Exciton crystallization and superfluidity in electron-hole bilayers and coupled quantum dots

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Structural phase transitions and superfluidity of macroscopic and mesoscopic ensembles of optically excited indirect excitons in spatially separated electron-hole bilayers and coupled quantum dots are investigated with path integral Monte Carlo simulations. At small inter-layer separation distances and low temperatures the indirect excitons are stable complexes with a permanent dipole moment "d". These excitons are treated as bosons with an effective pair interaction potential and bosonic exchange. We show that for d> 3a_B the exciton-exciton repulsion is sufficient to stabilize the excitons into a crystalline state. We analyse in detail quantum melting of this bosonic solid and the onset of the superfluid exciton liquid phase. The temperature of appearance of the superfluidity (Kosterlitz-Thouless transition temperature) agrees with the theoretical estimates for electron-hole bilayers [1]. Quantitative predictions on the superfluid fraction are given for typical materials like ZnSe and GaAs quantum wells.

In the present work we use quantum Monte Carlo simulations to give a first principle thermodynamic description of different phases which can be realized in a confined electron-hole system in a bilayer geometry.

The physical realization of the mass asymmetric bilayer can be a system of two coupled quantum wells filled with electrons and holes, or a single quantum well where the opposite charges are separated by a strong electric field applied normal to the QW plane.

The effect of the external field is not only to increase the recombination life time of electron hole pairs, but also to produce lateral in-plane confinement. Recently, we have quantitatively analysed a possible realization of a parabolic in-plane potential, confining neutral excitons, using the idea of the quantum Stark confinement [2]. In GaAs and ZnSe based QWs one can achieve harmonic trap frequencies from 1GHz to 1 THz for typical electric field strengths of 10-20kV/cm. For the accessible range of frequencies we consider small finite systems, i.e several tens of trapped particles, or a homogeneous macroscopic system where the trap effects are ignored.

First, we analyse the structural transitions in an electron-hole bilayer by varying the mass ratio [3], density [4] (e.g. via the trap frequency), temperature, electron-hole separation (e.g. via the electric field strength or the QW width). We predict the parameter range, in experiments on ZnSe- based QWs, where the excitons are stable and form a mesoscopic or macroscopic crystal.

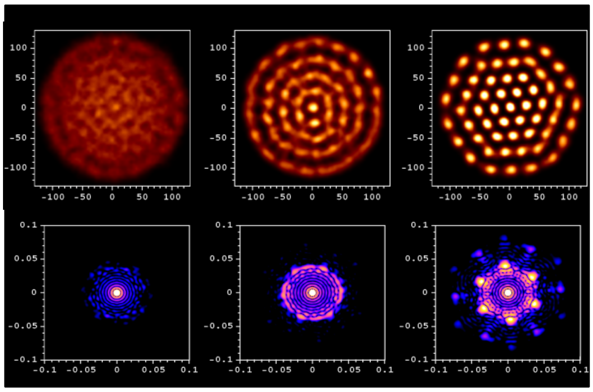

Fig 1: Upper panel: density plots of indirect excitons in a 2D parabolic trap for temperatures 3.35 K, 830mK, 210 mK (from left to right). Distances in units of a_B. Lower panel: corresponding diffraction patterns. Exciton dipole moment, d= 6.6 a_B.

As an example, in Fig.1 we show a picture from quantum Monte Carlo calculations for N=56 harmonically trapped indirect excitons in a ZnSe QW.

The static structure factor can be measured in Brag diffraction experiments and can serve as an indicator of appearance of translational order in the system. The inner part of the exciton cluster shows triangular symmetry and produces typical 6-peaks in the diffraction image. A similar effect is observed also for the macroscopic system.

For the macroscopic systems we can numerically estimate the superfluid fraction as an average from the so called "winding number" which is related to the frequency of quantum-mechanical exchanges, i.e particle permutations.

In Fig.2 we show our results for the superfluid fraction of excitons in a 30 nm wide ZnSe QW. The induced dipole moment, d=6.6 a_B, corresponds to the electric field, E=20kV/cm. Temperature, $k_B T$=1/3000 Ha (203mK). In the low density region we found the insulating phase (exciton crystal) and the superfluidity is zero. At the critical density (~$3.5 \cdot 10^9$ cm^{-2}) a finite superfluid fraction (~30%) is found.

The relative distance fluctuations, u_r, i.e. the Lindemann parameter, shows a jump at the same point indicating a structural phase transition: melting of the solid and transition to a superfluid exciton liquid.

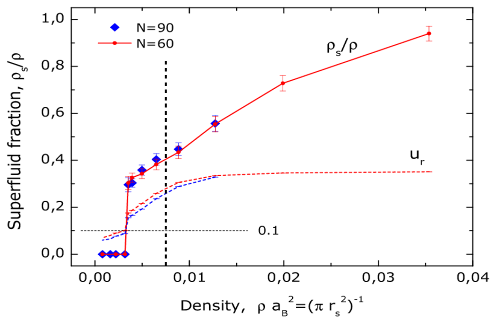

Fig. 2: Density dependence of the superfluid fraction for indirect excitons in ZnSe QW. Vanishing of the superfluid fraction at low densities corresponds to formation of the excitonic solid. Number of excitons in the simulation box is indicated by N. Dotted line corresponds to the Mott transition (exciton dissociation), and defines the validity region of the present bosonic simulations.

Investigation of the temperature-density dependence of the superfluid fraction and the Lindemann parameter allows us to draw the resulting phase boundary: exciton crystal-exciton liquid.

References

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