Stationary Dark-State Polaritons Dressed by Dipole-Dipole Interaction for the Realization of polariton Bose-Einstein Condensation

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Cooling bosonic atoms below the transition temperatures made dilute gases form the Bose-Einstein condensation (BEC). In atomic systems, particle-particle interactions are weak, and their scattering lengths are far less than mean particle spacings, which is the meaning of "diluteness". The development of optical microcavities enables the realization of exciton-polariton BEC in solid-state systems. Polaritons are also bosonic quasiparticles resulting from photons strongly coupled to excitons' electric dipoles. The effective mass, particle density, transition temperature, thermalization time, and lifetime of polariton BECs are orders of magnitude different from those of atomic BECs. For example, polariton BECs (atomic BECs) have transition temperatures of 1~300 K (< 1 μK) and thermalization times of 1~100 ps (1~100 ms). Concerning usages of Bose condensates, an exciton-polariton BEC is a two-dimensional system with a lifetime comparable to or shorter than thermalization time. In many aspects, the differences are rather significant. Can one create a new kind of BEC combining or comprising the merits of atomic BECs and exciton-polariton BECs?

A unique platform of stationary dark-state polaritons (SDSPs) to achieve the BEC was proposed in Ref. [1]. The SDSP is a bosonic quasi-particle made of the superposition of photon and ground-state coherence in the Λ-type electromagnetically induced transparency (EIT) system [2]. The authors in Ref. [1] proposed to utilize a nonlinear Kerr effect to mediate the interaction between the SDSPs for thermalization to achieve BEC. Nevertheless, the Kerr-type interaction is typically too weak to make a sufficient elastic collision rate for thermalization.

We proposed to substitute the dipole-dipole interaction (DDI) between Rydberg-state atoms for the Kerr-type interaction to make the SDSP BEC feasible, and experimentally demonstrated a many-body system of slow-light Rydberg polaritons based on the DDI effect. The medium with a high optical depth made the interaction time compatible with the elastic collision rate. Hence, we observed a cooling effect in the transverse direction of slowly-propagating Rydberg polaritons [3].

Furthermore, we experimentally demonstrated the SDSPs possessing the Rydberg-state DDI. Two more laser fields were applied to drive the two-photon transition (TPT) from the ground to Rydberg states. Due to the TPT-induced Rabi oscillation, the DDI resulted in the phase shift of the SDSP. We systematically measured the DDI-induced phase shift of the SDSP as functions of the DDI strength. The measured data are consistent with the theoretical predictions [4], verifying the creation of the stationary DSP dressed by the DDI [5]. The measured phase shift indicates that the elastic collision rate is approximately 33 MHz. Such the elastic collision rate enables the thermal equilibrium of SDSPs, and makes the BEC feasible, where the transition temperature, Tc, is about 4.0 mK based on Ref. [1]. To search for the BEC, we still need to eliminate the population in dark-Rydberg states [6], build an artificial trap, and produce SDSPs in the quasi-continuous mode.

Our studies have made a substantial advancement toward the realization of SDSP BEC. The proposed SDSP BEC can open a new avenue in the field of synthetic quantum matter and lead to a new platform of quantum simulators. This work was supported by the Grants No. 111-2639-M-007-001-ASP and No. 112-2112-M-007-020-MY3 of the National Science and Technology Council, and the Grants No. 112QI037E1 and No. 113Q1026EI of National Tsing Hua University.

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