Foundations of excitonic polaritons

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Getting into polaritons without knowing it: **1970**
The evidence of excitonic polaritons in ultra-pure GaAs

3D excitons in a 3D photon environment

Measurements of 3D X-polaritons **1976-1980**: dispersion curve, resonant fluorescence, resonant electron scattering

Moving to the 2D world of the **80'ies**: quantum wells and efficient luminescence (Bell laboratories)

2D excitons in a 3D photon environment

2D excitons in microcavities: 2D cavity polaritons **1991 –**

2D excitons in a 2D photon environment

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DE GRUYTER Nanophotonics 2021; 10(1): 549–577

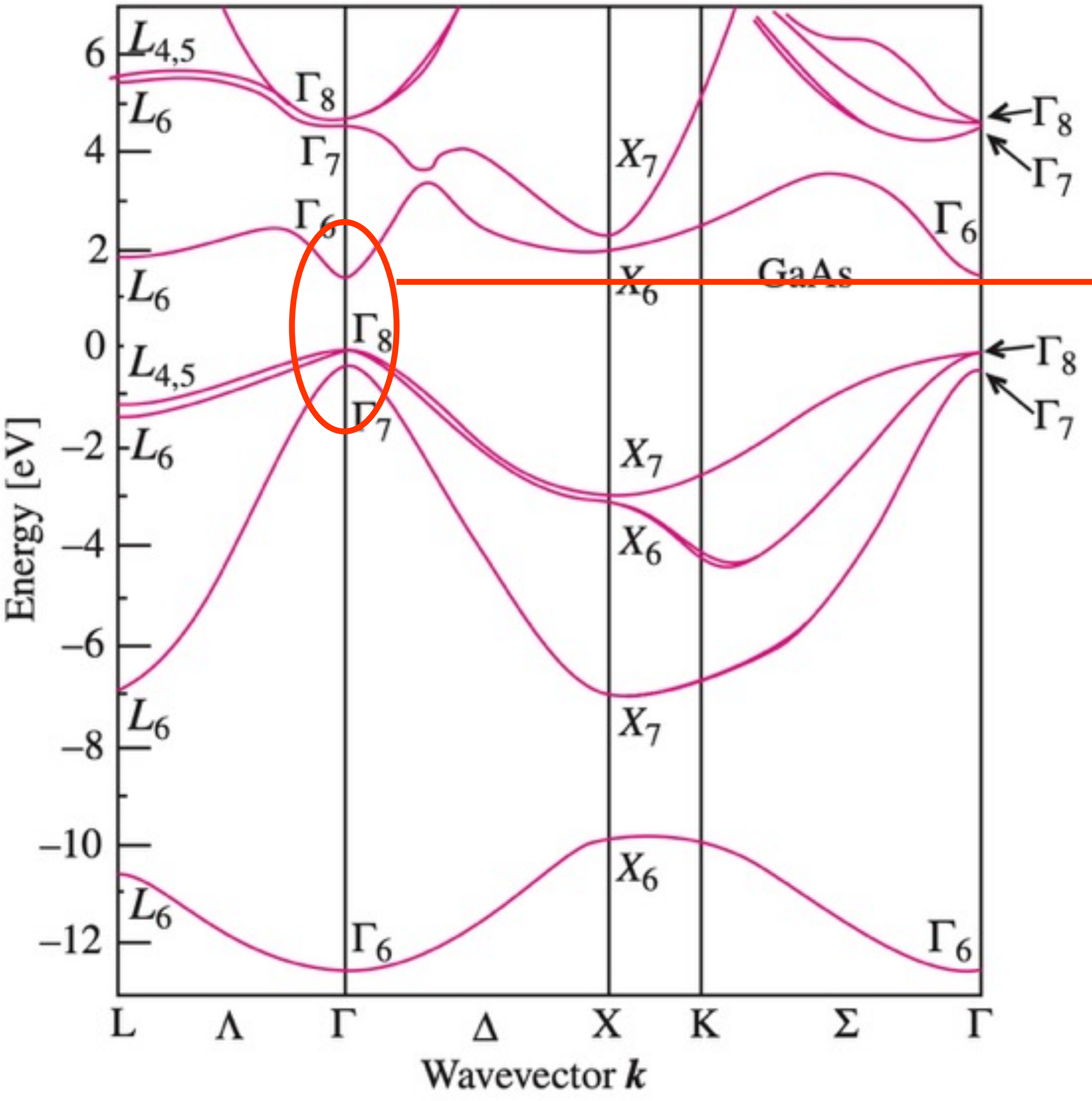
Review

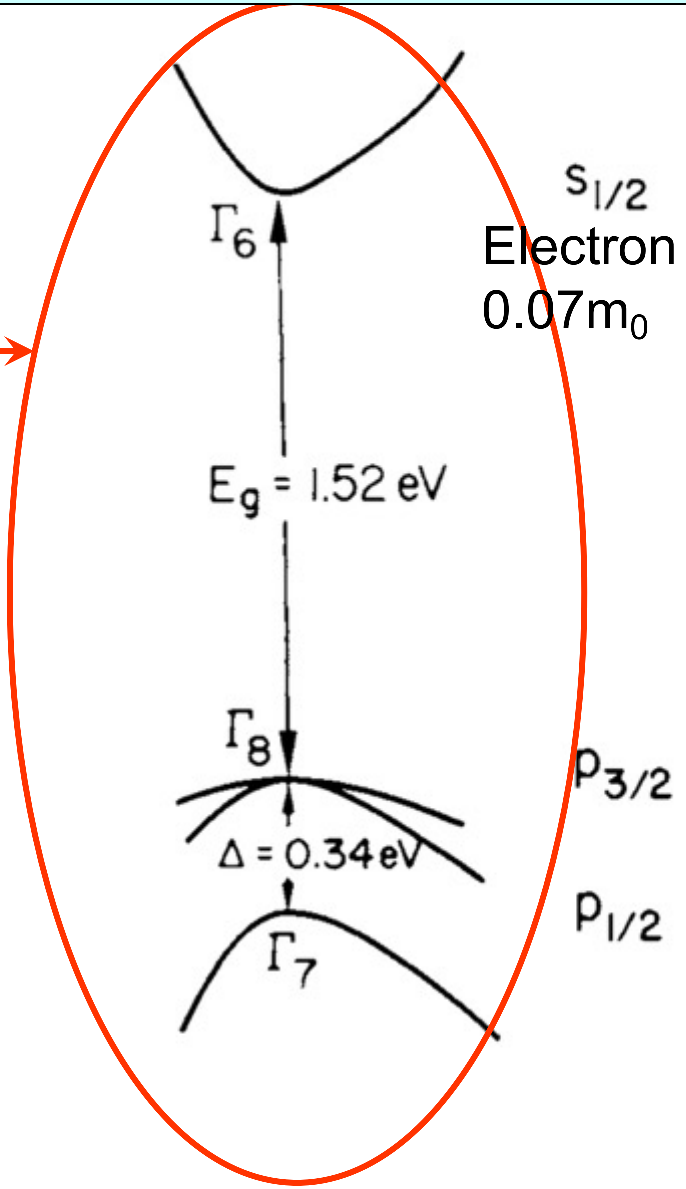
D. N. Basov*, Ana Asenjo-Garcia, P. James Schuck, Xiaoyang Zhu and Angel Rubio

Polariton panorama

Abstract: In this brief review, we summarize and elaborate on some of the nomenclature of polaritonic phenomena and systems as they appear in the literature on quantum materials and quantum optics. Our summary includes at least 70 different types of polaritonic light–matter dressing effects. This summary also unravels a broad panorama of the physics and applications of polaritons.

Band structure (electronic dispersion curves) for Gallium Arsenide (GaAs)



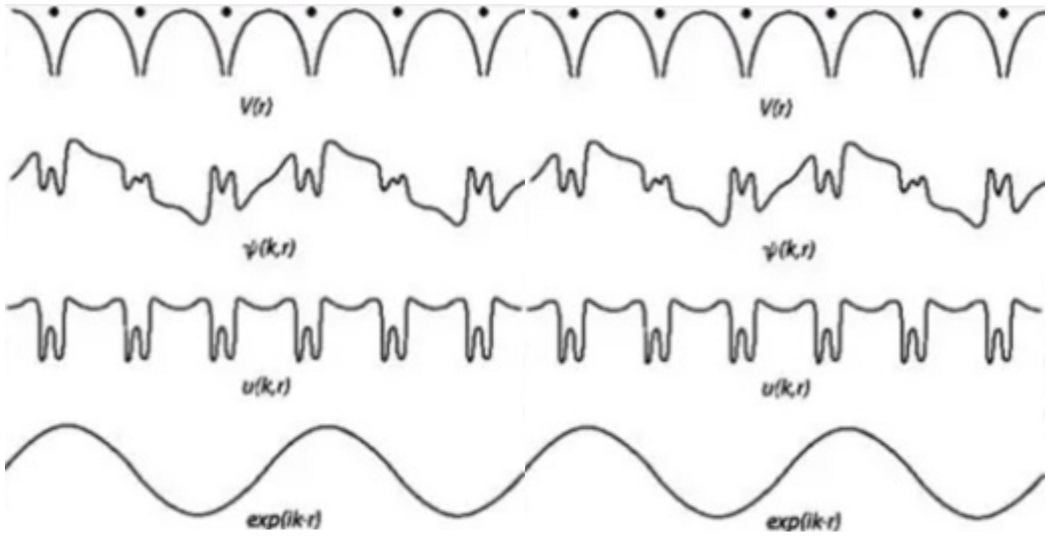


Electron effective mass
$0.07m_0$

Hole effective mass
Heavy hole $0.4\ m_0$
Light hole $0.06\ m_0$

Wavefunctions in an infinite perfect periodic crystal

Solution of the Schrödinger equation with a periodic potential are Bloch wavefunctions:
product of a periodic part and an enveloppe plane wave



Lattice ion periodic potential

Bloch wavefunction

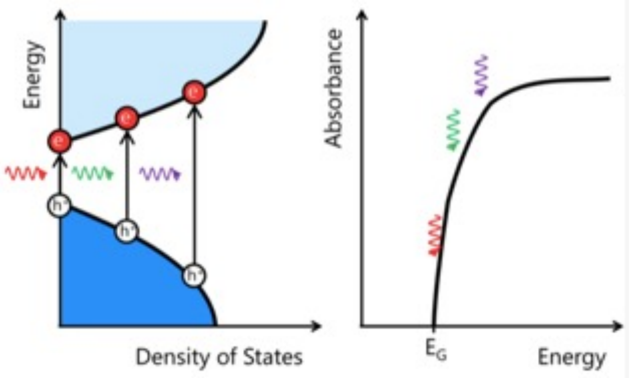
Periodic part of the Bloch wavefunction

Enveloppe wavefunction

This is true for electrons and holes, but …,
when there is Coulomb interaction, the true excitations are not separated electrons and holes,
but **excitons** (which also have translational symmetry), **Coulomb bound electrons and holes**

Electron-hole Coulomb interaction: exciton effects in ordered semiconductors

no Coulomb interaction



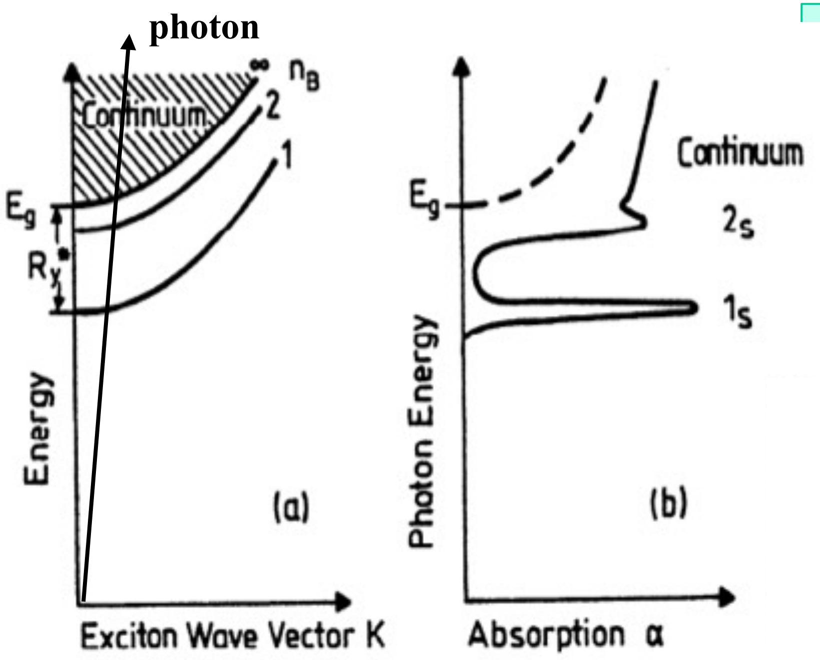
$$\left(-\frac{\hbar^2}{2m_e^*}\Delta_{\mathbf{r}_e} - \frac{\hbar^2}{2m_h^*}\Delta_{\mathbf{r}_h} - \frac{e^2}{\varepsilon_0\varepsilon_r|\mathbf{r}_e - \mathbf{r}_h|}\right)\Psi = E\Psi$$

- **Separation of variables:** $\mathbf{R} = \dfrac{m_e\mathbf{r}_e + m_h\mathbf{r}_h}{m_e + m_h}$, $\mathbf{r} = \mathbf{r}_e - \mathbf{r}_h$

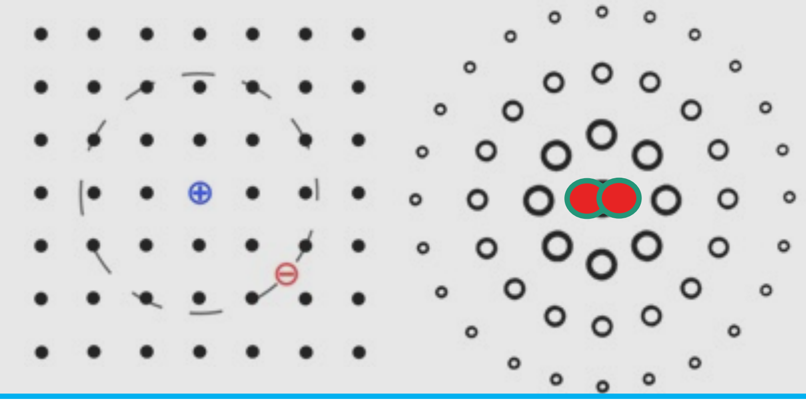
$$\Psi\ (r_e, r_h) = F(R)g(r_e\text{-}r_h)$$

$$E_{\text{ex}}(n_{\text{B}}, \boldsymbol{K}) = E_{\text{g}} - \text{Ry}^*\frac{1}{n_{\text{B}}^2} + \frac{\hbar^2\boldsymbol{K}^2}{2M}$$

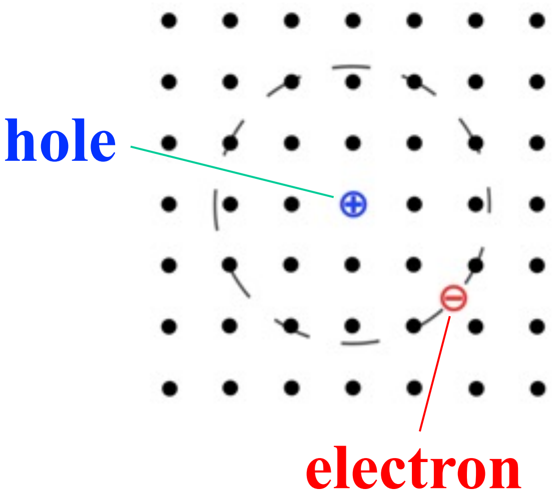
F(R) center of mass wavefunction is a plane wave e^{iKR}
g(r) relative electron-hole wavefunction is hydrogenoid with quantum numbers n=1, 2, 3…



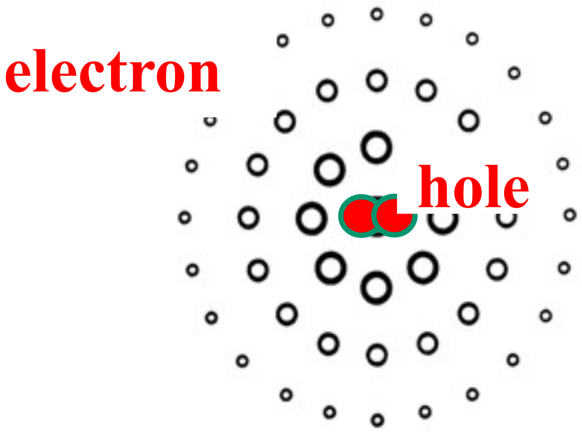
In homogeneous semiconductors - excitons
hydrogen-like wavefunction of electrons around hole



Free excitons parameters



$$\Psi(\mathbf{r}_e, \mathbf{r}_h) = f(\mathbf{R})\, g(\mathbf{r})$$



n=1 bounded pair hydrogenoid
wavefunction of relative e-h motion

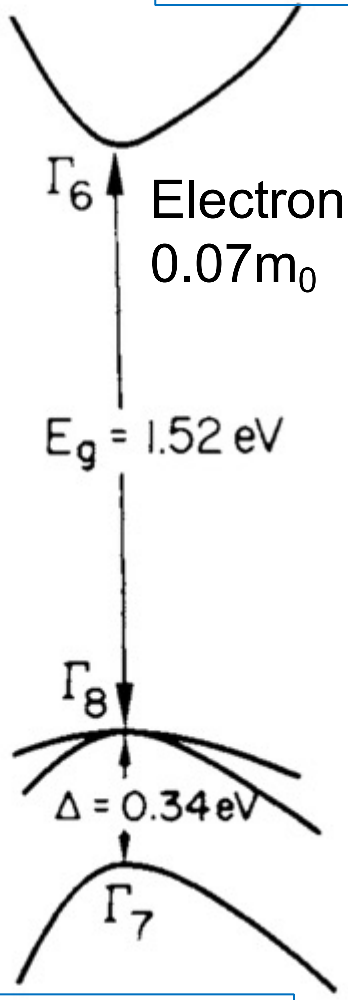
Inorganic semiconductors
Large exciton radius
Wannier excitons

Bohr radius $a^*_B = \epsilon_r \left(\frac{m_0}{\mu}\right) a^*_B$ — a few nm (μ effective mass)

Effective Rydberg Exciton energy $\mathrm{Ry}^* = 13.6\mathrm{eV}\frac{\mu}{m_0}\frac{1}{\epsilon^2}$ — a few to tens of meV

At the beginning: search for large optical spin orientations In ultra-pure GaAs

Conduction band



Valence band

$S_{1/2}$

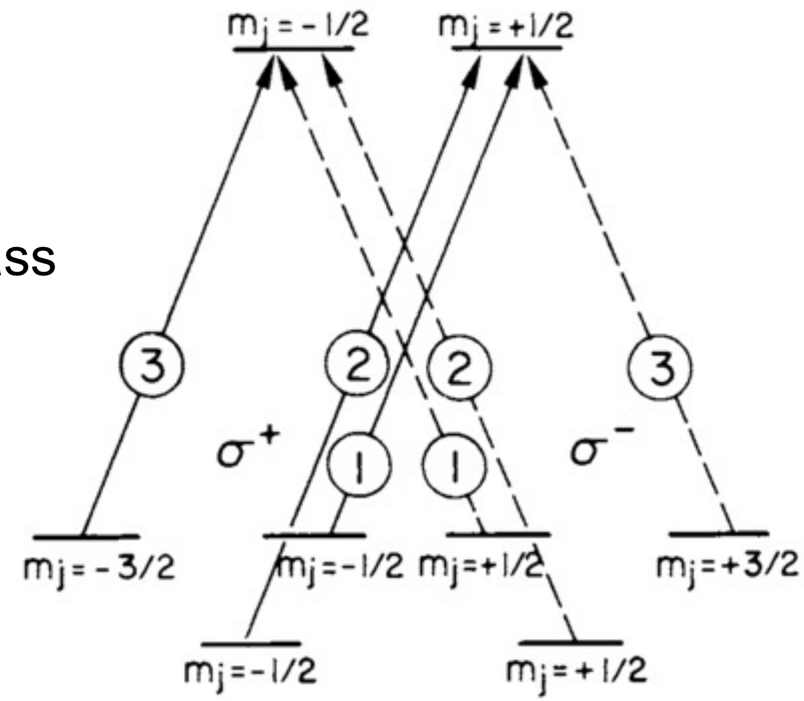
Electron effective mass
$0.07m_0$

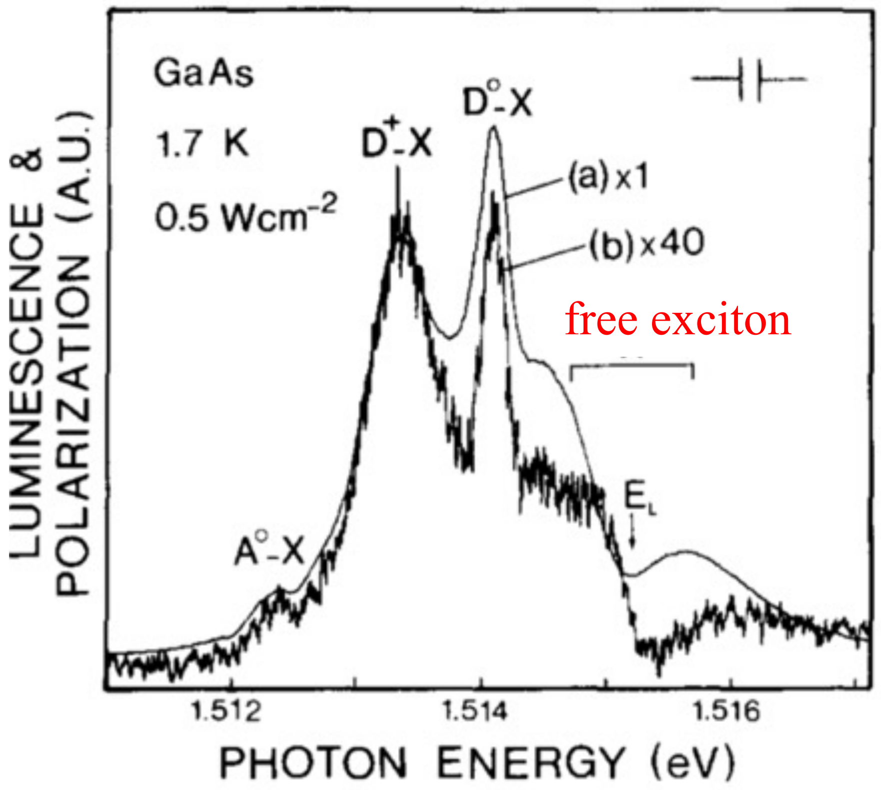
$P_{3/2}$

Hole effective mass
Heavy hole $0.4\ m_0$

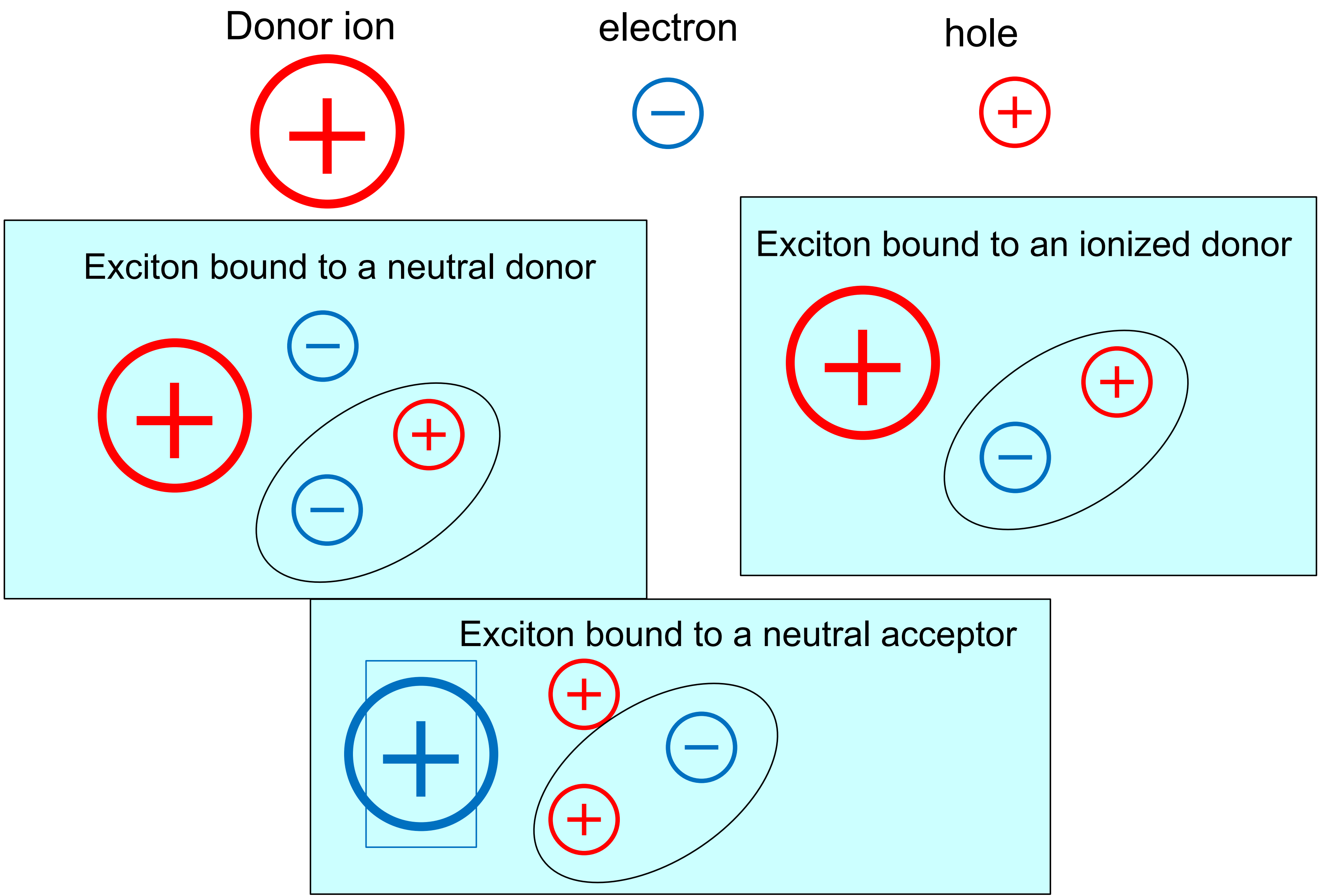
$P_{1/2}$

Light hole $0.06\ m_0$





Bound excitons



PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Theory of the Contribution of Excitons to the Complex Dielectric Constant of Crystals*†

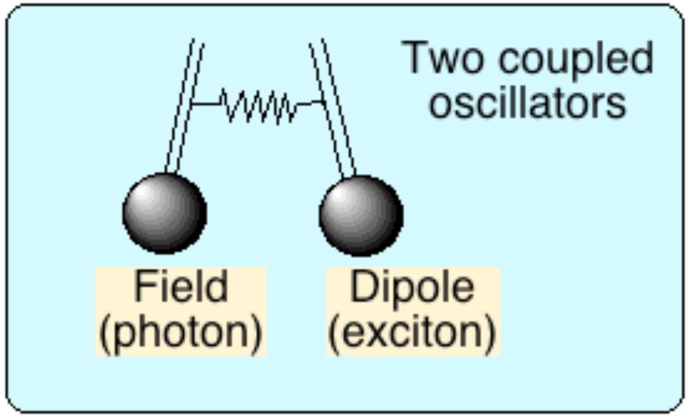
J. J. Hopfield‡
Physics Department, Cornell University, Ithaca, New York

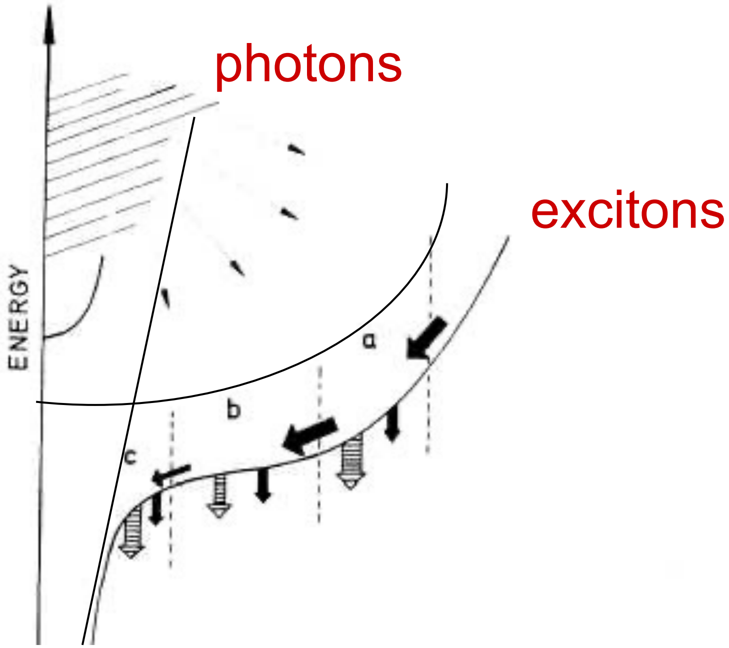
(Received July 16, 1958)

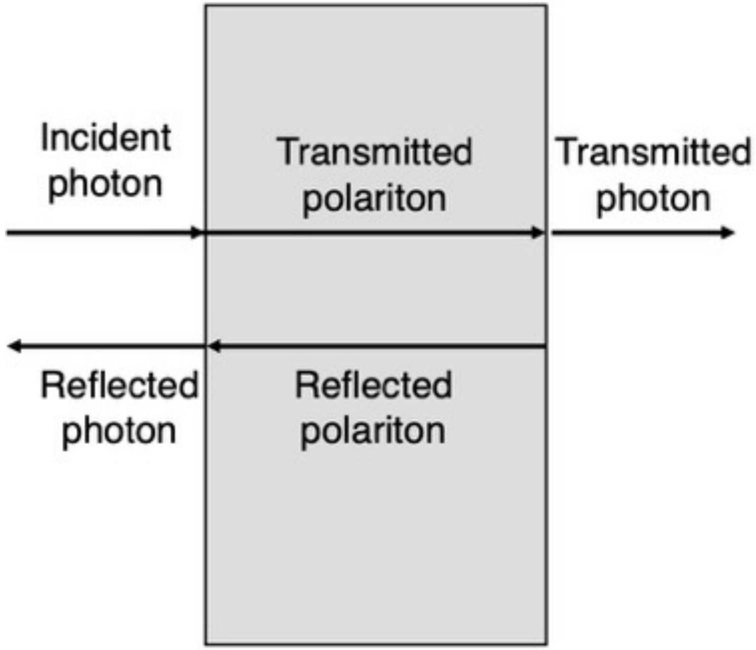
It is shown that the ordinary semiclassical theory of the absorption of light by exciton states is not completely satisfactory (in contrast to the case of absorption due to interband transitions). A more complete theory is developed. It is shown that excitons are approximate bosons, and, in interaction with the electromagnetic field, the exciton field plays the role of the classical polarization field. The eigenstates of the system of crystal and radiation field are mixtures of photons and excitons. The ordinary one-quantum optical lifetime of an excitation is infinite. Absorption occurs only when "three-body" processes are introduced. The theory includes "local field" effects, leading to the Lorentz local field correction when it is applicable. A Smakula equation for the oscillator strength in terms of the integrated absorption constant is derived.

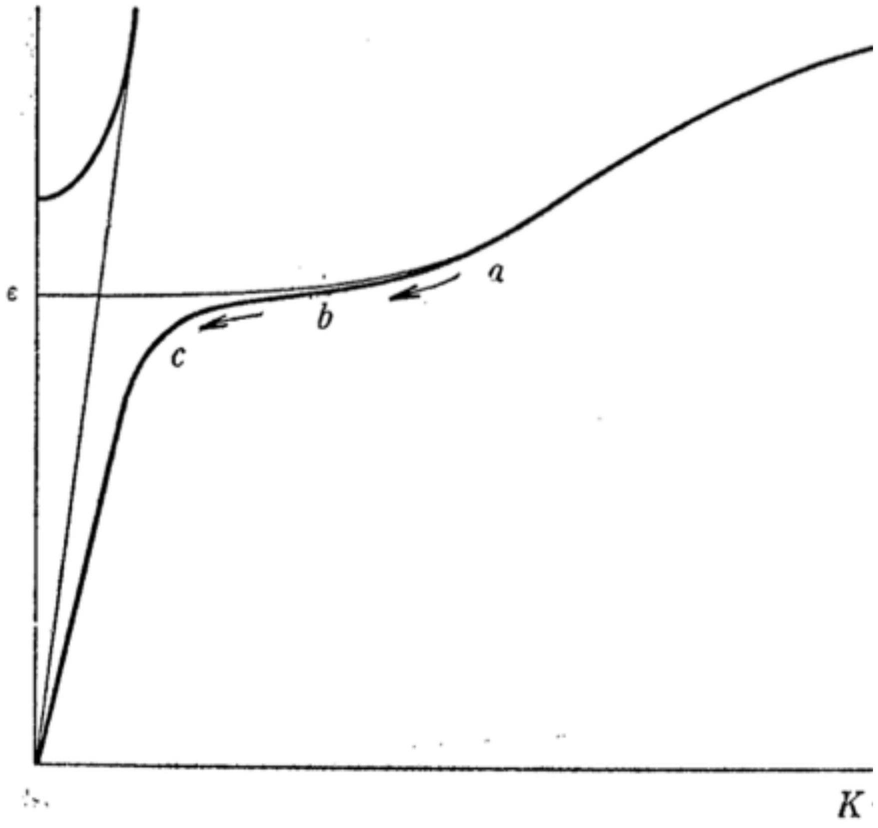
Strongly-coupled 3D excitons and photons, excitonic polaritons are the quasi particles of the system

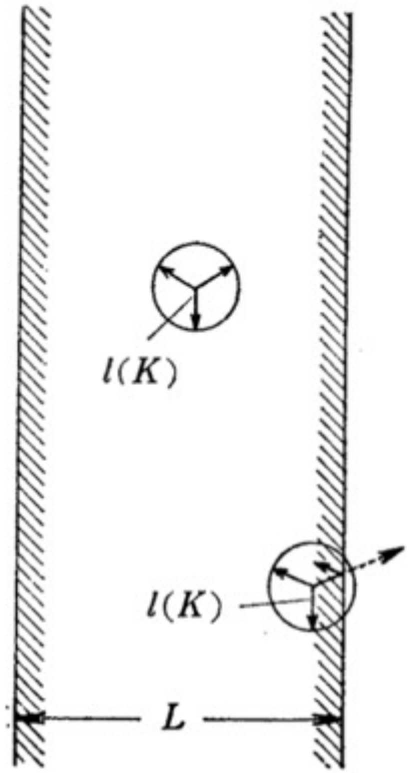
They retain translational invariance

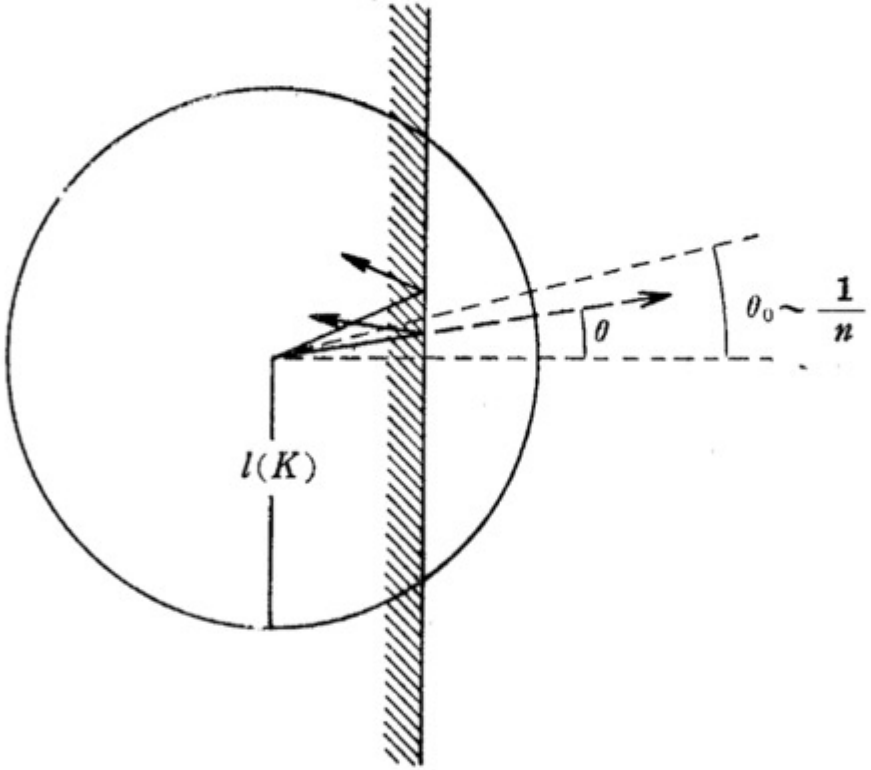










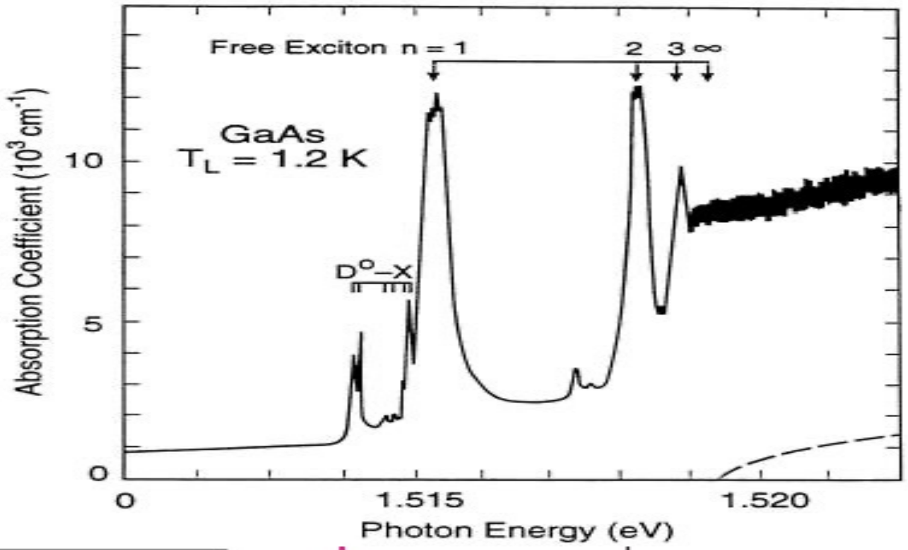


Direct radiative annihilation of an exciton (weak exciton-phonon coupling, and the band bottom at K=0)

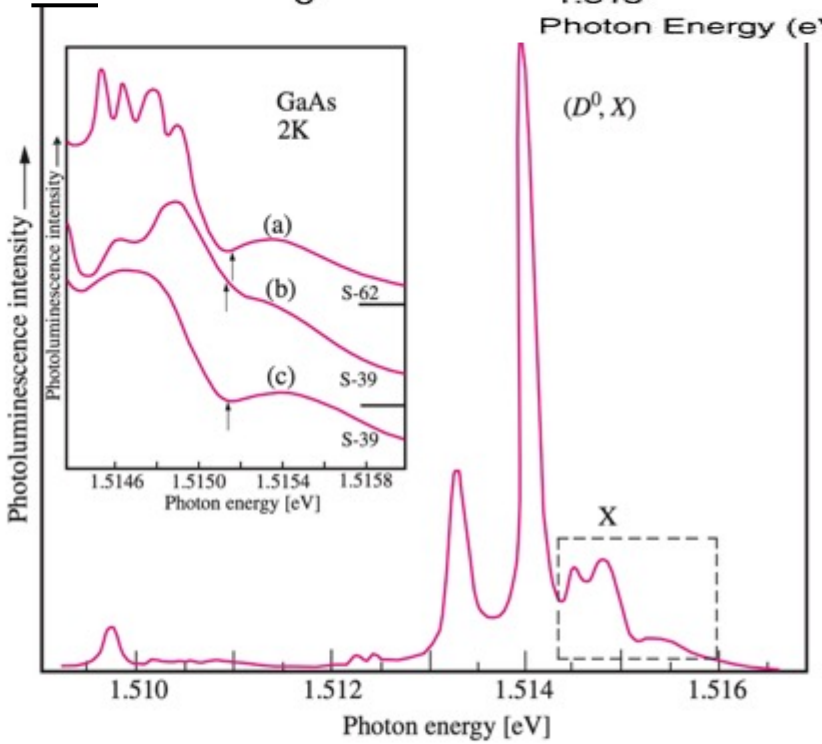
b c in Fig. 9 is indeed a neck because it is much longer than the thermalization time 10-12 sec. Thus we can take ta as the life-time for radiative annihilation of an exciton. It should be borne in mind that ta depends on the boundary condition (L in the present model) as well as on the mean depth (from the surface) of the excitons initially produced.

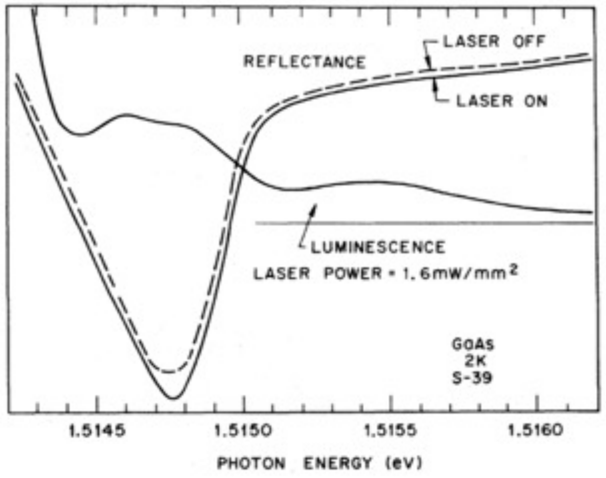
Yutaka Toyozawa, On the Dynamical Behavior of an Exciton Suppl. Progress Theoretical Physics, 12, 111 (1959)

A breakthrough in 1973: identification of polaritons luminescence in high-purity GaAs



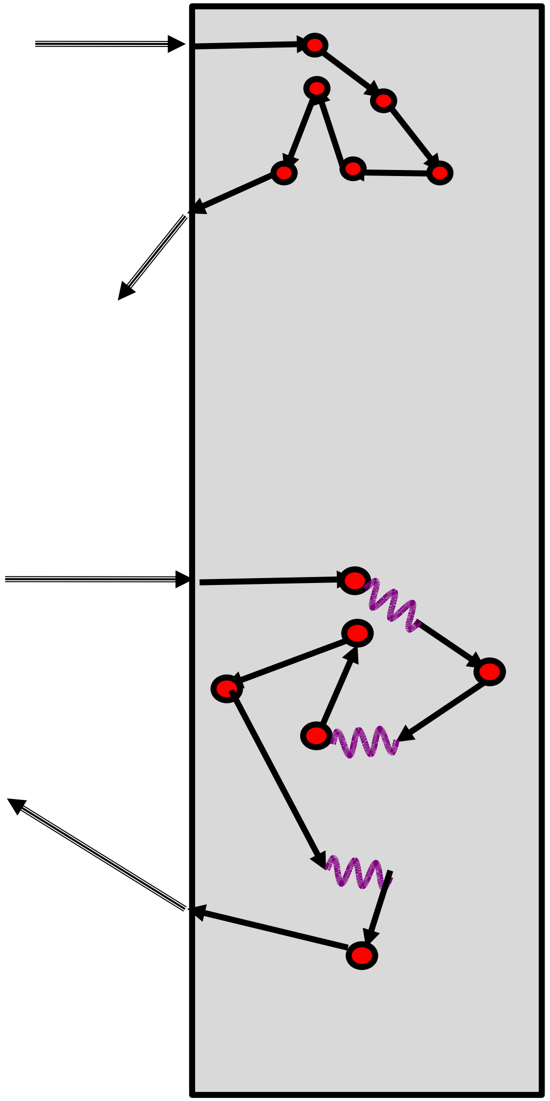
Sell et al., Polariton Reflectance and Photoluminescence in High-Purity GaAs, Phys. Rev. B7, 4568 (1973)





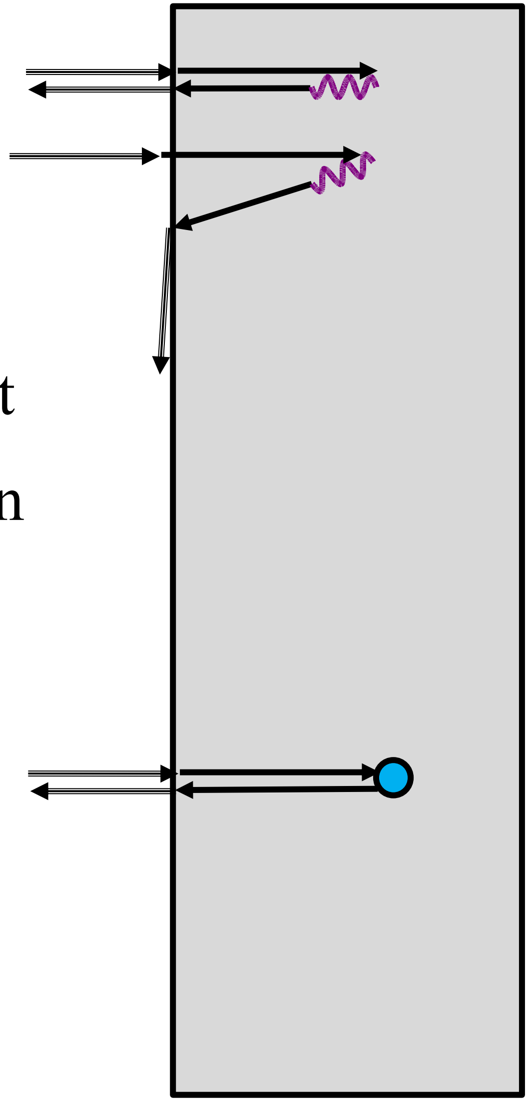
direct comparison of the luminescence and reflectance (laser on, solid; laser off, dashed curve)

Scattering phenomena for excitonic polaritons



• Scattering point defect

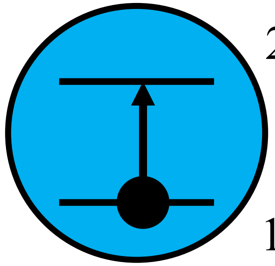
Lattice vibration phonon



Single phonon scattering
Energy conservation

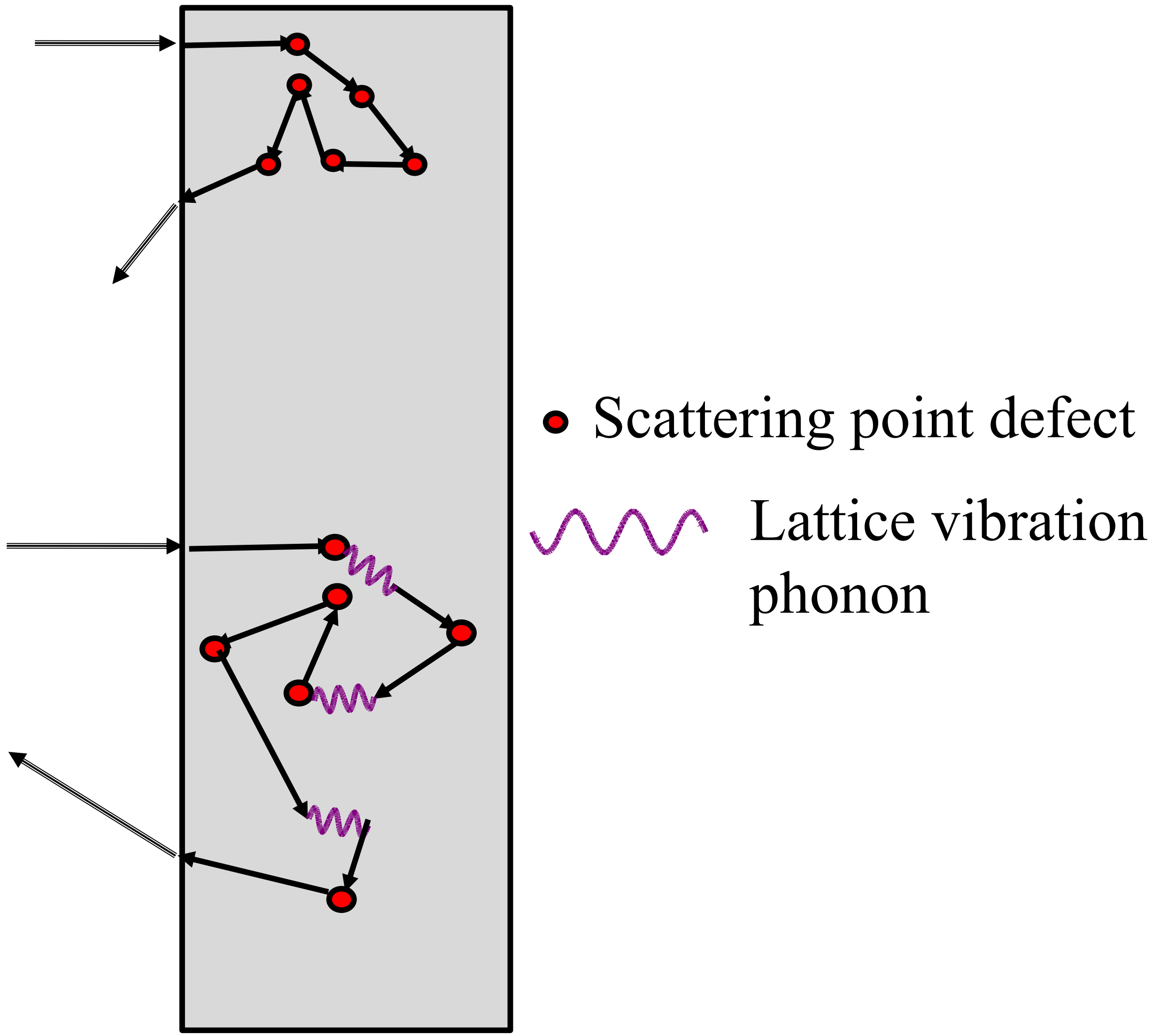
Acoustic phonon energy
$$\Delta E = \hbar c_s k$$

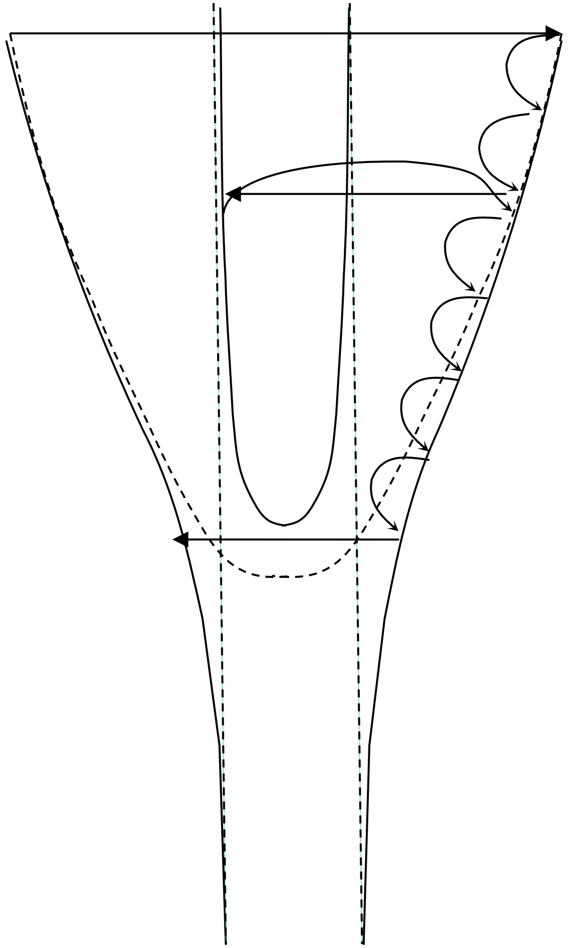
Inelastic electron scattering by an electron bound to a donor



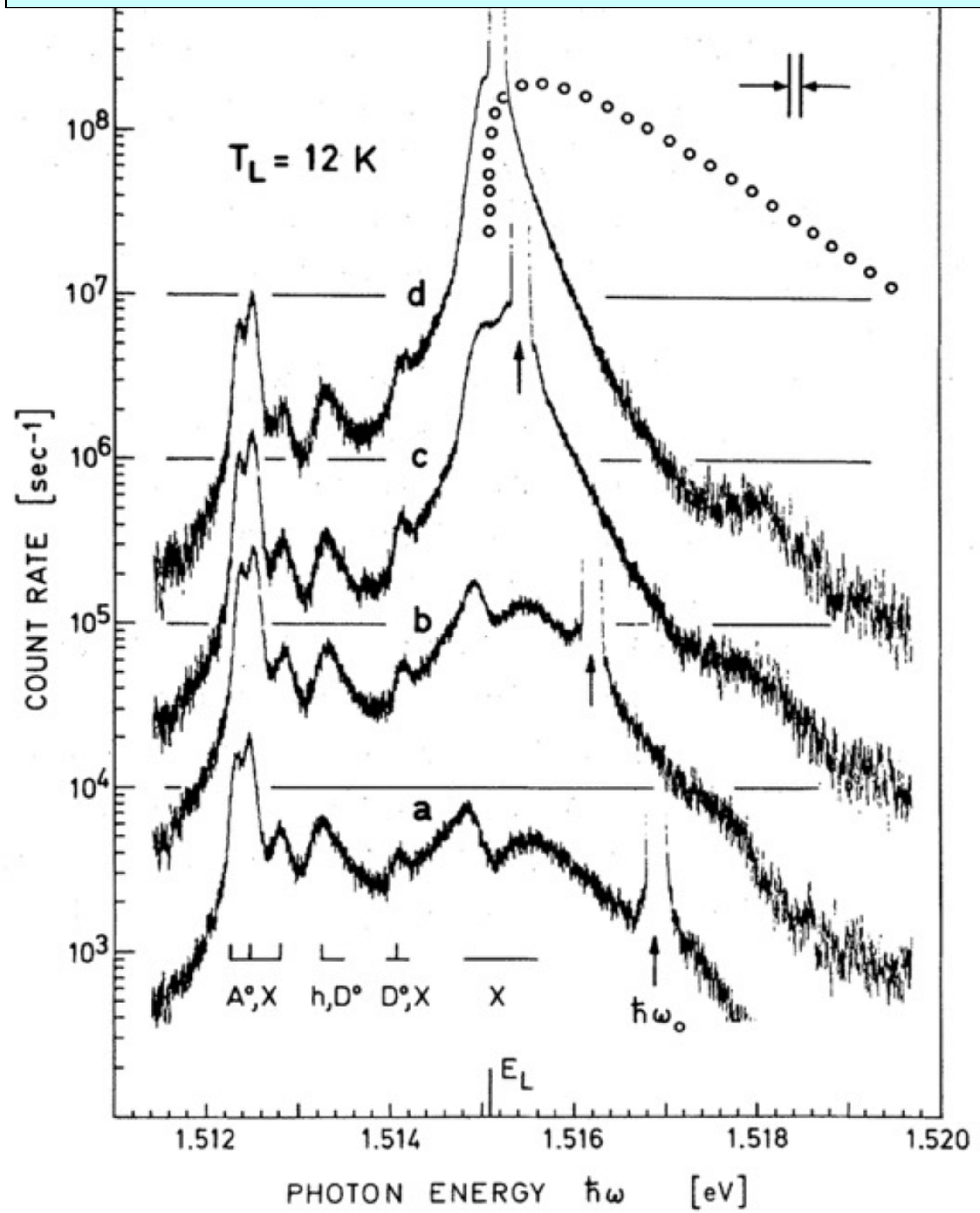
$$\Delta E = E_{2s} - E_{1s}$$
$$E_{3s} - E_{1s}$$

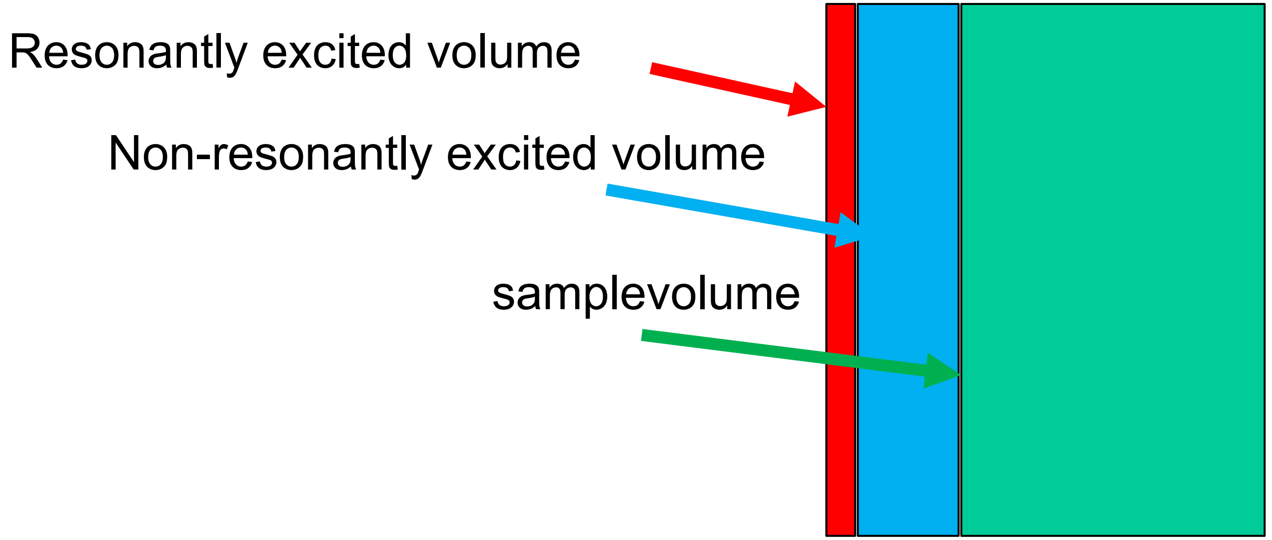
Scattering phenomena for excitonic polaritons

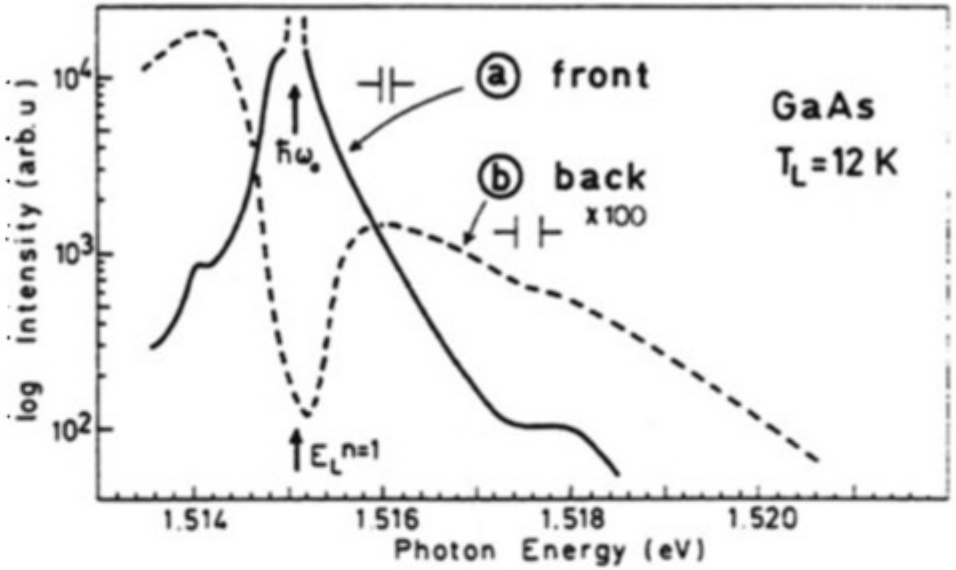




Fluorescence of resonantly excited polaritons



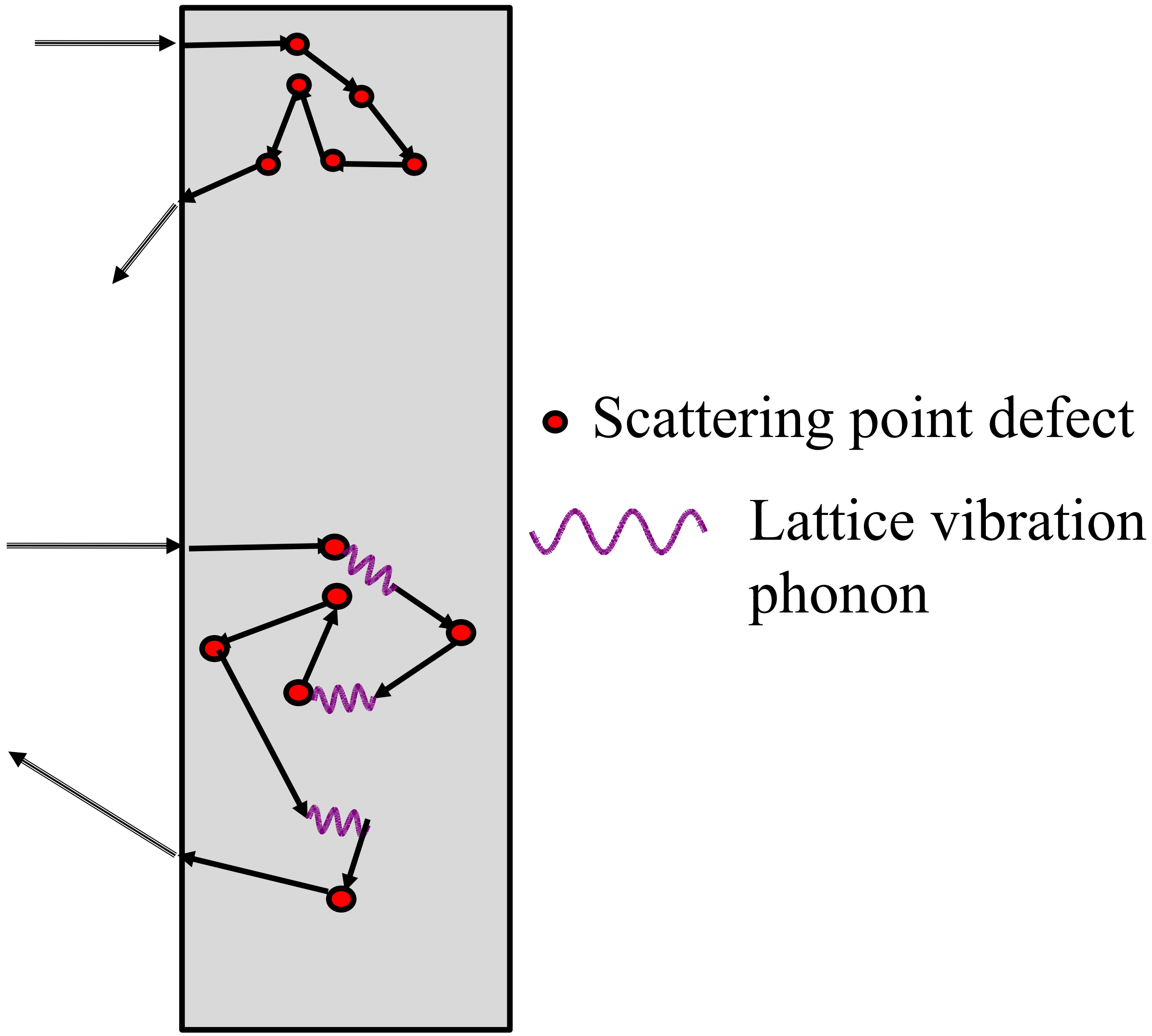


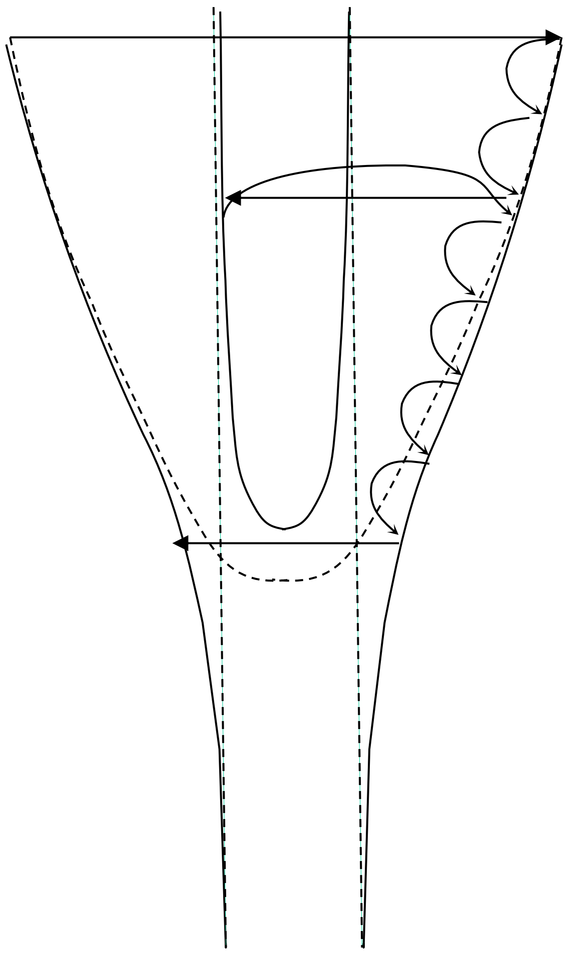


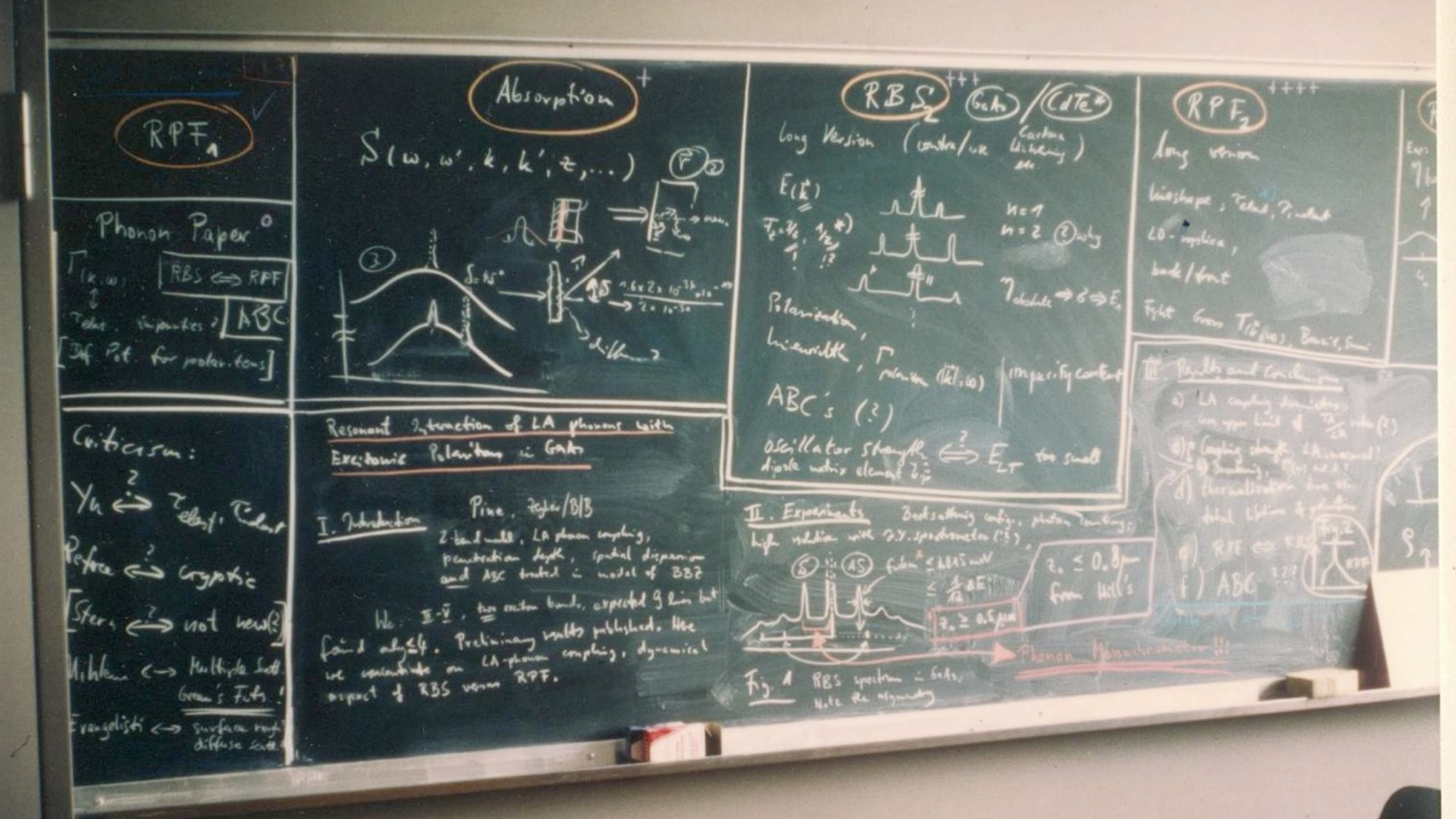
Thick sample : 2µm

Resonant excitation depth: 0,1µm, time of flight 10^{-11}s

Scattering phenomena for excitonic polaritons

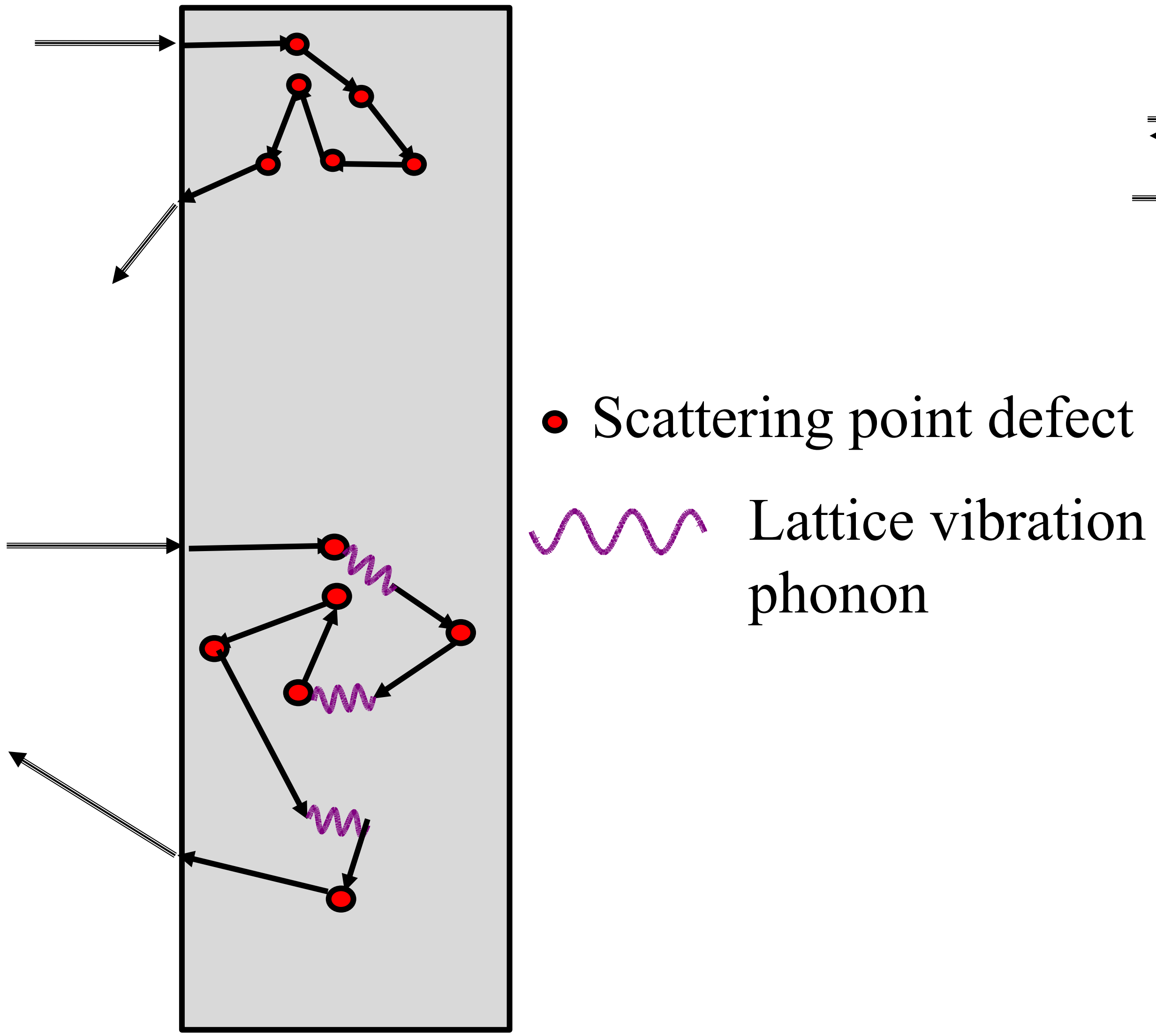


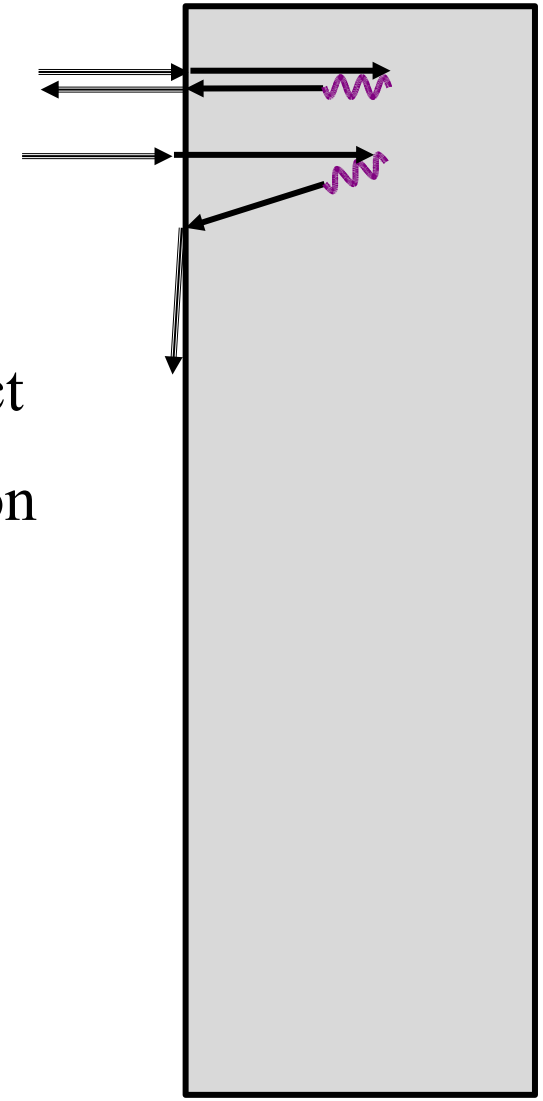




RPF1
Absorption
RBS2
GaAs
CdTe*
RPF2
Long Version
long version
Phonon Paper
RBS ⟺ RPF
ABC
Criticism:
Resonant Interaction of LA phonons with Excitonic Polaritons in GaAs
I. Introduction
Polarization,
ABC's (?)
oscillator strength
II. Experiments
Fig. 1 RBS spectrum in GaAs.
Note the asymmetry
Phonon Absorption
III. Results and Conclusions
f) ABC
Pine
not new(?)

Scattering phenomena for excitonic polaritons





Single phonon scattering
Energy conservation

Acoustic phonon energy
$\Delta E = \hbar c_s k$

Light Scattering in the Polariton Framework

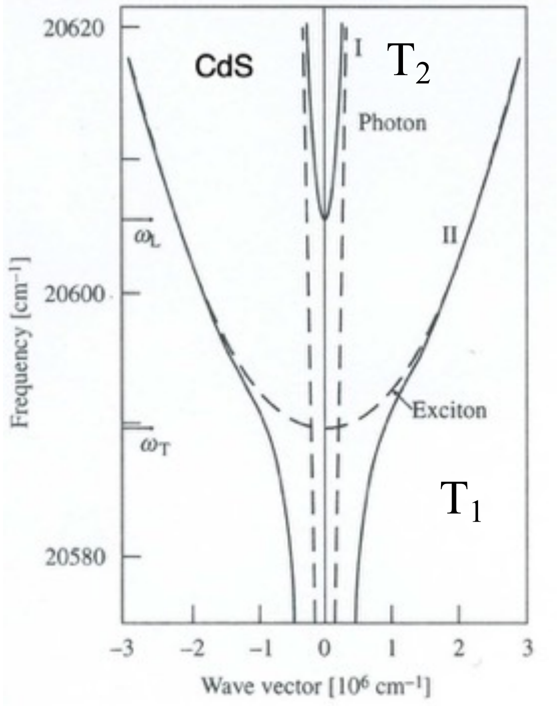
A scattering event is the *succession of three steps*:

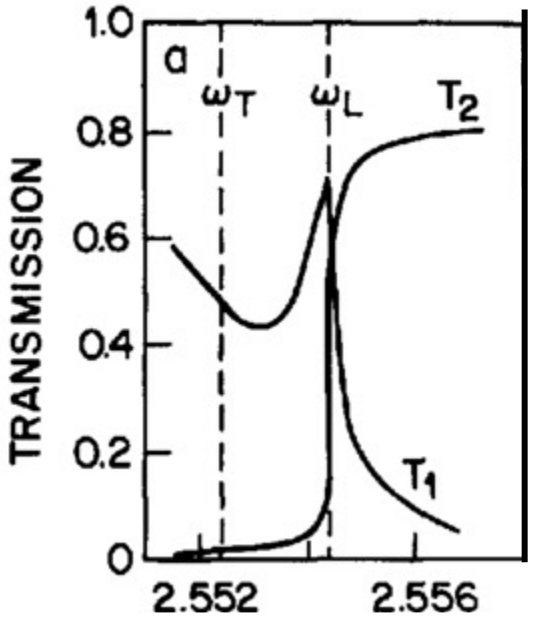
1) transmission of an incoming photon at the interface as a polariton inside the crystal;
2) scattering from one polariton state to another inside the crystal;
3) propagation and transmission of the scattered polariton outside the crystal as a photon.

the scattering probability Pout (or efficiency) can be factorized as

$P_{out} = T((\omega_i)\, P_{scatt,\, in}\, T(\omega_s),$

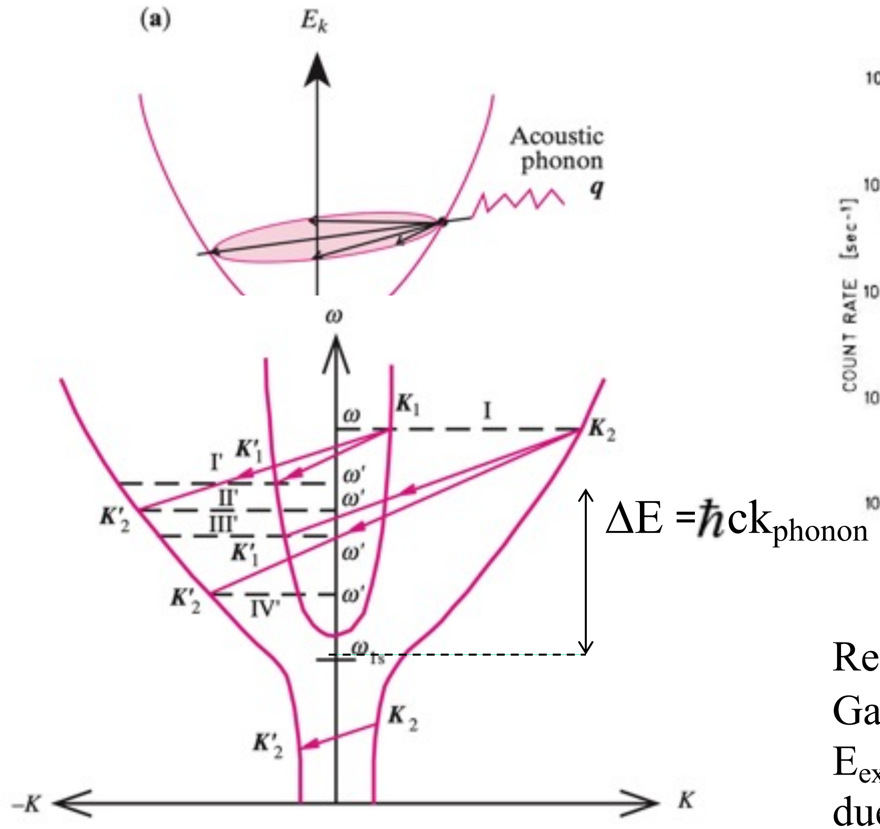
$T((\omega_i)$ and $T(\omega_s)$ transmission coefficients of ingoing and outgoing polaritons at the crystal interface and $P_{scatt,\, in}$ scattering probability of polaritons inside the crystal.



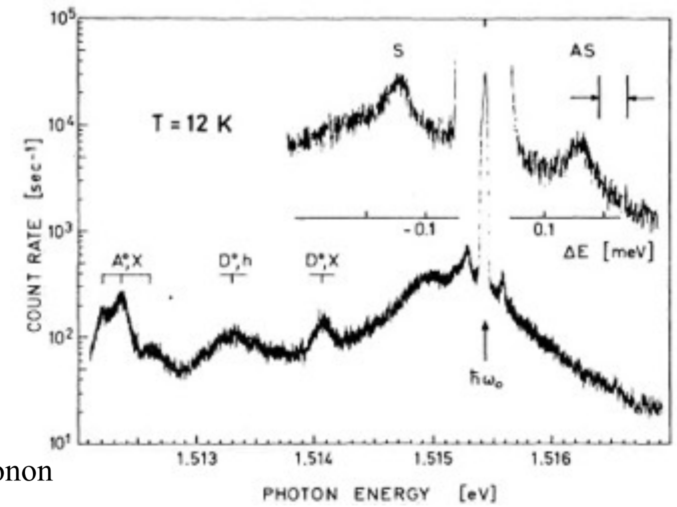


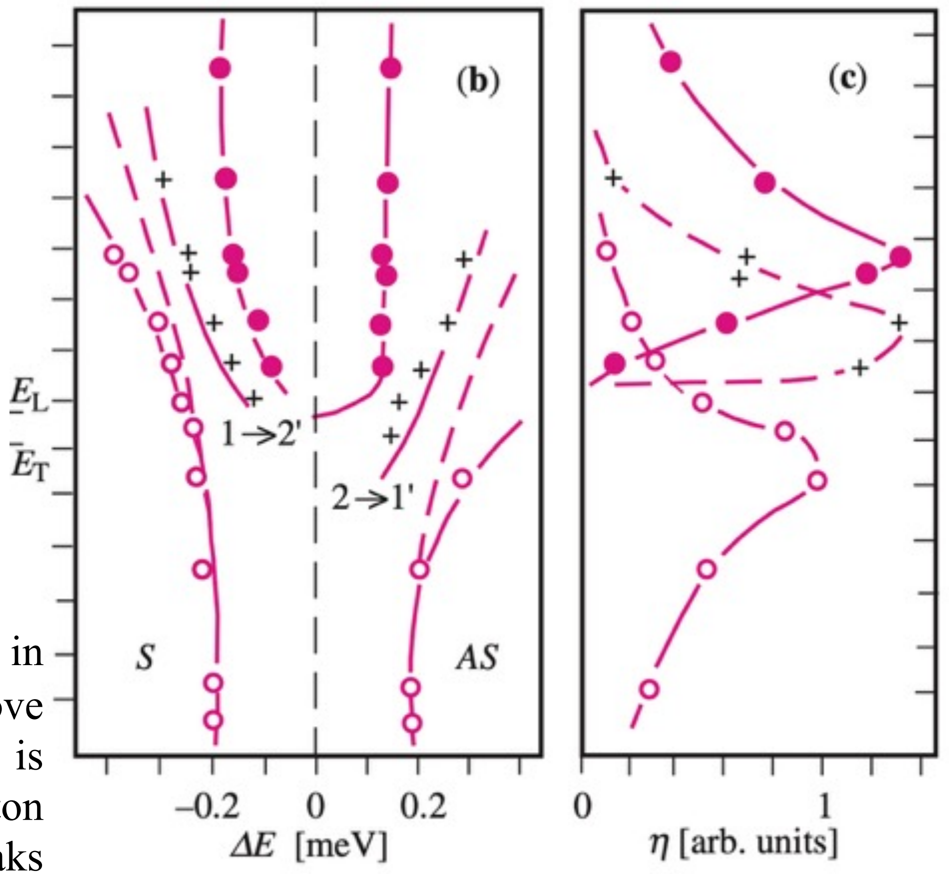
Transmission coefficients of outside photons as excitonic polaritons as a function of incoming photon energy in CdS (normal incidence, E, KIc). T_1 and T_2 are the transmission coefficients of photons as LPB or UPB polaritons Γ=0.05meV

Resonant Brillouin scattering by bulk excitonic polaritons: single acoustic phonon (sound waves) scattering



Brillouin scattering as back-scattering of an excitonic polariton by an acoustic phonon.

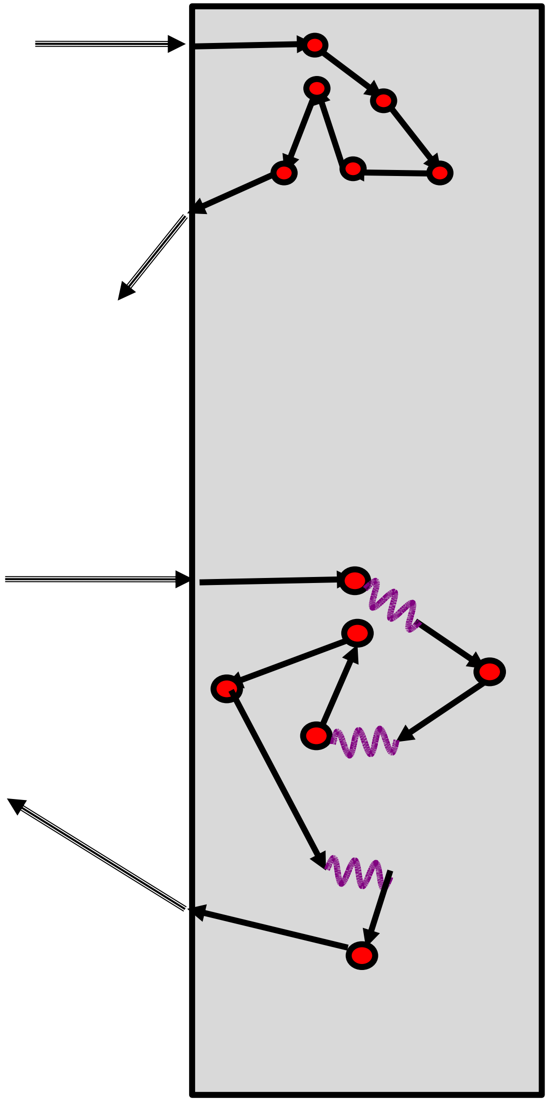


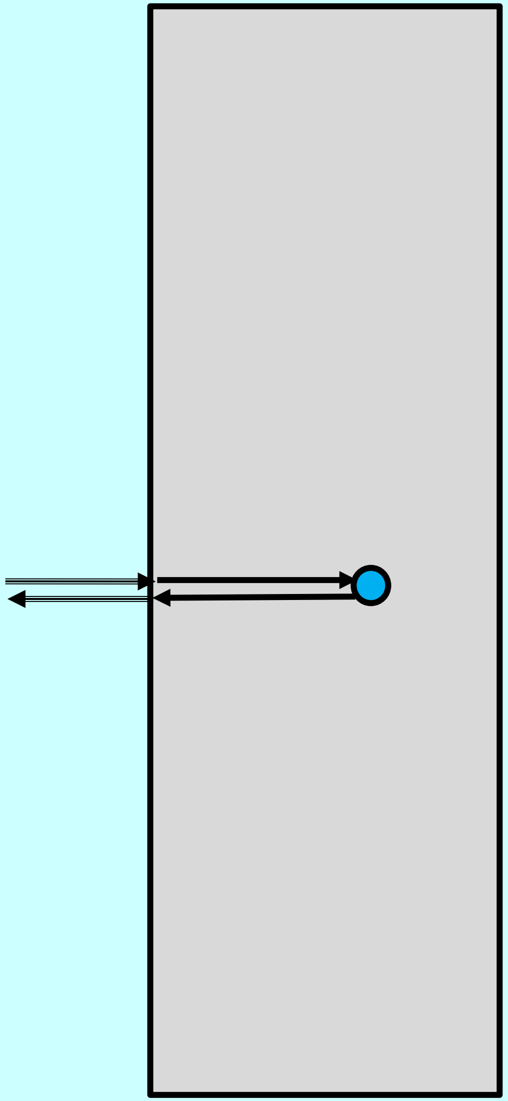


Resonant Brillouin scattering (RBS) in GaAs near-resonant hω, slightly above E_{exc}. The broad band around 1.515 eV is due to n = 1 exciton-polariton luminescence. Other luminescence peaks according to the corresponding electronic transitions.

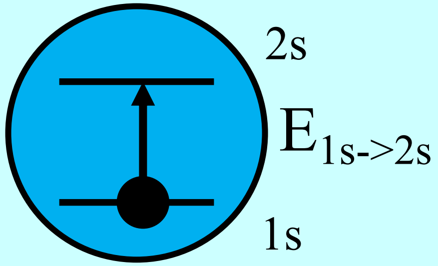
R. Ulbrich & cw, Resonant Brillouin Scattering of Excitonic Polaritons in Gallium Arsenide, Phys. Rev. Lett. 38, 865,1977

Inelastic electron scattering phenomena for excitonic polaritons





Inelastic electron scattering by an electron bound to a donor



$$\Delta \mathbf{E} = \begin{array}{l} E_{2s} - E_{1s} \\ E_{3s} - E_{1s} \end{array}$$

Resonant Electronic Raman Scattering in Semiconductors

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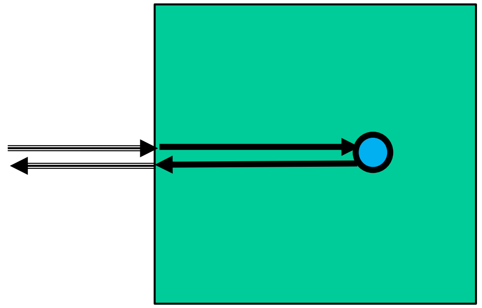
Institut für Physik der Universität Dortmund, D-4600 Dortmund, Germany

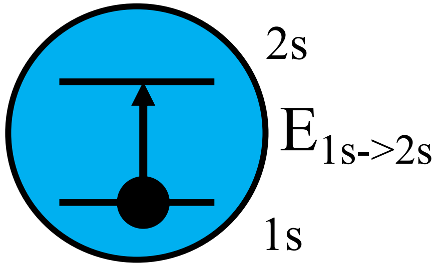
and

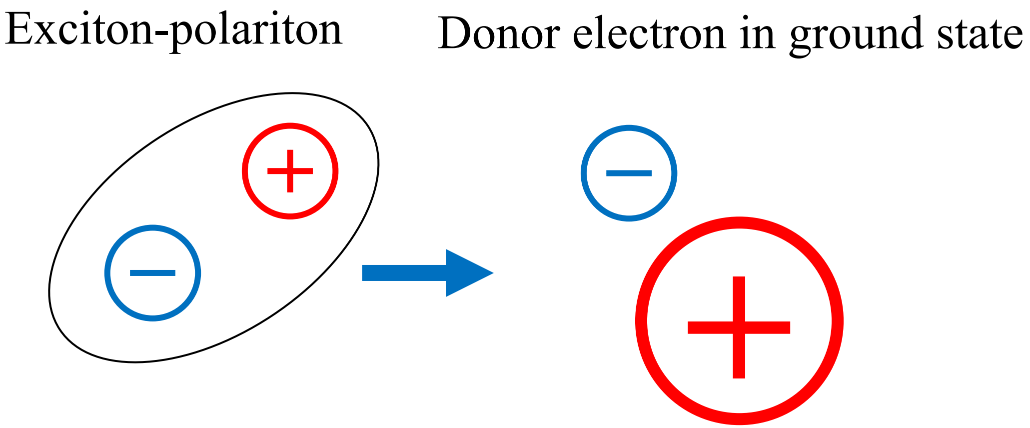
Nguyen Van Hieu
Institute for Physics, Nghia Do, Tu Liem, Hanoi, Vietnam

and

Claude Weisbuch
Laboratoire de Physique de la Matière Condensée, Ecole Polytechnique, F-91128 Palaiseau, France



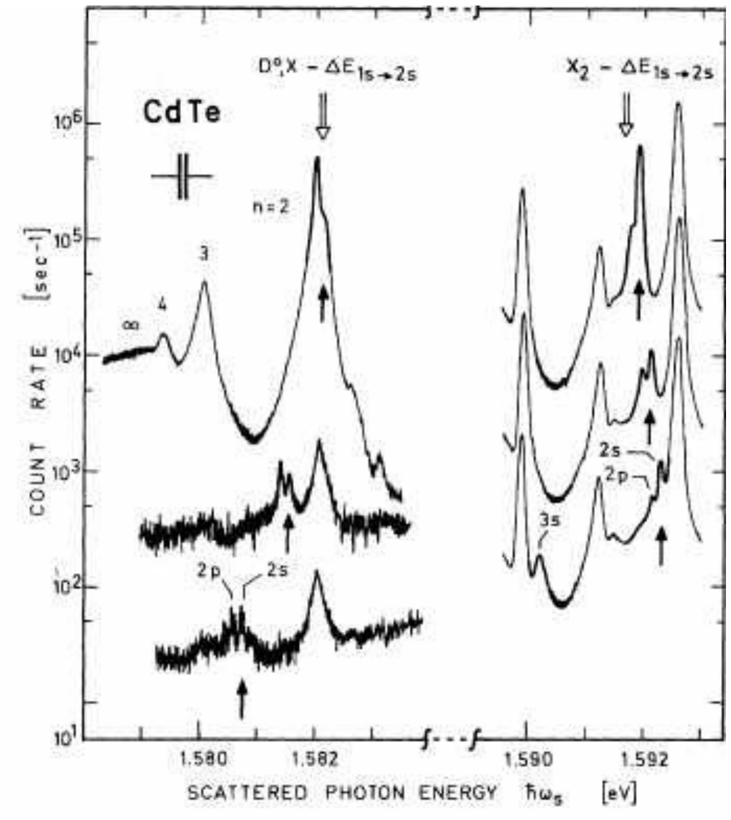


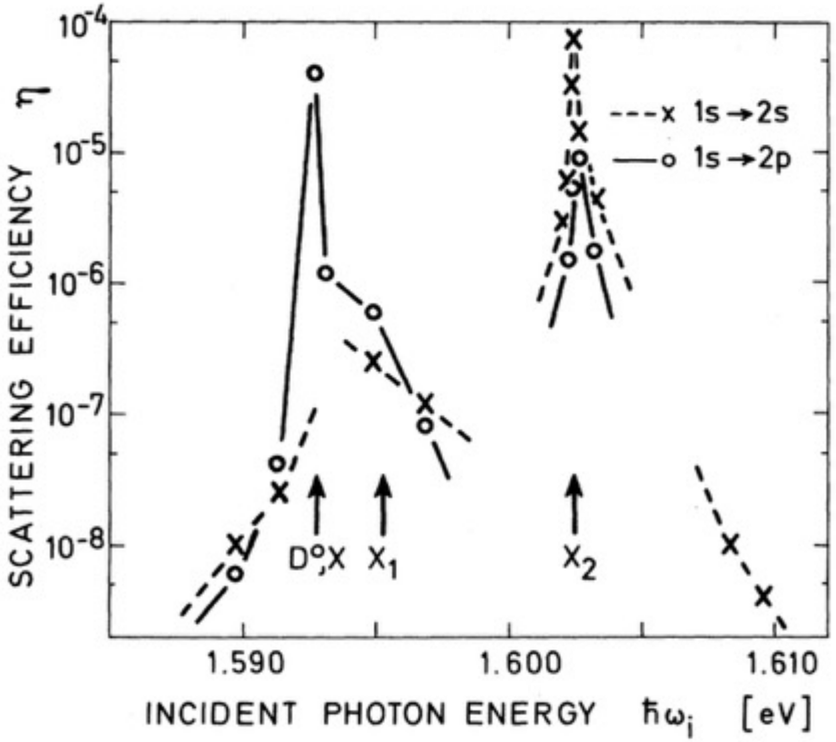


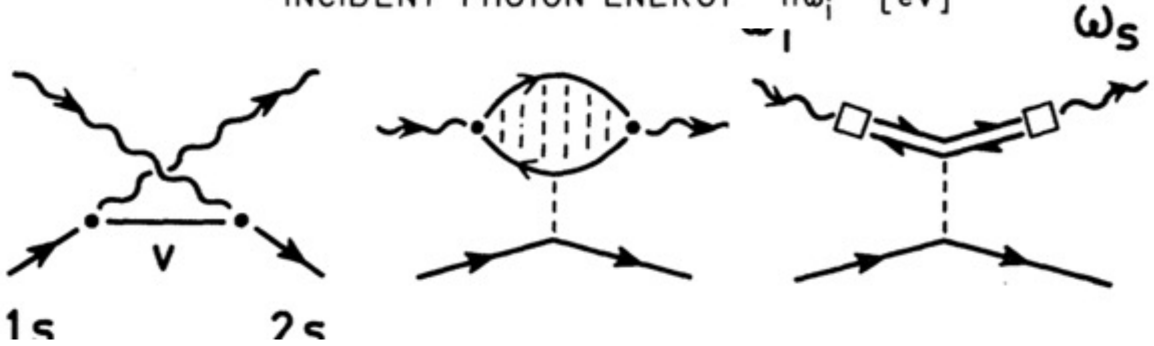
Electronic Raman scattering on shallow donors is enormously enhanced when the incident photon energy approaches the fundamental exciton region. This excitonic resonance was observed for the first time and it was found that $\sigma_{peak} \approx 5 \times 10^{-14}$ cm^2 for CdTe and GaAs in the n =2 free-exciton resonance. The **enhancement of $\gtrsim 10^{10}$** over off-resonance excitation

R. Ulbrich, Nguyen van Hieu & cw, Phys. Rev. Lett. 46, 531(981)

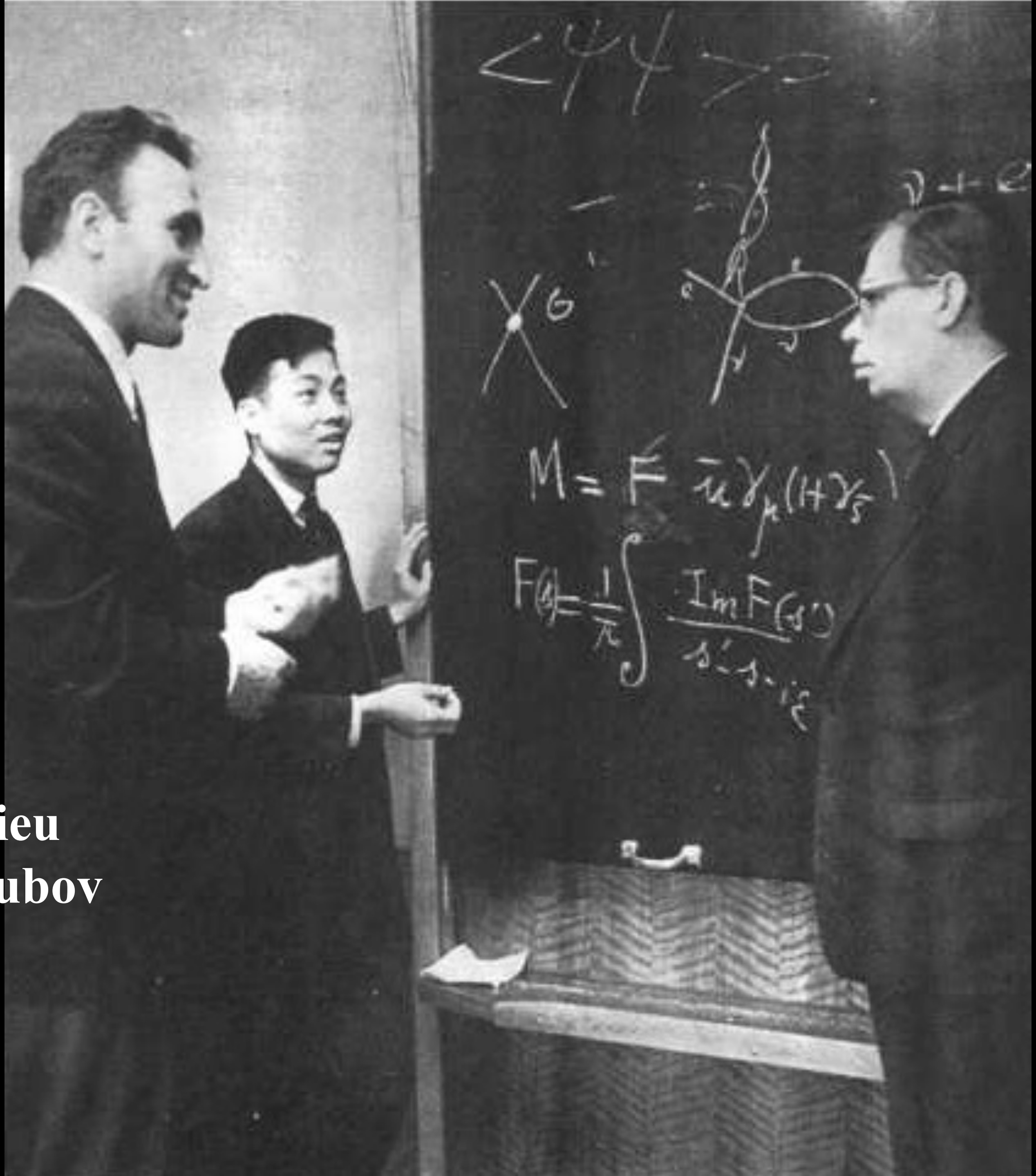
Resonant Electronic Raman scattering







R. Ulbrich, Nguyen van Hieu & cw, Phys. Rev. Lett. 46, 531(981)



Center
Nguyen Van Hieu
Right: Bogolioubov
Dubna 1962

$$T_{ex\gamma} \approx e\frac{\Pi}{m}\frac{a_0^{3/2}}{\sqrt{2\varepsilon E_g}}\cdot I_{ex\gamma}, \qquad a_0^{3/2} = a_0^2\cdot e\sqrt{\frac{m_e^*}{\varepsilon}},$$

$$I_{ex\gamma} = \int \tilde{F}_\nu(\pi)\,\tilde{\Phi}_{1s}(\pi)\,\tilde{\Phi}^*_{2s}(\pi)\,\frac{d^3\pi}{(2\pi)^3}$$

$$T_{ex\gamma} = e a_0^2\frac{\Pi}{m}\frac{1}{\varepsilon}\sqrt{\frac{m_e^*}{2E_g}}\, I_{ex\gamma}$$

atom electron

electron in exciton

hole

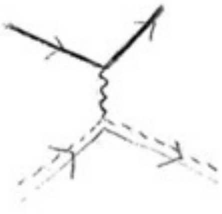
Coulomb potential

ex + e → ex + e

$\nu+(1s) \to \nu'+(2s)$

$\Delta Q = Q' - Q$

$$\frac{e^2}{\varepsilon}\frac{1}{(\vec{Q}-\vec{Q}')^2}\iint F_\nu(p)\Phi_{1s}(q)F^*_{\nu'}\left(p+\frac{\Delta Q}{2}\right)\Phi^*_{2s}(q-\Delta Q)\,\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$



$$-\frac{e^2}{\varepsilon}\frac{1}{(Q-Q')^2}\iint F_\nu(p)\Phi_{1s}(q)F^*_{\nu'}\left(p-\frac{\Delta Q}{2}\right)\Phi^*_{2s}(q+\Delta Q)\,\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$\frac{e^2}{\varepsilon}\iint\frac{F_\nu(p)\Phi_{1s}(q)F^*_{\nu'}\left(p+\frac{\Delta Q}{2}\right)\Phi^*_{2s}(q-\Delta Q)}{\left(q-p+\frac{Q}{2}-Q'\right)^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$\approx\frac{e^2}{\varepsilon}\iint\frac{F_\nu(p)\Phi_{1s}(q)F^*_{\nu'}(p)\Phi^*_{2s}(q)}{(p-q)^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}.$$

$$-\frac{e^2}{\varepsilon_0}\iint\frac{F_\nu(p)\Phi_{1s}\left(p+Q'-\frac{Q}{2}\right)F^*_{\nu'}(p')\Phi^*_{2s}\left(p+\frac{Q}{2}\right)}{\left(p-p'+\frac{\Delta Q}{2}\right)^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$\approx-\frac{e^2}{\varepsilon_0}\iint\frac{F_\nu(p)\Phi_{1s}(p)\Phi^*_{2s}(p)F_{\nu'}(p')}{(p-p')^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$-\frac{e^2}{\varepsilon}\iint\frac{F_\nu(p)\Phi_{1s}\left(p-\frac{Q'}{2}\right)F^*_{\nu'}(p')\Phi^*_{2s}\left(p-\frac{Q'}{2}+Q\right)}{\left(p-p'+\frac{\Delta Q}{2}\right)^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$\approx-\frac{e^2}{\varepsilon}\iint\frac{F_\nu(p)\Phi_{1s}(p')\Phi^*_{2s}(p')F^*_{\nu'}(p')}{(p-p')^2}\frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3}$$

$$T_{exex} = \frac{e^2}{\varepsilon_0}a_0^2\, I_{exex'}$$

$$I_{exex} = \iint\frac{\tilde{F}_\nu(\pi)\tilde{\Phi}_{1s}(\pi')\tilde{F}^*_{\nu'}(\pi')\tilde{\Phi}^*_{2s}(\pi')}{(\pi-\pi')^2}\frac{d^3\pi}{(2\pi)^3}\frac{d^3\pi'}{(2\pi)^3} - \iint\frac{\tilde{F}_\nu(\pi)\tilde{\Phi}_{1s}(\pi)\tilde{F}^*_{\nu'}(\pi')\tilde{\Phi}^*_{2s}(\pi)}{(\pi-\pi')^2}\frac{d^3\pi}{(2\pi)^3}\frac{d^3\pi'}{(2\pi)^3} - \iint\frac{\tilde{F}_\nu(\pi)\Phi_{1s}(\pi')\tilde{F}^*_{\nu'}(\pi')\Phi^*_{2s}(\pi')}{(\pi-\pi')^2}\frac{d^3\pi}{(2\pi)^3}\frac{d^3\pi'}{(2\pi)^3}$$

Computations published in Nguyen Ba An, Nguyen Van Hieu et al., J. Physique 41, 1067 (1980)

Free Exciton Recombination with the Excitation of Donor Electron

State vector of free electron – hole pair with momenta

$$p_e = \frac{P}{2} + p$$
$$p_h = \frac{P}{2} + p$$

$$|\vec{p}_e, \vec{p}_h\rangle = |\vec{P}, \vec{p}\rangle =$$

$$e^{+}_{\frac{\vec{P}}{2}+\vec{p}} \, h^{+}_{\frac{\vec{P}}{2}-\vec{p}} |0\rangle$$

Normalization condition :

$$\langle \vec{p}_e{}', \vec{p}_h{}' | \vec{p}_e, \vec{p}_h \rangle = \langle \vec{P}', \vec{p}' | \vec{P}, \vec{p} \rangle =$$

$$\delta_{\vec{p}_e \vec{p}_e{}'} \delta_{\vec{p}_h \vec{p}_h{}'} = \delta_{\vec{P} \vec{P}'} \delta_{\vec{p} \vec{p}'}$$

State vector of exciton

$$|\vec{P}, \nu\rangle = \sum_{\vec{p}} f_\nu(\vec{p}) \, |\vec{P}, \vec{p}\rangle$$

①

(12)

$\omega = 1\ eV = 1{,}5 \cdot 10^{15}\ sec^{-1}$

$$W_0 = \underbrace{2 \cdot 10^{-5}}_{\frac{P^2}{m}} \cdot \underbrace{2 \cdot 10^{-3}}_{\frac{d_0}{\pi}} \cdot \underbrace{4 \cdot 10^{6}}_{2^{22}} \left(\underbrace{10^{-18}\ cm^3}_{a_{ex}^3} \ \underbrace{1.5 \cdot 10^{15}\ sec^{-1}}_{\omega_m} I^2 \right.$$

26
21

$$= 24 \cdot 10^{-8}\, 10^{6} \cdot 10^{-18}\, 10^{15} \cdot I^2$$

$$= 2 \cdot 10^{-4}\ cm^3\ sec^{-1} \cdot I^2$$

Probability on an unite of volume :

$$W = N W_0 \qquad N = 10^{12}\ cm^{-3}$$

$$\boxed{W = 2 \cdot 10^{8}\ sec^{-1} I^2}$$

Hanoi April 19, 1979

Dear Claude

I am sorry that the manuscript was in our embassy too long. I received it only recently. During this time I have finished together with my post-graduated students all calculations. Today I send to you our work to your consideration. I suggest the following.

1/ You can include <u>completely</u> our works with An, Thang, Viet and write a complete article with six co-author.

2/ You can take <u>any</u> results from this theoretical work, <u>any</u> part you like, for improving ~~our~~ my work with you and Ulbricht. In this case I would like to ask you and George to submit our work to Journal de Physics.

Classification
Physics Abstracts
71.35 — 71.36 — 78.20B

Polariton theory of resonant electronic Raman scattering on neutral donor levels in semiconductors with a direct band gap

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(*Reçu le 18 janvier 1980, révisé le 21 avril, accepté le 9 mai 1980*)

Résumé. — Dans ce travail nous présentons la théorie de la diffusion de Raman sur les électrons liés aux donneurs neutres dans les semiconducteurs avec une bande interdite directe, quand la fréquence du photon incident est en résonance avec l'exciton. La section efficace de diffusion du polariton avec transition de l'électron de l'état fondamental au premier état excité a été calculée.

Abstract. — The theory is presented for the Raman scattering on bound electrons of neutral donors in the semiconductors with a direct band gap at the incident photon frequency in the resonance with the exciton. The cross-section of the polariton scattering with the transition of the donor electron from the ground state to the first excited state is calculated.

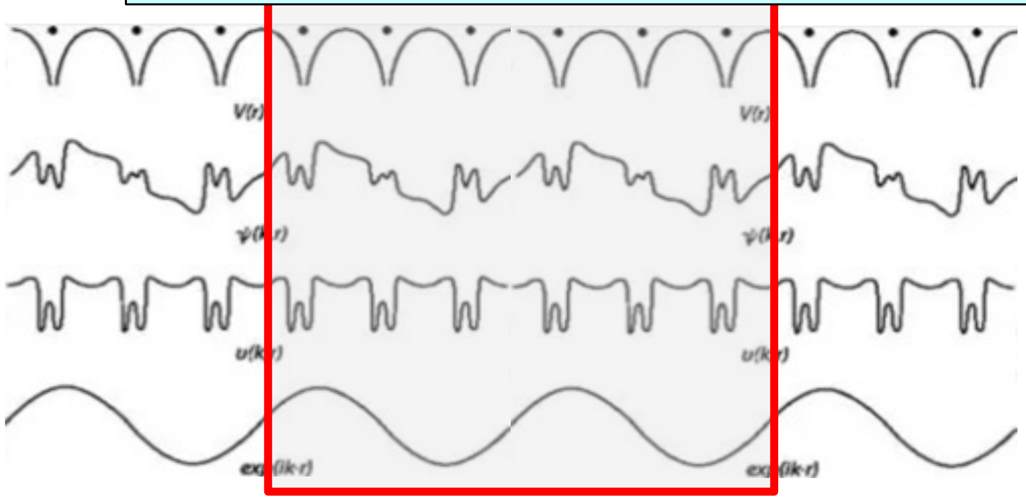
1. **Introduction.** — Different electronic Raman scattering processes in semiconductors were investigated both theoretically and experimentally by many authors. In the case of the scattering on a gas of mobile carriers (electrons or holes) there may be the scattering with the single particle excitation or the scattering on collective excitations in this gas. The scattering processes of this type were studied widely by Platzman, Tzoar, Wolff *et al.* [1-13]. The interband scattering processes, in which the initial and final states of electrons or holes belong to different energy bands, were studied in many works [14-17]. The initial and final states of the charge carriers may be also their bound states in the Coulomb field of the donor or acceptor ions. In this case we have the scattering on the impurity levels [18-27]. The role of different external electromagnetic fields on the electronic Raman scattering processes was also studied in details [28-31]. Recently Weisbuch and Ulbrich have investigated experimentally the resonant electronic Raman scattering on neutral donor levels at the energy of the incoming photon near that of the exciton [32]. The present work is devoted to the theoretical investigation of the resonant electronic Raman scattering on neutral donor levels in a two band semiconductor with the direct band gap and the allowed electrical dipole transition from the valence to the conduction band. In the case of the material with a very low concentration of donors the electron-hole pair can exist in their bound states — the excitons.

Due to the virtual transition between the photons and the excitons there arises in the semiconductor a new kind of elementary excitations — the polaritons or more precisely the excitonic polaritons discovered by Hopfield [33] and Pekar [34] and studied further in many works [35-42]. As in the case of the resonant Raman scattering, at the photon energy near that of the exciton the polariton effect becomes very important. The polariton theory of the resonant Raman scattering was developed by Mills, Burstein *et al.* [43] and also by Bendow and Birman [44].

In the present work we apply the method of Bendow and Birman [44] to the study of the resonant electronic Raman scattering on the neutral donor levels at the energy of the incoming or outgoing photon near that of an exciton. We assume that the semiconductor has a direct band gap with the allowed electrical dipole transition and consider only the case of the material with a high purity, when the donor concentration is very small. In this case there will be no screening of the Coulomb interaction between the electrons and the holes, the excitons will exist, and therefore the polariton effect must be taken into account. We shall use the unit system with $\hbar = c = 1$.

2. **Electromagnetic interaction and polariton scattering.** — The existence of the polariton and all the scattering processes considered in this work are the consequences of the electromagnetic interaction in the semiconductor. We begin our study by discussing the

Two-dimensional electronic systems: quantum wells



Potentiel ion potential

Bloch wavefunction

Periodic part of the Bloch wavefunction

Enveloppe wavefunction

Puits quantique infini:

$$\Phi(\mathbf{r}) = e^{i(k_x x + k_y y)}\ \Phi_n(z)$$

$$-\frac{\hbar^2}{2m}\frac{d^2\Phi}{dx^2} = E\,\Phi$$

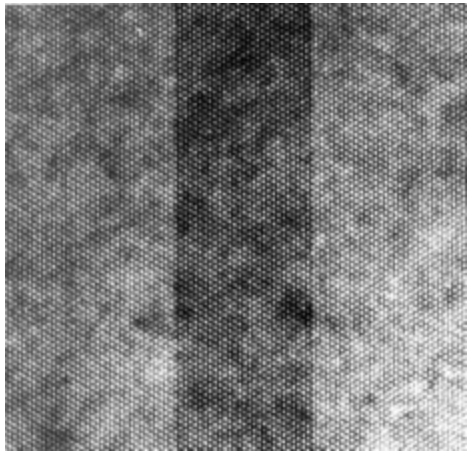
M electron effective mass

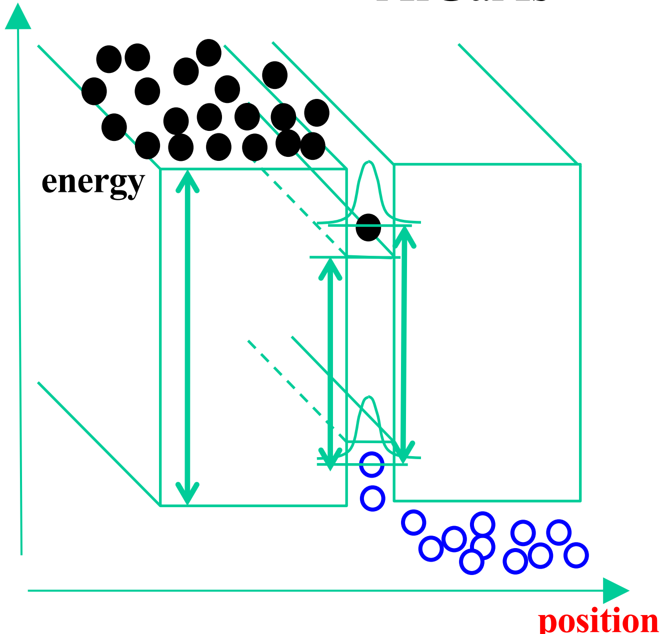
$$\Phi_n(x) = \sqrt{\frac{2}{\pi}}\sin\left(\frac{n\pi z}{L}\right)$$

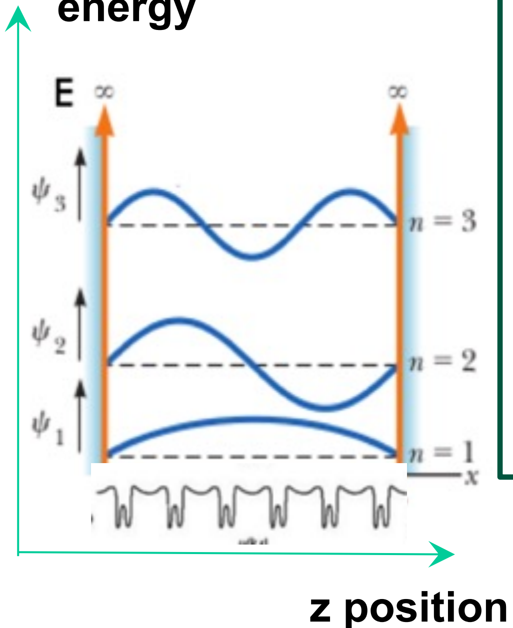
$$E_n = \frac{\pi^2\hbar^2}{2mL^2}n^2$$

$$\Psi_n(\mathbf{r}) = \Phi_n(\mathbf{r})\,w_0(\mathbf{r})$$

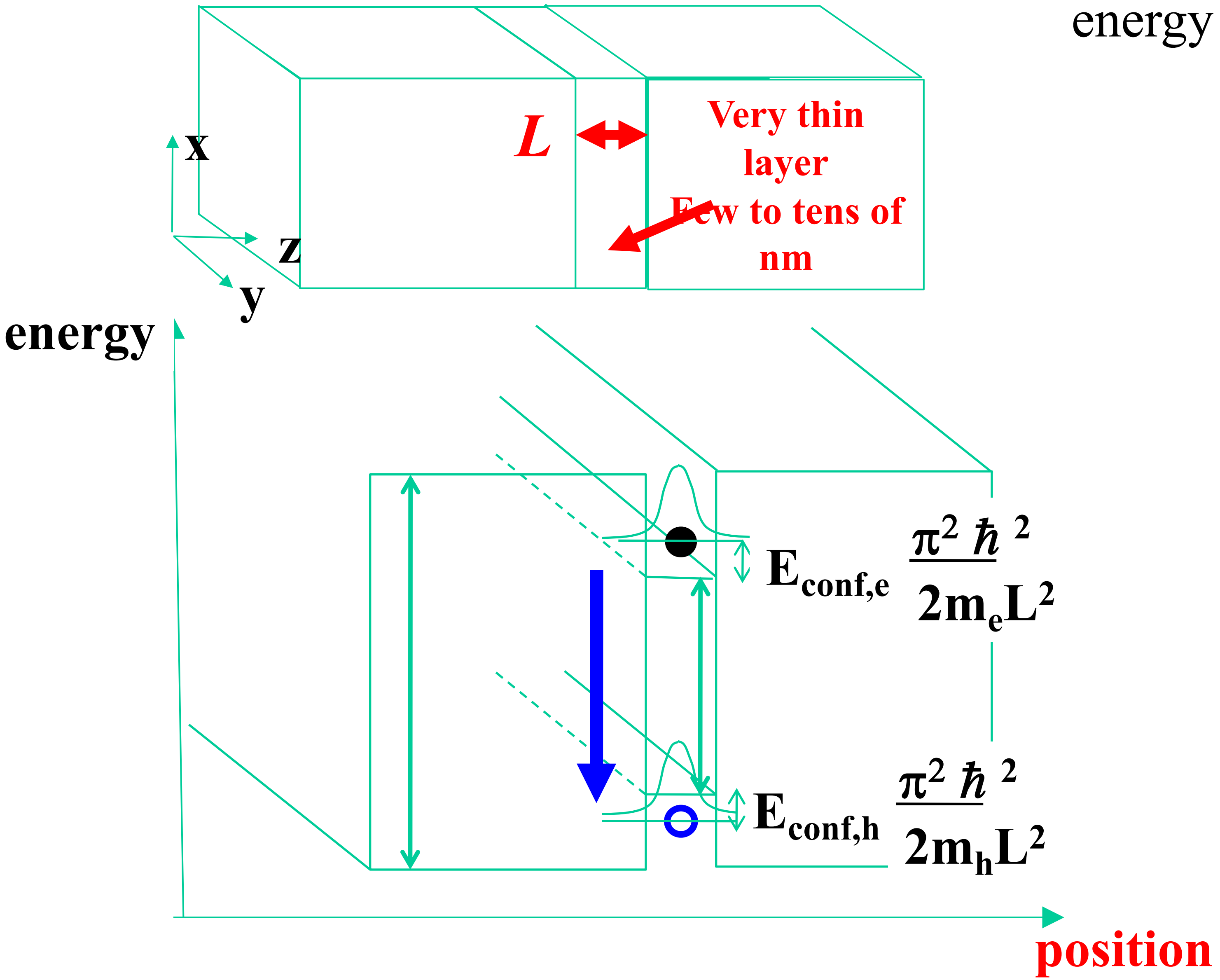
22 atomic layers

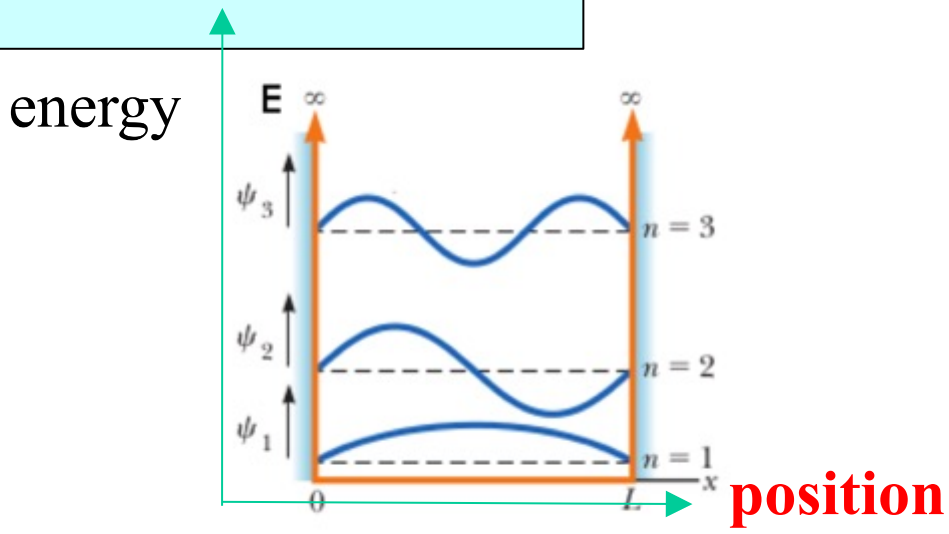






Two-dimensional electronic systems: quantum wells





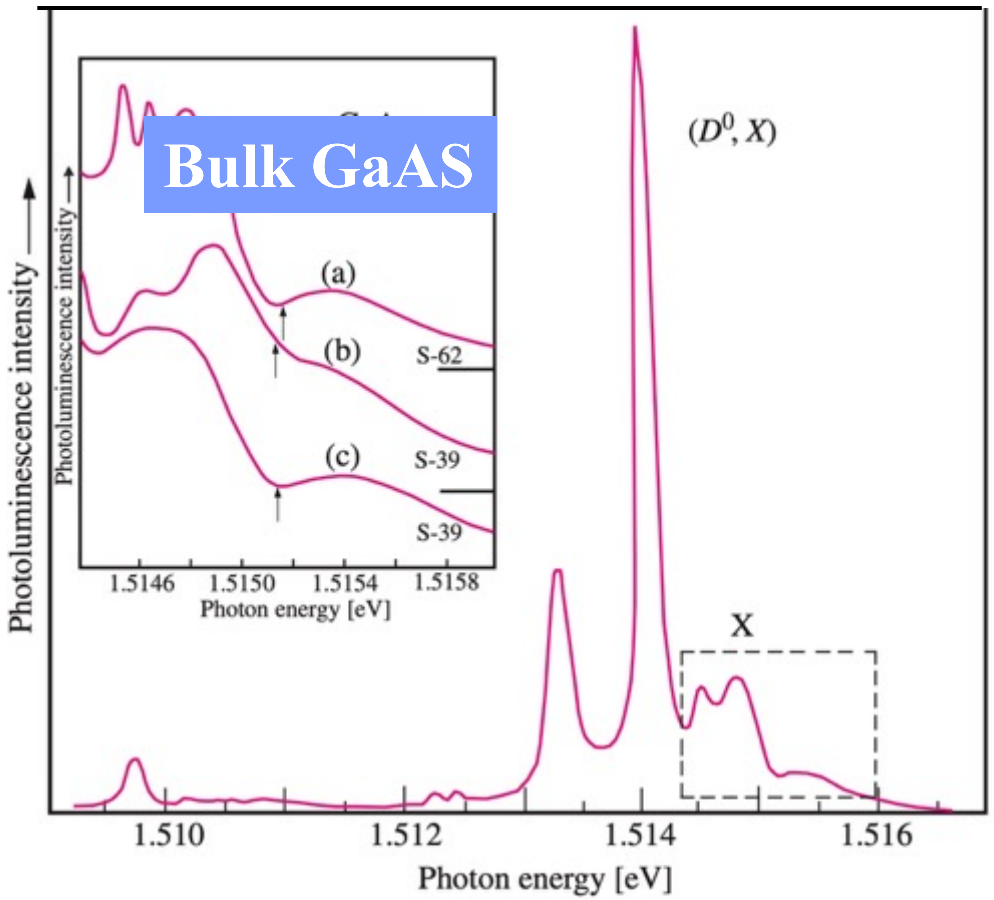
Infinite well approximation

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\psi(x) = E\cdot\psi(x)$$

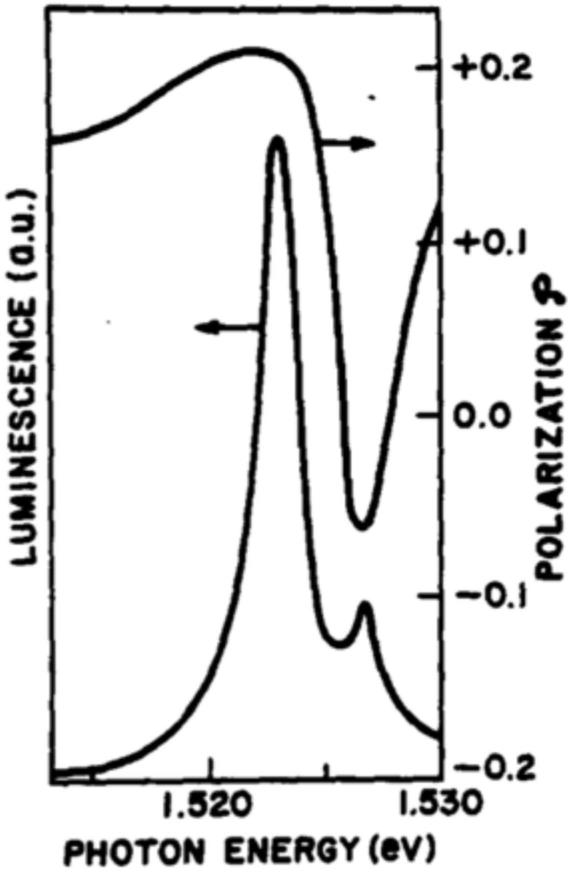
$$\psi_n(x) = \sin\left(\frac{n\pi}{L}x\right)$$

$$E(n) = \frac{\hbar^2\pi^2}{2mL^2}n^2$$

Surprise: in quantum wells, free excitons dominate light emission !

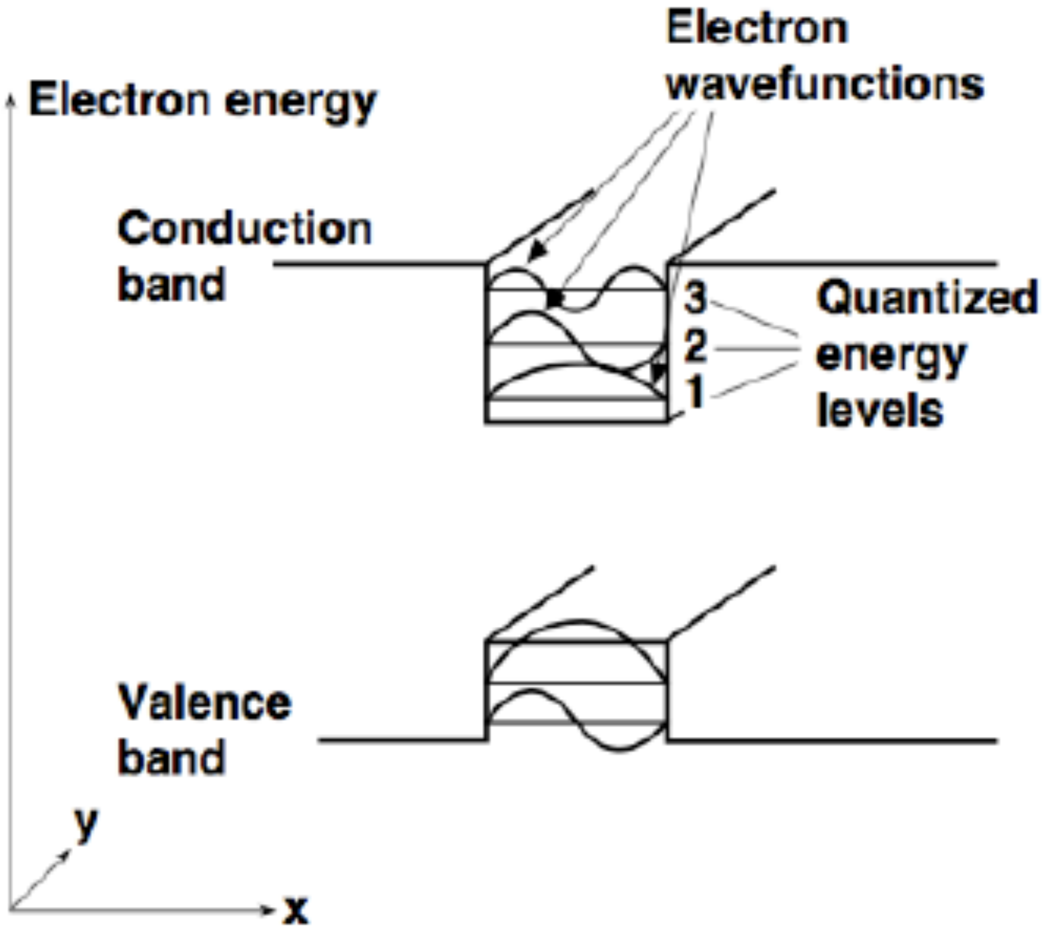


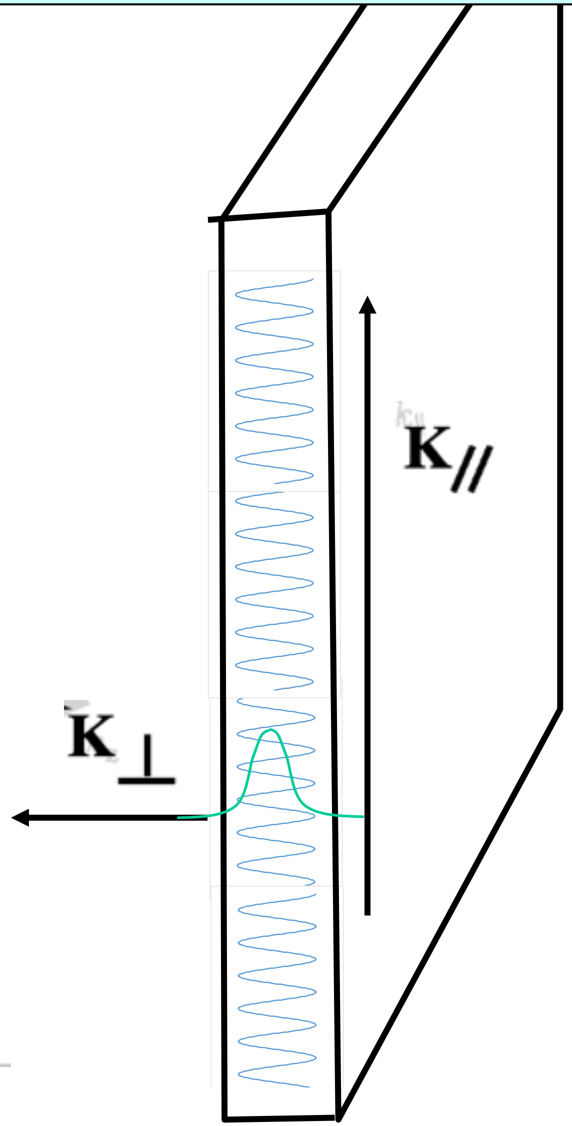
GaAS QW



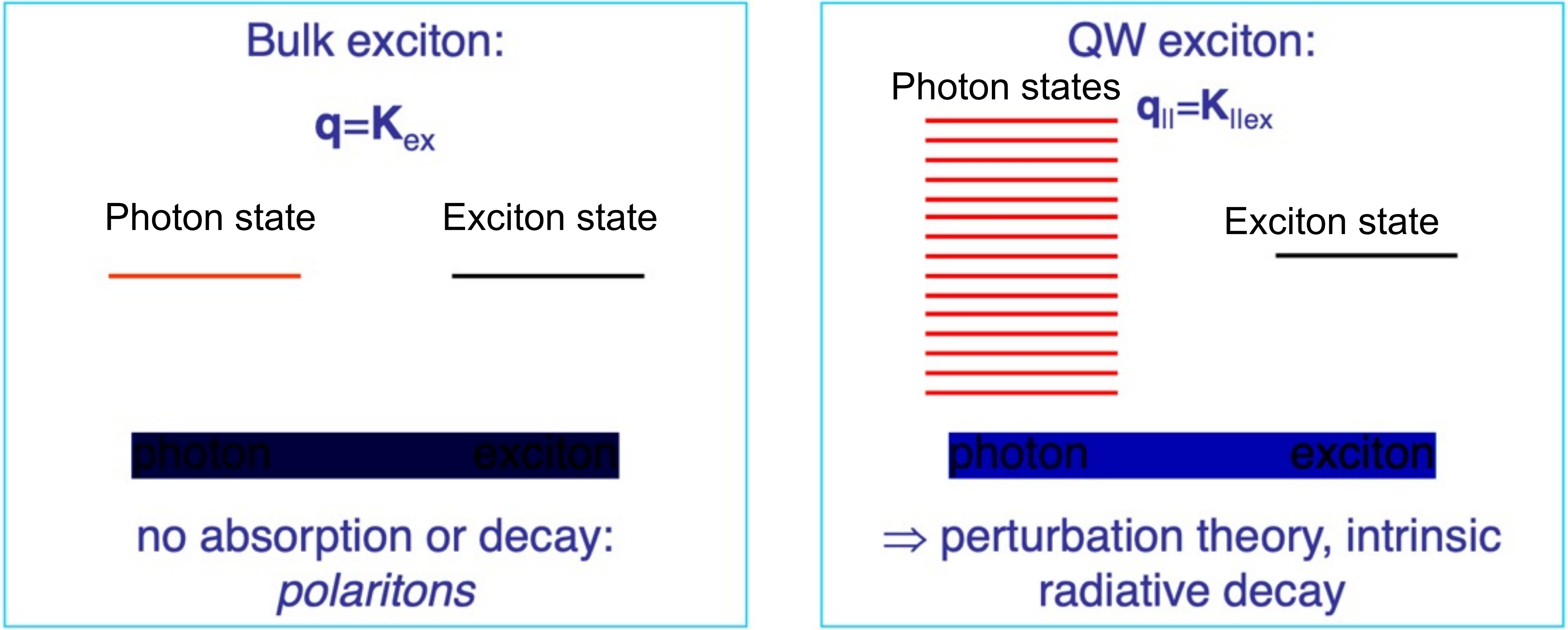
Weisbuch et al., Intrinsic Radiative Recombination From Quantum States in GaAs-AlGaAs Multi-Quantum Well Structures, Solid Sate Commun. 37, 219 (1981)

In quantum wells recombination, no conservation of momentum
Excitons are coupled to a continuum of states





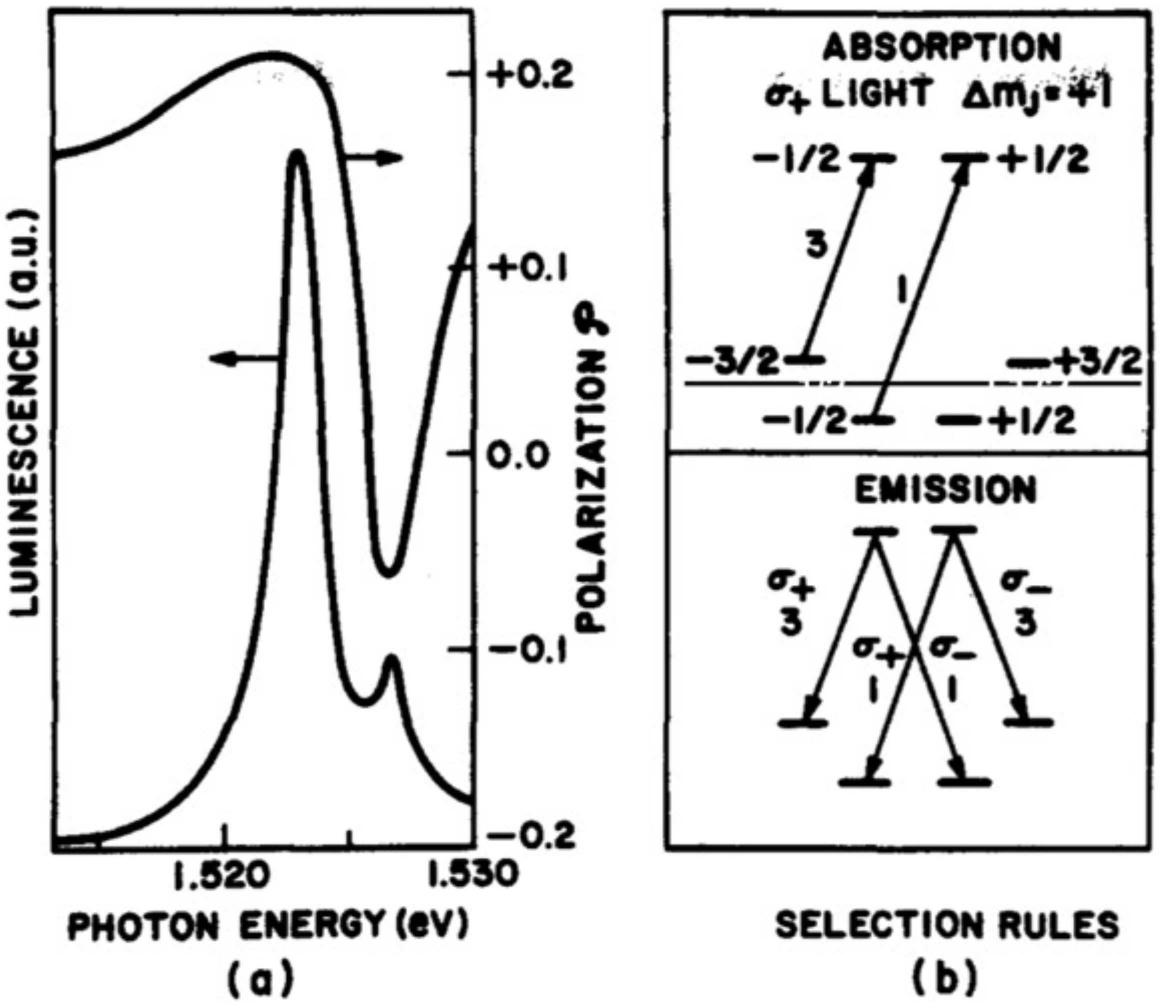
Intrinsic radiative decay of free QW excitons

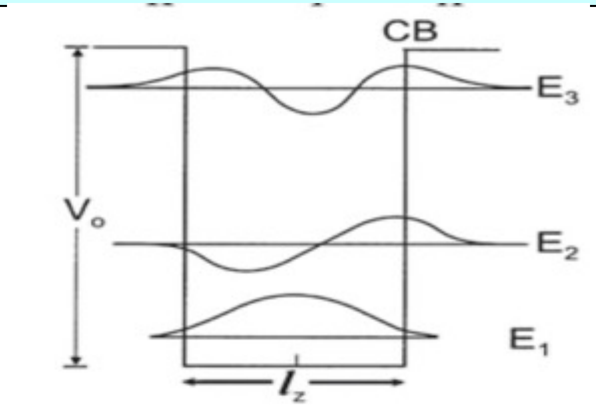


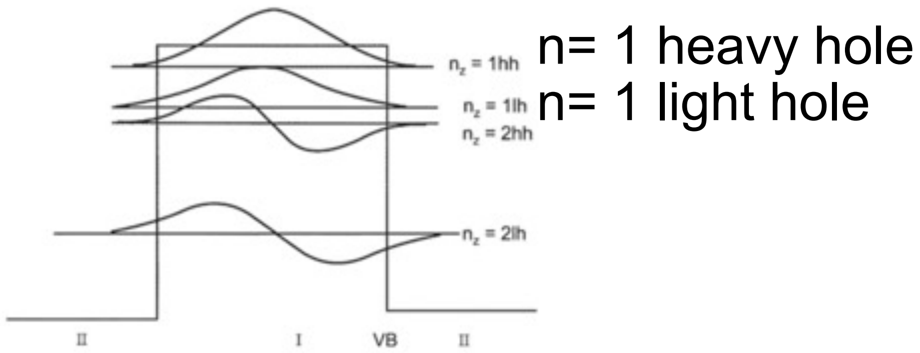
A QW exciton with given in-plane wavevector $K_{||ex}$ interacts with a continuum of photons with wavevectors $q=(q_{||}=K_{||ex}, q_z)$ perturbative regime with irreversible decay *intrinsic radiative recombination mechanism*.

L. C. Andreani, F. Tassone, and F. Bassani, Solid State Commun. 77, 641 (1991)

Intrinsic radiative decay of free QW excitons





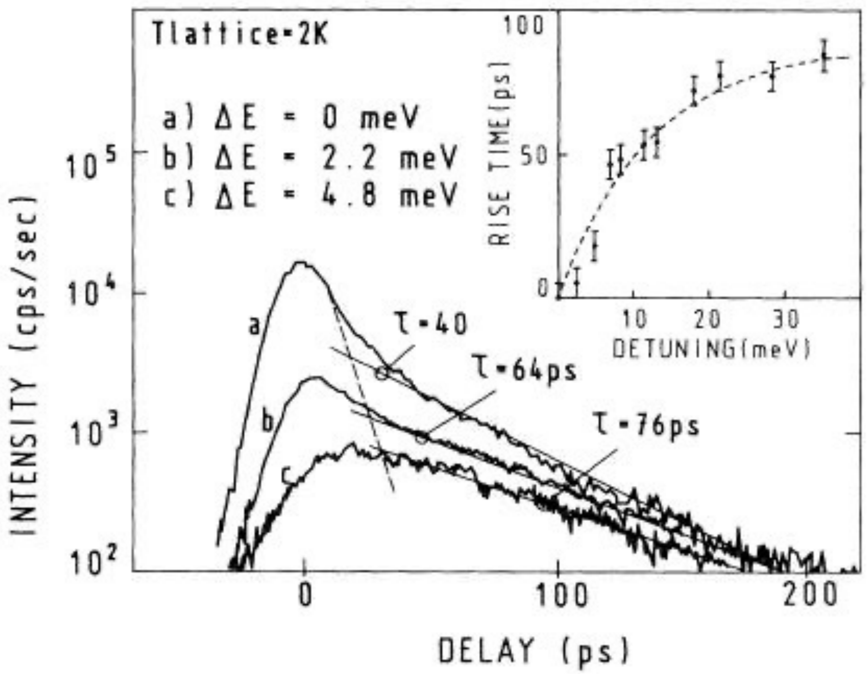


High efficiency
For all semiconductors, efficiency much higher for QWs than in bulk 3D material

Weisbuch et al., Intrinsic Radiative Recombination From Quantum States in GaAs-AlGaAs Multi-Quantum Well Structures, Solid Sate Commun. 37, 219 (1981)

Intrinsic radiative decay of free QW excitons explained: very short radiative lifetime measured

Radiative properties of free excitons in a single GaAs quantum well are studied under resonant excitation. Enhanced radiative recombination of the excitons, caused by the breakdown of the translational symmetry of the system, is evidenced by the very short lifetime as well as by the strong intensity of the signal. Dephasing mechanisms, by transferring the excitons to nonradiative states, increase the observed lifetime. We deduce a radiative lifetime of 10 4 ps in the absence of dephasing mechanisms.



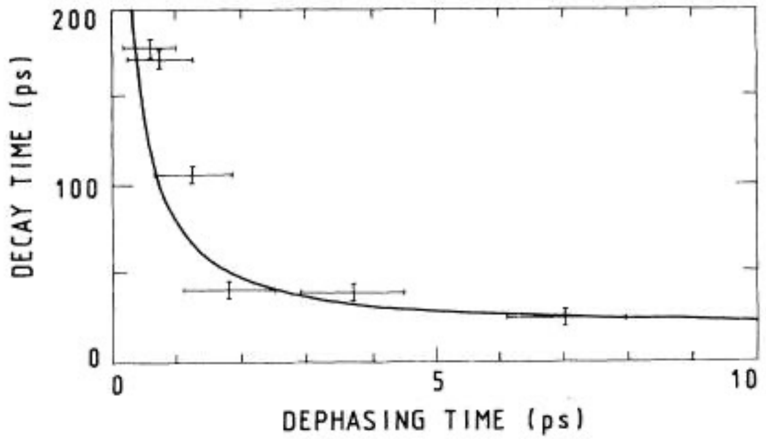
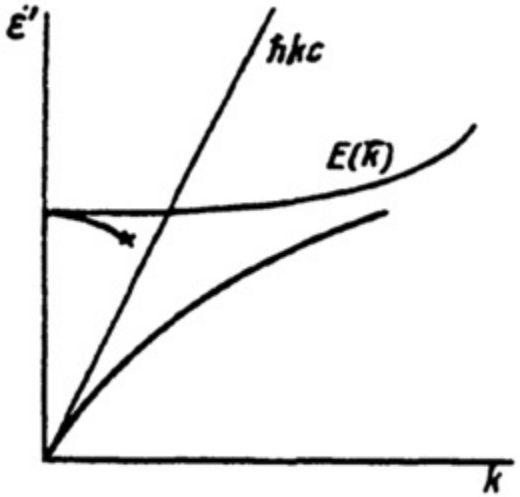


FIG. 3. Measured exciton lifetime, under resonant excitation, as a function of the dephasing time (deduced from fits similar to those of Fig. 2). The fit corresponds to Eq. (3), with $\tau_0=8$ ps and $\tau'=8$ ps, and $\tau_{tun}=1000$ ps.

B. Deveaud et al., Enhanced Radiative Recombination of Free Excitons in GaAs Quantum Wells, Phys. Rev. Lett. 67, 2355, 1991

Intrinsic radiative decay of 2D excitons :
very short radiative lifetime predicted in 1962 !

"Unlike three-dimensional crystals, allowance for retarded interaction in one- and two-dimensional periodic structures 1eads to several singularities in the exciton spectra …."

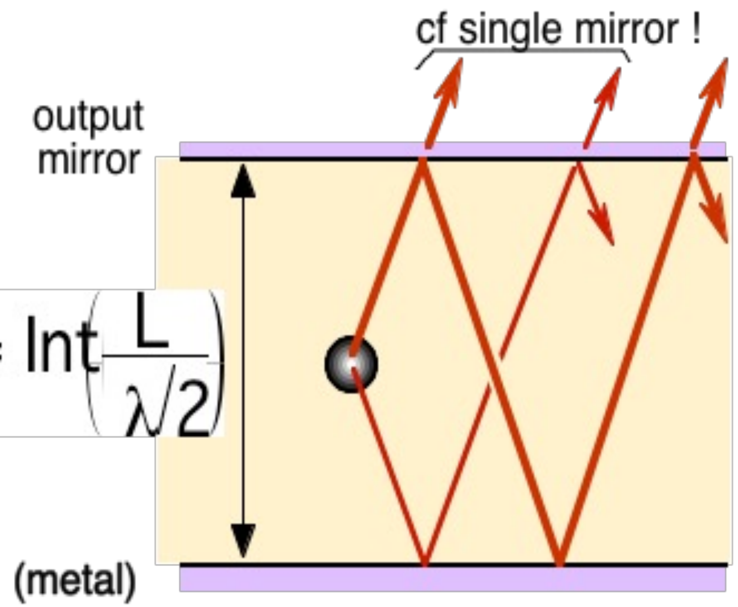


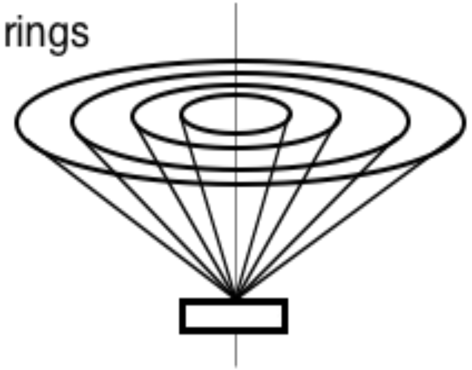
"The excitons should have in such crystals a lifetime -10^{-13}- 10^{-15} sec, which can be discerned from the luminescence damping time, from the absorption and emission line shapes, etc. "

Agranovich and O. A. Dubovskii, Effect Of Retarded Interaction on the Exciton Spectrum In One-Dimensional and Two-Dimensional Crystals, JETP Lett. 3, 796, 1962

Atomes a l'Interieur d'un Interferometre Perot-Fabry
Microcavity emission: atoms in a Fabry-Pérot resonator

$$m_c = \mathrm{Int}\left(\frac{L}{\lambda/2}\right)$$





For a point source :

(Fabry-Perot interf.) × (2-beam interf)

$$|E|^2 = |E_o|^2 \times \frac{T_1}{\left|1 - r_1 r_2 e^{2i\phi}\right|^2} \times \left|1 + r_2 e^{2i\phi'}\right|^2 = |E_o|^2 \times \frac{T_1}{\left|1 - r_1 r_2 e^{2i\phi}\right|^2} \times 2\zeta(z,\theta)$$

Exaltation or Inhibition due to the modal structure of the whole cavity

Factor from 0 to 4 depending on the source location with respect to the mode antinodes at the considered angles

A.Kastler, Appl. Optics 1, 17 (1962)

Microcavities : Weak Coupling Régime

Spontaneous and stimulated emissions are NOT intrinsic properties of an electronic state. They also depends of the electromagnetic field they are coupled to.

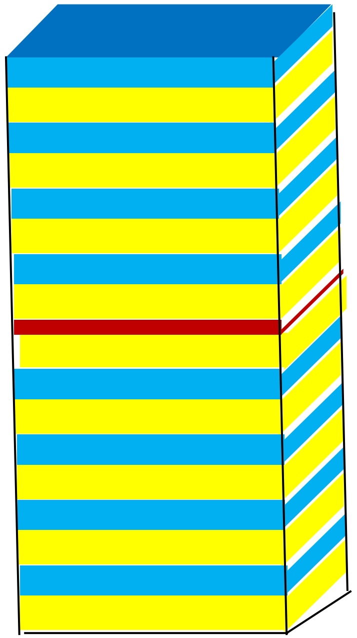
Discrete state coupled to a continuum of final states
Fermi's golden rule:
Perturbation theory, transition rate:

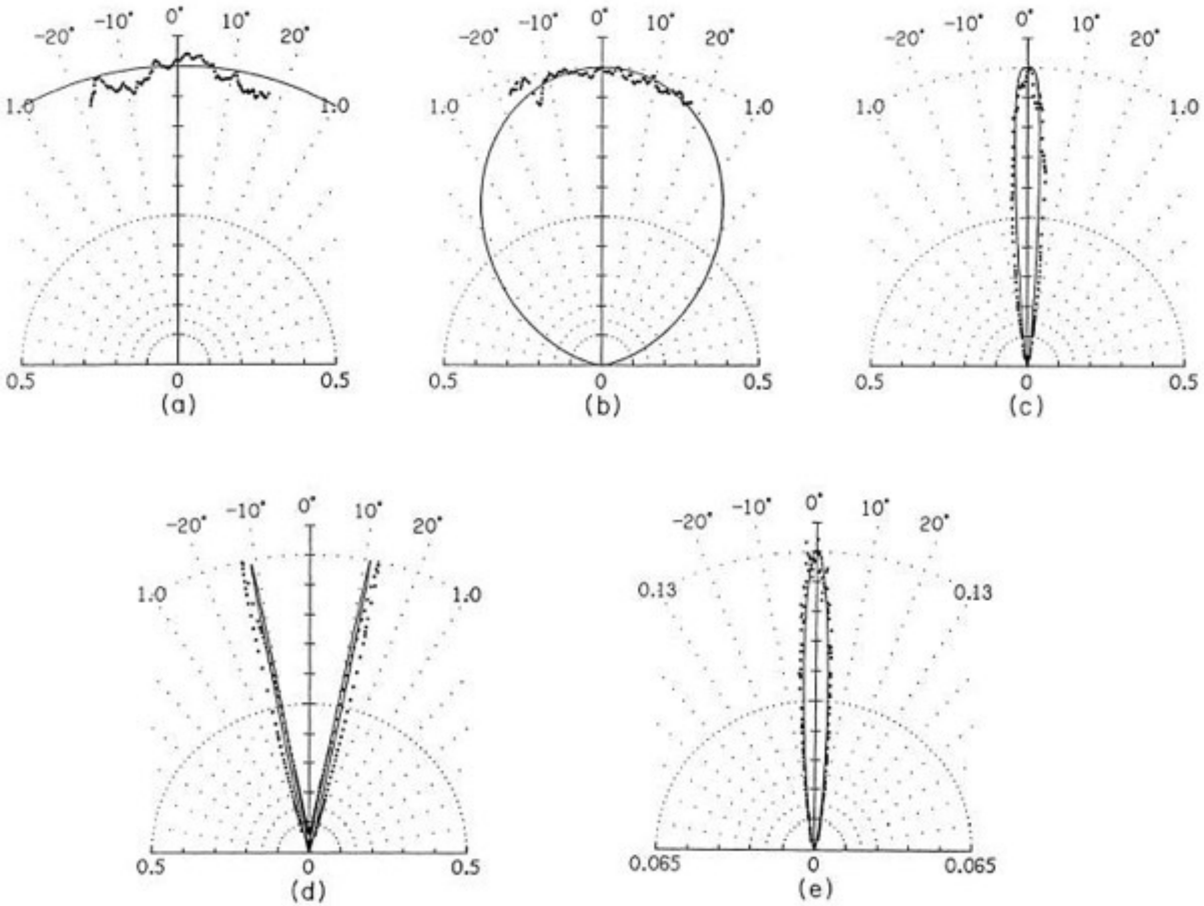
$$\Gamma_{i \to f} = \frac{2\pi}{\hbar} \left| \langle f | H' | i \rangle \right|^2 \rho(E_f)$$

density of photon modes

Microcavities provide the means to modify the "natural" spontaneous **emission direction**. Changing emission efficiency and **rate** (**Purcell effect**) is more difficult.

Semiconductor microcavities in weak coupling



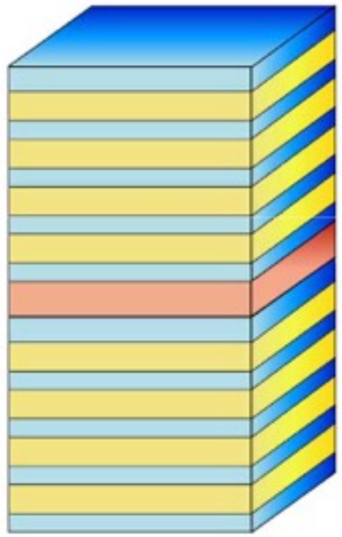


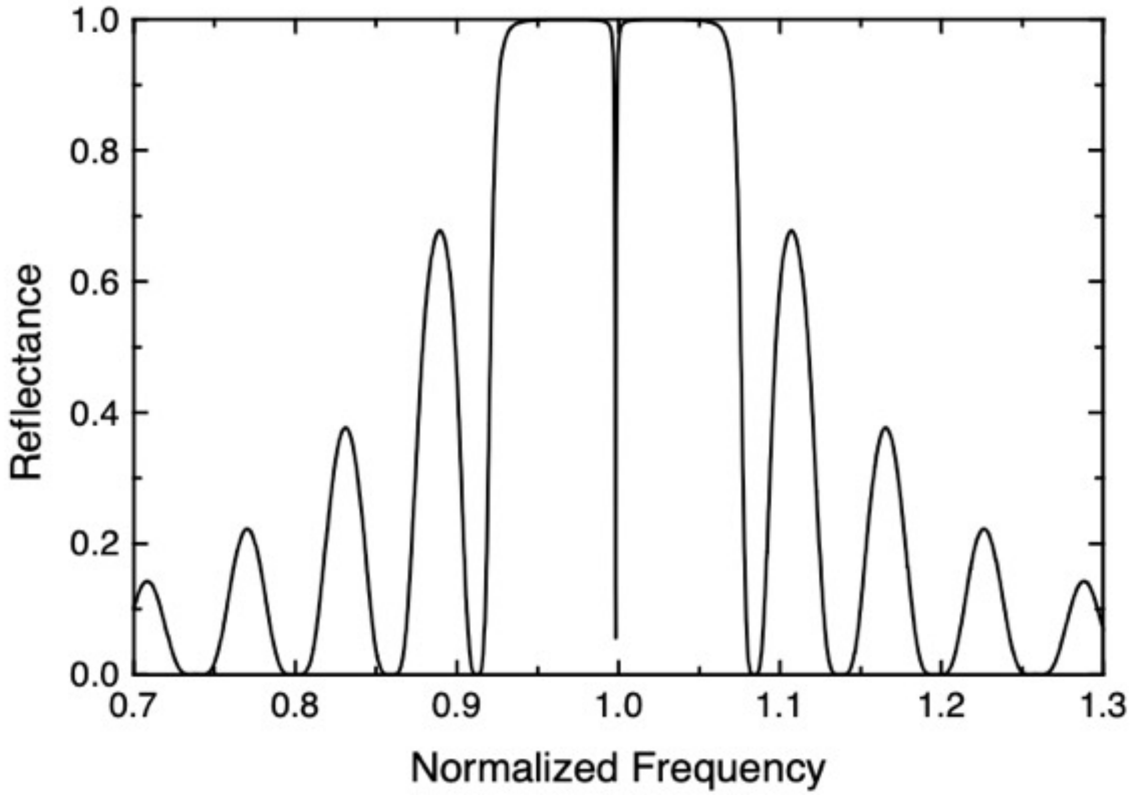
Experimental and theoretical radiation patterns from the GaAs quantum well. (a) a thick Al Ga 0.8 As layer (s wave); (b) a thick $Al_{0.2}Ga_{0.8}As$ layer (p-wave); (c) λ cavity ($\lambda_{em} = \lambda_{cav} =$ 800nm); (d) λ cavity ($\lambda_{em} =$ 800 nm $\lambda_{cav} =$ 815nm); (d) λ cavity ($\lambda_{em} =$ 800 nm $\lambda_{cav} =$ 790nm)

Björk, Yamamoto et al., Modification of spontaneous emission rate in planar dielectric microcavity structures, Phys. Rev. A 44, 669, 1991

Planar dielectric microcavity: Fabry-Pérot and leaky modes

15 pairs GaAs/AlAs Distributed Bragg Reflector (n_1=3, n_2=3.6), normal incidence

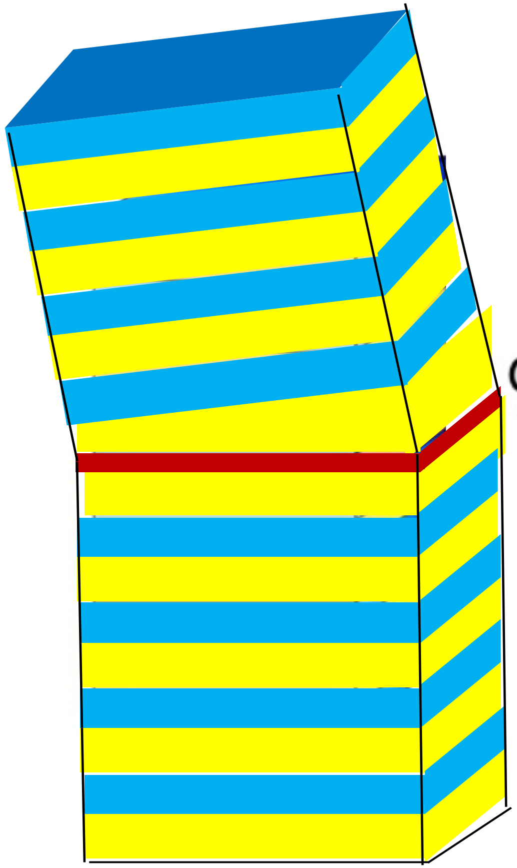


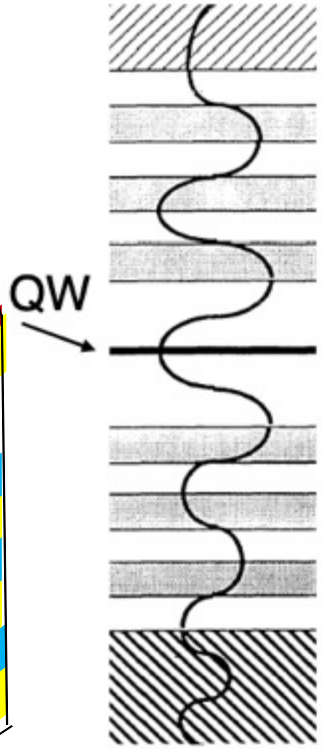


The Fabry-Pérot mode is localized within (or close to) the cavity region

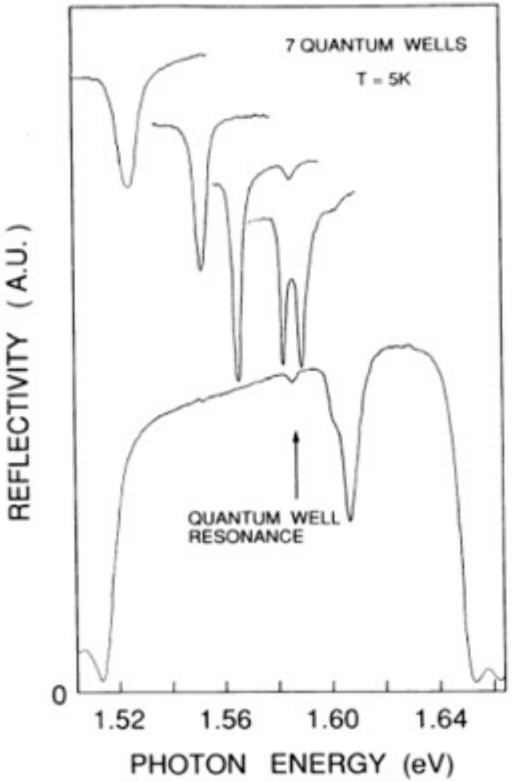
→ **quasi-2D photon states**

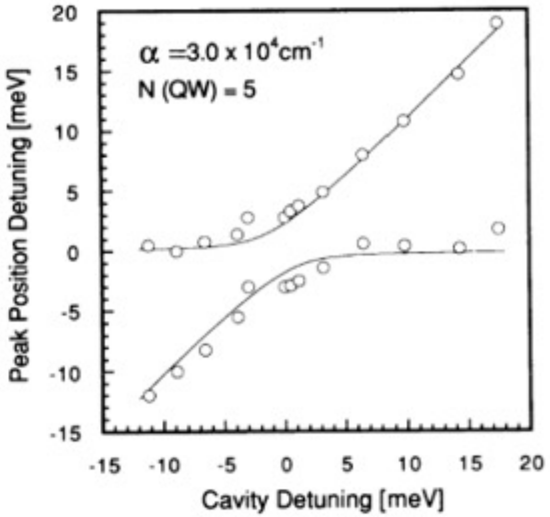
Strong coupling regime in semiconductor microcavities: cavity polaritons





Cavity with 7 quantum wells: splitting at resonance





The coupling between cavity mode and exciton gives rise to a vacuum-field Rabi splitting (~5 meV) at resonance and to mixed modes:

cavity polaritons

Weisbuch, Arakawa et al., Observation of the Coupled Exciton-Photon Mode Splitting in a Semiconductor Quantum Microcavity, Phys. Rev. Lett. 69, 3314, 1992

"This effect can be seen as the Rabi vacuum-field splitting of the quantum-well excitons, or more classically as the normal-mode splitting of coupled oscillators, the excitons and the electromagnetic field of the microcavity. An exciton oscillator strength of 4.10^{12} cm^{-2} is deduced for 76-A quantum wells".

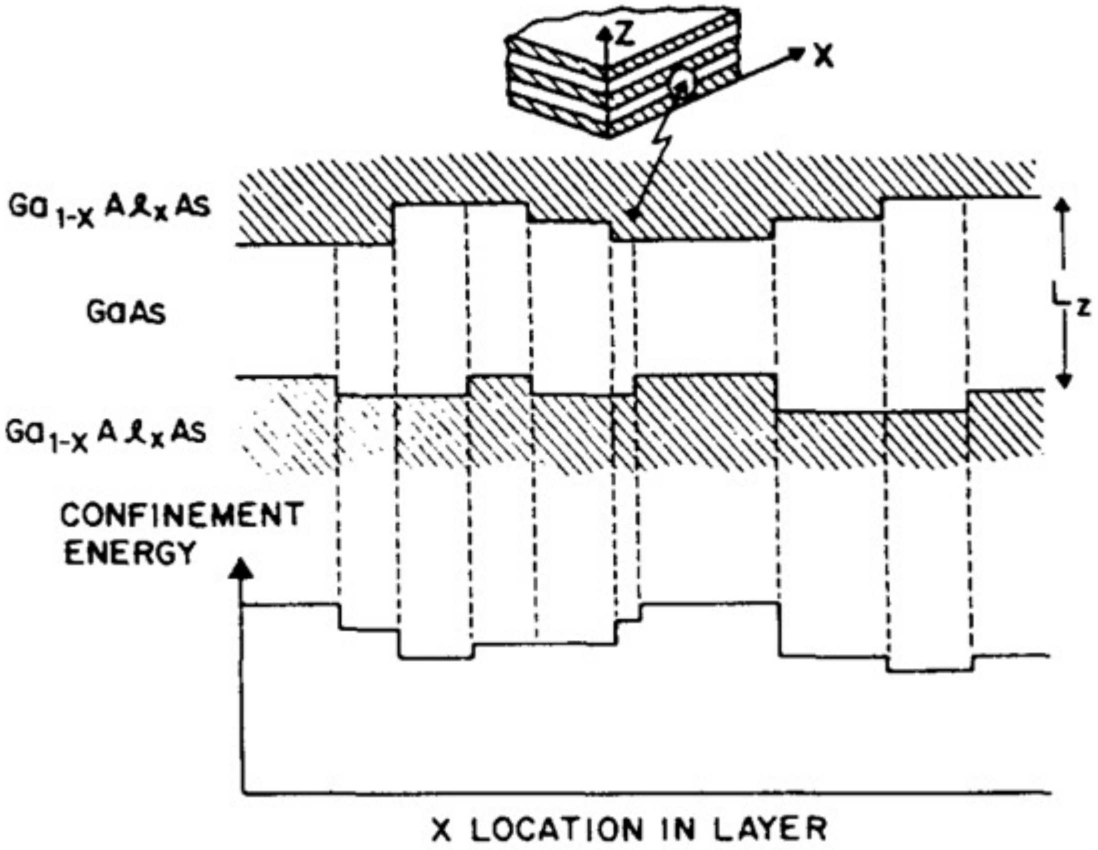
`A very disturbing paper – "Vacuum Rabi Splitting as a Feature of Linear Dispersion Theory: Analysis and Experimental Observations"

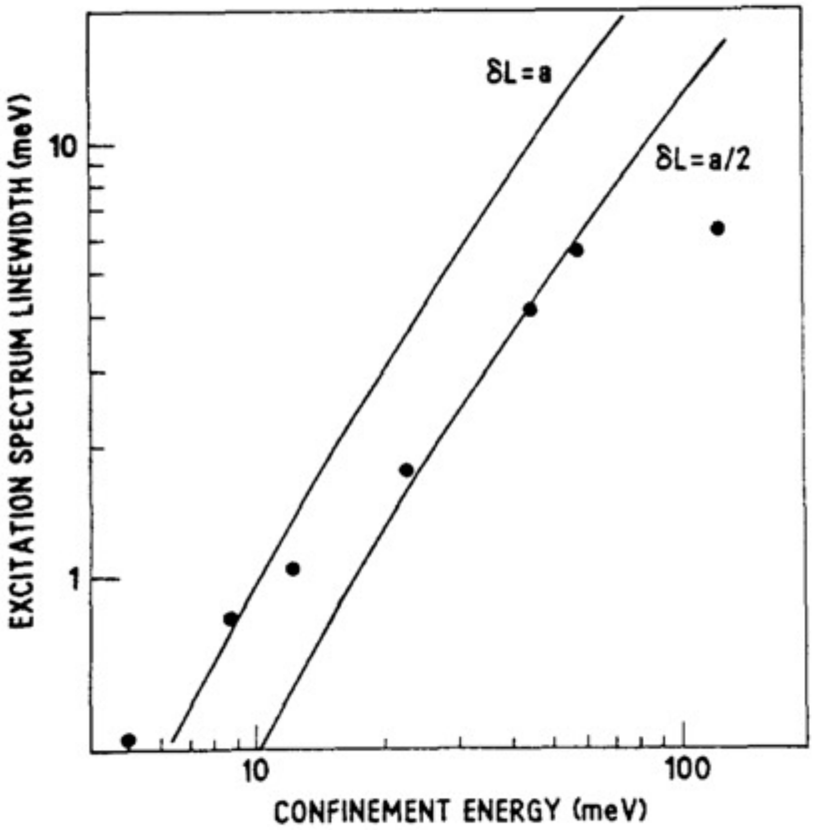
The spectral and temporal response of an optical cavity resonantly coupled to an ensemble of barium atoms has been investigated experimentally. The empty-cavity transmission resonances are found to split in the presence of the atoms and, under these conditions, the cavity's temporal response is found to be oscillatory. **These effects may be viewed as a manifestation of a vacuum-field Rabi splitting, or as simple consequence of the linear absorption and dispersion of the intracavity atom**

In summary, we have shown that the steady-state and transient transmission characteristics of a cavity coupled to a collection of atoms can be understood using an entirely classical, steady-state multibeam interference analysis of an optical cavity. In particular, it is found that the empty-cavity resonances can be split due to the effects of linear absorption and dispersion and that this mode splitting is identical to the vacuum-field Rabi splitting predicted by a fully quantum electrodynamical formalism. This of course implies that the **mere** observation of oscillatory transmission and/or mode splitting is no more intrinsically quantum than the observation of linear absorption and dispersion.

Yifu Zhu et al., Vacuum Rabi Splitting as a Feature of Linear-Dispersion Theory: Analysis and Experimental Observations, Phys. Rev. Lett. 54, 2499 (1990)

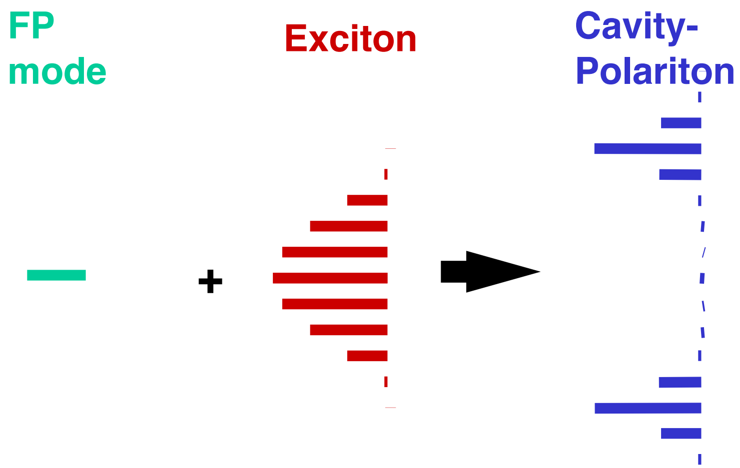
An inhomogeneously broadened system: Interface fluctuations in quantum wells lead to position-dependent energy

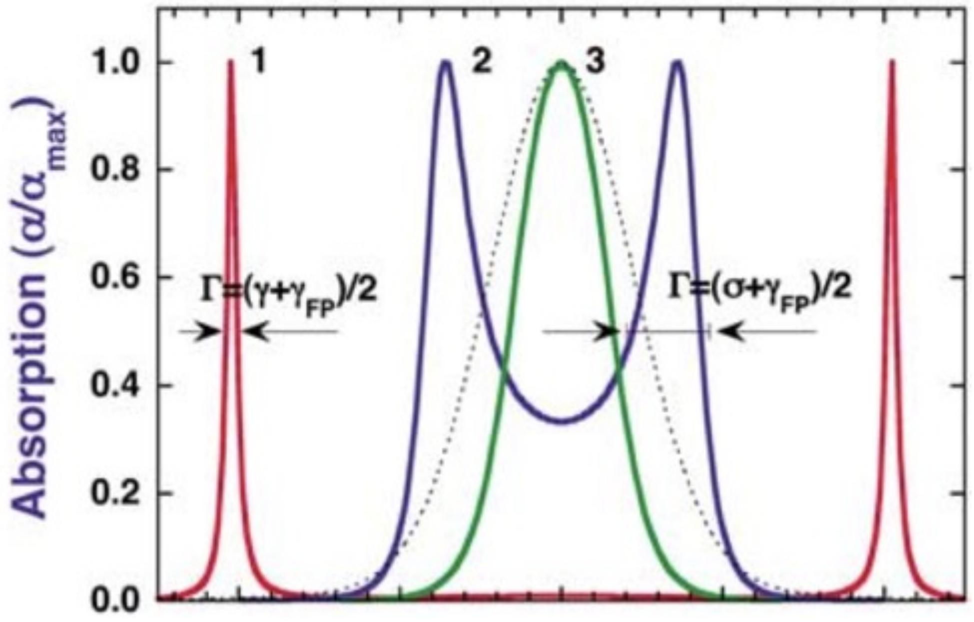




C. Weisbuch et al., Optical characterization of interface disorder in GaAs-Ga_xAl1-xAs multi-quantum well structures, Solid State Commun. 38, 709-712 (1981)

Strong coupling in an inhomogeneously broadened system





If the Rabi splitting is larger than inhomogeneous broadening

$\gamma_c / E_0 = 3.10^{-5}$, $\gamma / E_0 = 1.10^{-4}$, $\sigma / E_0 = 1.10^{-3}$
coupling strength are 50 (1), 5 (2) and 1 (3)

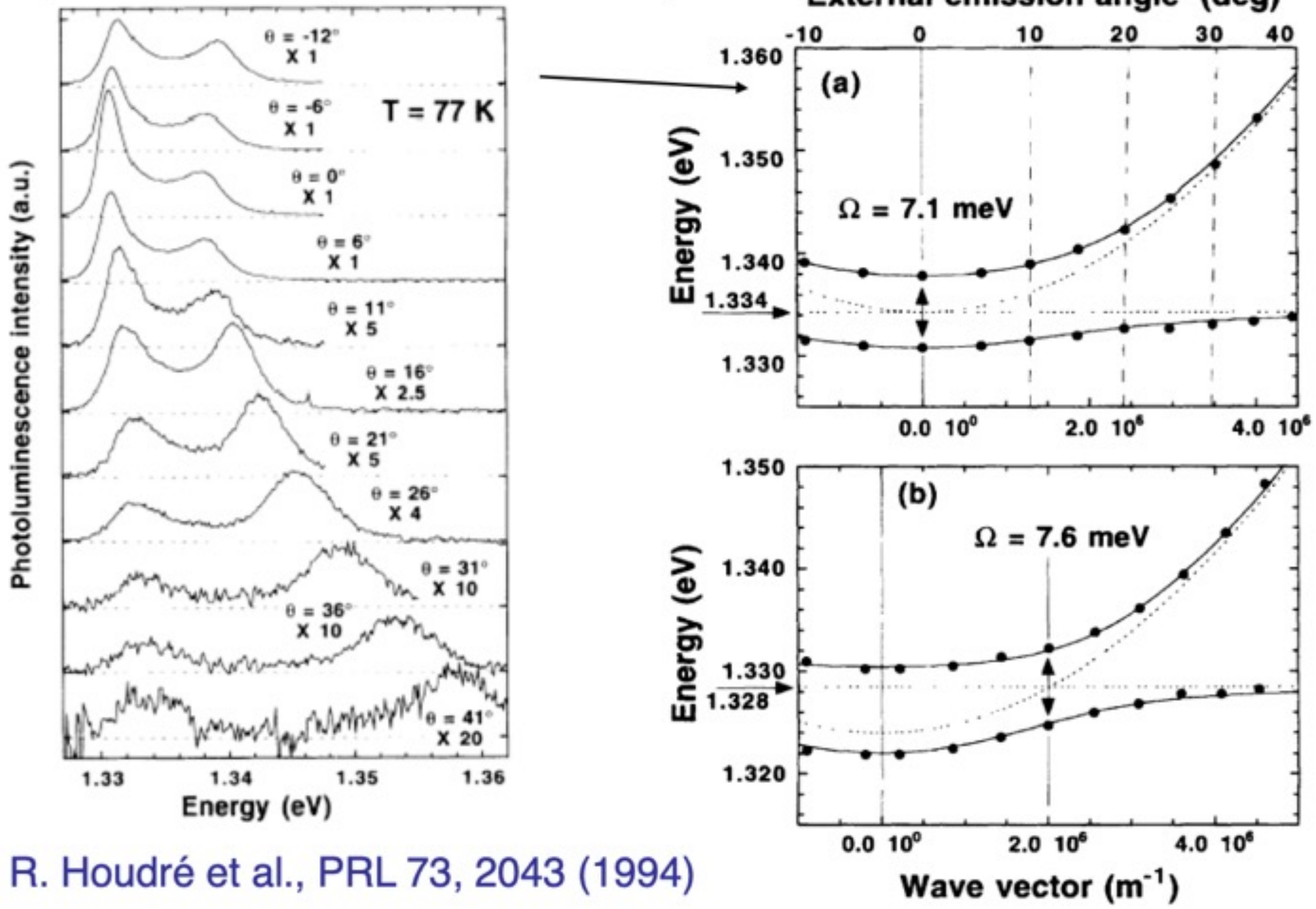
Houdré et al., Phys. Rev. A 53 (1996) 2711

All exciton states are coupled together through cavity photon exchange
Splitting is hardly perturbed

While QW inhomogeneous linewidth is >1 meV, polariton linewidth can be as small as 50 μeV
QW fluctuations are averaged over polariton wavefunction, i.e. photon mode size, ≈ tens of μm, vs exciton size, ≈ ten nm.

Angle-dependent photoluminescence delivers the polariton dispersion curve

Angle-resolved PL (resonance at θ=0)



R. Houdré et al., PRL 73, 2043 (1994)

Romuald Houdré

Ursula Oesterle

Ross Stanley

Evidence of strong coupling (vs cavity dielectric response)
The detuning variation of emission

R. Stanley et al.
Phys. Rev. B 53, 10995 (1996)

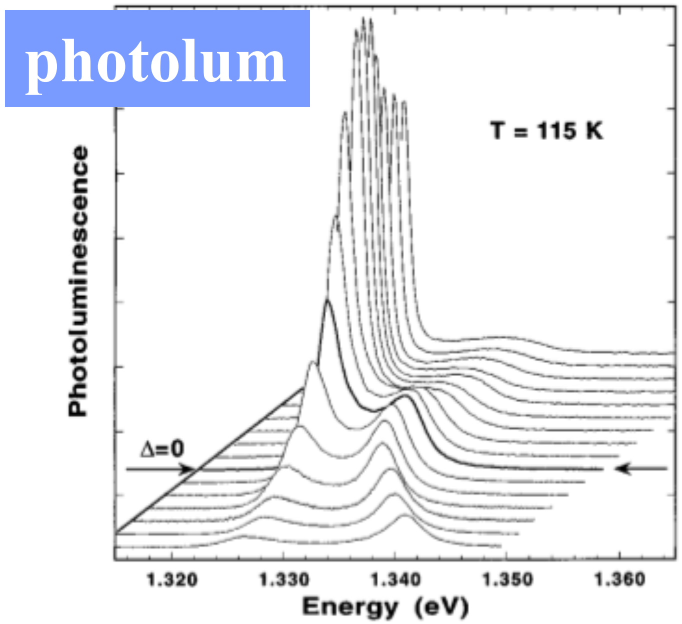


FIG. 5. Photoluminescence spectra for a range of FP-exciton detuning, ranging from −10 meV to +12 meV. The spectra have been shifted laterally, so that the unperturbed exciton PL (as seen in the edge PL) stays at the same energy (1.326 eV). The thicker l denotes the spectrum at zero detuning.

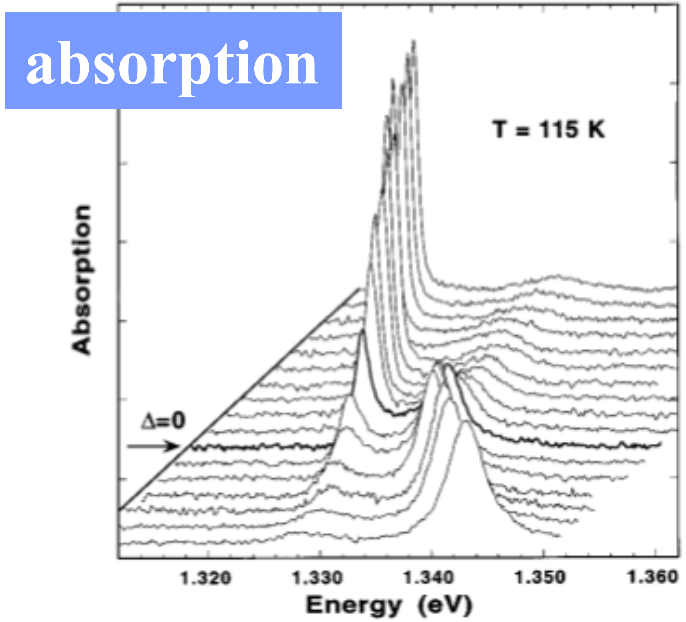


FIG. 6. Absorption spectra for a range of FP-exciton detuning, where the absorption is approximated by 1-reflectivity, ranging from −10 meV to +12 meV. The spectra have been shifted later-

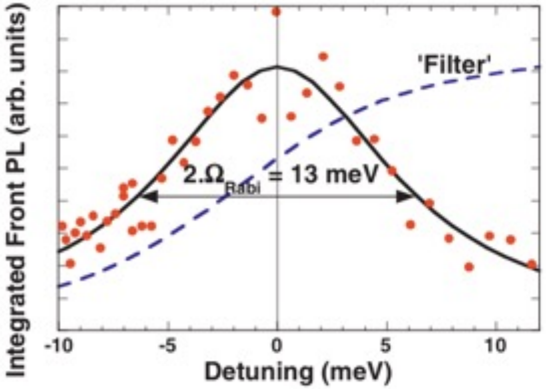


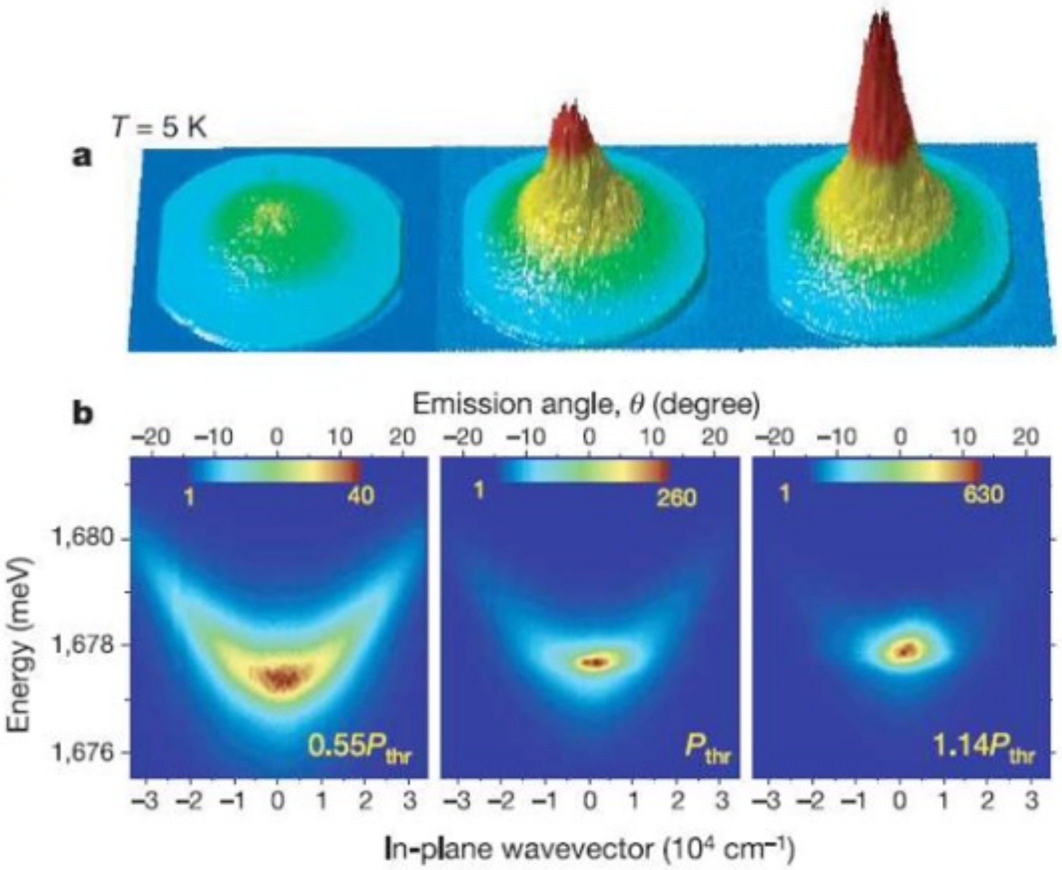
Fig. 11 (online colour at: www.pss-b.com) Integrated front surface photoluminescence as a function of detuning (dots). The dashed line labeled ‘filter’ shows the asymmetry expected from the exciton in a Fabry–Pérot filter. Adapted from [38].

Bose-Einstein condensation of cavity-polaritons

in a CdTe/CdMgTe microcavity with 16 quantum wells at 5 K / 19 K

Parameters for BEC

Parameter	Atom	Polariton
$m\ [m_e]$	10^4	10^{-4}
T [K]	10^{-6}	20
$\lambda_{dB}\ [\mu m]$	0.7	3
$n_{cr}\ [cm^{-2}]$	10^8	$5 \cdot 10^8$
Life Time	"long" s	"very short" $10^{-12} s$



J. Kasprzak et al., Nature 443, 409 (2006)