Polariton- electron mixtures

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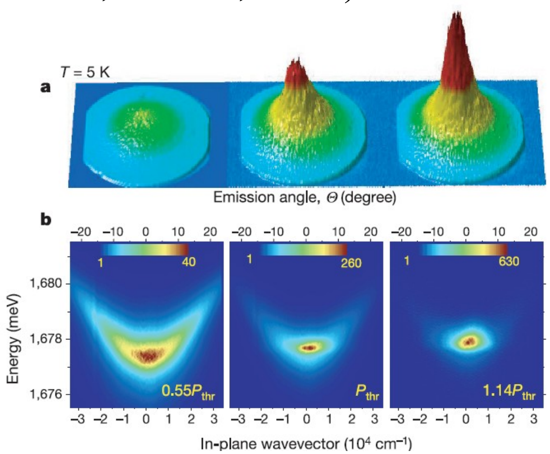
Outline

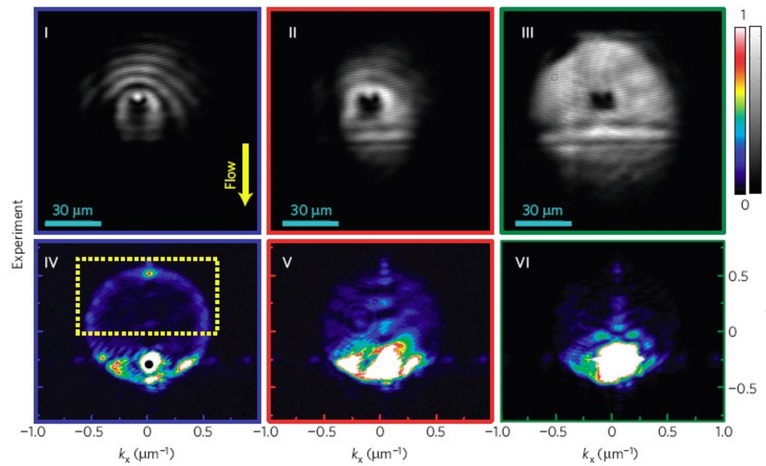
- Short introduction: collective phenomena in electronic and excitonic systems
- Hybrid exciton- electron and polariton- electron system
- Exciton- mediated attraction between the electrons and BCS instability
- Effect of the electronic system on excitonic BEC: roton minimum and distruction of the condensate
- Spin related effects

Quantum collective phenomena: polariton BEC and superfluidity

The group of Le Si Dang claimed the **existence of the polariton BEC** in Cd Te cavity at 20K (Kasprzak et al, Nature, 2006)

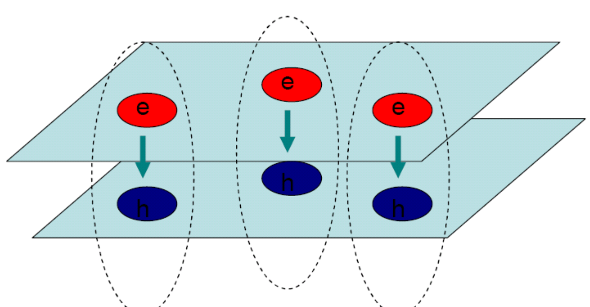


Polariton superfluidity was demonstrated in 2009 by A.Amo et al (Nature, Nature Phys.)



Advantage of excitonic and polaritonic systems: small effective mass compare to cold atoms, and thus quantum collective phenomena become more pronounced: high critical temperature and critical velocity

The groups of L. Butov and V. Timofeev claimed the existence of the BEC in a system of 2D indirect excitons



Renormalized dispersions of elementary excitations:

$$E(k)=\sqrt{E_0(k)\left[E_0(k)+2UN_0\right]}\approx v_s k$$

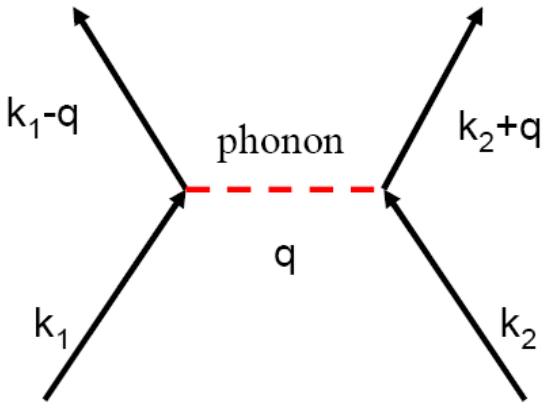
Bare dispersion — Interaction strength — Condensate occupancy

$$v_s=\sqrt{\frac{UN_0}{m}}$$

Question: are there other means to tune the renormalized Bogoliubov dispersions?

BCS instability in the electronic system

Intreraction between the electrons: direct Coulomb repulsion plus exchange of phonons



$$H = \sum_{\mathbf{k}} E_{el}(\mathbf{k})\, a^{+}_{\mathbf{k}} a_{\mathbf{k}} + \sum_{\mathbf{k}} \hbar\omega_{ph}(\mathbf{k})\, b^{+}_{\mathbf{k}} b_{\mathbf{k}} +$$

$$+ \sum_{\mathbf{k},\mathbf{q}} D(\mathbf{q})\, a^{+}_{\mathbf{k}+\mathbf{q}} a_{\mathbf{k}} \left(b^{+}_{-\mathbf{q}} + b_{\mathbf{q}} \right)$$

$$V_{eff} = V_C(\mathbf{q}) + \frac{2\omega_{ph}(\mathbf{q})}{\omega^2 - \omega^2_{ph}(\mathbf{q})} D^2(\mathbf{q})$$

$$k_B T_c = \hbar\omega_D \exp\left(- \frac{1}{D\aleph(E_F)} \right)$$

Debye energy

Electron -phonon coupling

Density of states

Phonon Green function. Dependence on frequency corresponds to the retarding nature of the phonon- mediated attraction

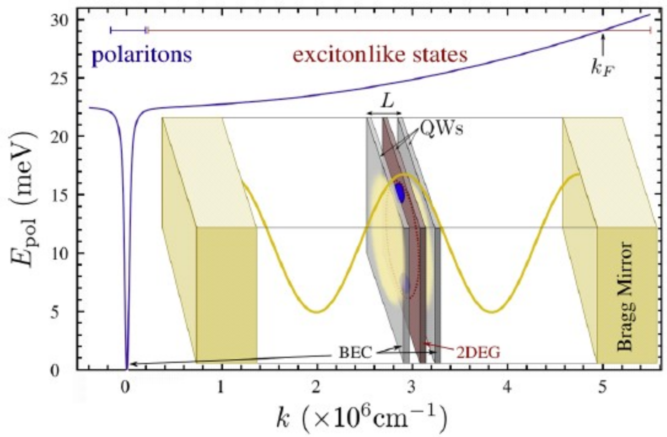
Question: can we organize BCS attraction using mediator other then phonon?

As a result of the phonon- mediated attraction the Cooper pairs are formed and in the spectrum of the elementary excitations appears a gap, leading to the onset of superconductivity

Hybrid polariton- electron system

F.P. Laussy, A.V. Kavokin, I.A. Shelykh, PRL (2010)

$$H=\sum_{\mathbf{k}}\left[E_{\rm pol}(\mathbf{k})a^\dagger_{\mathbf{k}}a_{\mathbf{k}}+E_{\rm el}(\mathbf{k})\sigma^\dagger_{\mathbf{k}}\sigma_{\mathbf{k}}\right]+\sum_{\mathbf{k_1},\mathbf{k_2},\mathbf{q}}\left[V_{\rm C}(\mathbf{q})\sigma^\dagger_{\mathbf{k_1+q}}\sigma^\dagger_{\mathbf{k_2-q}}\sigma_{\mathbf{k_1}}\sigma_{\mathbf{k_2}},+XV_{\rm X}(\mathbf{q})\sigma^\dagger_{\mathbf{k_1}}\sigma_{\mathbf{k_1+q}}a^\dagger_{\mathbf{k_2+q}}a_{\mathbf{k_2}}+Ua^\dagger_{\mathbf{k_1}}a^\dagger_{\mathbf{k_2+q}}a_{\mathbf{k_1+q}}a_{\mathbf{k_2}}\right]$$



$$V_{\rm C}(\mathbf{q})=\frac{e^2}{2\epsilon A}\frac{1}{|\mathbf{q}|+\kappa}\qquad V_X=V_{dir}+V_{ex}$$

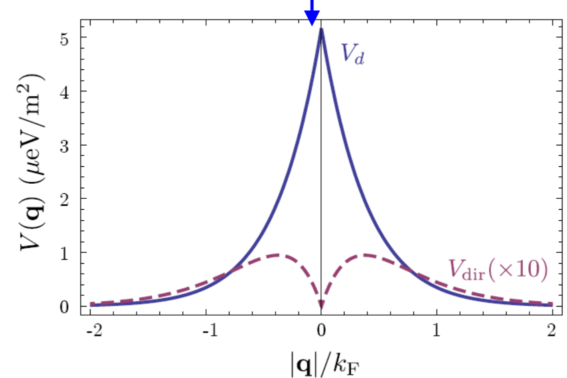
$$V_{dir}(q)=\frac{e^2}{2\epsilon A}\frac{e^{-qL}}{q}\left\{\frac{1}{[1+(\beta_e q a_B/2)^2]^{3/2}}-\frac{1}{[1+(\beta_h q a_B/2)^2]^{3/2}}\right\}+\frac{ed}{2\epsilon A}e^{-qL}\left\{\frac{\beta_e}{[1+(\beta_e q a_B/2)^2]^{3/2}}+\frac{\beta_h}{[1+(\beta_h q a_B/2)^2]^{3/2}}\right\}$$

Dipole moment. The bigger the better!

$$H=\sum_{\mathbf{k}}E_{el}(\mathbf{k})\sigma^+_{\mathbf{k}}\sigma_{\mathbf{k}}+\sum_{\mathbf{k}}E_{bog}(\mathbf{k})b^+_{\mathbf{k}}b_{\mathbf{k}}+\sum_{\mathbf{k},\mathbf{q}}M(\mathbf{q})\sigma^+_{\mathbf{k+q}}\sigma_{\mathbf{k}}\left(b^+_{\mathbf{-q}}+b_{\mathbf{q}}\right)$$

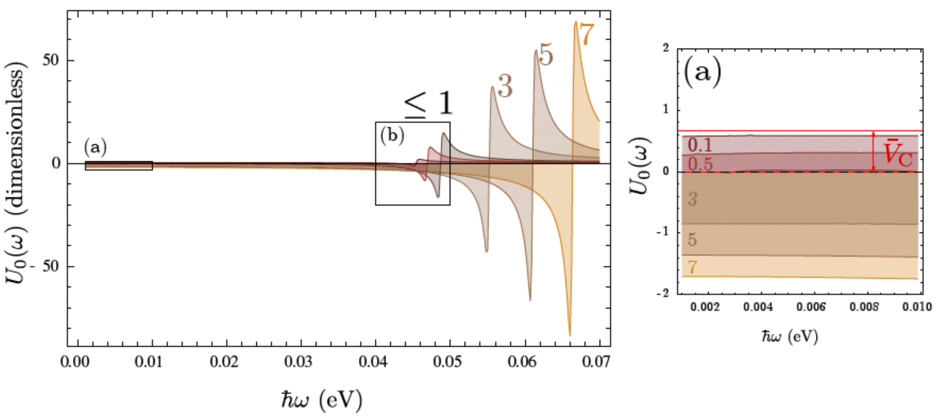
$$V_A=\frac{2E_{bog}(\mathbf{q})}{E^2-E^2_{bog}(\mathbf{q})}M^2(\mathbf{q})\propto N_0$$

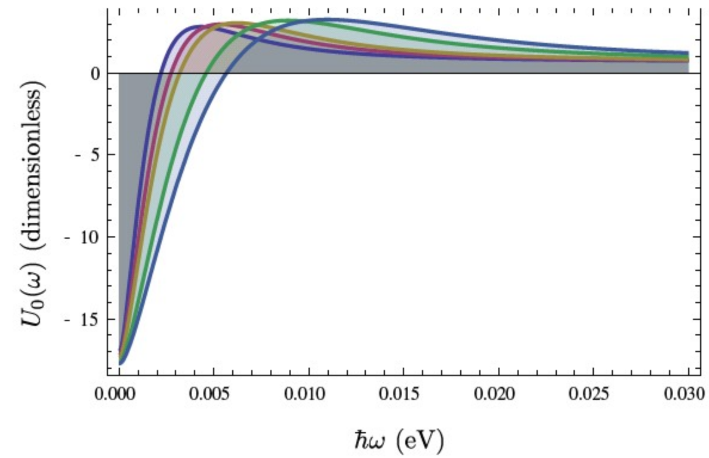
Important: the attraction strength increases linearly with the concentration of the condensate!

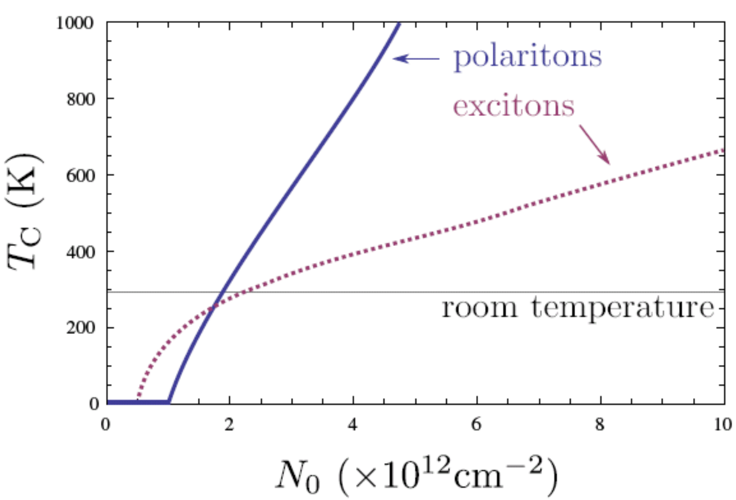


Exciton and polariton mediated superconductivity

Effective frequency dependent potential of electron- electron interaction for polaritons (left) and indirect excitons (right)







Critical temperature of the transition into superconducting state for polariton and exciton mediated superconductivity as a function of the surface density of excitons and polaritons. The critical temperature increases with N_0, because

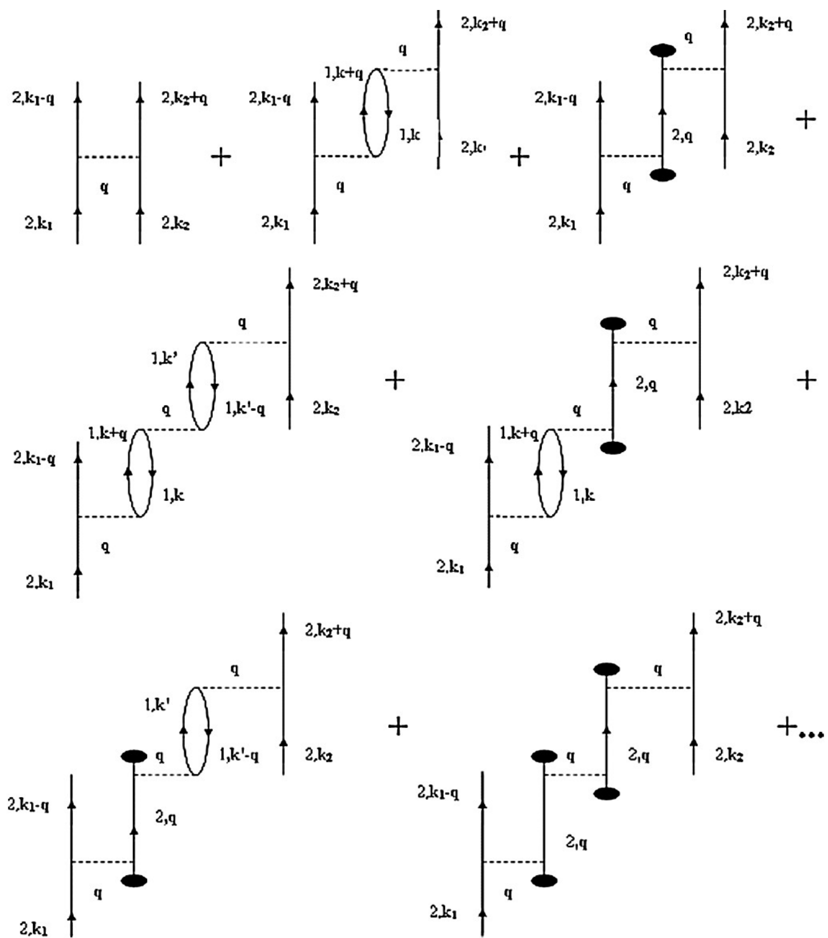
$$V_A = \frac{2E_{bog}(\mathbf{q})}{E^2 - E_{bog}^2(\mathbf{q})} M^2(\mathbf{q}) \propto N_0$$

Diagrammatic calculation of the effective interactions in the system

I.A. Shelykh, T. Taylor, A.V. Kavokin, PRL (2010)

How to account for the effect of the electron gas on excitonic system? One can use diagrammatic representation of the interaction using RPA approximation

$$V_{eff} = V\,(1 - \Pi V)^{-1}$$



$$V = \begin{pmatrix} V_{el-el} & V_{el-ex} \\ V_{el-ex} & V_{ex-ex} \end{pmatrix}, \quad \Pi = \begin{pmatrix} \Pi_{el} & 0 \\ 0 & \Pi_{ex} \end{pmatrix}$$

$$\Pi_{el}(\mathbf{q},\omega) = \sum_{\mathbf{k}} \frac{f(\mathbf{k}-\mathbf{q}) - f(\mathbf{k})}{\omega - E_{el}(\mathbf{k}-\mathbf{q}) + E_{el}(\mathbf{k}) + i\delta},$$

$$\Pi_{ex}(\mathbf{q},\omega) = \frac{2N_0 E_{ex}(\mathbf{q})}{\omega^2 - E_{ex}^2(\mathbf{q})}$$

$$V_{el-el}^{eff} = \frac{V_{el-el}(\mathbf{q}) + V_{el-ex}^2(\mathbf{q})\,\Pi_{ex}(\mathbf{q},\omega)}{1 - \Pi_{el}(\mathbf{q},\omega)\,V_{el-el}(\mathbf{q}) - F(\mathbf{q},\omega)}$$

Coulomb repulsion

BCS attraction

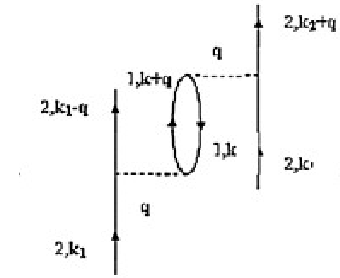
$$V_{el-el}^{eff} = \frac{V_{el-el}(\mathbf{q}) + V_{el-ex}^2(\mathbf{q})\,\Pi_{ex}(\mathbf{q},\omega)}{1 - \Pi_{el}(\mathbf{q},\omega)\,V_{el-el}(\mathbf{q}) - F(\mathbf{q},\omega)}$$

Screening

Renormalization of the condensate spectrum

Renormalized dispersion of the condensate

$$E(k) = \sqrt{E_0(k)\left[E_0(k) + 2U_0 N\right]} \approx v_s k$$

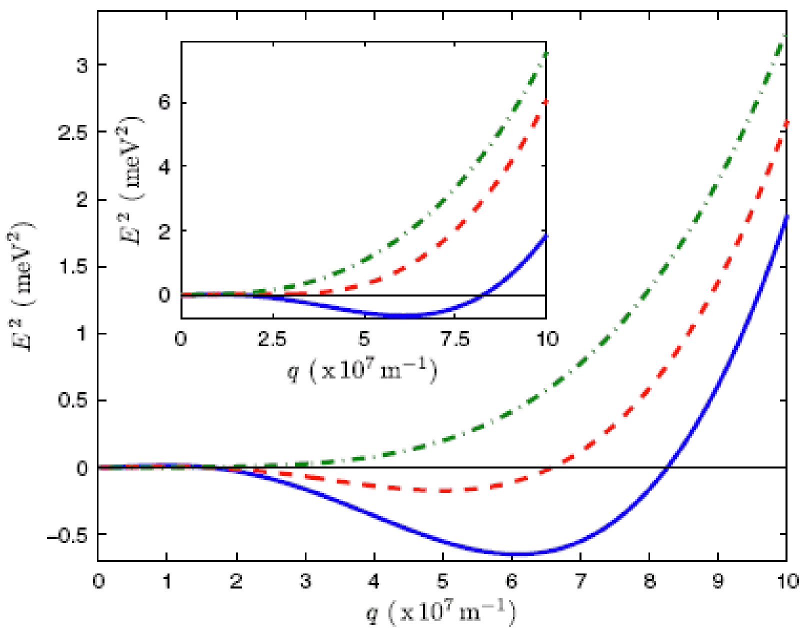


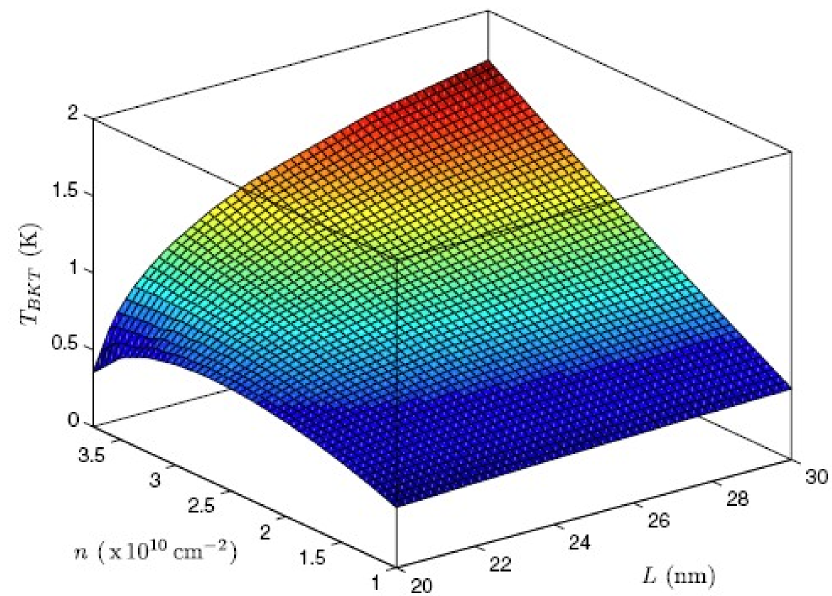
Exciton-exciton repulsion

Electron mediated attraction

$$V^{eff}_{ex-ex} = \frac{V_{ex-ex}(\mathbf{q}) + \dfrac{V^2_{el-ex}(\mathbf{q})\Pi_{el}(\mathbf{q},\omega)}{1-\Pi_{el}(\mathbf{q},\omega)V_{el-el}(\mathbf{q})}}{\omega^2 - \left\{E^2_{ex}(\mathbf{q}) + 2N_0\left[V_{ex-ex}(\mathbf{q}) + \dfrac{V^2_{el-ex}(\mathbf{q})\Pi_{el}(\mathbf{q},\omega)}{1-\Pi_{el}(\mathbf{q},\omega)V_{el-el}(\mathbf{q})}\right]E_{ex}(\mathbf{q})\right\}}$$

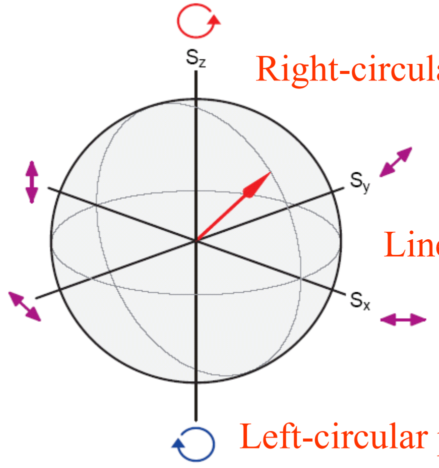
$$\Pi_{el} \approx -\frac{mA}{\pi}$$





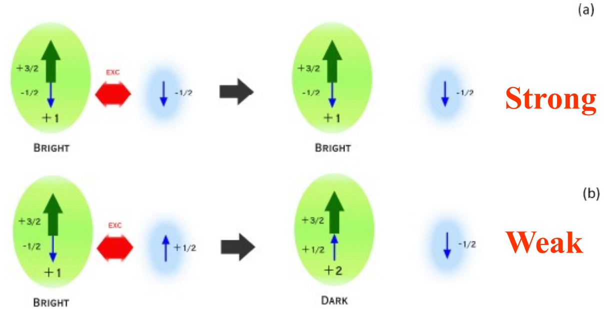
Spin related phenomena

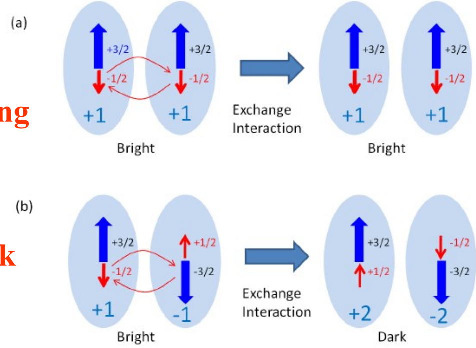
Polaritons have two spin projections on structure growth axis

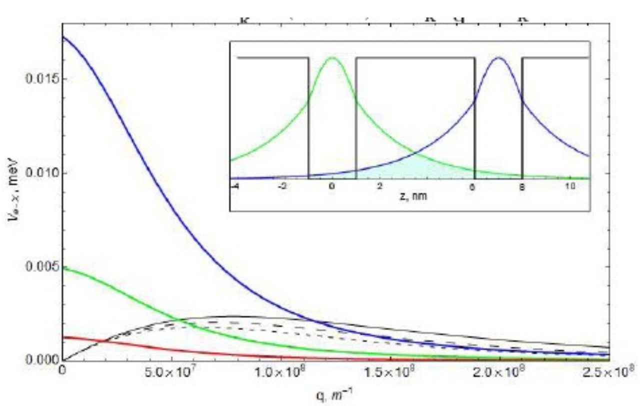


If there is an overlap between exciton and electron wavefunctions, the electron- polariton interaction becomes spin dependent as well

Important: Due to the dominance of the exchange polariton-polariton interactions are strongly anizotropic!







In the absence of the external magnetic field the polarization of the condensate is lenear.

Spin dependent Bogoliubov dispersions and different sound velocities for excitations co and cross polarized with the condensate

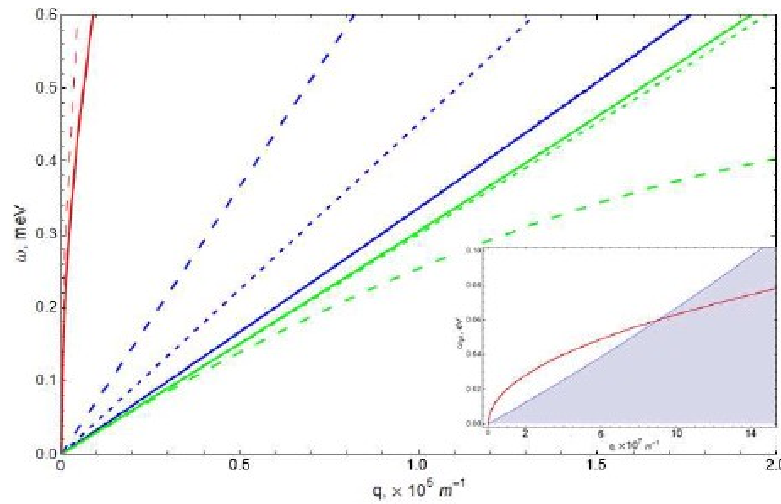
$$E^2 = E_0^2(k) + 2(\alpha_1 \pm \alpha_2) N E_0(k)$$

Spin dependent 2D plasmon- bogolon coupling

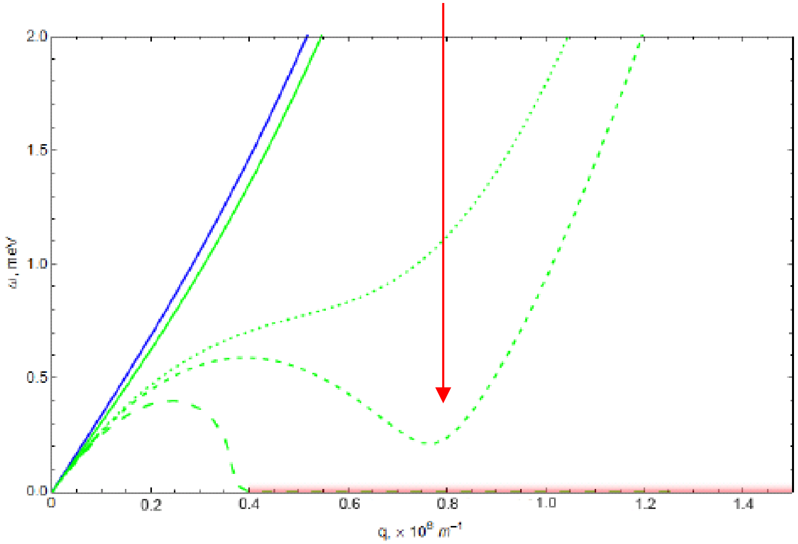
O. Kyriienko, I.A. Shelykh, condmatt (2011)

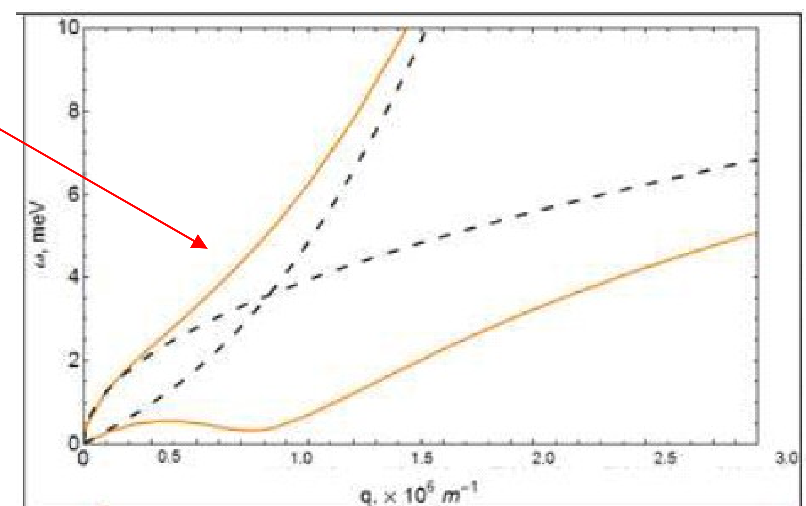
In the decoupled polariton- electron system there are 3 modes: 2 spinor Bogoliubov modes and plasmon mode.

$$E_{pl} \propto \sqrt{k}, \quad E_{bog} \propto k$$



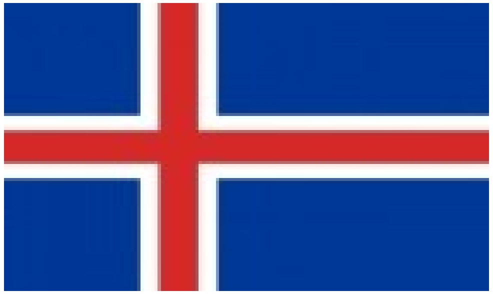
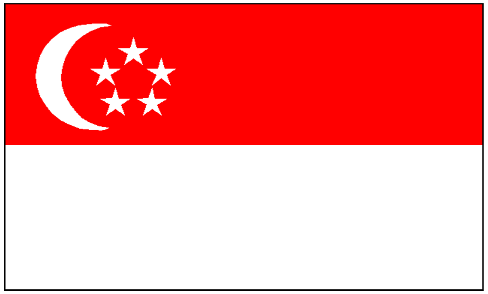
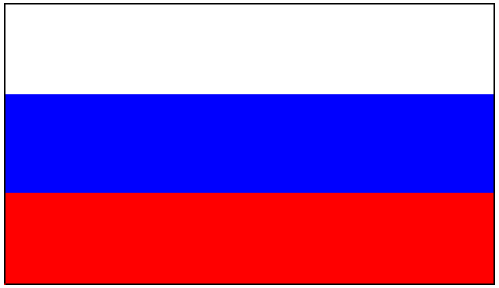
As a result of polariton- electron interaction plasmonic and condensate modes become coupled. In the hybrid plasmon- bogolon modes one can see the appearence of the roton minimum





Conclusions

- New mechanism of exciton and polariton mediated superconductivity was predicted
- The effective interactions in the hybrid exciton- electron system were analyzed
- The renormalization of the dispersions of the condensate and bogolon- plasmon strong coupling was investigated

Thank you for attention

Спасибо за внимание

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