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Excitons

- An **exciton** is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force.

- Attraction between the electron and the hole causes their motion to be correlated and the resultant electron-hole pair is known as an exciton.

- It is an electrically neutral quasiparticle that exists in insulators, semiconductors and some liquids.

- The exciton is regarded as an elementary excitation of condensed matter that can transport energy without transporting net electric charge.

- As in any two particle systems, the exciton motion can be decomposed into two parts: a center-of-mass (CM) motion and a relative motion of the two particles about the CM.

- With this decomposition, the potential acting on the exciton CM still has translational invariance since the Coulomb interaction depends only on the relative coordinate of the electron and hole.

- Within the effective mass approximation, the exciton CM behaves like a free particle with mass

$$M=m_e+m_h$$

The relative motion of the electron and the hole in the exciton is similar to that of the electron and the proton inside the H atom.

How Exciton formed?

- ✓ An exciton in semiconducting materials can form when a material absorbs a photon of higher energy than its bandgap (hv is greater than Eg).

- ✓ The photon, excites an electron from the valence band into the conduction band consecutively, this leaves behind a positively charged hole.

- ✓ The electron in the CB is then effectively attracted to this localized hole by the repulsive Coulomb forces from large numbers of electrons surrounding the hole and excited electron.

- ✓ This attraction provides a stabilizing energy balance. Consequently, the exciton has slightly less energy than the unbound electron and hole.

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Classifications of excitons:

Typically excitons have been studied in the two limiting cases:

(1) Frenkel excitons

- ✓ For strong electron-hole attraction, as in ionic crystals, the electron and the hole are tightly bound to each other within the same or nearest-neighbor unit cells.
- ✓ In materials with a relatively small dielectric constant, the Coulomb interaction between an electron and a hole may be strong and the excitons thus tend to be small, of the same order as the size of the unit cell.
- ✓ Molecular excitons may even be entirely located on the same molecule, as in fullerenes.
- ✓ This *Frenkel exciton*, named after Yakov Frenkel, has a typical binding energy on the order of 0.1 to 1 eV.
- ✓ Frenkel excitons are typically found in alkali halide crystals and in organic molecular crystals composed of aromatic molecules, such as anthracene and tetracene.

(2) Wannier-Mott excitons

- ✓ In most semiconductors, the Coulomb interaction is strongly screened by the valence electrons via the large dielectric constant, i.e. electrons and holes are only weakly bound.
- ✓ Wannier-Mott excitons are typically found in semiconductor crystals with small energy gaps and high dielectric constants, but have also been identified in liquids, such as liquid xenon. They are also known as *large excitons*.
- ✓ In semiconductors, the dielectric constant is generally large. Consequently this tends to reduce the Coulomb interaction between electrons and holes, which has a radius larger than the lattice spacing
- ✓ Small effective mass of electrons that is typical of semiconductors also favors large exciton radii
- ✓ The Wannier-Mott excitons and their properties can be calculated with the effective mass approximation.
- ✓ Within this approximation, the electron and the hole are consider two particles moving with the effective masses of the conduction and the valence bands, respectively.
- ✓ In single-wall carbon nanotubes, excitons have both Wannier-Mott and Frenkel character. This is due to the nature of the Coulomb interaction between electrons and holes in one-dimension.

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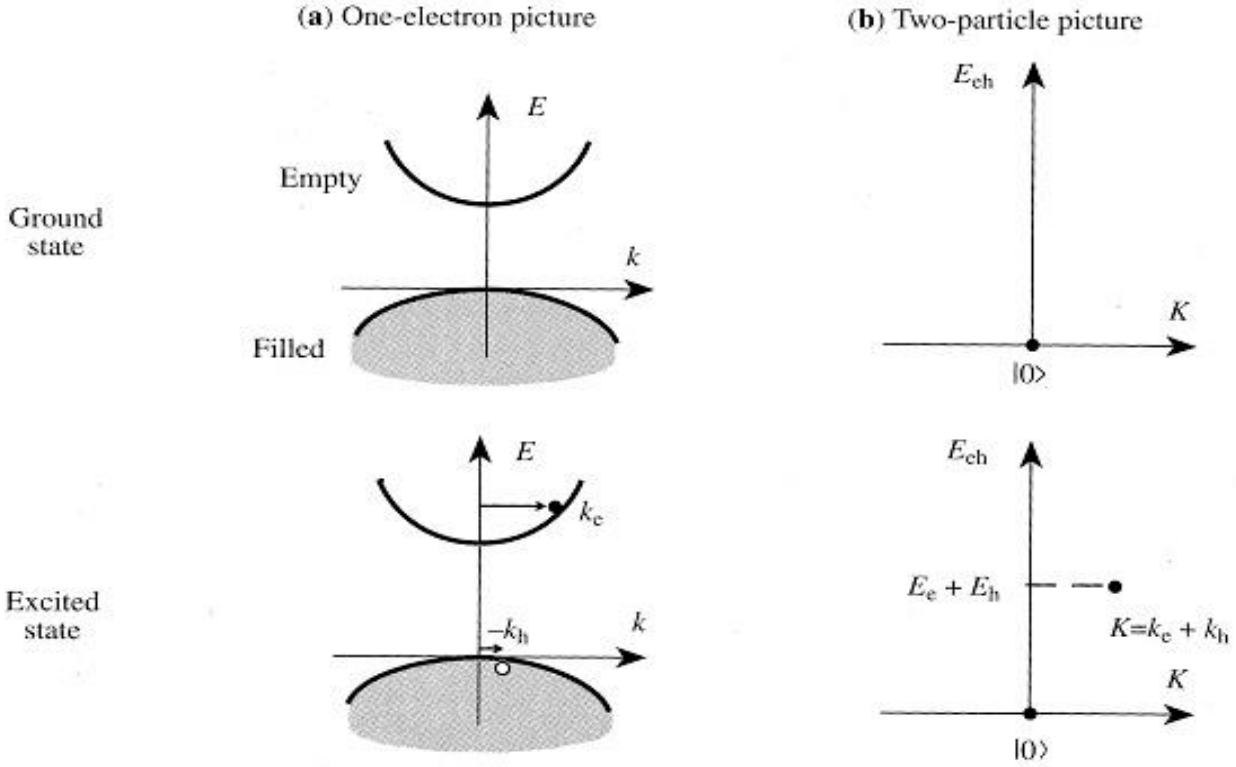
Note: Generally, diagrams in which the exciton energy levels are shown superimposed to a one-electron energy band structure. This is incorrect, since the exciton is a two-particle state and its energy levels cannot be represented by one electron energy levels.



- Ground state: no e-h pairs, this state is represented by the origin in the two-particle picture.
- Excited state is an exciton $E_{eh}=E_e+E_h$
- In the two-particle picture, the exciton wavevector $\mathbf{K}=\mathbf{k}_e+\mathbf{k}_h$

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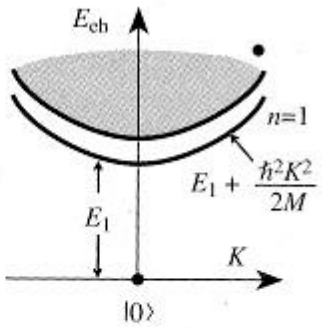
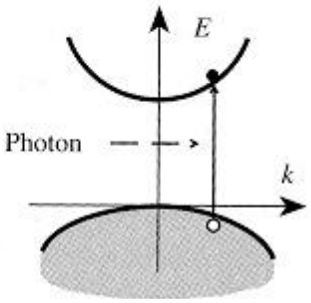
One or two- particle picture: Optical transitions:

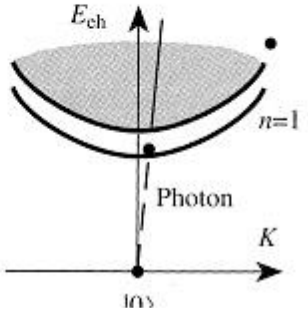
Correlated e – h pair (exciton)

Cannot be represented in one-electron picture



Optical absorption





$$E_{ke} = \frac{\hbar^2 K^2}{2M}$$

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Table 6.4. Exciton binding energy (R^*) and Bohr radius (a_0) in some direct bandgap semiconductors. The three semiconductors labeled (W) have the wurtzite crystal structure while the others have the zinc-blende structure. Experimental values of R^* and a_0 are from [Ref. 6.40, p. 155, 41]. The theoretical values of R^* are from [6.38]

Semiconductor	R^* [meV]	R^* (theory) [meV]	a_0 [Å]
GaAs	4.9	4.4	112
InP	5.1	5.14	113
CdTe	11	10.71	12.2
ZnTe	13	11.21	11.5
ZnSe	19.9	22.87	10.7
ZnS	29	38.02	10.22
ZnO (W)	59		
CdSe (W)	15		
CdS (W)	27		