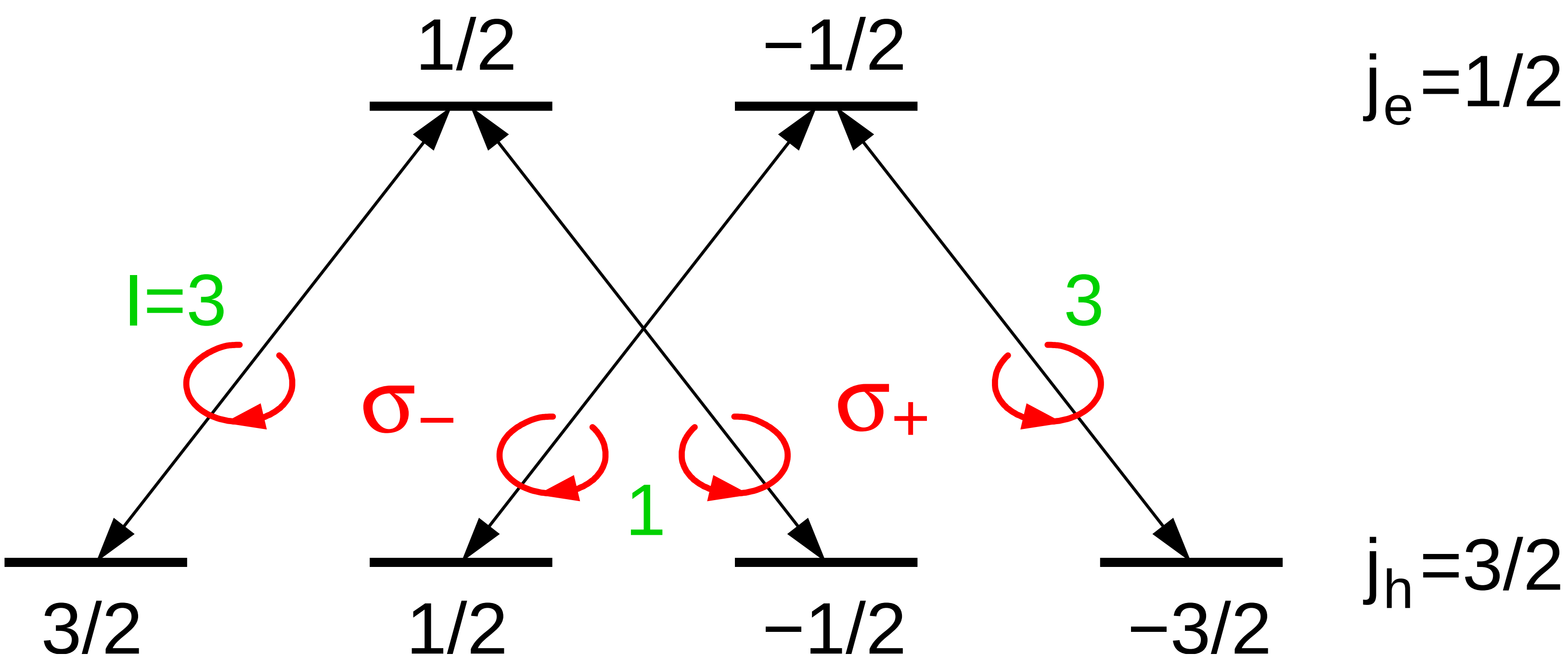
Optical Spin Orientation



Free Electron-Hole Transitions

electrons in a radiation field

$$\mathbf{A} = \hat{\mathbf{e}}\, A_0\, \mathrm{e}^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \qquad \hat{\mathbf{e}} = \text{polarization vector}$$

$$\Rightarrow \quad H = H_0 + \frac{e}{m}\mathbf{A}\cdot\mathbf{p} + \cancel{\frac{e^2}{2m}|\mathbf{A}|^2}$$

absorption coefficient

$$\alpha(\omega) = \frac{\text{energy absorbed per unit time and area}}{\text{energy flux of the radiation field}}$$

$$\propto \quad W_{v\to c}(\omega) \qquad \text{(transition probability } v \to c\text{)}$$

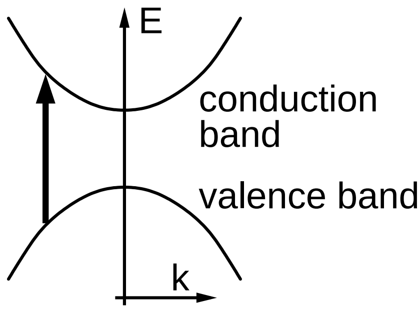
Fermi's golden rule

$$W_{v\to c}(\omega) = \frac{2\pi}{\hbar} \sum_{\substack{c,\,v \\ \mathbf{k}_c,\,\mathbf{k}_v}} \left| \left\langle c\mathbf{k}_c \left| \frac{e}{m} A_0\, \mathrm{e}^{i\mathbf{k}\cdot\mathbf{r}}\, \hat{\mathbf{e}}\cdot\mathbf{p} \right| v\mathbf{k}_v \right\rangle \right|^2 \times \delta[E_c(\mathbf{k}_c) - E_v(\mathbf{k}_v) - \hbar\omega]$$

dipole approximation

$$\mathrm{e}^{i\mathbf{k}\cdot\mathbf{r}} = 1 \cancel{+ i\mathbf{k}\cdot\mathbf{r} + \ldots}$$

$$\Rightarrow \quad \mathbf{k}_c = \mathbf{k}_v$$



finally

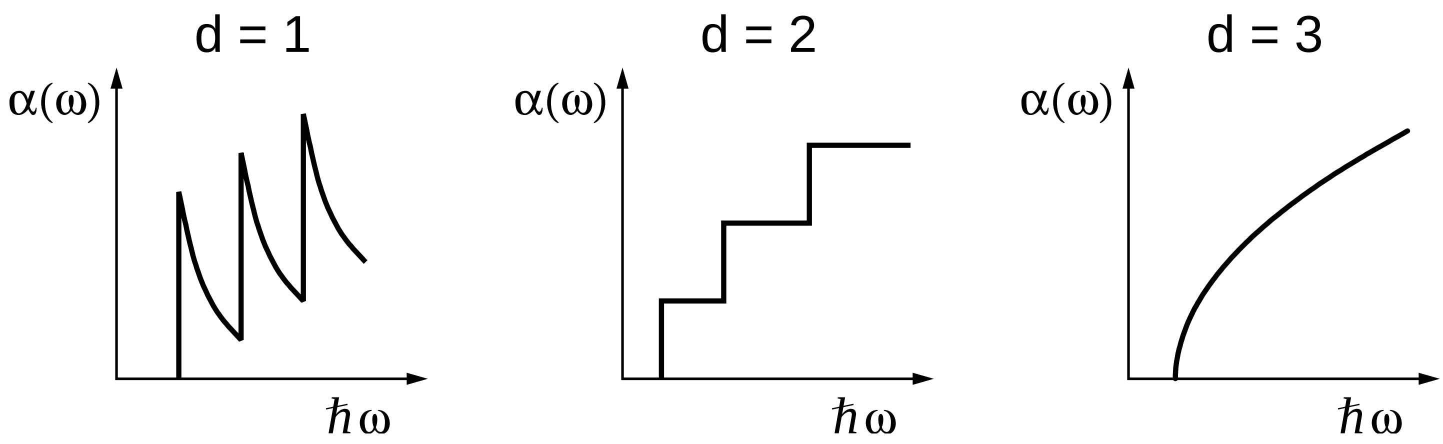
$$\boxed{\begin{aligned} \alpha(\omega) &\propto \sum_{c,v,\mathbf{k}} f_{cv}(\mathbf{k})\, \delta[E_c(\mathbf{k}) - E_v(\mathbf{k}) - \hbar\omega] \\ f_{cv}(\mathbf{k}) &= \frac{2}{m\,[E_c(\mathbf{k}) - E_v(\mathbf{k})]}\, |\langle c\mathbf{k}|\hat{\mathbf{e}}\cdot\mathbf{p}|v\mathbf{k}\rangle|^2 \\ &\qquad \text{(oscillator strength)} \end{aligned}}$$

Free Electron-Hole Transitions (2)

often $\quad f_{cv}(\mathbf{k}) \approx \mathrm{const}(\mathbf{k})$

$\Rightarrow$ joint density of states $\qquad d =$ dimensionality

$$\alpha(\omega) \propto \sum_{c,v} f_{cv} \cdot [\hbar\omega - E_c(0) + E_v(0)]^{d/2-1}$$



selection rules

$$f_{cv} \neq 0 \quad \Leftrightarrow \quad \langle c|\hat{\mathbf{e}} \cdot \mathbf{p}|v\rangle \neq 0$$

2D Excitons (strictly 2D)

assumptions

- ignore perpendicular motion of electrons & holes
- parabolic energy dispersion

$$\left(\frac{p_e^2}{2m_e^*}+\frac{p_h^2}{2m_h^*}-\frac{e^2}{\varepsilon\,|\mathbf{r}_e-\mathbf{r}_h|}\right)\Psi_{\text{ex}}(\mathbf{r}_e,\mathbf{r}_h)=E_{\text{ex}}\,\Psi_{\text{ex}}(\mathbf{r}_e,\mathbf{r}_h)$$

$\sim$ 2D hydrogen

effective Rydberg $$\mathcal{R}^* = \left(\frac{e^2}{2\,\epsilon}\right)^2\frac{2m_r}{\hbar^2} = \frac{m_r}{m_0}\frac{1}{\epsilon^2}\cdot\mathcal{R}$$

effective Bohr radius $$a_B^* = \frac{2\,\epsilon}{e^2}\frac{\hbar^2}{2m_r} = \frac{m_0}{m_r}\epsilon\cdot a_B$$

where $$\frac{1}{m_r}=\frac{1}{m_e}+\frac{1}{m_h}$$

excitonic absorption

$$\begin{aligned} f_{\text{ex}} &= \frac{2}{m_0\,E_{\text{ex}}}\left|\sum_{\mathbf{k}}\Psi_{\text{ex}}(\mathbf{k})\,\langle c\mathbf{k}|\hat{\mathbf{e}}\cdot\mathbf{p}|v\mathbf{k}\rangle\right|^2 \\ &\approx \frac{2}{m_0\,E_{\text{ex}}}\left|\langle c|\hat{\mathbf{e}}\cdot\mathbf{p}|v\rangle\right|^2\ \underbrace{\left|\sum_{\mathbf{k}}\Psi_{\text{ex}}(\mathbf{k})\right|^2}_{=\left|\Psi_{\text{ex}}(\mathbf{r}=0)\right|^2} \end{aligned}$$

Effective Rydberg and effective Bohr radius

effective Rydberg $\mathcal{R}^* = \left(\frac{e^2}{2\,\epsilon}\right)^2 \frac{2m_r}{\hbar^2} = \frac{m_r}{m_0}\frac{1}{\epsilon^2}\cdot\mathcal{R}$

effective Bohr radius $a_B^* = \frac{2\,\epsilon}{e^2}\frac{\hbar^2}{2m_r} = \frac{m_0}{m_r}\epsilon\cdot a_B$

where $\frac{1}{m_r} = \frac{1}{m_e} + \frac{1}{m_h}$

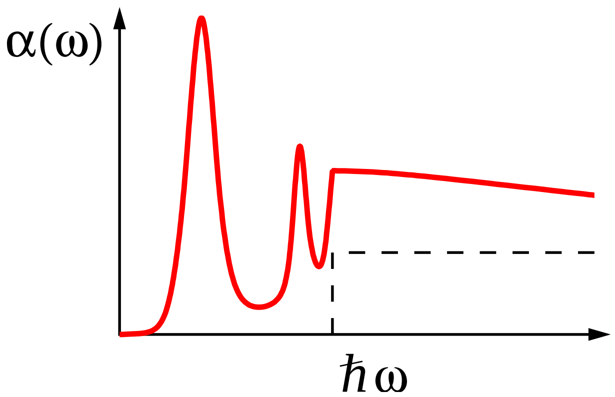
	H	ZnSe	CdTe	GaAs	InAs	InSb
m_r/m_0	1	0.103	0.0683	0.0453	0.0156	0.0092
ε	1	8.66	10.23	12.87	14.6	17.9
$\mathcal{R}^*$ (meV)	$13.6\cdot 10^3$	18.68	8.876	3.722	0.996	0.389
a_B^* (Å)	0.529	44.5	79.3	150.3	495.0	1032.9

2D Excitons

$$E_n = -\frac{\mathcal{R}^*}{\left(n+\frac{1}{2}\right)^2} \qquad n = 0, 1, 2 \ldots$$

$$f_n \propto \frac{1}{\pi\, {a_B^*}^2 \left(n+\frac{1}{2}\right)^3}$$

$$S(E) \propto \frac{\mathrm{e}^{\pi\lambda}}{\cosh(\pi\lambda)} \qquad \lambda = \sqrt{\mathcal{R}^*/E}, \quad E > 0$$

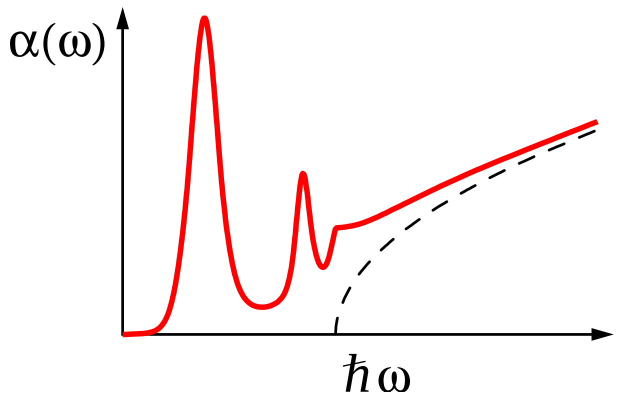


3D Excitons

$$E_n = -\frac{\mathcal{R}^*}{n^2} \qquad n = 1, 2, 3 \ldots$$

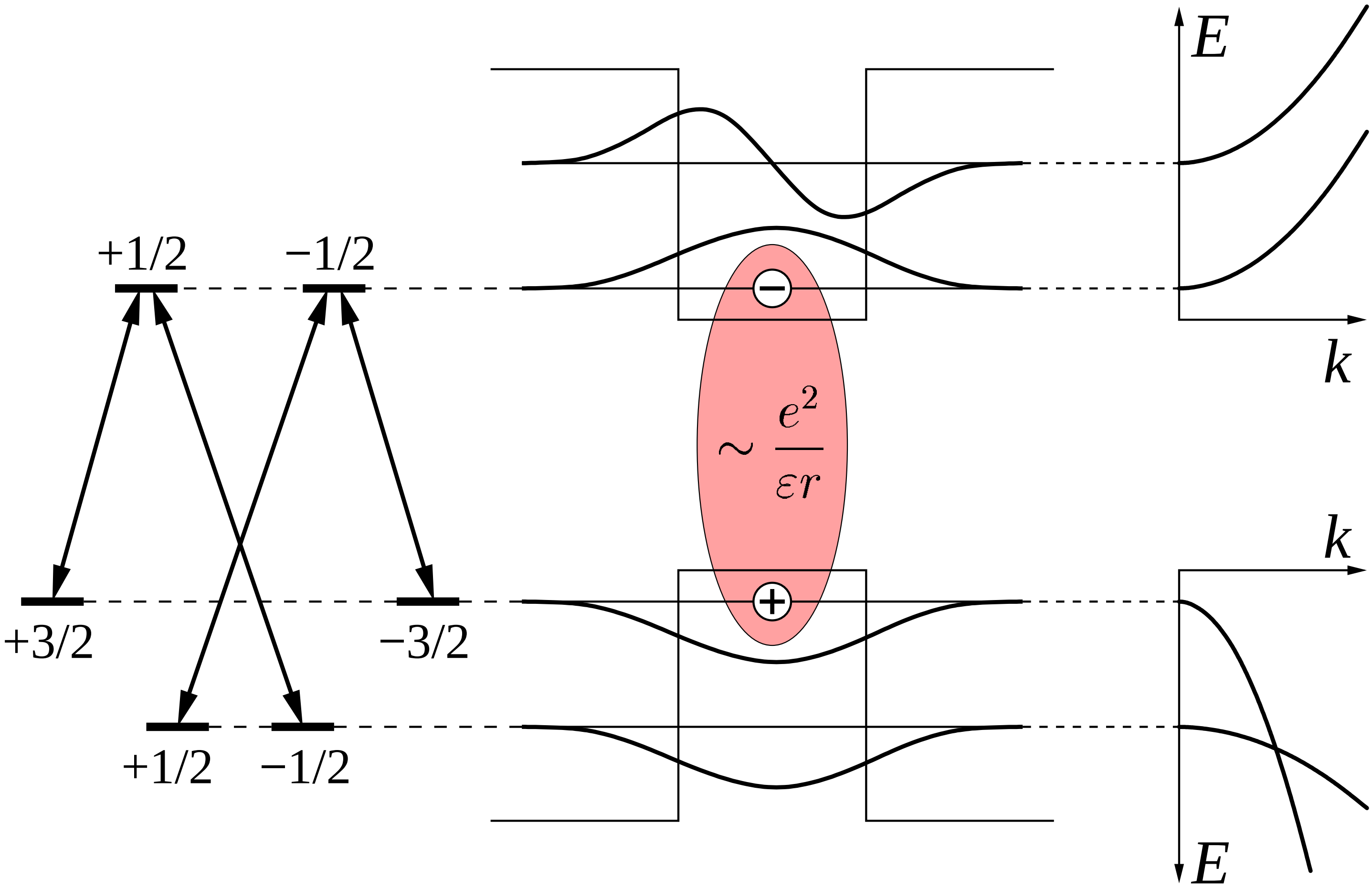
$$f_n \propto \frac{1}{\pi\, {a_B^*}^3\, n^3}$$

$$S(E) \propto \frac{\pi\, \mathrm{e}^{\pi\lambda}}{\sinh(\pi\lambda)} \qquad E > 0$$

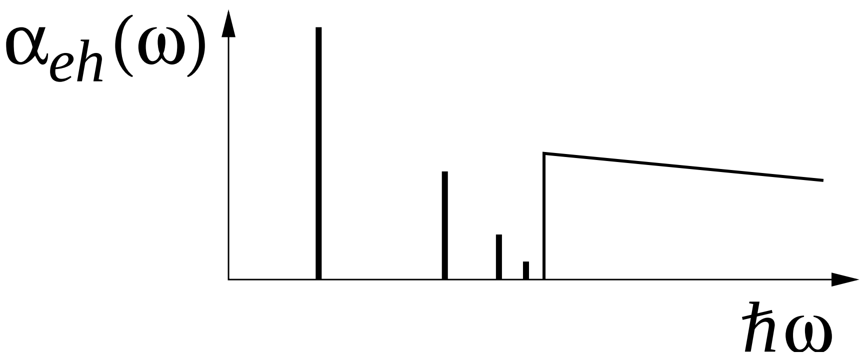


2D Excitonic Absorption:

Simple Picture

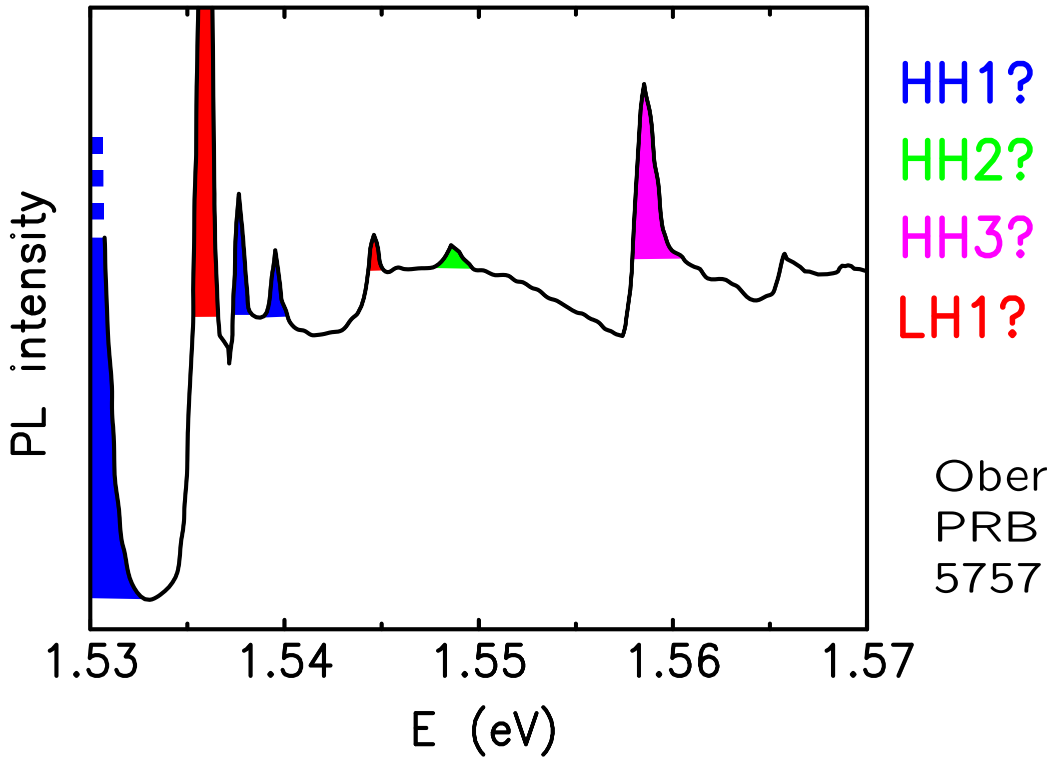


each subband pair (e, h) contributes independently to absorption coefficient $\alpha(\omega) = \sum_{e,h} \alpha_{eh}(\omega)$



Optical Spectra

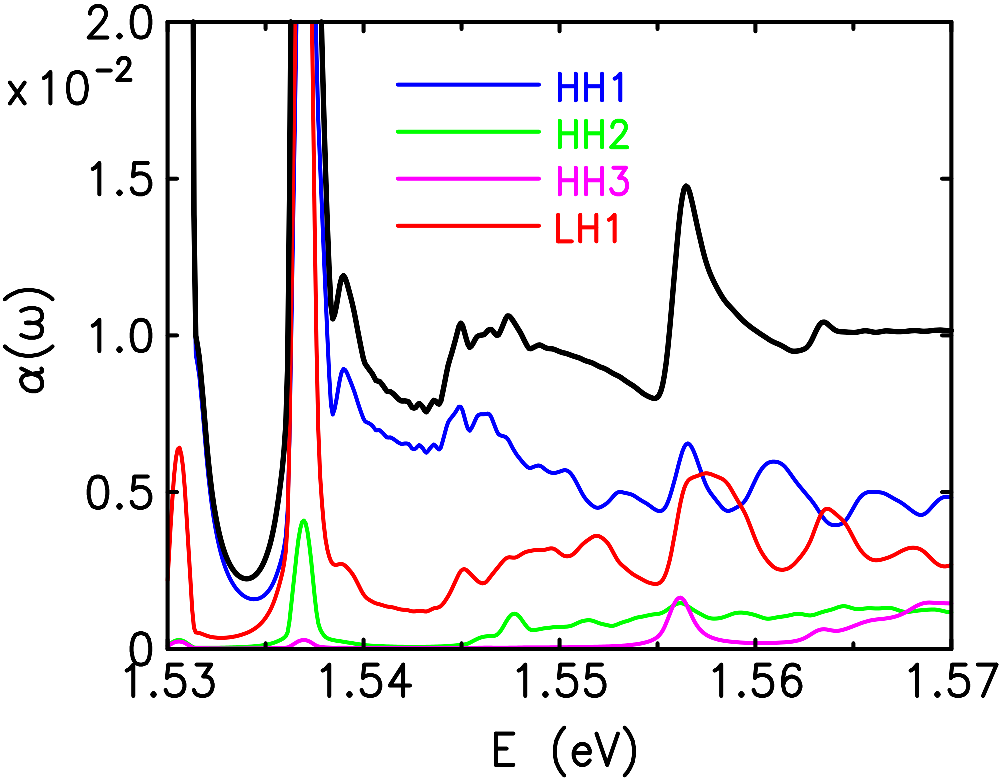
Experiment



Oberli et al.
PRB **49**
5757 (1994)

Theory

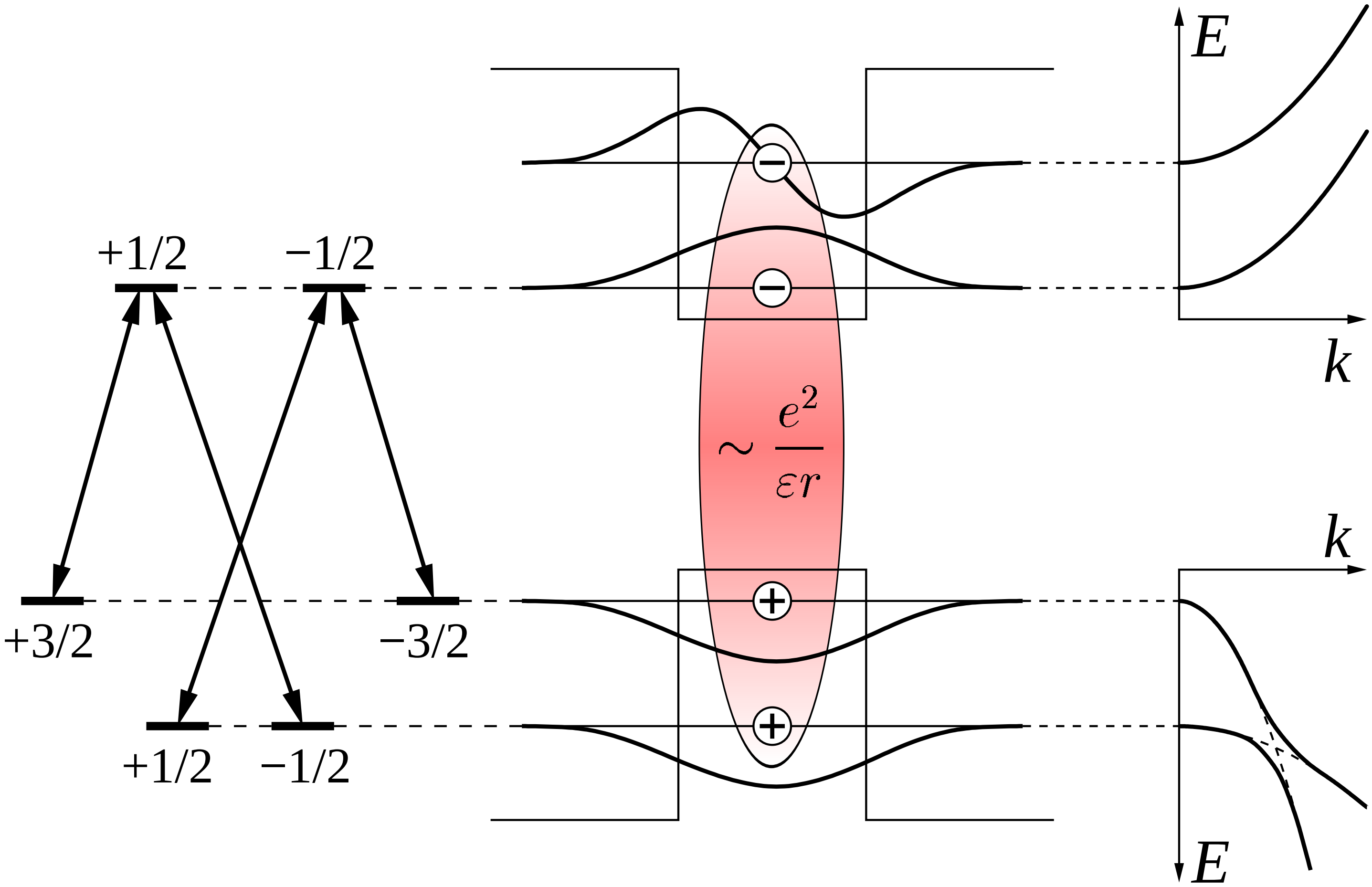
GaAs QW
165 Å



Winkler
PRB **51**
14 395 (1995)

2D Excitonic Absorption:

"in real life"



$$\Psi_{\text{ex}} = \overbrace{\sum_c \sum_v}^{\text{Coulomb coupling}} \underbrace{\int \mathrm{d}k^2 \; \Psi_{cv}^{\text{ex}}(\mathbf{k})}_{\text{HH-LH coupling}} \; \psi_c(\mathbf{k}) \; \psi_v^*(\mathbf{k})$$

$$f_{\text{ex}} = \frac{2}{m\,E_{\text{ex}}} \left| \sum_{c,v,\mathbf{k}} \Psi_{\text{cv}}^{\text{ex}}(\mathbf{k})\, \psi_c(\mathbf{k}) \; \psi_v^*(\mathbf{k}) \; \langle c\mathbf{k} | \hat{\mathbf{e}} \cdot \mathbf{p} | v\mathbf{k} \rangle \right|^2$$