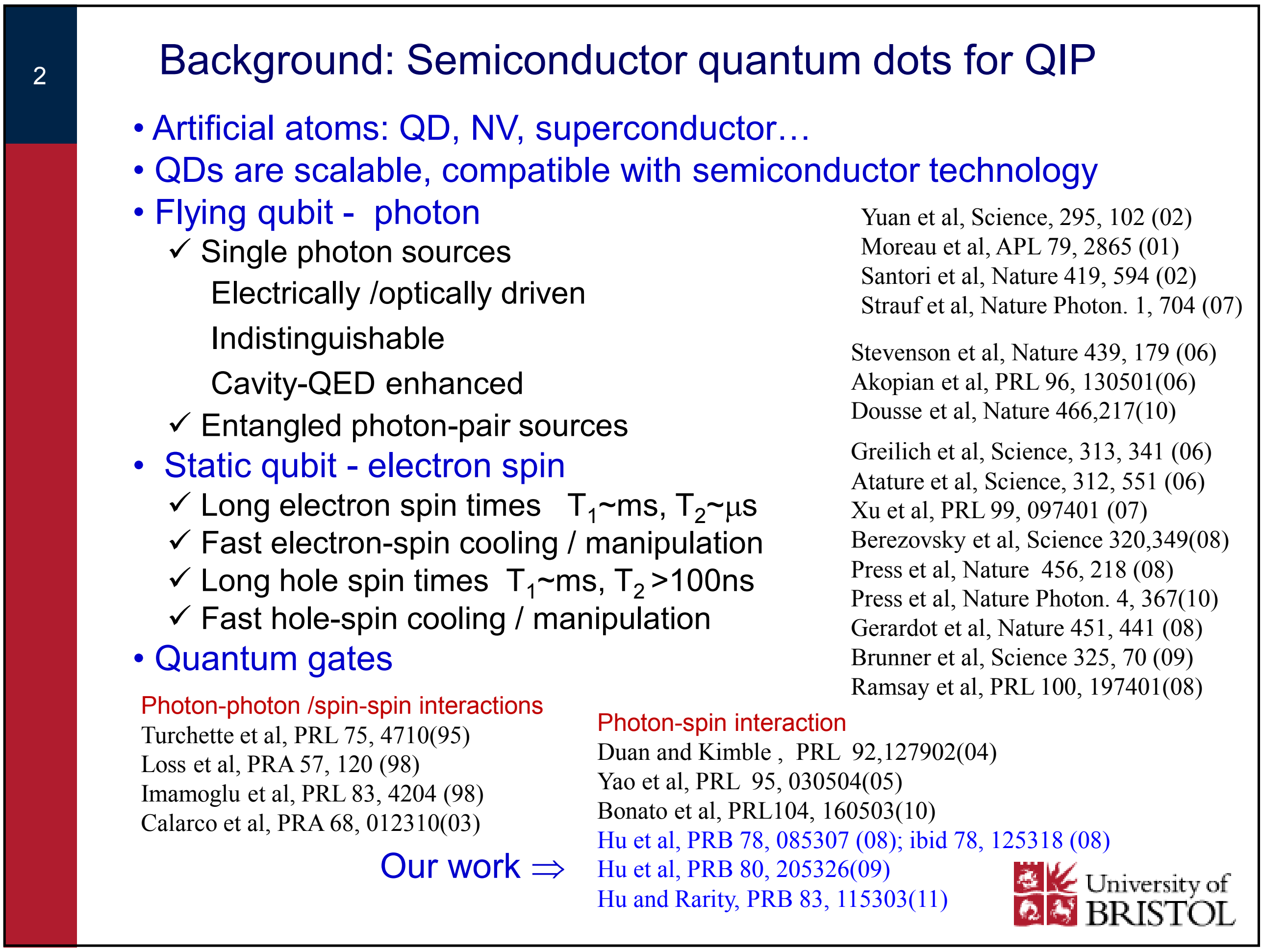

Background: Semiconductor quantum dots for QIP

- Artificial atoms: QD, NV, superconductor…
- QDs are scalable, compatible with semiconductor technology
- Flying qubit - photon
  - ✓ Single photon sources
    - Electrically /optically driven
    - Indistinguishable
    - Cavity-QED enhanced
  - ✓ Entangled photon-pair sources
- Static qubit - electron spin
  - ✓ Long electron spin times T_1~ms, T_2~μs
  - ✓ Fast electron-spin cooling / manipulation
  - ✓ Long hole spin times T_1~ms, T_2>100ns
  - ✓ Fast hole-spin cooling / manipulation
- Quantum gates

Yuan et al, Science, 295, 102 (02)
Moreau et al, APL 79, 2865 (01)
Santori et al, Nature 419, 594 (02)
Strauf et al, Nature Photon. 1, 704 (07)

Stevenson et al, Nature 439, 179 (06)
Akopian et al, PRL 96, 130501(06)
Dousse et al, Nature 466,217(10)

Greilich et al, Science, 313, 341 (06)
Atature et al, Science, 312, 551 (06)
Xu et al, PRL 99, 097401 (07)
Berezovsky et al, Science 320,349(08)
Press et al, Nature 456, 218 (08)
Press et al, Nature Photon. 4, 367(10)
Gerardot et al, Nature 451, 441 (08)
Brunner et al, Science 325, 70 (09)
Ramsay et al, PRL 100, 197401(08)

Photon-photon /spin-spin interactions
Turchette et al, PRL 75, 4710(95)
Loss et al, PRA 57, 120 (98)
Imamoglu et al, PRL 83, 4204 (98)
Calarco et al, PRA 68, 012310(03)

Photon-spin interaction
Duan and Kimble , PRL 92,127902(04)
Yao et al, PRL 95, 030504(05)
Bonato et al, PRL104, 160503(10)

Our work ⇒
Hu et al, PRB 78, 085307 (08); ibid 78, 125318 (08)
Hu et al, PRB 80, 205326(09)
Hu and Rarity, PRB 83, 115303(11)

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Outline

- Giant optical Faraday rotation / Giant circular birefringence
- Photon-spin entangling gates: universal, deterministic, fast (~tens ps)

  Conditional phase gate (type I)

  $$\hat{U}(\pi/2) = e^{i\frac{\pi}{2}\left(|L\rangle\langle L|\otimes|\uparrow\rangle\langle\downarrow|+|R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow|\right)}$$

  Entanglement beam splitter (type II)

  $$\hat{t} = |R\rangle\langle R|\otimes|\uparrow\rangle\langle\uparrow| + |L\rangle\langle L|\otimes|\downarrow\rangle\langle\downarrow|$$

  $$\hat{r} = |R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow| + |L\rangle\langle L|\otimes|\uparrow\rangle\langle\uparrow|$$

- Single-photon based spin measurement, preparation, control
- Entanglement generation: photon-spin /spin-spin /photon-photon
- Photon-spin interfaces /spin memory
- Complete Bell-state analysers
- On-chip quantum repeaters
- Loophole-free Bell test
- Single-photon devices: switch, isolator, circulator, modulator, …
- Conclusions

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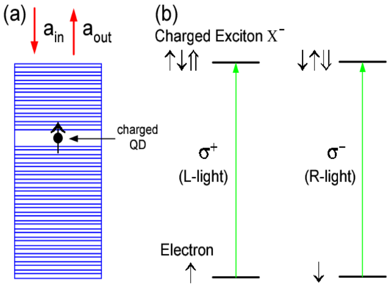
Giant Faraday rotation & photon-spin entangling gate (type I)

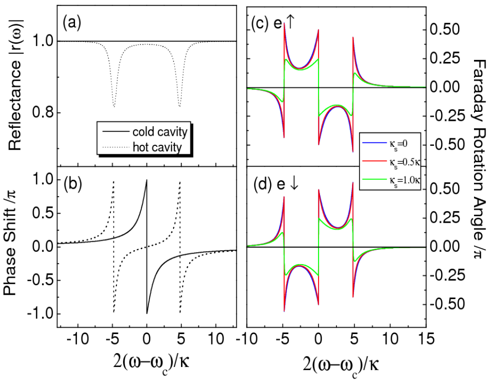


Heisenberg equations of motion

$$\begin{cases} \frac{d\hat{a}}{dt} = -[i(\omega_c-\omega)+\frac{\kappa}{2}+\frac{\kappa_s}{2}]\hat{a} - g\sigma_- - \sqrt{\kappa}\hat{a}_{in} + \hat{h} \\ \frac{d\sigma_-}{dt} = -[i(\omega_a-\omega)+\frac{\gamma}{2}]\sigma_- - g\sigma_z\hat{a} + \hat{f} \\ \hat{a}_{out} = \hat{a}_{in} + \sqrt{\kappa}\hat{a} \end{cases}$$

Reflection coefficient (under weak-excitation limit)

$$r(\omega) = 1 - \frac{\kappa[i(\omega_{ex}-\omega)+\frac{\gamma}{2}]}{[i(\omega_{ex}-\omega)+\frac{\gamma}{2}][i(\omega_c-\omega)+\frac{\kappa}{2}]+g^2}.$$



Hu et al, Phys. Rev. B 78, 085307 (08)

Giant optical Faraday rotation
— single-spin magneto-optical effect

- **Spin ↑, L-light feels a hot cavity and R-light feels a cold cavity**
- **Spin ↓, R-light feels a hot cavity and L-light feels a cold cavity**
- **Large phase difference between cold and hot cavity**

$$\theta_F^{\uparrow} = \frac{\varphi_0 - \varphi}{2} = -\theta_F^{\downarrow}$$

- **Switch, isolator, circulator, router …**
- **Quantum gates**

Photon-spin entangling gate (type I)

Reflection operator

$$\hat{r}(\omega) = |r_0(\omega)| e^{i\varphi_0} \left(|R\rangle\langle R| \otimes |\uparrow\rangle\langle\uparrow| + |L\rangle\langle L| \otimes |\downarrow\rangle\langle\downarrow| \right) + |r_h(\omega)| e^{i\varphi_h} \left(|R\rangle\langle R| \otimes |\downarrow\rangle\langle\downarrow| + |L\rangle\langle L| \otimes |\uparrow\rangle\langle\uparrow| \right)$$

Phase shift operator [when $r_0(\omega) = r_h(\omega)$]

$$\hat{U}(\Delta\varphi) = e^{i\Delta\varphi\left(|L\rangle\langle L| \otimes |\uparrow\rangle\langle\uparrow| + |R\rangle\langle R| \otimes |\downarrow\rangle\langle\downarrow| \right)} \Rightarrow \hat{U}(\pi/2) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$\Delta\varphi$ is tunable between $[-\pi, +\pi]$
$\Delta\varphi = \pi/2$ can be achieved in Purcell
and strong coupling regime if $\kappa_s/\kappa < 1.3$

Ideal quantum measurement of spin

Gate features

- ✓ Universal (conditional phase gate, or parity gate)
- ✓ Unity efficiency
- ✓ High fidelity
- ✓ Fast (~ tens ps) << spin decoherence time (~μs)

Hu et al, Phys. Rev. B 78, 085307 (08)

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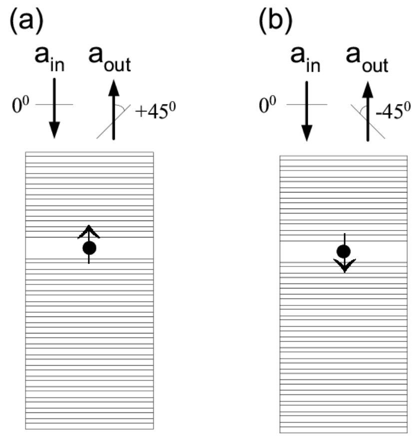
Quantum non-demolition measurement of spin (type I)



Input photon $|H\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$

Spin ↑

$$|H\rangle \otimes |\uparrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|+45^0\rangle|\uparrow\rangle$$

Spin ↓

$$|H\rangle \otimes |\downarrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|-45^0\rangle|\downarrow\rangle$$

Spin superposition state $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

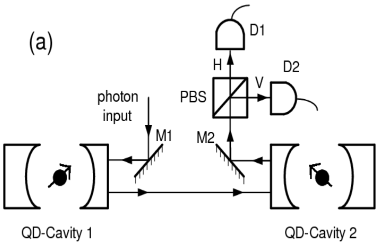
$$|H\rangle \otimes (\alpha|\uparrow\rangle + \beta|\downarrow\rangle) \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}(\alpha|+45^0\rangle|\uparrow\rangle + \beta|-45^0\rangle|\downarrow\rangle)$$

Photon-spin entangler!

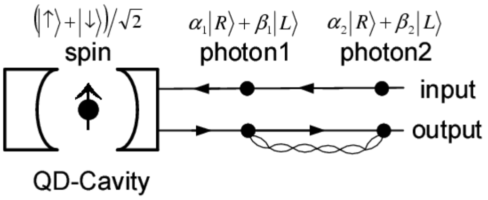
- Unity efficiency and fast(~tens ps)
- Single-photon based
- Spin projective measurement
- Spin initialisation
- Quantum feedback control

Hu et al, Phys. Rev. B 78, 085307 (08)

Spin entangler

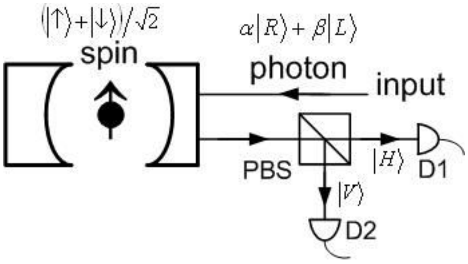


Photon entangler

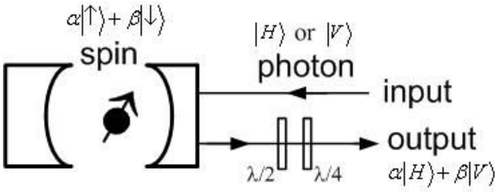


Photon-spin quantum interface / spin memory

(a) Write in



(b) Read out



Hu et al, Phys. Rev. B 78, 085307 (08); 78, 125318(08)

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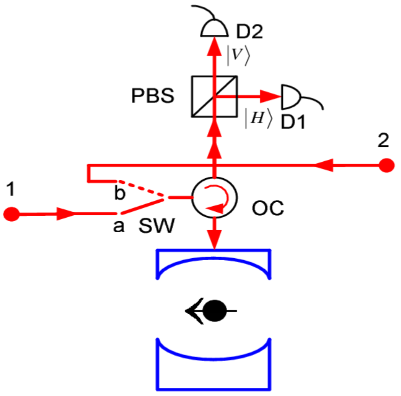
Complete Bell-state analyzer (type I)



Four Bell States

$$|\Psi^{\pm}\rangle = \left(|R\rangle_1 |L\rangle_2 \pm |L\rangle_1 |R\rangle_2\right)/\sqrt{2}$$

$$|\Phi^{\pm}\rangle = \left(|R\rangle_1 |R\rangle_2 \pm |R\rangle_1 |R\rangle_2\right)/\sqrt{2}$$

$$\hat{U}(\pi/2)|\Psi^{\pm}\rangle|+\rangle = i|\Psi^{\pm}\rangle|+\rangle$$

$$\hat{U}(\pi/2)|\Phi^{\pm}\rangle|+\rangle = |\Phi^{\mp}\rangle|-\rangle$$

✓ Spin measurements check parity $|\Psi^{\pm}\rangle$ and $|\Phi^{\pm}\rangle$
Polarization measurements check phase $|\Psi^{+}\rangle$ and $|\Psi^{-}\rangle$, $|\Phi^{+}\rangle$ and $|\Phi^{-}\rangle$

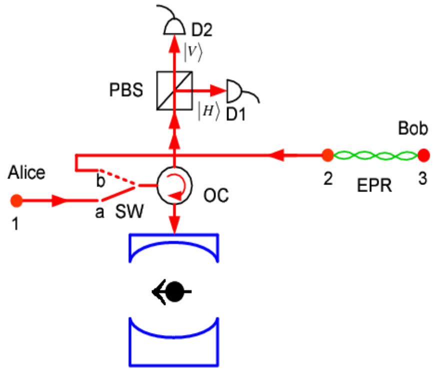
✓ Complete and loss-resistant due to built-in spin memory

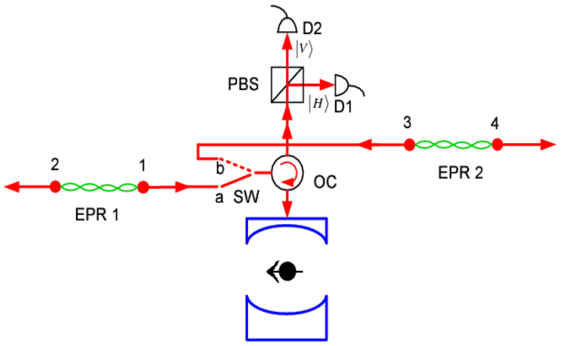
✓ No photon synchronization, no indistinguishability

✓ Global quantum networks via satellites

Hu and Rarity, Phys. Rev. B 83, 115303(11)

Loss-resistant teleportation and entanglement swapping





Photons 1, 2	Spin	Photon 3
$|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$	$|-\rangle$	$\alpha|L\rangle_3-\beta|R\rangle_3$
$|H\rangle_1|V\rangle_2$ or $|V\rangle_1|H\rangle_2$	$|-\rangle$	$\alpha|L\rangle_3+\beta|R\rangle_3$
$|H\rangle_1|H\rangle_2$ or $|V\rangle_1|V\rangle_2$	$|+\rangle$	$\alpha|R\rangle_3+\beta|L\rangle_3$
$|H\rangle_1|V\rangle_2$ or $|V\rangle_1|H\rangle_2$	$|+\rangle$	$\alpha|R\rangle_3-\beta|L\rangle_3$

Photons 1, 3	Spin	Photons 2, 4
$|H\rangle_1|H\rangle_3$ or $|V\rangle_1|V\rangle_3$	$|-\rangle$	$[|L\rangle_2|L\rangle_4-|R\rangle_2|R\rangle_4]/\sqrt{2}$
$|H\rangle_1|V\rangle_3$ or $|V\rangle_1|H\rangle_3$	$|-\rangle$	$[|L\rangle_2|L\rangle_4+|R\rangle_2|R\rangle_4]/\sqrt{2}$
$|H\rangle_1|H\rangle_3$ or $|V\rangle_1|V\rangle_3$	$|+\rangle$	$[|L\rangle_2|R\rangle_4+|R\rangle_2|L\rangle_4]/\sqrt{2}$
$|H\rangle_1|V\rangle_3$ or $|V\rangle_1|H\rangle_3$	$|+\rangle$	$[|L\rangle_2|R\rangle_4-|R\rangle_2|L\rangle_4]/\sqrt{2}$

Three-step teleportation process

(a) On detecting photon 1, photon 1 state is transferred to spin

(b) On detecting photon 2, spin and photon 3 get entangled

(c) On measuring spin, spin state is transferred to photon 3

Hu and Rarity, Phys. Rev. B 83, 115303(11)

Single-photon based spin control (type I)

- Spin in ↑, ↓ states → giant optical Faraday rotation
- Photon in R, L states → giant spin rotation

one photon pulse in |R〉 or |L〉 — π/2 pulse

$$\hat{U}(\pi/2)|R\rangle\big(\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)=|R\rangle\big(\alpha|\uparrow\rangle+i\beta|\downarrow\rangle\big)$$
$$\hat{U}(\pi/2)|L\rangle\big(\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)=|L\rangle\big(i\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)$$

two photon pulses in |R〉 or |L〉 — π pulse

$$\hat{U}(\pi/2)|R\rangle_1|R\rangle_2\big(\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)=|R\rangle_1|R\rangle_2\big(\alpha|\uparrow\rangle-\beta|\downarrow\rangle\big)$$
$$\hat{U}(\pi/2)|L\rangle_1|L\rangle_2\big(\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)=|L\rangle_1|L\rangle_2\big(-\alpha|\uparrow\rangle+\beta|\downarrow\rangle\big)$$

- Spin echo/dynamic decoupling to preserve the spin coherence

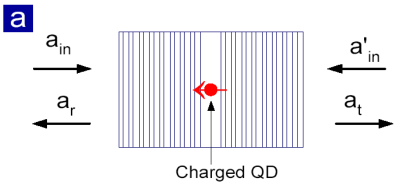
$$\left(\frac{\pi}{2}\right)_x-(\pi)_z-\left(\frac{\pi}{2}\right)_x$$

compatible with QIP protocols

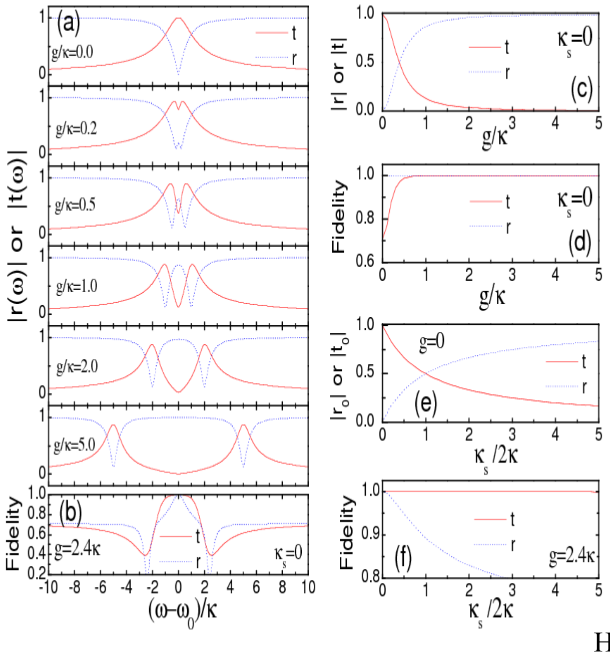
Spin rotation around z with single photons
Spin rotation around x with laser pulse (optical Stark effect) or B in Voigt

Hu and Rarity, Phys. Rev. B 83, 115303(11)

Giant circular birefringence & photon-spin entangling gate II



universal, deterministic, fast(~tens ps)



In Purcell or strong coupling regime

If ↑, R-photon transmitted
L-photon reflected

If ↓, R-photon reflected
L-photon transmitted

Transmission operator

$$\hat{t}(\omega) \approx t_0(\omega)\Big(|R\rangle\langle R|\otimes|\uparrow\rangle\langle\uparrow| + |L\rangle\langle L|\otimes|\downarrow\rangle\langle\downarrow|\Big)$$

Reflection operator

$$\hat{r}(\omega) \approx r(\omega)\Big(|R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow| + |L\rangle\langle L|\otimes|\uparrow\rangle\langle\uparrow|\Big)$$

$$t_0(\omega_0) \approx -1, r(\omega_0) \approx 1 \quad \text{if} \quad \kappa_s << \kappa$$

Hu et al , PRB 80, 205326(09)

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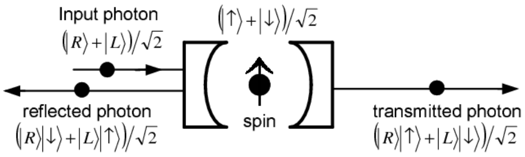
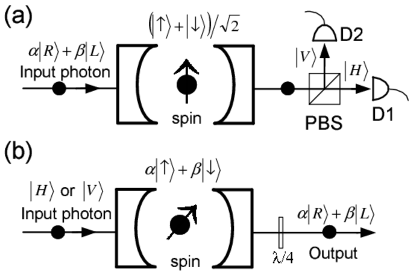
Photon-spin entangler
– Entanglement beam splitter

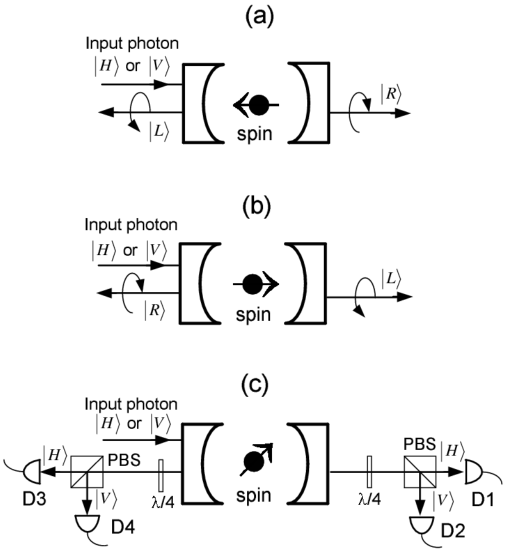


Photon-spin interface



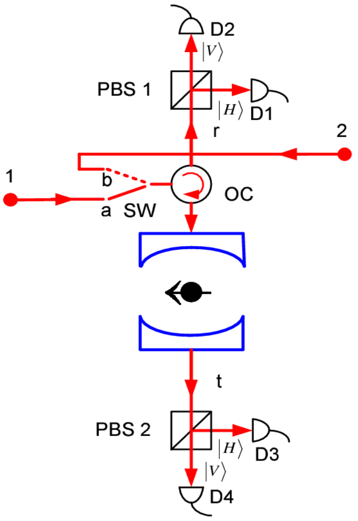
Hu et al , PRB 80, 205326(09)

QND measurement of spin



Spin entangler
Photon entangler

Complete Bell-state Analyzer (type II)



- ✓ Path measurements check parity $|\Psi^{\pm}\rangle$ and $|\Phi^{\pm}\rangle$
  Polarization measurements check phase
  $|\Psi^{+}\rangle$ and $|\Psi^{-}\rangle$, $|\Phi^{+}\rangle$ and $|\Phi^{-}\rangle$
- ✓ Complete and loss-resistant due to built-in spin memory
- ✓ No photon synchronization, no indistinguishability
- ✓ Global quantum networks via satellites

$$\left|\Psi^{\pm}\right\rangle|+\rangle \xrightarrow{\hat{r},\hat{t}} -\left[|R\rangle_1^t|L\rangle_2^r \pm |L\rangle_1^r|L\rangle_2^t\right]|\uparrow\rangle - \left[|R\rangle_1^r|L\rangle_2^t \pm |L\rangle_1^t|L\rangle_2^r\right]|\downarrow\rangle$$

$$\left|\Phi^{\pm}\right\rangle|+\rangle \xrightarrow{\hat{r},\hat{t}} \left[|R\rangle_1^t|R\rangle_2^t \pm |L\rangle_1^r|L\rangle_2^r\right]|\uparrow\rangle + \left[|R\rangle_1^r|R\rangle_2^r \pm |L\rangle_1^t|L\rangle_2^t\right]|\downarrow\rangle$$

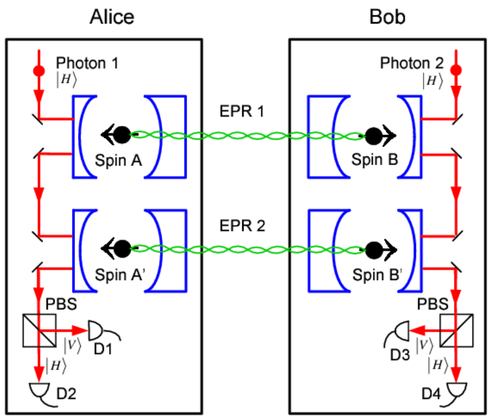
Hu and Rarity, Phys. Rev. B 83, 115303(11)

On-chip quantum repeaters (two types)

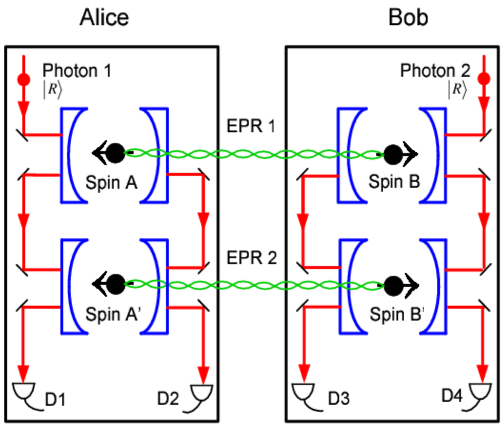
- Spin-cavity units as quantum repeaters

  Entanglement generation, swapping, purification and storage can all be performed with the spin-cavity units
- Global quantum networks via quantum repeaters

Purification (type-I)



Purification (type-II)



Challenges for entanglement purification

- Quantum repeaters need gate errors on the percent level
- Gate imperfections

  Imperfect spin selection rules (error <10%)

  Side-leakage from cavity

  Short spin dephasing time (~ns)
  Solutions: spin echo/dynamic decoupling
  electron spin → hole spin

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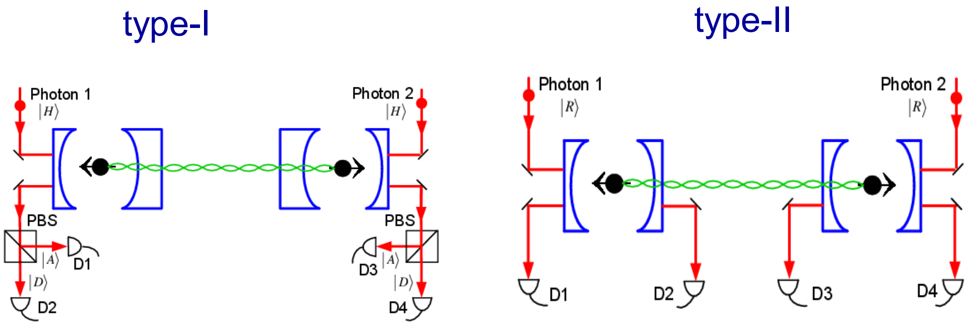
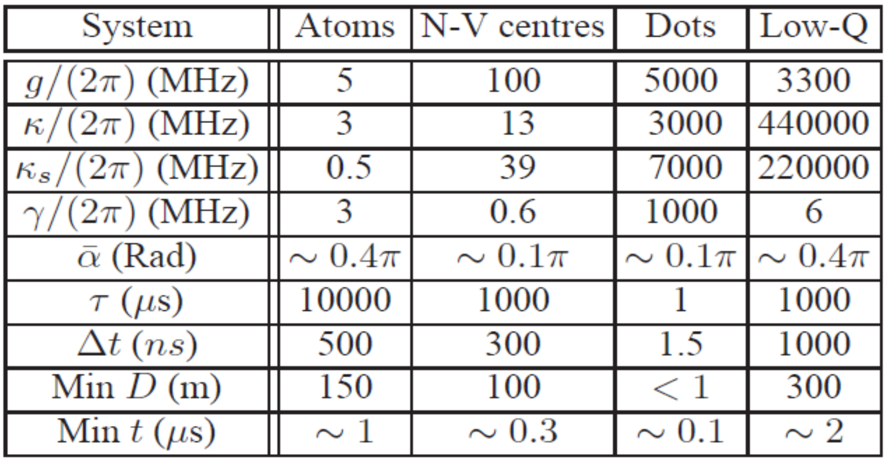
Loophole-free Bell test (two types)


type-I

type-II

- Generate spin-spin entanglement
  via a single photon or
  photon-photon entanglement → spin-spin entanglement
- Close detection loophole
  Single-photon based spin measurement with unity efficiency
- Close locality loophole
  Spin measurement time Δt < signal transfer time d/c
  Δt ~tens ps, d>3mm
- Device independent protocols, such as DIQKD, certified random number generation

Comparison of different cavity-QED systems with type-I gate in non-ideal case U(Δφ)



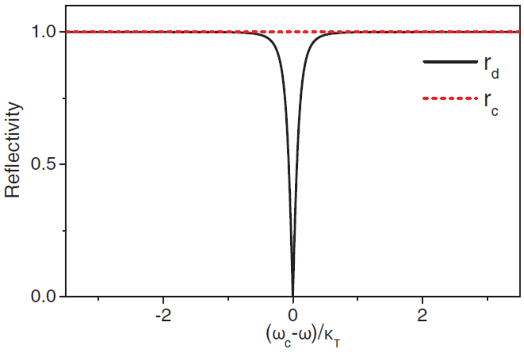
System	Atoms	N-V centres	Dots	Low-Q
$g/(2\pi)$ (MHz)	5	100	5000	3300
$\kappa/(2\pi)$ (MHz)	3	13	3000	440000
$\kappa_s/(2\pi)$ (MHz)	0.5	39	7000	220000
$\gamma/(2\pi)$ (MHz)	3	0.6	1000	6
$\bar{\alpha}$ (Rad)	$\sim 0.4\pi$	$\sim 0.1\pi$	$\sim 0.1\pi$	$\sim 0.4\pi$
τ (μs)	10000	1000	1	1000
Δt (ns)	500	300	1.5	1000
Min D (m)	150	100	< 1	300
Min t (μs)	~ 1	~ 0.3	~ 0.1	~ 2

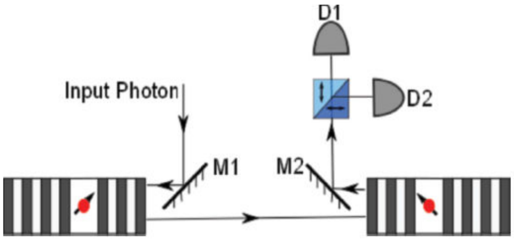
QD spin-cavity system is better than atom or NV for loophole-free Bell test

N. Brunner et al, arXiv: 1303.6522(quan-ph)

Entanglement generation with low-Q microcavities (single-sided)

Non-deterministic scheme





Resonant scattering regime

$g^2 = \kappa\gamma/4$ at $\omega = \omega_0$

$r_d = 0$

$r_c = 1$

$$|R\rangle \otimes |\uparrow\rangle \rightarrow r_d|R\rangle|\uparrow\rangle,$$

$$|R\rangle \otimes |\downarrow\rangle \rightarrow r_c|R\rangle|\downarrow\rangle,$$

$$|L\rangle \otimes |\uparrow\rangle \rightarrow r_c|L\rangle|\uparrow\rangle,$$

$$|L\rangle \otimes |\downarrow\rangle \rightarrow r_d|L\rangle|\downarrow\rangle.$$

Suitable for QD-spin, NV

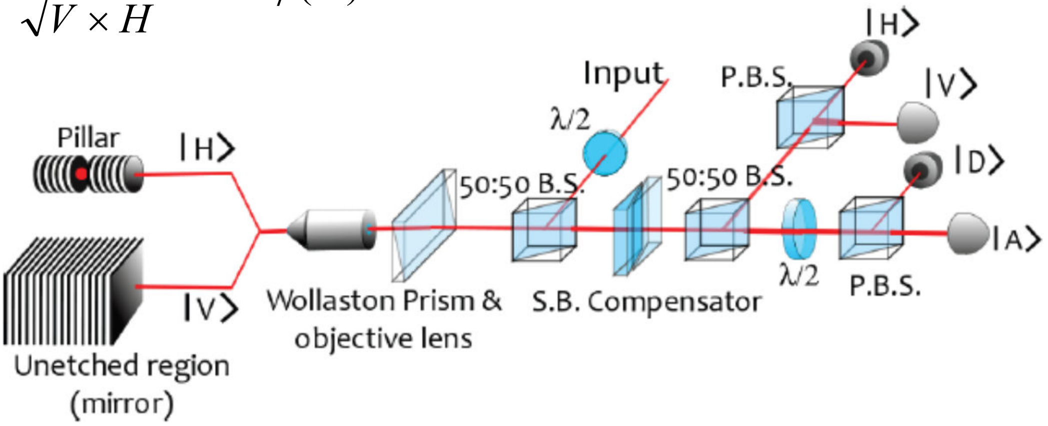
Advantage: low-Q, easy to implement
Disadvantage: non-deterministic

Young et al, Phys. Rev. A 87, 012332(11)

Recent experimental progress with uncharged dots towards type-I gate

Reflection spectroscopy
— Conditional phase shift interferometer

$$\frac{D-A}{\sqrt{V\times H}}=\sin\phi(\omega)$$



Young et al, Phys. Rev. A 84, 011803(R) (2011)

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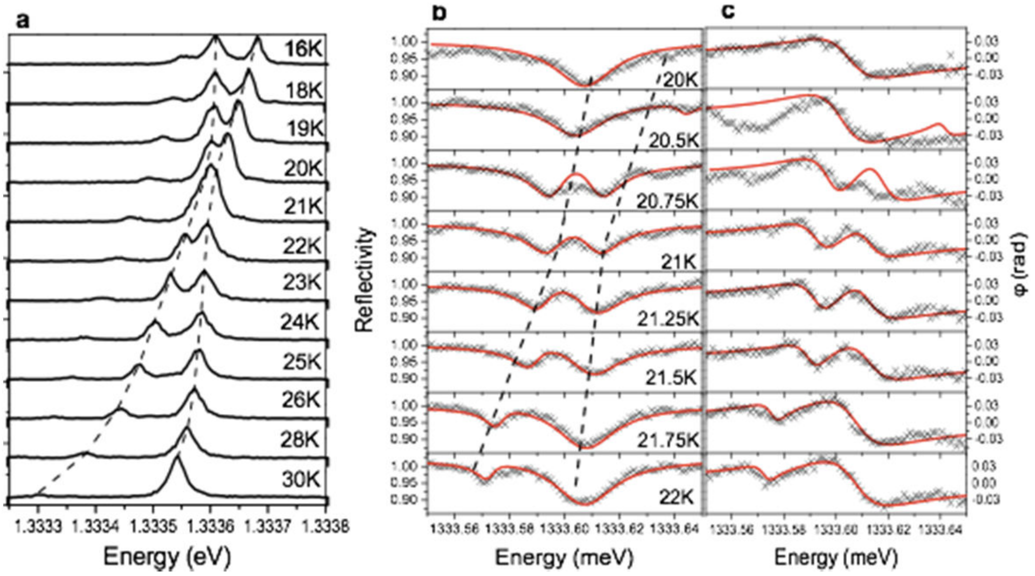
Comparing PL and resonant spectroscopy

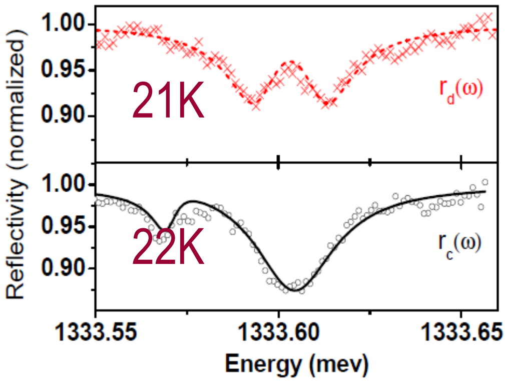


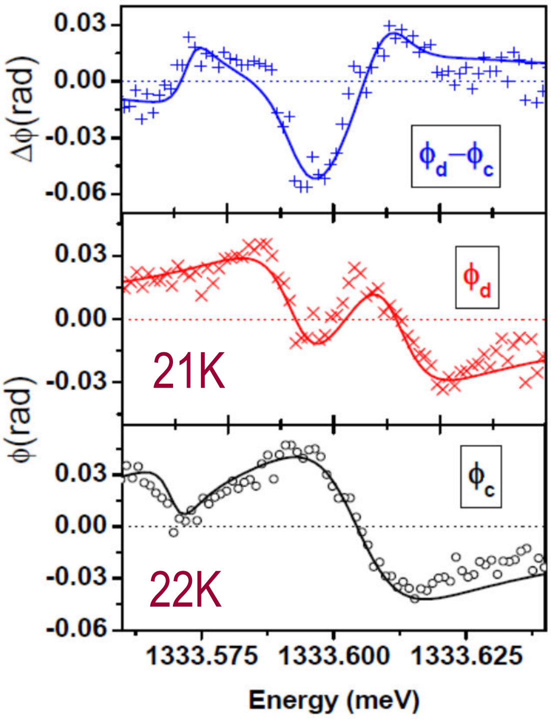
Young et al, Phys. Rev. A 84, 011803(R) (2011)

Conditional phase of 3° observed between a dot on and off-resonance with cavity

g~9.4ueV *κ*+ *κs* ~ 26ueV *γ*~5ueV

g> (*κ*+ *κs* + *γ*)/4 Δφ~ 3°



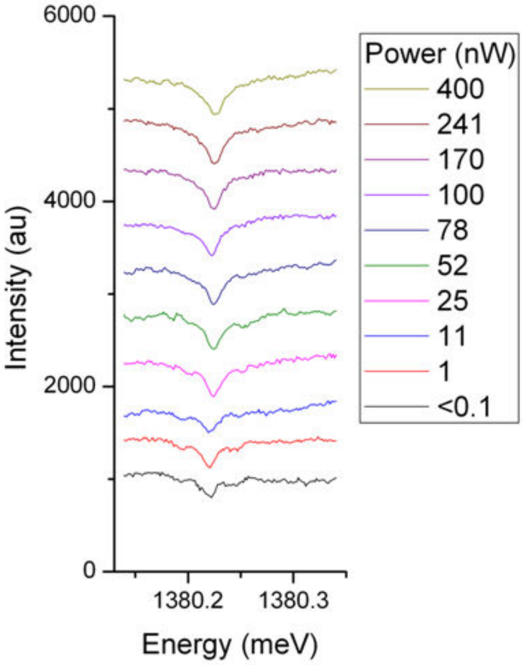


Young et al, Phys. Rev. A 84, 011803(R) (2011)

Latest results from the laboratory

Optical nonlinearity at ~10 photons per cavity lifetime

- Dot on resonance with a cavity studied in reflection
- We see a dot-cavity feature which saturates at 100nW
- If this is strongly coupled the timescale is that of the cavity decay, ie ~30ps
- Thus 100nW in 30ps gives optical nonlinearity at ~10 photons per cavity lifetime



Requirements to realize the photon-spin gates

- ✓ Charged QDs
  Modulation-doping
  Distinguish between charged and neutral excitons is non-trivial.

- ✓ High-quality microcavity
  Weak and strong coupling
  Low side leakage

- ✓ Spin initialization via spin measurement with single photons

- ✓ Spin control
  Rotation around z with single photons
  Rotation around x with laser pulse (optical Stark effect) or B in Voigt

- ✓ Spin echo or dynamical decoupling to preserve spin coherence
  Compatible with QIP protocols

Summary and Outlook

- Two spin-cavity units — photon-spin entangling gates
  - ✓ Conditional photon-spin interaction
  - ✓ GFR and GCB are optical linear effects
  - ✓ Universal
  - ✓ Deterministic (if optimized)
  - ✓ Fast (~tens ps)

    Spin coherence time (μs) > 100,000 gate time
  - ✓ Single-photon based spin initialisation, measurement, and control
  - ✓ BSM, repeaters, photon-spin interface/spin memory
  - ✓ Realizable with current semiconductor technology

    Q=40,000 for d=1.5 μm micropillars, Reitzenstein et al., APL 90, 251109 (07)

    Purcell enhancement and strong coupling are achieved
- Global and secure quantum networks
  - ✓ Via satellites or quantum repeaters
  - ✓ Detection and locality loopholes can be closed simultaneously
- Practical solid-state quantum computers are possible

  DiVincenzo's criteria are all met!
- Single-photon devices: switch, isolator, circulator, router, …
- Spin-cavity units can be applied in all aspects of QIP

University of BRISTOL

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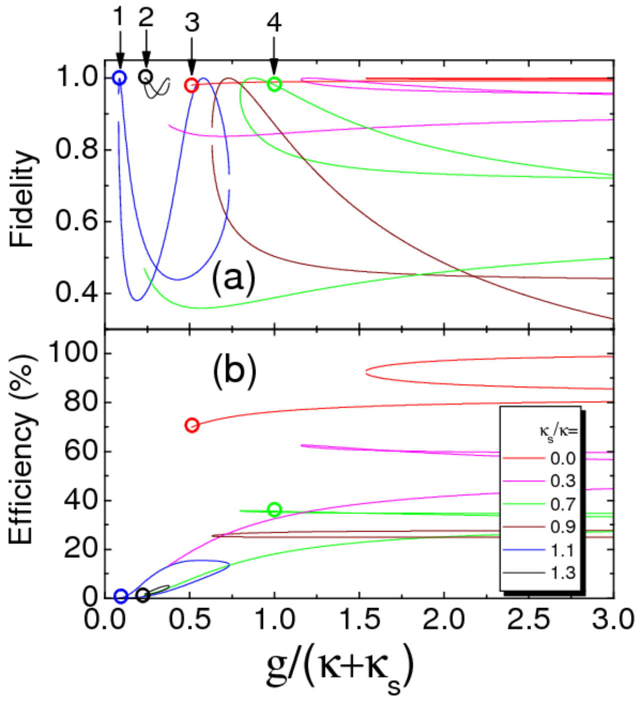
Fidelity and Efficiency of BSA (Type I)



$$F^{(\Psi^{\pm})} = 1$$

$$F^{(\Phi^{\pm})} = \frac{1}{\sqrt{1+\frac{1}{4}\left(\left|\frac{r_0(\omega')}{r_h(\omega')}\right| - \left|\frac{r_h(\omega')}{r_0(\omega')}\right|\right)^2}}$$

$$\eta = \frac{1}{4}\left(\left|r_0(\omega')\right|^2 + \left|r_h(\omega')\right|^2\right)^2$$

Hu and Rarity, Phys. Rev. B 83, 115303(11)