Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 133-135

Invited

Particle Statistics and Quantum Dynamics in a Semiconductor Quantum-Well Microcavity

J. Jacobson, H. Cao, G. Björk, S. Pau and Y. Yamamoto†

ERATO Quantum Fluctuation Project, Edward L. Ginzton Laboratory, Stanford University
Stanford CA 94305, U.S.A.
Phone: (415)-725-7699//Fax: (415)-723-5320
E-mail: jacobson@sierra.stanford.edu
†Also with NTT Basic Research Laboratories, Atsugishi, Kanagawa, Japan

At low excitation a system of particles obeying arbitrary statistics is indistinguishable from a system composed of particles obeying Bose-Einstein statistics in their internal excitation coordinate. At higher excitation the actual underlying particle statistics become important. We have observed a spectral signature of the underlying exciton statistics in a semiconductor quantum-well microcavity.

1.INTRODUCTION

Recently there has been tremendous interest in the dynamics of simple quantum systems which have just now become experimentally accessible. Of particular note are analogs to atomic systems in semiconductors such as the quantum well-microcavity coupled system. Weisbuch et. al. has observed the so called 'vacuum Rabi-splitting' in a quantum well microcavity system in the spectral domain[1)]. Shortly thereafter Norris and Jacobson independently observed the conjugate process in the time domain[2)].

Such splitting arises from the coupling between the quantum well excitons and the vacuum field. In the study by Jacobson it was noticed that the evolution of the system was invariant with the excitation intensity for several orders of magnitude variation in the pump intensity. At higher intensities however, new temporal (or equivalently spectral) components begin to emerge.

At low intensities, excitons are normally treated as bosons (obeying Bose statistics) and the dynamics of the system are independent of the pump intensity. However, at higher densities, excitons deviate from purely bosonic statistics. In this paper we point out the deep connection between a particle's statistics and the dynamics of the quantum system involving such particles. We then show experimental results from a quantum- well microcavity.

2. THEORY

Consider a lattice of m particles excited with n quanta. Each particle can hold q quanta however the probability of a particle accepting another quanta will in general depend on the number which it already holds. If the probability of accepting another quanta is critically dependent on the number already held we then have Fermi-Dirac (F.D.) statistics in which the probability of accepting another quanta is zero if one is already held. On the other hand if the probability of accepting another quanta of excitation is independent of the number held we have the Bose-Einstein (B.E.) statistics. Intermediate statistics are of course possible.

As is easy to discern, a lattice of two-level atoms obey the Fermi-Dirac statistics. Once a two-level atom has received a quanta of excitation it cannot receive another. On the other hand a large ensemble of particles, excited by only a few quanta, can be viewed as a single particle which obeys Bose-Einstein statistics. (E.g. the probability of the system as a whole to accept another quanta is hardly dependent on the particular statistics of the constituent particles in the low excitation regime).

In quantum statistical mechanics each statistics (B.E., F.D. or an intermediate statistics such as Maxwell-Boltzmann (M.B.)) has associated with it a quantum mechanical commutator. We may write the interaction Hamiltonian between the photon field and the particles as

$$\hat{H} = \hat{H}_0 + \hbar g \sum_{i=1}^{M} \hat{a}\hat{b}_i^\dagger + \hat{a}^\dagger \hat{b}_i \tag{1}$$

where,

$$\begin{aligned} \left[\hat{a},\hat{a}^\dagger\right] &= 1 \\ \left[\hat{b}_i,\hat{b}_j^\dagger\right] &= \delta_{ij}\left(1-2\chi\hat{b}_j^\dagger\hat{b}_i\right) \end{aligned} \tag{2}$$

Note that the photon field, $\hat{a}$, follows the Bose commutator whereas the particle field, $\hat{b}_i$, obeys a continuously variable commutator parameterized by χ. (χ=0 ->B.E., χ=1->F.D., χ=1/2 ->M.B.).

In the exciton system we take each Bohr area (or several Bohr areas) as our particle. As noted above, for many particles and weak excitation the system is independent of the statistics of the excitons. However at higher excitation we must take into account that the particle commutator deviates from purely Bosonic. The deviation comes about from coulomb-coulomb interactions between excitons[3)].

We give a simple example of a single particle coupled to two quanta (m=1, n=2) and show how transitions which are not allowed when the particle is a boson become allowed when the particle becomes non-bosonic. We employ the dressed state picture and show that additional emission peaks emerge as the particle makes the tranformation from bosonic to non-bosonic.

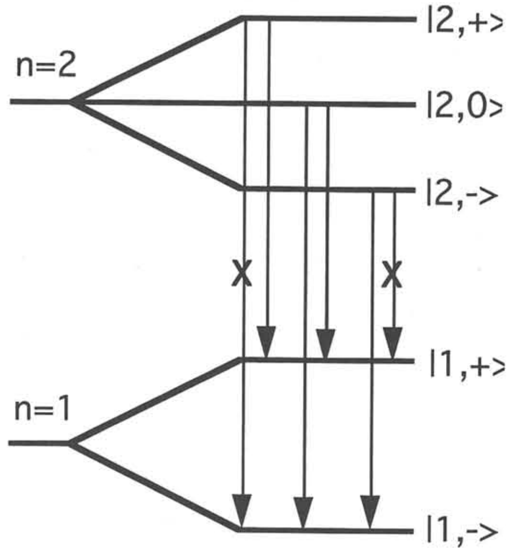

Fig. 1 Dressed state diagram of transitions from the n=2 manifold to the n=1 manifold. The X's denote transitions which are unallowed for bosons. As the particle deviates from bosonic these transitions become allowed.

Figure 1. shows the dressed state diagram for transitions from the n=2 manifold to the n=1 manifold. The X's indicate transitions which are not allowed when the particle is bosonic but become allowed as the particle deviates from a pure boson.

Figure 2. shows the resulting optical spectrum for the single particle system as a function of the particle statistics. We note that when the particle is bosonic there are exactly two allowed transitions. As the statistics are varied new transitions become allowed.

4. EXPERIMENT

We have carried out experiments using a GaAs quantum well microcavity at 4K [2)]. The system was excited by means of a modelocked laser and the emitted optical spectrum was recorded. Figure 3. shows the spectrum for several different excitation intensities. At low excitation we have the vacuum rabi splitting where we have only two transitions. At higher intensities the underlying particle statistics become important and new transitions emerge.

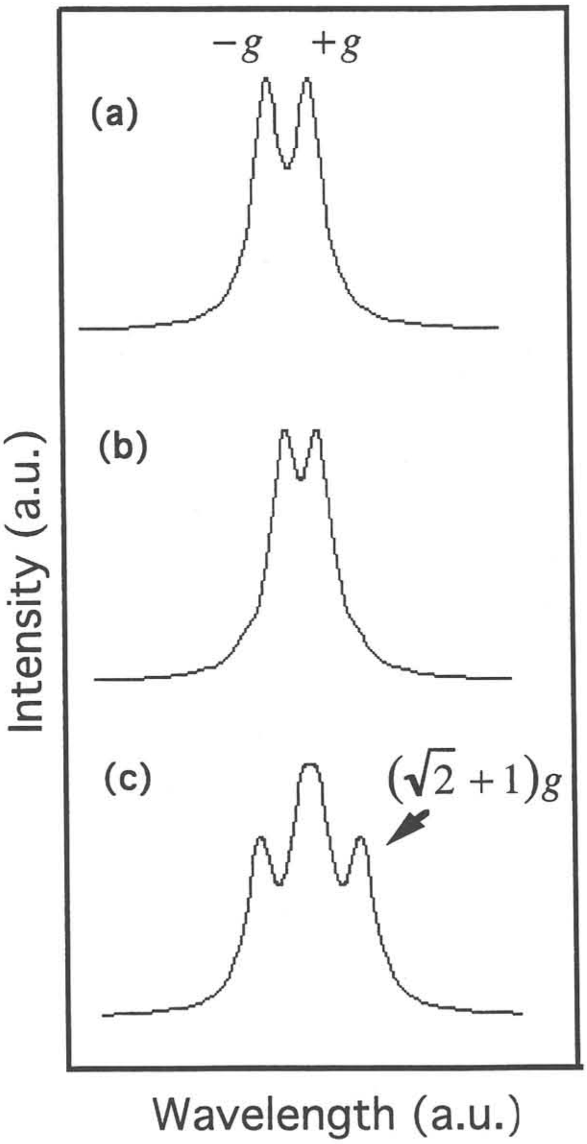

Fig. 2. Spectrum from a single particle coupled to the radiation field and excited with two quanta for several different statistics. (a) χ = 0, Bose-Einstein. (b) χ = 1/2, Maxwell-Boltzmann, (c) χ = 1, Fermi-Dirac.

Therefore, we have illustrated the connection between particle statistics and the dynamics of a simple quantum system made of such particles. We have demonstrated experimentally how transitions which are not allowed for a purely bosonic system become allowed in the semiconductor exciton system as the excitons deviate from pure bosonic at high excitation.

5. REFERENCES

1) C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. 69(1992) 3314

2)T.B. Norris, J.-K. Rhee, C.Y. Sung, Y. Arakawa, M. Nishioka and C. Weisbuch, QELS QPD19-1/42 Baltimore (1993)

J. Jacobson,H. Cao,S.PAu,G. Bjork and Y. Yamamoto QELS QPD21 Anaheim (1994)

3)M. Combescot, Phys. Reports 221(1992) 167

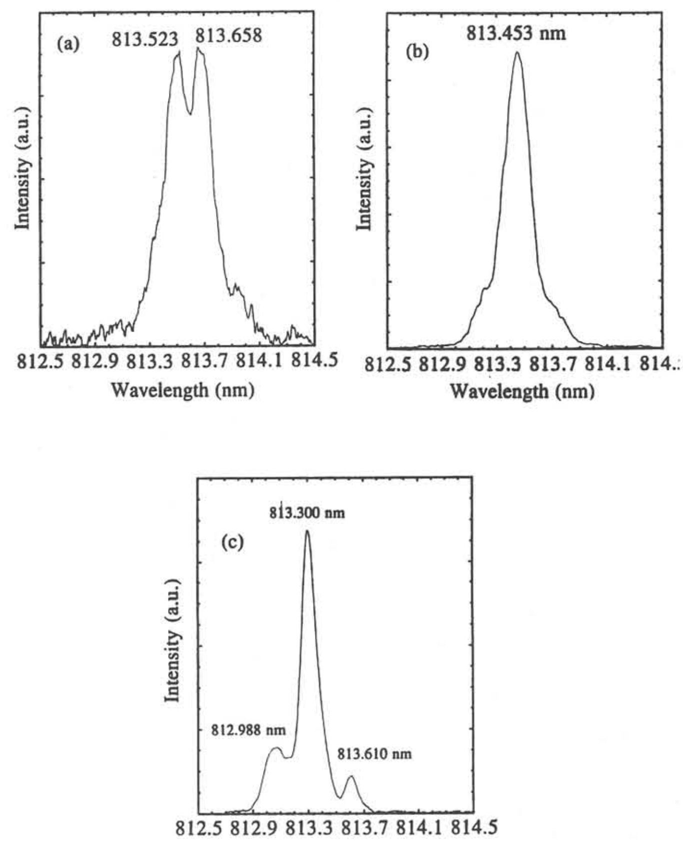

Fig. 3. Optical Spectrum from GaAs Quantum-Well Microcavity at 4K for several excitation intensities. (a) 15 mW. (b) 80 mW. (c) 445 mW.