P-shell exciton complexes with neutral-exciton-like exchange interaction in CdTe/ZnTe quantum dots

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Carrier-carrier interactions are an important factor determining energy of exciton complexes in self-assembled quantum dots (QDs). In particular, the fine structure of a given excitonic complex is a result of the exchange interaction. For example, in the simplest case of the neutral exciton consisting of a single electron and a single hole there are four eigenstates with characteristic energy spectrum of a pair of bright states separated from a pair of dark states by energy commonly denoted by δ_0. This *isotropic* exchange splitting is usually accompanied by a smaller *anisotropic* exchange splitting of the two bright states by energy δ_1. Such a picture is known to be valid for the ground state neutral exciton in different material systems. In general, more complex excitons exhibit more complex spectra. However, in our work we demonstrate that the same pattern of exchange interaction can be observed for a few other excitonic complexes.

Here we focus on two exciton complexes: a "hot" neutral exciton with both carriers on the *p*-shell and a doubly negatively charged exciton (X^{2-}) recombining to a two-electron singlet state. By using either the excitation spectroscopy or the non-resonant photoluminescence we show that in both cases the optical spectrum features a single pair of orthogonally polarized lines, in close analogy to the neutral exciton. Similarly, in each case the magnetic field in Faraday configuration increases the observed splitting according to a general formula: $\sqrt{(g\mu_B B)^2 + \delta_1^2}$. By applying the magnetic field in Voigt configuration or by comparison against the emission to the triplet state in the case of X^{2-} we additionally determine the corresponding isotropic exchange constant δ_0. As a result, we fully describe three cases of exchange interaction: between *s*-shell electron and *s*-shell hole (from the neutral exciton), between *p*-shell electron and *p*-shell hole (from the "hot" neutral exciton), and between *p*-shell electron and *s*-shell hole (from the doubly negatively charged exciton).

We conclude that both *p*-shell neutral exciton and doubly negatively charged exciton are viable substitutes for the neutral exciton regarding the structure of the energy spectrum, which opens a possibility to explore different regimes of exchange parameter values. A proof-of-concept for this idea is an observation of a characteristic 6-fold splitting of doubly negatively charged exciton in a QD doped with a single Mn^{2+} ion.

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