Magnetic field effect on quaternion excitonic complexes in bilayer structures near metals

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Two-dimensional monolayer structures of transition metal dichalcogenides (TMDCs) have been shown to allow many higher order excitonic bound states such as trions (charged excitons), biexcitons (excitonic molecules), and charged biexcitons. Recently [1], an atom-like excitonic structure was reported experimentally in bilayer TMDs in accord with theory predictions – the quaternion (Fig.1, left) – a complex of a free charge carrier in top layer bound to a like-charge trion in bottom layer placed close to a parallel metal layer to screen the excessive repulsive interaction in the system. Because they carry two net charges and are also bosonic, a Bose-Einstein condensate (BEC) of these would be a superfluid, and therefore also a Schafroth superconductor [2,3]. Here, we develop a theoretical framework to explain the latest experimental observations of the Zeeman effect for quaternion complexes in perpendicular magnetostatic field [4]. Our theory is based on group theoretical analysis and spin-Hamiltonian formalism. We show that, contrary to the linear Zeeman shift known for excitons/trions in TMDC monolayers [5], the quaternion ground state is the spin triplet to exhibit a quadratic magnetic field shift (Fig1, right) similar to that known for hydrogen-like atoms (with difference being that their ground state is singlet). In addition to a novel superconductivity mechanism, another fascinating possibility is that, since quaternion complexes have long-range Coulomb repulsion, they could form a bosonic Wigner crystal at low temperature, and in principle, could even become an ‘atom-like’ supersolid. The process of Wigner crystallization is controlled by the ratio of the Coulomb repulsion energy over the average kinetic energy of an ensemble of charged particles [6]. Due to their double charge and triple mass as compared to electrons, this ratio is at least 10 times greater for quaternions, suggesting a much higher Wigner crystallization temperature than that of the order of 10 K recently reported for quasi-2D electrons in TMDC nanostructures [7].

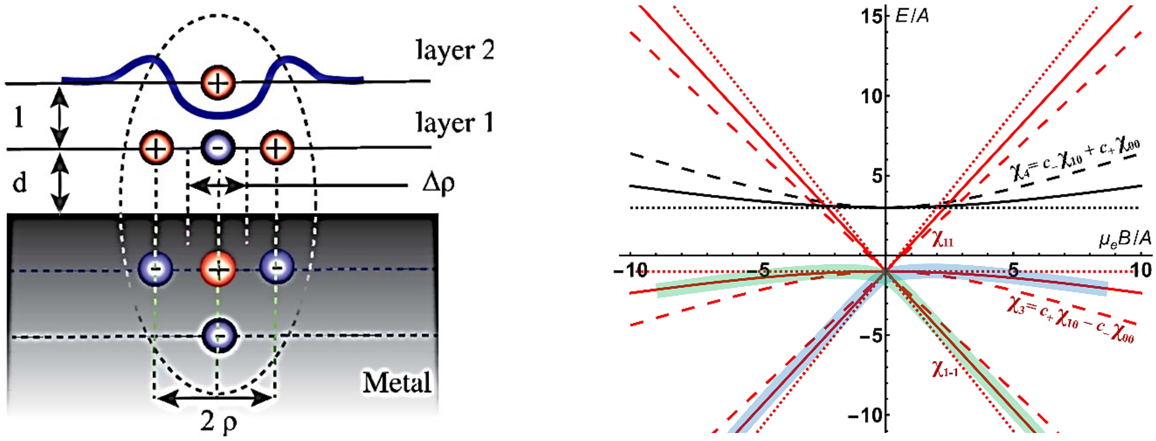

Figure 1: (*Left*) Schematic of the quaternion excitonic complex formed by an electron and three holes near metallic surface due to the partial screening of excessive repulsion by image charges inside metal [1]. (*Right*) Theoretical magnetic field dependences for the spin states (indicated) of the quaternion treated as coupled (with constant A) system of spin-1/2-trion and electron in bottom and top layer, respectively [4]. Shown are the triplet (red) and singlet (black) quaternion energy levels calculated for trion-to-electron magnetic moment ratio $\zeta = 0.5$, 0.73 and 1 (dashed, solid and dotted lines, respectively). The green and purple bands show the lowest energy quaternion states that emit photons of right and left circular polarizations measured experimentally [4].

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