Dipolar interactions in bilayers of indirect excitons

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Abstract: We studied both experimentally and theoretically attractive dipolar interaction in bilayers of indirect excitons (IXs) with built-in dipole moments and found monotonic IX energy reduction with density and spatial attraction between IX clouds.

A spatially indirect excitons (IX) is a bound pair of an electron and a hole confined in separated layers. IXs have built-in electric dipole moment *ed* (*d* is the distance between the electron and hole layers, *e* electron charge). Furthermore, IXs have long lifetimes allowing them to cool below the temperature of quantum degeneracy. These properties make IXs a platform for exploring quantum gases with dipolar interaction.

For one layer of IXs in a single pair of coupled quantum wells (CQW), the out-of-plane IX electric dipoles lead to repulsive dipolar interaction between IXs. The repulsive dipolar IX interactions were extensively studied in the past. The phenomena originating from the repulsive dipolar interaction in a single IX layer include the enhancement of IX energy with density, screening of in-plane disorder potential by IXs that leads to IX delocalization and long-range IX transport, strong correlations, and predicted crystal phases ([1] and references therein). Attractive dipolar interactions lead to new phenomena in quantum systems and are intensively explored with cold atoms ([2] and references therein). However, attractive interactions have yet to be similarly explored in IXs and in materials systems in general.

In this contribution, we study attractive dipolar interaction in bilayers of IXs. Each layer of IXs forms in a single pair of CQW. The interaction between IXs within each IX layer is repulsive. The attractive interaction appears between IXs in different IX layers created in 2-CQW heterostructures with 2 layers of IX dipoles.

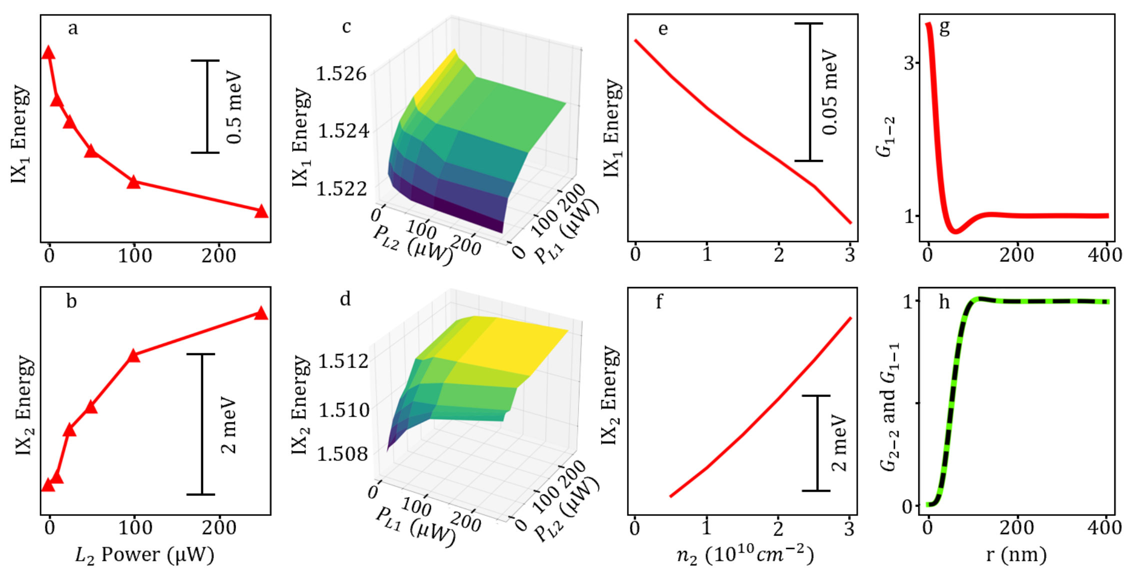

Figure 1: (a,b) The measured IX_1 (a) and IX_2 (b) energy vs L_2 power (P_{L2}) and, in turn, IX_2 density (n_2). An energy decrease (a) and increase (b) correspond to attractive IX_1–IX_2 interaction and repulsive IX_2–IX_2 interaction, respectively. P_{L1} = 10 μW in (a), 0 in (b). (c,d) The measured IX_1 (c) and IX_2 (d) energy as a function of both P_{L1} and P_{L2}. (e,f) The calculated IX_1 (e) and IX_2 (f) energy vs n_2. $n_1 = 1.5\times10^{10}$ cm^{-2} in (e), 0 in (f). (g,h) IX_1–IX_2 (g), IX_2–IX_2 [(h), green solid line], and IX_1–IX_1 [(h), black dashed line] density correlation functions. $n_1 = n_2 = 10^{10}$ cm^{-2}.

IX_1 form in CQW_1, IX_2 form in CQW_2. CQW_2 (CQW_1) consist of two 15 nm (12 nm) GaAs QWs separated by 4 nm $Al_{0.33}Ga_{0.67}As$ barrier. CQW_2 and CQW_1 are separated by 12 nm $Al_{0.33}Ga_{0.67}As$ barrier. Voltage creates electric field in the structure. The IX_2 energy is lower than the IX_1 energy. Excitons are generated by lasers L_2 and L_1 at the energies resonant to spatially direct excitons (DXs) in CQW_2 and CQW_1, respectively. L_2 generates IX_2. L_1 generates IX_1 and ~2 times smaller concentration of IX_2 due to nonresonant absorption of L_1 light in CQW_2. L_2 and L_1 excitation spots are separated by 50 μm that allows exploring the effects of IX interactions on the IX cloud position. IX luminescence is measured in a 20 ns time window starting 20 ns after the end of the L_1 and/or L_2 excitation pulses. This allows for studying of long-lived IXs after DXs recombined. Both IX_2 and IX_1 have long lifetime in the range of hundreds of ns allowing them to travel over long distances reaching hundreds of microns. The measurements are performed at 1.7 K.

Figures 1a,c show that the increase of L_2 power and, in turn, IX_2 density leads to a monotonic decrease of IX_1 energy. An energy decrease corresponds to attractive IX_1–IX_2 interaction. In comparison, the increase of L_2 power leads to a monotonic increase of IX_2 energy (Fig. 1b,d). An energy increase corresponds to repulsive IX_2–IX_2 interaction, which has been studied in single layers of IXs [1]. Figure 1d shows that in the combined effect of attractive and repulsive interactions, the repulsive interaction dominates the IX_2 energy shift, consistent with their relative strength (Fig. 1a,b).

We analyze the dipolar interaction in IX bilayers theoretically. The numerical simulation of such two-species many-body system is done through the hyper-netted chain formalism. The simulations show that the increase of n_2 leads to a monotonic decrease of IX_1 energy due to the attractive IX_1–IX_2 interaction (Fig. 1e), in qualitative agreement with the experimental data in Fig. 1a. In contrast, the increase of n_2 leads to a monotonic increase of IX_2 energy (Fig. 1f) due to the repulsive IX_2–IX_2 interaction, in qualitative agreement with the experimental data in Fig. 1b.

The density correlation functions for the cases of attractive IX_1–IX_2 and repulsive IX_1–IX_1 and IX_2–IX_2 interactions are presented in Fig. 1g and 1h, respectively. For the attractively interacting IXs, the correlation peak (Fig. 1g) increases the interaction energy compared with the vanishing interlayer interaction in the mean-field approximation. On the contrary, the repulsively interacting IXs avoid each other (Fig. 1h) that lowers the intralayer IX interaction energy compared with the uncorrelated state assumed in the mean-field approximation.

We also studied the effects of IX dipolar interactions on the IX cloud position. Both our experimental measurements and theoretical simulations show that the IX_1 cloud attracts to the IX_2 cloud (Fig. 2). In comparison, both our measurements and simulations show that two clouds of repulsively interacting IX_2 repel each other.

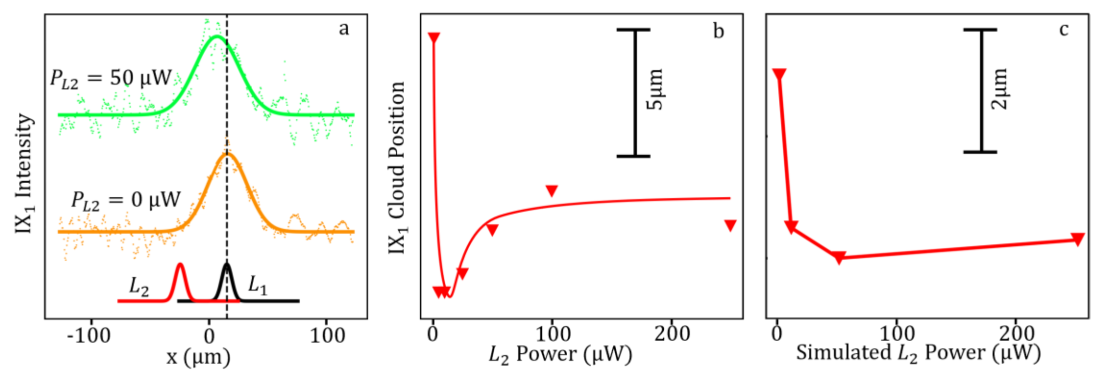

Figure 2: (a) The measured IX_1 cloud profiles at different P_{L2} and, in turn, IX_2 densities. P_{L1} = 10μW. The profiles of L_1 and L_2 laser excitation spots are shown by black and red lines, respectively. Dashed line indicates the center of L_1 excitation spot. (b,c) The measured (b) and calculated (c) center of mass position of the IX_1 cloud as a function of P_{L2}. P_{L1} = 50 μW. The IX_1 cloud attracts to the IX_2 cloud.

In both experimental measurements and theoretical simulations, we found that increasing the density of IXs in one layer causes a monotonic energy reduction for IXs in the other layer. We also found an attraction of a cloud of IXs in one layer to a cloud of IXs in the other layer. This behavior originates from the attractive dipolar interaction. The measured IX energy reduction and IX cloud shifts are higher than the values given by the correlated liquid theory.

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