Cold excitons

Introduction
- Excitons and electron-hole plasma in semiconductors
- Exciton condensation
- Experimental systems
- Indirect excitons in coupled quantum wells

Phenomena in cold exciton gases
- Stimulated scattering
- Pattern formation and transport
- Coherence and condensation

Control of excitons, excitons in potential landscapes
- Optical traps
- Excitonic circuits
- Excitons in traps
- Excitons in lattices

Spin transport of excitons

Most recent studies
- Topological defects in interference pattern
- Spin pattern formation
exciton – bound pair of electron and hole

\[ M = m_e + m_h \ll m_{\text{atom}} \]

light bosonic particle in semiconductor

\[ e^2 \rightarrow \frac{e^2}{\varepsilon} \]

Hydrogen atom → exciton

\[ m \rightarrow \mu \]

\[ a_0 = \frac{\hbar^2}{me^2} \rightarrow a_{\text{ex}} = \frac{\hbar^2 \varepsilon}{\mu e^2} \]

\[ Ry = \frac{me^4}{2\hbar^2} \rightarrow Ry_{\text{ex}} = \frac{\mu e^4}{2\varepsilon^2 \hbar^2} \]

\[ E_n(k) = E_g + \frac{\hbar^2 k^2}{2M} - \frac{\mu e^4}{2\varepsilon^2 \hbar^2 n^2} \]

\[ M = m_e + m_h \]

\[ \mu^{-1} = m_e^{-1} + m_h^{-1} \]

exciton dispersion

exciton binding energy

exciton density is controlled by excitation \n\[ n = G \tau \]

photon energy \( \sim E_g \)
Hydrogen-like excitons at low densities $e-h$ plasma at high densities

Mott transition at $na_B^D \sim 1$

Emission of $e-h$ plasma and magnetoplasma in QW:
- linewidth $\rightarrow$ Fermi energy
- energy shift $\rightarrow$ band gap renormalization
- shift of Landau levels $\rightarrow$ mass renormalization
- broadening of Landau levels $\rightarrow$ damping of one-particle states

many-body effects

Types of excitons:

**Hydrogen-like excitons**

In dilute gases \((na_B^D << 1)\)

**Cooper pair-like excitons**

In dense e-h system \((na_B^D >> 1)\)
Require matched e and h Fermi surfaces

**Magnetoexcitons**

In high magnetic fields
Internal structure and center of mass motion are coupled
Types of exciton condensate

**electron-hole liquid**
condensation in real space to
electron-hole droplets (EHL) forming
degenerate Fermi gas of electrons and holes
L.V. Keldysh (1968)

**Bose Einstein condensate**
in dilute exciton gas \(na_B^D \ll 1\)
excitons are (interacting)
Bose particles similar to hydrogen atoms
below \(T_c\) thermal distribution of excitons
leads to their condensation in \(k\)-space
L.V. Keldysh, A.N. Kozlov (1968)

**polariton laser**
macroscopic occupation of
coupled exciton-photon mode
thermal equilibrium is not required
A. Imamoglu, R.J. Ram, S. Pau, Y. Yamamoto (1996)

**excitonic insulator (BCS-like condensate)**
in dense electron-hole system \(na_B^D \gg 1\)
excitons are similar to Cooper pairs
below \(T_c\) electrons and holes bind to pairs –
excitons – forming BCS-like condensate
L.V. Keldysh, Yu.E. Kopaev (1964)

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Graph showing the transition from an exciton gas to an electron-hole plasma and BEC at \(na_B^D \sim 1\). The graph illustrates the condensation of bosons and pairing of fermions.
**Experimental systems**

**electron-hole liquid**
- Ge
- Si

**Bose Einstein condensate**
- Cu$_2$O
- Indirect excitons in CQW

**polariton laser**
- Microcavity polaritons

**Excitonic insulator (BCS-like condensate)**
- Electron bilayers in high magnetic fields at $\nu=1$

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Diagram showing phase transitions:
- Exciton gas to excitonic insulator
- Pairing of fermions
- K-space condensation of bosons
- BEC to BCS transition
- $n a_B D \sim 1$
What temperature is “cold” for exciton gas?

Transition from classical to quantum gas takes place when thermal de Broglie wavelength is comparable to interparticle separation.

3D: \( \lambda_{dB} = n^{-1/3} \)

\[
T_{dB} = \frac{2\pi\hbar^2}{mk_B} n^{2/3}
\]

\( T_{BEC} = 0.527T_{dB} \)

2D: \( \lambda_{dB} = n^{-1/2} \)

\[
T_{dB} = \frac{2\pi\hbar^2}{mk_B} n
\]

\( m_{\text{exciton}} \approx 10^{-6} m_{\text{atom}} \)

Kelvin for excitons is like microKelvin for atoms.

**3D gas of Rb atoms:**

\( n = 10^{15} \text{ cm}^{-3}, \ m_{\text{atom}} = 10^5 m_e \rightarrow T_{dB} \approx 5 \times 10^{-6} \text{ K} \)

**2D gas of excitons in GaAs QW**

\( n = 10^{10} \text{ cm}^{-2}, \ m_{\text{exciton}} = 0.2 m_e \rightarrow T_{dB} \approx 3 \text{ K} \)
estimates for characteristic temperatures for cold 2D Bose gases

for \( n = 10^{10} \) cm\(^{-2}\) per spin state (\( < n_{\text{Mott}} \sim 1/a_B^2 \sim 10^{11} \) cm\(^{-2}\)), \( M = 0.22 \) \( m_0 \)

\[ \lambda_{\text{dB}} \]

\[ \lambda_{\text{dB}} \text{ is comparable to interexcitonic separation} \]

\[ T_{\text{dB}} = \frac{2\pi \hbar^2 n}{Mk_B} \approx 3K \]

\[ \lambda_{\text{dB}}^2 n = 1 \]

\[ \text{thermal de Broglie wavelength} \]

\[ \lambda_{\text{dB}} = \left( \frac{2\pi \hbar^2}{Mk_B T} \right)^{1/2} \approx 160 \text{nm} \quad \text{at } T = 1 \text{ K} \]

\[ \text{temperature of quantum degeneracy} \]

\[ T_0 = T_{\text{dB}} \approx 3K \]

\[ N_{E=0} = \exp\left(\frac{T_{\text{dB}}}{T}\right) - 1 \]

\[ \text{BEC in finite 2D system} \]

\[ T_{\text{CS}} = T_{\text{dB}} \frac{1}{\ln(nS)} \approx 0.3K \quad \text{for } N=nS\sim10^5 \]

\[ \text{temperature of onset of local superfluidity} \]

\[ T_c = T_{\text{dB}} \frac{1}{\ln\ln(1/na^2)} \approx 1.7K \]

\[ \ln\ln(1/na^2)=1-3 \text{ for } 1/na^2=10-10^8 \quad \text{for } \ln\ln(1/na^2)=1.5 \]

\[ \text{Kosterlitz-Thouless temperature} \]

\[ T_{\text{KT}} \approx T_{\text{dB}} \frac{\ln\ln(1/na^2)}{1 + \ln\ln(1/na^2)} \approx 1K \]

\[ \text{for not so dilute gas} \]

\[ T_c \approx T_{\text{dB}} \frac{1}{\ln(\xi/4\pi) + \ln\ln(1/na^2)} \approx 0.6K \]

\[ \xi \approx 380 \]


Y.M. Kagan, lectures
W. Ketterle, N.J. van Drutten, PRA 54, 656 (1996)

D.S. Fisher, P.C. Hohenberg, PRB 37, 4936 (1988)

N. Prokof’ev, O. Ruebenacker, B. Svistunov, PRL 87, 270402 (2001)
How to realize cold exciton gases?

$T_{\text{lattice}} \ll 1 \text{ K in He refrigerators}$

finite lifetime of excitons could result in high exciton temperature: $T_{\text{exciton}} > T_{\text{lattice}}$

find excitons with \underline{lifetime} $\gg$ \underline{cooling time} $\Rightarrow T_{\text{exciton}} \sim T_{\text{lattice}}$

<table>
<thead>
<tr>
<th>Challenges for realization of exciton condensates</th>
<th>To solve: Find or design semiconductor structures where</th>
</tr>
</thead>
<tbody>
<tr>
<td>short lifetime</td>
<td>excitons have long lifetimes $\gg$ cooling times</td>
</tr>
<tr>
<td>competing ground states, e.g. EHL</td>
<td>excitons form the lowest energy state</td>
</tr>
<tr>
<td>exciton destruction, e.g. due to Mott transition</td>
<td>excitons have large binding energy</td>
</tr>
<tr>
<td>disorder</td>
<td>disorder is weak</td>
</tr>
</tbody>
</table>
Excitons in bulk semiconductors

<table>
<thead>
<tr>
<th>materials with low $e-h$ recombination rate</th>
<th>challenges for experimental realization of cold exciton gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge, Si</td>
<td>ground state – metallic $e-h$ liquid (EHL) rather than exciton</td>
</tr>
<tr>
<td>Cu$_2$O</td>
<td>slow cooling high rate of Auger recombination</td>
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</tbody>
</table>


$E = E_{\text{kin}} + E_{\text{exc}} + E_{\text{cor}}$

EHL density corresponds to degenerate Fermi gases of electrons and holes: $e-h$ plasma

\[
E_{\text{kin}}(n) = \frac{3}{5} E_F \sim n^{2/3}
\]

\[
E_{\text{exc}}(n) = -\frac{3}{4} \frac{e^2 k_F}{\pi} \sim -n^{1/3}
\]

\[
E_{\text{cor}} \sim -n^{1/4}
\]


two elements of the $e-h$ droplet repel each other due to the phonon wind generated in each of the elements → explosion of large droplets → $R_{c-Si} \sim 1 \mu$m, $R_{c-Ge} \sim 10 \mu$m

huge droplets with $R \sim 200 \mu$m can be created due to confinement

Search for exciton BEC in Cu$_2$O

**exciton transport**

expansion of exciton cloud front at near sonic velocity $\rightarrow$ **exciton condensate superfluidity**

D.W. Snoke, J.P. Wolfe, A. Mysyrowicz,

PRL 64, 2543 (1990)

reduction in velocity dispersion $\rightarrow$ **quasistable wave packet of exciton superfluid**

E. Fortin, S. Fafard, A. Mysyrowicz, PRL 70, 3951 (1993)

amplification of directed beam of excitons $\rightarrow$ **stimulated exciton scattering**


**PL lineshape**

enhanced PL intensity at low energies $\rightarrow$ **BE distribution of excitons**


$\rightarrow$ **PL of exciton BEC**


S.G. Tikhodeev et al. (1992-1998): **exciton transport** data are quantitatively explained by **phonon wind** effect

K.E. O'Hara, J.P. Wolfe et al. (1999-2000): **PL lineshape** data are quantitatively explained with **inhomogeneous classical exciton gas**, exciton densities reached in Cu$_2$O are $\sim$100 times below that required to achieve BEC presumably due to the high Auger recombination rate in Cu$_2$O

Excitons in Cu$_2$O form a very interesting system and search for exciton BEC in Cu$_2$O is in progress
Types of coherent state in MC

**weak coupling regime**

polaritons are destroyed → cavity photons and $e–h$ pairs
because of dephasing, screening and phase space filling owing to carrier Coulomb interaction

analogous to a conventional laser (VCSEL)


**strong-coupling, or polariton, regime**

a) resonant pumping with photons at specific angle

polariton parametric amplifier


b) non-resonant pumping

such coherent state has been realized in GaAs and CdTe MC


Polariton laser

a coherent state of e-m waves – a laser
a coherent state of matter waves – a BEC

A polariton is a mixture of an e-m wave and matter

Is this polariton coherent state similar to a laser, to a BEC, or somehow to both?

the coherent states of MC polaritons disappear when the photon component vanishes
but remain strong when the exciton component vanishes

implies that the coherence of the MC polaritons arises from the coherence of an e-m field
as in a laser

Thermal equilibrium

Lifetime of MC polaritons is short: 1-3 ps

Can thermal equilibrium be established within such short lifetime?

Is it required for formation of polariton condensate?

Dashed line fits exp. distribution marked 20 K and theor. distribution marked 25 K at high $E$.

Exp. distribution at $E > 0$ gives much stronger occupancy enhancement at $E = 0$ (left) than that corresponding to thermal distribution (right).

\( \text{no thermal equilibrium between condensate and noncondensed cloud} \)

From Fig. 1 in J. Kasprzak, D. D. Solnyshkov, R. André, Le Si Dang, G. Malpuech, PRL 101, 146404 (2008)

Indirect excitons in coupled quantum wells

Electron-electron bilayers in magnetic fields at $\nu=1$

Electron-hole bilayers with gate-induced carriers

Electron-hole bilayers with photoexcited carriers

Experiments:
- Caltech
- Columbia
- Pisa
- Princeton
- Stuttgart
- Bell Labs
- Cambridge
- IBM
- Sandia
- Bell Labs
- Berkeley
- Chernogolovka
- Hebrew
- IBM
- Munich
- St. Petersburg
- Weizmann
- UCSB
- UCSD
Why indirect excitons in CQW?

10^3-10^6 times longer exciton lifetime due to separation between electron and hole layers

realization of cold exciton gas in separated layers was proposed by Yu.E. Lozovik, V.I. Yudson (1975); S. I. Shevchenko (1976); T. Fukuzawa, S.S. Kano, T.K. Gustafson, T. Ogawa (1990)

10^3 times shorter exciton cooling time than that in bulk semiconductors

T_X \approx 100 \text{ mK} has been realized experimentally

30 times below T_{dB}

3D: coupling of E=0 state to single state E=E_0

2D: coupling of E=0 state to continuum of energy states E > E_0

effective cooling of 2D excitons by bulk phonons

A.L. Ivanov et al in PRL 86, 5608 (2001)

\begin{align*}
E_0 &= 2M_x v_s^2 \\
&\approx 0.05 \text{ meV}
\end{align*}
Interaction between indirect excitons

Repulsive dipole-dipole interaction
- stabilizes exciton state against formation of metallic EHL
  Yu. E. Lozovik, O. L. Berman, JETP Lett. 64, 573 (1996)

the ground state is excitonic

- results in effective screening of in-plane disorder
  R. Zimmermann
  also high quality CQW samples with small initial disorder are required

Repulsive interaction in experiment
exciton energy increases with density

energy shift: \( \delta E \sim n/C \) → estimate for exciton density
approximation for short-range \( 1/r^3 \) interaction \( C = \varepsilon/4\pi e^2 d \)

C. Schindler, R. Zimmermann, PRB 78, 045313 (2008)
→ \( C \) and \( n \) in experiments are higher
How to overcome exciton dissociation due to Mott transition: Make $d$ small

**dilute exciton gas** $n a_B^D << 1$

<table>
<thead>
<tr>
<th>$T$</th>
<th>$n \sim 1/a_B^D$</th>
<th>$n \sim 1/a_B^D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>exciton gas</td>
<td>large $d$</td>
<td>small $d$</td>
</tr>
<tr>
<td>electron-hole plasma</td>
<td>large $a_B$</td>
<td>small $a_B$</td>
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</table>

**dense e-h system** $n a_B^D >> 1$

- $d$ smaller
- smaller exciton radius
- larger $T_c$ at high $n$

in CQW with $L_B = 4$ nm, $L_{QW} = 8$ nm
$d \approx 12$ nm, exciton radius $a_B \approx 20$ nm

2D gas of excitons in GaAs QW
$n = 10^{10}$ cm$^{-2}$, $m_{\text{exciton}} = 0.2 m_e \rightarrow T_{dB} \sim 3$ K

$n < n_{Mott} \sim 1/a_B^2 \sim 2 \times 10^{11}$ cm$^{-2}$

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M.M. Dignam, J.E. Sipe, PRB 43, 4084 (1991)

$a_0 = \hbar^2 \varepsilon / \mu e^2 \quad L_{QW} = 0.6 a_0$
Indirect excitons in coupled quantum wells

Electron-electron bilayers in magnetic fields at $\nu=1$

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- St. Peterburg
- Weizmann
- UCSB
- UCSD
exciton recombination in e-h ↔ electron tunneling in e-e
for both: exciton in initial state, no exciton in final state

coupled electron and hole layers

collective electron state in QH bilayers at ν = 1
J.P. Eisenstein, G.S. Boebinger, L.N. Pfeiffer, K.W. West, S. He, PRL 68, 1383 (1992)


no exciton above $T_c$, e-h pairing below $T_c$ → BCS-like condensate

particle – hole transformation

transport of e-h pairs: Hall voltage drops at ν=1 ↔ neutral excitons

excitons above and below $T_c$
Indirect excitons in coupled quantum wells

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UCSD
The Coulomb drag measurement: current in one layer induces a voltage in the other for weakly coupled Fermi liquid bilayers: the drag resistance $\rho_{\text{drag}} = V/I \sim T^2$


for an exciton condensate: the drag resistance will increase dramatically at $T_c$

G. Vignale, A.H. MacDonald, PRL 76, 2786 (1996)

an increase in the drag resistance as $T$ is reduced

$\rho_{\text{D}} = \frac{V}{I} \sim T^2$

$\frac{d_{QW}}{d_B} = 18 \text{ nm}$

$\frac{d}{d_B} = 20 \text{ nm}$

$d \sim 38 \text{ nm}$

$n_e \sim n_h \sim 10^{11} \text{ cm}^{-2}$


challenge: hard to achieve condensation

large $d \rightarrow$ large $a_B$, large $n$

$n > 1/a_B^2$?