行政院國家科學委員會專題研究計畫　成果報告

介觀物理系統在光子晶體中的量子散粒雜訊(2/2)

計畫類別：個別型計畫
計畫編號：NSC94-2112-M-009-019-
執行期間：94 年 08 月 01 日至 95 年 07 月 31 日
執行單位：國立交通大學電子物理學系(所)

計畫主持人：陳岳男
共同主持人：鄭舜仁

報告類型：完整報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 95 年 8 月 25 日

行政院國家科學委員會補助專題研究計畫 ☐成果報告 ☐期中進度報告

介觀物理系統在光子晶體中的量子散粒雜訊(2/2)

計畫類別：☐個別型計畫 ☐整合型計畫
計畫編號：NSC 94－2112－ M－ 009－ 019－
執行期間： 2005 年 8 月 1 日至 2006 年 7 月 31 日

計畫主持人：陳岳男
共同主持人：鄭舜仁
計畫參與人員：

成果報告類型(依經費核定清單規定繳交)：☐精簡報告 ☐完整報告

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中 華 民 國 95 年 8 月 24 日

中文摘要

在執行將近二年的的研究計畫後，已獲致不錯的成果：首先，我們已先算出由微型共振腔所包夾之量子環 p-i-n junction 的量子散粒雜訊，除了發現到藉由觀測量子散粒雜訊可以反應量子環激子在共振腔的自發輻射特性，也可以得到傳統量測直流電所得不到的資訊。我們更將此一方法推廣到量子點 p-i-n junction 在 one-band 或是 two-band 光子晶體中的情形，也同樣可以反應光子晶體能隙(photonic band gap)的特性，值得一提的是將 p-i-n junction 與光子晶體光學性質的結合，有可能在這樣的元件中製造出量子糾纏態與完成所謂的量子隱形傳輸(quantum teleportation)。在此計畫的資助下，已發表五篇論文在國際期刊、一篇收錄在書中的邀搞文章。

關鍵詞：量子點、量子傳輸、量子資訊。

Abstract

Shot-noise spectrum of quantum ring (QR) excitons in a *p-i-n* junction surrounded by a microcavity is derived analytically. Radiative decay properity of a QR exciton can be obtained from the observation of the current noise, which also gives the extra information about the tunnel barriers. Different noise feature between the quantum dot (QD) and QR is pointed out, and may be observed in a suitably designed experiment. Furthermore, we have also investigated the shot-noise spectrum of a quantum dot *p-i-n* junction embedded inside a three-dimensional photonic crystal is investigated. The characteristic of the photonic band gap is revealed in the current noise with discontinuous behavior. Applications of such a device in entanglement generation and quantum teleportation are pointed out, and may be achieved with current technologies.

Keywords: Quantum Dots, Quantum Transport, and Quantum Information Science.

目錄

報告內容

1. 前言

Historically, the idea of controlling the spontaneous emission (SE) rate by using a cavity was first introduced by Purcell in 1946 [1]. The reason for modified spontaneous emission rate is that spontaneous emission can be viewed as stimulated emission, stimulated by vacuum-field fluctuations. Hence, the lifetime can be altered by modifying the photon density of states. In 1987, Yablonovitch first proposed using a photonic crystal for spontaneous emission suppression [2]. After that, much attention has been directed to photonic bandgap microcavities. As known, photonic-crystal defect microcavities can provide extremely small mode volumes, and large theoretical *Q* values have been predicted for certain designs [3]. Recently, a *Q* of 4,000 for an H2 (seven holes removed to form the hexagon) defect cavity [4] and a *Q* of 13,000 [5] for a donor-mode cavity (calculated mode volume of 1.2 $(\lambda/n)^3$) were reported. Purcell enhancement has also been studied in this system [6].

Turning to the electronic story, the manifestation of quantum mechanical effects in the transport properties of electronic systems has become one of the central issues of condensed matter physics in the 21st century. In fact, we are now entering an era where quantum coherence is used to design and to control optical and transport properties of devices [7, 8] of submicron, nano- or even molecular size. Low dimensional structures such as quantum wells, quantum wires and quantum dots differ very markedly from three-dimensional systems, especially in their electronic, thermal, vibration and optical properties. The reduced size of these structures allows, e.g., to control the flow of single electrons (Coulomb blockade, single electron transistor), or the preparation of single boson states (photon or phonon cavities). Reduced dimensions and low temperatures define a `mesoscopic' regime where the underlying physics is governed by the combination of quantum coherence, many-body correlations, and non-equilibrium dynamics. Understanding how this `triangle' of phenomena leads to new and exciting properties of matter is the main challenge and primary goal of mesoscopic physics.

Although quantum shot noise has been identified as a valuable tool to extract valuable information not available in conventional dc transport experiments [9], the theoretical understanding of the interactions of electrons with each other and with bosonic degrees of freedom (photons, phonons) in low dimensions is still at a relatively rudimentary level. The combination of the non-equilibrium, the interaction, and the quantum coherence aspects is one of the main challenges for the theoretical description of electronic transport.

2. 研究目的

The aim of the present project is the development of a transport theory for quantum systems coupled to external particle reservoirs, classical and non-classical boson fields (AC fields, photon modes in photonic crystals), and dissipative environments. Primary examples are coupled semiconductor quantum dots.

The theory will be developed with the goal to be applicable to a large class of electronic systems, in particular those that are expected to have the future potential to act as possible devices for quantum information processing, based on the electron charge and its spin. The following summarizes the primary objectives of the research.

- to develop a theory for the stationary and non-stationary electron transport (current, current fluctuations, quantum noise) through few-level systems interacting with confined bosonic modes (`phonon cavity', photon cavity) and dissipative baths.
- to work out a theory of nano-electromechanical transport through freestanding nanostructures or individual molecules, to understand a class of related recent experimental results(`phonon blockade' in semiconductor dots), and to predict novel properties and phenomena for such systems.

3. 研究方法

Because electrons share the particlewave duality with photons, one might expect fluctuations in the electrical current to play a similar role. Current fluctuations due to the discreteness of the electrical charge are known as shot noise. Although the first observations of shot noise date from work on vacuum tubes in the 1920s, our quantum mechanical understanding of electronic shot noise has progressed more slowly than our understanding of photon noise. Much of the physical information shot noise contains has been appreciated only recently, from experiments on nanoscale conductors [9], where classical mechanics breaks down. At that scale, shot noise can reveal a rich variety of details about charge transport.

In the cases we are interested, the quantum systems are usually coupled to environments, such as photon fields or electron reservoirs. Although the environment is affected by the coupling, in general we can assume the coupling is weak, and the environment remains unchanged. This assumption will allow us to derive the master equation in a simple fashion.

Following the derivation of Y. Yamanoto and A. Imamoglu [10], we consider a system S interacting with a reservoir R via interaction V. If we assume initially (t=0) the system and reservoir is uncoupled, the initial density operator ρ(0) is then given by

$$\rho(0) = \rho_S(0) \otimes \rho_R(0).$$

Time evolution of ρ(t) in the interaction picture obeys the Liouville-von Neumann equation

$$\frac{d}{dt}\rho(t) = \frac{1}{i\hbar}[V_{\text{int}}(t), \rho(t)].$$

If we further assume the number of degrees of freedom of the reservoir is very large, then the *reduced* density operator satisfies

$$\frac{d}{dt}\rho_S(t) = \frac{1}{i\hbar}Tr_R[V_{\text{int}}(t), \rho(t)].$$

After integration and successive substitution one gets

$$\frac{d}{dt}\rho_S(t) = \left(\frac{1}{i\hbar}\right)^2 \int_0^t dt' Tr_R([V_{\text{int}}(t), [V_{\text{int}}(t'), \rho(t')]]).$$

Usually, it is impossible to solve the above equation exactly. However, one can employ Born-Markov approximation to solve it. In this limit, we find

$$\frac{d}{dt}\rho_S(t) = \left(\frac{1}{i\hbar}\right)^2 \int_0^t dt' Tr_R([V_{\text{int}}(t), [V_{\text{int}}(t'), \rho_S(t) \otimes \rho_R(0)]]).$$

With this equation, the remained step is to find out the specific system-reservoir interactions, and work out the integration finally. We shall apply our result to study the non-equilibrium behavior of a coupled quantum system.

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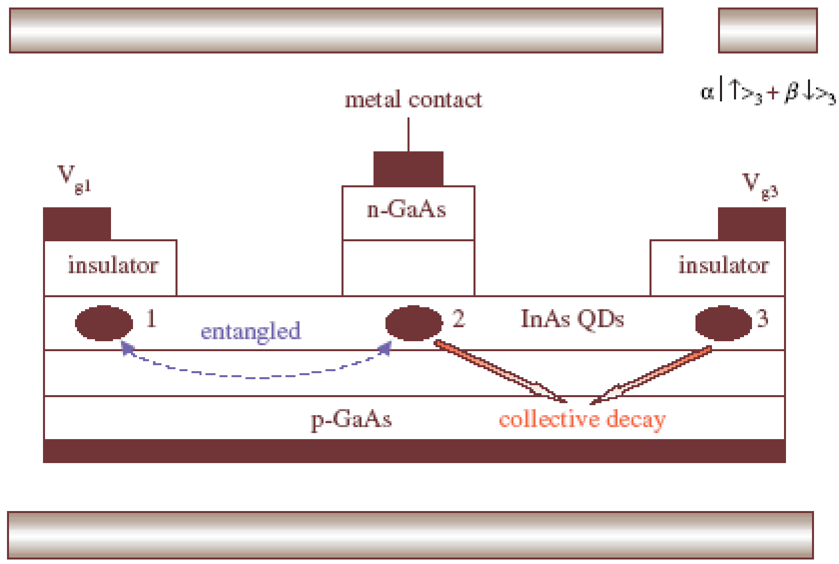
4. 結果與討論

I. <u>Proposal for teleportation of charge qubits via superradiance</u>

A scheme is proposed to teleport charge qubits via super-radiance.Reservoir-induced entanglement is generated between two semiconductor dots in a microcavity where a quantum state encoded in a third quantum dot is then tunedinto collective decay with one of the entangled dots. Teleportation is achieved automatically in our scheme in which we also extend to quantum wire.

(a)



(b)

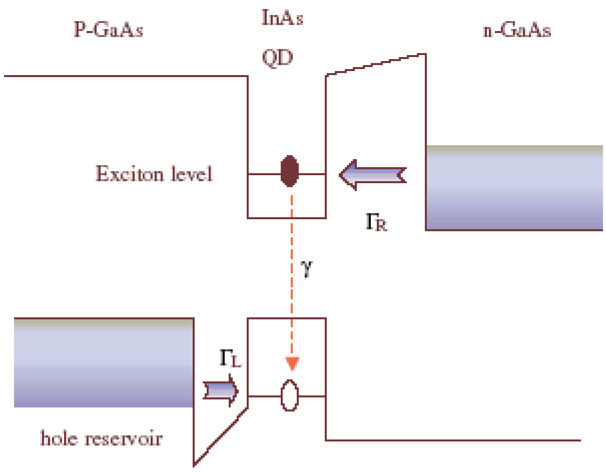


Fig.1 (a) Schematic description of teleportation by the Dicke effect in QDs. Firstly, a sub-radiance–induced singlet entangled state is generated between QDs 1 and 2. The energy bandgap of the exciton in QD 3 (1) is then tuned to be (non)-resonant with that in QD 2. Finally, a joint measurement is performed naturally by collective decay of QDs 2 and 3. (b) Energy band diagram of an InAs QD embedded inside a p-i-n junction.

II. <u>Current noise of quantum ring excitons incorporated inside a *p-i-n* junction</u>

We have considered a QR embedded in a p-i-n junction as shown in Fig. 2. Both the hole and electron reservoirs are assumed to be in thermal equilibrium. For the physical phenomena we are interested in, the fermi level of the *p* (*n*)-side hole (electron) is slightly lower (higher) than the hole (electron) subband in the dot. After a hole is injected into the hole subband in the QR, the *n*-side electron can tunnel into the exciton level because of the Coulomb interaction between the electron and hole.

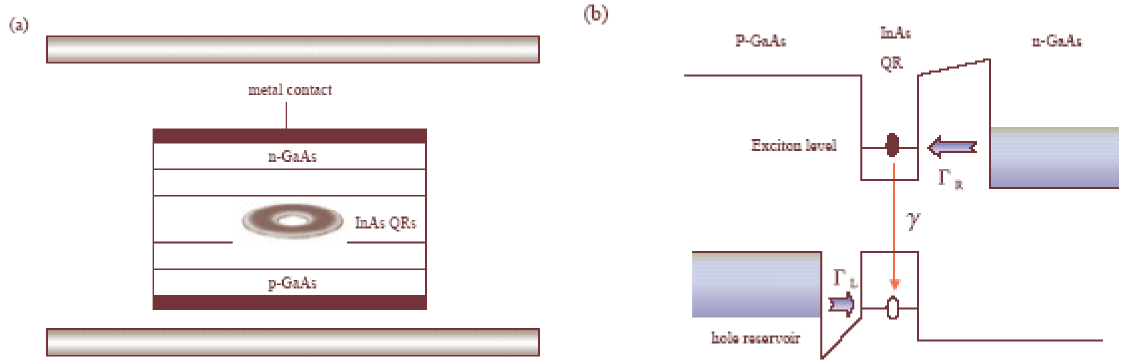


Fig.2 (a) Schematic description of a QR inside a p-i-n junction surrounded by a planar microcavity with length L. (b) Energy-band diagram of a QR in the p-i-n junction.

By applying the master equation technique and the MacDonald formula, the noise spectrum can be obtained. The zero-frequency noise (Fano factor) as a function of cavity length is given in Fig.3.

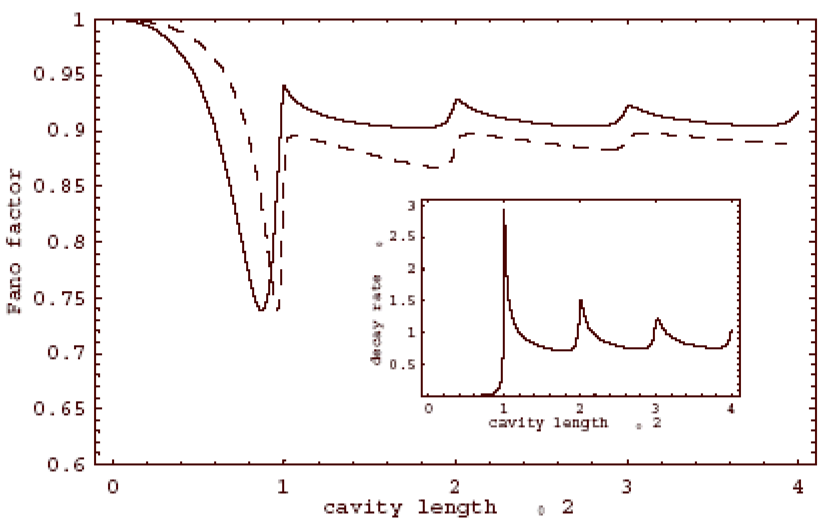


Fig.3

Since the current noise depends sensitively on the decay properties of a QR exciton, its emission rate inside a planar microcavity is numerically displayed in the inset of Fig. 3. As the cavity length is shorter than one half the wavelength of the emitted photon, the decay rate is inhibited because of the cut-off frequency of the cavity. One also notes that, at each resonant mode, there exists singular behavior, which is similar to that of a one- dimensional quantum wire in a microcavity. This is because the ring geometry preserves the angular momentum of the exciton, rendering the formation of exciton-polariton in the direction of circumference. This kind of behavior can also be found in the calculations of Fano factor as demonstrated by the solid line in Fig. 3. Comparing to the zero-frequency noise of the QD excitons (dashed line), the Fano factor of the QR excitons shows the "cusp" feature at each resonant mode.

Another interesting point is that below the lowest resonant mode, both the solid and dashed curves have a dip in the Fano factor. It is not seen from the radiative decay rate. The origin of this dip comes from that the zero-frequency noise is not a monotonic dependent function on the decay rate. If one plots Eq. (9) as a function of **g**, it can be shown that the only minimum point appears at $\mathbf{g} = \mathbf{G}_L \mathbf{G}_R (\mathbf{G}_L + \mathbf{G}_R)/(\mathbf{G}^2_L + \mathbf{G}^2_R)$. This extra information about the tunneling rates of the two side barriers is extracted from the shot-noise spectrum, and is not available form dc transport measurement (steady state current).

III. Current noise of a quantum dot p-i-n junction incorporated inside a three-dimensional photonic crystal

We have also considered a QD *p-i-n* junction embedded in a three-dimensional photonic crystal (PC) as shown in Fig. 4. Similar to the case in above, the shot-noise can be obtained straightforwardly. However, one should note that the correlation function (in z-space) of the photon reservoir in a one-band PC is as follows:

$$C_\varepsilon(z) = \frac{-i\omega_0^2 \beta^{3/2}}{\sqrt{\omega_c} + \sqrt{-iz - (\omega_0 - \omega_c)}}.$$

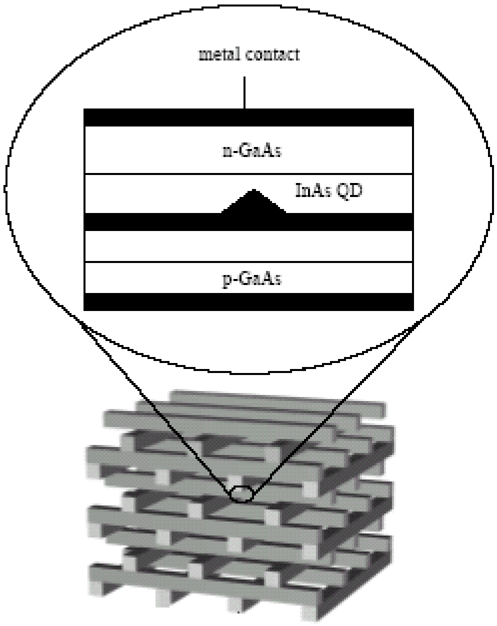


Fig.4 QD inside a p-i-n junction surrounded by a three-dimensional PC.

The corresponding current noise is shown in Fig. 5. As seen, the Fano factor shows the discontinuity as the exciton transition frequency is tuned across the photonic band gap (PBG) frequency (ω_c=101β). It also reflects that below the band edge frequency spontaneous (SE) of the QD exciton is inhibited. To observe this experimentally, the dc electric field (or magnetic field) can be applied to vary the band gap energy of the QD exciton. Another way to examine the PBG frequency is to measure the frequency-dependent noise as shown in the inset of Fig. 5, where the exciton band gap is set equal to 104β. As can be seen, discontinuities also appear as ω is equal to the *detuned* frequency between PBG and QD exciton.

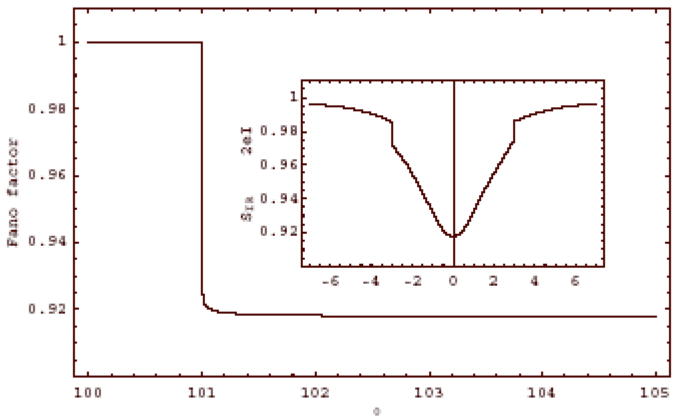


Fig. 5

We have also calculated the shot-noise spectrum of the QD *p-i-n* junction in a ***two-band*** PC. The photon correlation function is now written as

$$C_\varepsilon(z) = \frac{-i\omega_0^2\beta_1^{3/2}}{\sqrt{\omega_{c_1}} + \sqrt{-iz - (\omega_0 - \omega_{c_1})}} + \frac{i\omega_0^2\beta_2^{3/2}}{\sqrt{\omega_{c_2}} + \sqrt{iz + (\omega_0 - \omega_{c_2})}}.$$

One notes that there are two band edge frequencies, and the current noise should reveal this characteristic as shown in Fig. 6.

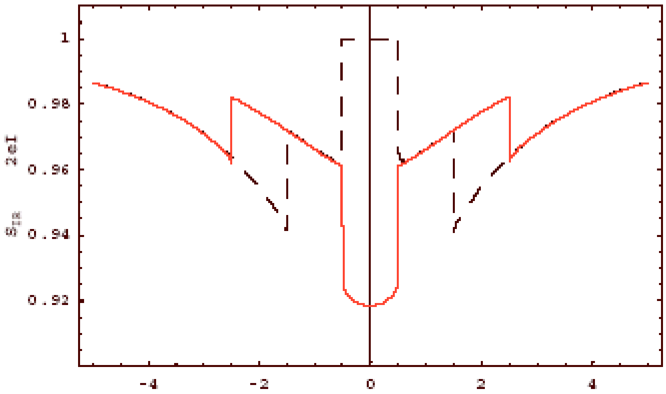


Fig. 6

The two band edge frequencies ω_{c1} andω_{c2} are set equal to 101β and 99β, respectively. There are three regimes for the choices of the exciton band gap: $\omega_0 > \omega_{c1}$, $\omega_0 < \omega_{c2}$, and $\omega_{c1} > \omega_0 > \omega_{c2}$. When ω_0 is tuned above the upper band edge ω_{c1} (or lower the lower band edge ω_{c2}), the QD exciton is allowed to decay, such that the shot noise spectrum (red curve) is downward in the range of $\omega < |\omega_0 - \omega_{c1}|$. On the other hand, however, if ω_0 is between the two band edges, SE is inhibited. As shown by the dashed curve, the behavior of the current noise in the central region is upward, and the value is equal to unity. Similar to the one-band PC, the curves of the shot noise spectrum reveal two discontinuities, demonstrating the possibility to extract information from a PC by the current noise.

A few remarks about the applications of the QDs inside a PC should be mentioned here. As known, controlling the propagation of light (waveguide) is one of the optoelectronic applications of PCs. If two QD *p-i-n* junctions can be incorporated inside a PC (and on the way of light propagation), the cavity-like effect can be used to create the entangled state between two QD excitons with remote separation. The advantages are that the decoherence of the entangled state can be suppressed because of the feature of the PBG, and observation of the enhanced shot noise could be an identification of the entangled state. Furthermore, if the entangled state is created between two dots, teleportation may be accomplished by the inclusion of the third dot with unknown exciton state.

5. 成果

I. Invited Talks from abroad

1. Korea Institute for Advanced Study (Nov. 2005, Korea)
   - Current detection of superradiance and induced entanglement of double QDs
   - Teleportation of charge qubits via superradiance
2. University of Heidelberg (July 2006, Germany)
   - Entanglement and teleportation via superradiance

II. Publications

- Book chapters

  1. *Effect of cavity and superradiance on the electrical transport through quantum dots*, **Y. N. Chen**, D. S. Chuu, and T. Brandes, Invited chapter in "Quantum Dots: research development", Nova Science Publishers (2005).

- Journals

1. Teleportation of charge qubits via superradiance, **Y. N. Chen**, C. M. Li, D. S. Chuu, and T. Brandes,
   New Journal of Physics **7**, 172 (2005)
2. Current noise of quantum ring excitons incorporated inside a p-i-n junction, **Y. N. Chen** and D. S. Chuu,
   Phys. Rev. **B 72**, 233301 (2005)
3. Current noise of a quantum dot p-i-n junction incorporated inside a three-dimensional photonic crystal, **Y. N. Chen**, D. S. Chuu, and T. Brandes,
   Phys. Rev. **B 72**, 153312 (2005)
4. Spin relaxation in a GaAs quantum dot embedded inside a suspended phonon cavity, Y. Y. Liao, **Y. N. Chen**, D. S. Chuu, and T. Brandes,
   Phys. Rev. **B 73**, 085310 (2006)
5. Orientation of adsorbed dipolar molecules: A conical well model, Y. Y. Liao, **Y. N. Chen**, W. C. Chou, and D. S. Chuu
   Phys. Rev. **B 73**, 115421 (2006)

In summary, we have successfully worked out the shot-noise spectrum of a QR in a planar microcavity or QD in a photonic crystal. As expected the current noise indeed reflect the characteristic of the *restricted* photons. This is remarkable since the *p-i-n* junction can in principle be used as a detector of photon noise. Moreover, we have also extended its applications in generating entangled states and achieving quantum teleportation. These findings are very interesting, and have attracted attention, e.g. ***our work was invited to become a chapter in the forthcoming book, "Quantum Dots: research development"***. We believe it certainly has important impact on the field of quantum information science.

6. 國際會議

出席 2006 年 8 月 26~30 日在東京舉行的「ERATO conference on QIS 2005」。(見附件)

附件一

『ERATO conference on Quantum Information Science 2005』

國際會議心得報告

撰寫人：陳岳男

8/24 由台北搭乘長榮航空經關西機場出發到東京

8/26 第一天是報到與註冊。

8/27 第二天一開始的演講便是邀請到德國Max Planck研究所的Cirac教授演講，講題為”Efficient representation of certain many-body quantum states”，讓大家可以從量子資訊的角度再去思考多體物理中的許多問題。晚上的時間是第一場的Poster，總共有三個人來到我的海報前，我也一一的為大家解釋我們的論文內容，達到了國際交流的目的。

8/28 這一天的行程大概就是聆聽演講以及與各國學者討論。晚上的晚宴時間，是在東京台場的一家飯店舉行，主持人宣布了再接下來的三年，分別由北京、京都與韓國的首爾來舉辦這個會議。在晚宴中，韓國高等科學院(Korea Institute for Advanced Study)的計算科學部學部長金在浣教授，邀請我到他們的研究所訪問一個禮拜，我想這是此行的最大收穫。

8/29 這一天的行程大概就是聆聽演講以及與第二場Poster。

8/30 最後一天也是聆聽演講，以及最後的致詞，包括由下一屆的主辦單位北京代表邀請大家再次與會。

綜觀這次會議，很多做固態方面實驗的專家並沒有與會，其原因並不明朗！也因為如此，使得這次的會議精采度不如從前。此外，由下三屆主辦的單位來看，台灣明顯的被排擠在外，可見我們實在有必要再加強我們在這個領域的國際能見度，否則在十年之後，恐怕要遠遠落後於南韓與中國了！

此次會議的發表論文：

Proposal for Teleportation of Quantum Dot Exciton States

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(Dated: June 14, 2005)

A scheme is proposed to teleport charge qubits via superradiance. Entanglement is generated between a two-level atom and a cavity photon. A quantum state encoded in another atom is then collective decay with the previous entangled atom. Teleportation is achieved automatically in our scheme which we also extend to quantum dots.

Keywords:Quantum Dots, Teleportation, and Superradiance.

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PACS numbers:

Quantum entanglement has achieved a prime position in current research due to its central role in quantum information science, e.g., in quantum cryptography, quantum computing, and teleportation [1]. Many efforts have been devoted to the study of entanglement induced by a direct interaction between the individual subsystems. Very recently, attention has been focused on *reservoir-induced* entanglement [2] with the purpose of shedding light on the generation of entangled qubits at remote separation.

Entangled states can also be generated via sub- and superradiance, i.e. the collective spontaneous decay first introduced by Dicke [3]. For the simplest case of two identical two level atoms interacting with the vacuum fluctuations of a common photon reservoir, entanglement naturally appears in the two intermediate states

$$|T_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle), \quad |S_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \quad (1)$$

of the two decay channels from the excited state $|T_1\rangle = |\uparrow\uparrow\rangle$ to the ground state $|T_{-1}\rangle = |\downarrow\downarrow\rangle$. An experimental demonstration of two-ion collective decay as a function of inter-ion separation was shown by Devoe and Brewer in 1996 [4]. On the other hand, the possibility to modify decay rates of individual atoms inside cavities (Purcell effect) [5] has been known for a long time, and enhanced and inhibited spontaneous rates for atomic systems were intensively investigated in the 1980s [6] by passing atoms through cavities.

Experiments of teleportation have already been realized in NMR [7], photonic [8], and atomic [9] systems. Turning to solid state systems, however, experimental demonstration of teleportation in charge qubits is still lacking, and only few theoretical schemes are proposed. [10] In this work, we propose a teleportation scheme for atomic and solid state qubits (quantum dots (QD) or quantum wells), which is based on the Dicke effect and achieves a "one-pass" teleportation by a joint measurement.

The simplest case. — To address the role of superradiance in teleportation, let us first consider a two-level atom passing through a cavity as shown in Fig.1. The interaction between the atom and the cavity photon is

$$H' = \hbar g(\sigma_+ b^- + \sigma_- b^+), \quad (2)$$

where g is the atom-cavity coupling strength, $b^{\pm}$ and the Pauli matrices $\sigma^{\pm}$ are the cavity photon and atom operators, respectively. With the appropriate preparation of the initial state of atom-1 and the control of its passing time through the cavity, the singlet entangled state $\frac{1}{\sqrt{2}}(|1\rangle_c |\downarrow\rangle_1 - |\uparrow\rangle_1 |0\rangle_c)$ is created between atom-1 and the cavity photon. The notations $|\uparrow\rangle_1$ ($|\downarrow\rangle_1$) and $|0\rangle_c$ ($|1\rangle_c$) refer, respectively, to atom-1 in the excited (ground) state and no (one) photon in the cavity. If the quantum state $\alpha |\uparrow\rangle_2 + \beta |\downarrow\rangle_2$, generated by the coherent excitation of atom-2 with a laser pulse, is to be teleported, the next step to complete the teleportation is to trap both atoms close to each other. In this case, the total wave function of the system is given by

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_c |\downarrow\rangle_1 - |\uparrow\rangle_1 |0\rangle_c) \otimes (\alpha |\uparrow\rangle_2 + \beta |\downarrow\rangle_2)$$
$$= |1\rangle_c \otimes (-\frac{\alpha}{\sqrt{2}} |T_1\rangle_{12}) + |0\rangle_c \otimes (\frac{\beta}{\sqrt{2}} |T_{-1}\rangle_{12}) \quad (3)$$
$$+ (\alpha |1\rangle_c + \beta |0\rangle_c) \otimes \frac{|S_0\rangle_{12}}{2} + (\alpha |1\rangle_c - \beta |0\rangle_c) \otimes \frac{|T_0\rangle_{12}}{2}.$$

Since atom-1 and 2 are now close enough, the common photon reservoir will drive them to decay collectively with four possibilities for the detector's results: zero photon, two photons, one photon via the superradiant channel, or one photon via the subradiant channel. If the measurement outcome is a single photon with a suppressed decay rate, the teleportation is achieved automatically. As for

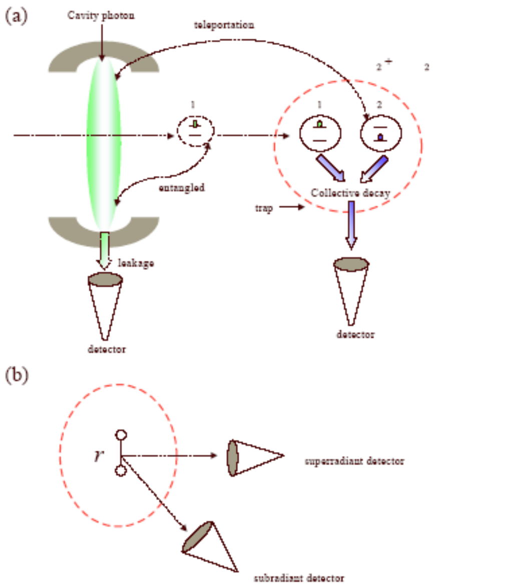

FIG. 1: (a) Schematic description of teleportation by collective decay in a cavity QED system. First, the singlet entangled state is generated between atom-1 and the cavity photon as the atom has passed through the cavity. Atom 1 and 2 then decay collectively. If the measurement outcome is a single photon with subradiant decay rate, the teleportation to the cavity photon state is achieved automatically. (b) To distinguish between super- and subradiant decay, two detectors are placed at appropriate angles such that the emitted photon momentum $\overrightarrow{k}$ satisfy the condition of $\overrightarrow{k}\cdot\overrightarrow{r}=0$ and π, respectively.

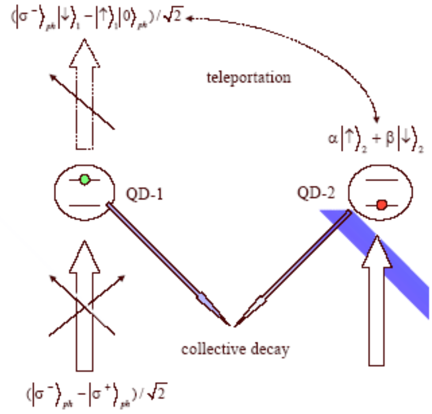

FIG. 2: Schematic description of teleportation by the Dicke effect in quantum dots. First, the exciton-photon entangled state, $\frac{1}{\sqrt{2}}(|\sigma^-\rangle_{ph}|\downarrow\rangle_1 - |\uparrow\rangle_1|0\rangle_{ph})$, is created when a superposition polarized photon, $|\phi_{ph}\rangle = \frac{1}{\sqrt{2}}(|\sigma^-\rangle_{ph} - |\sigma^+\rangle_{ph})$, passes through QD-1. In the mean time, the unknown state is coded in QD-2. The teleportation is then accomplished by collective decay.

the result of one photon with enhanced decay rate, all we have to do is to perform a phase-gate operation on the cavity photon state to complete the teleportation.

Since decay time is a statistical average, one might ask how to distinguish between sub- and superradiant photons via the decay time in one single shot ? We would like to point out that because of the collective decay, the momentum of the emitted photon $\overrightarrow{k}$ depends on the separation of the two atoms $\overrightarrow{r}$, i.e. $\overrightarrow{k}\cdot\overrightarrow{r}=0$ or π corresponds to the emission of super- or sub-radiant photon, respectively. [4] Therefore, sub- and super-radiance can be distinguished by placing detectors at appropriate angles as shown in Fig. 1 (b). The teleportation can then be tested by repeating this scheme over many cycles and probing the state of the cavity (one or no photon) after each cycle.

Quantum dots. — The spin structure of the self-assembled Ga(In)As QD exciton states are constructed from electron (e) and heavy hole (h) single-particle basis states with spin projections along the QD growth axis (z) of $J_{e,z}=+\hbar/2$ or $-\hbar/2$ and $J_{h,z}=-3\hbar/2$ or $3\hbar/2$ respectively. When a circularly polarized photon conveys a unit of angular momentum ($\hbar$ for σ^+ and $-\hbar$ for σ^-), optical transition from the crystal ground state takes place under the condition of $J_z = J_{e,z}+J_{h,z}=\pm\hbar$ ($e\downarrow h\uparrow$ and $e\uparrow h\downarrow$). The $e\downarrow h\uparrow$ and $e\uparrow h\downarrow$ eigenstates are often mixed in dots, forming two linearly polarized eigenstates separated by the anisotropic e–h exchange splitting of a few times $10\mu eV$. [11] Recently experiment has shown that with appropriate magnetic field applied parallel to the growth axis of the dots Zeeman splitting energy is larger than the e–h exchange splitting. This transforms the mixed eigenstates into pure $e\downarrow h\uparrow$ and $e\uparrow h\downarrow$ ones. Electrons with up or down spin orientation can then be generated via circularly polarized light with σ^- or σ^+ helicity, respectively.

We now proceed to describe the teleportation scheme in two QDs. One first prepares a single photon source with superposition of σ^- and σ^+ polarized photon, i.e. $|\phi_{ph}\rangle = \frac{1}{\sqrt{2}}(|\sigma^-\rangle_{ph} - |\sigma^+\rangle_{ph})$. Making use of the optically selective rule, QD-1 can be controlled to absorb σ^+ polarization photon only. In this case the exciton-photon entangled state, $\frac{1}{\sqrt{2}}(|\sigma^-\rangle_{ph}|\downarrow\rangle_1 - |\uparrow\rangle_1|0\rangle_{ph})$, is created when the photon passes through QD-1 (Fig. 2). On the other hand, a laser pulse, which generates the quantum state $\alpha|\uparrow\rangle_2 + \beta|\downarrow\rangle_2$, is applied to QD-2 at the same time. Similar to the purely quantum optic system mentioned above, teleportation can be achieved if the measurement outcome is single photon with sub- or superradiance.

A few remarks about the comparisons between our scheme and other proposals should be mentioned here. In usual teleportation scheme, one has to perform Hadamard and CNOT transformations on one of the entangled particles and the teleported quantum state. After that, the information from the joint measurements of the two particles has to be sent to the other entangled particle in order to allow proper unitary operations. In our proposal, however, the Hadamard and CNOT transformations are omitted and the joint measurements are performed naturally by collective decay. This kind of "one-pass"teleportation is similar to S. Bose 's proposal, where the teleportation between two trapped atoms in two independent cavities is achieved by the leaked cavity photons impinging on a 50-50 beam splitter. [12] Very recently, Beenakker *et al.* have also theoretically pointed out that "one-pass" teleportation of spin states in quantum Hall system is possible. [13] The key is the recombination of the electron and hole at the tunnel barrier. A disadvantage is that the success rate is small.

Just like S. Bose 's protocol [12], our probabilistic proposal can be modified to teleportation with insurance, so that in the cases when the protocol is unsuccessful the original teleported state is not destroyed, but mapped onto another reserve atom (or dot) r. To accomplish this, the key step is the local redundant encoding of the teleported state [14] before the collective decay:

$$|\Psi\rangle_{code} = \beta(|\uparrow\rangle_2 |\downarrow\rangle_r + |\downarrow\rangle_2 |\uparrow\rangle_r) + \alpha(|\downarrow\rangle_2 |\downarrow\rangle_r + |\uparrow\rangle_2 |\uparrow\rangle_r).$$

If the teleportation is unsuccessful, the coded state is left with either state $\alpha |\uparrow\rangle_r + \beta |\downarrow\rangle_r$ or or a state that can be converted $\alpha |\uparrow\rangle_r + \beta |\downarrow\rangle_r$ by a known unitary transformation. In this case, one can repeat this procedure until teleportation is successful.

In conclusion, we have proposed in this work a novel way to achieve "one-pass" teleportation. To the best of our knowledge, it is the first time that superradiance is pointed out to be useful in quantum teleportation. Experiments in both quantum optic and semiconductor systems are suggested and deserved to be tested with current technologies.

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