Phenomena in cold exciton gases: Condensation, macroscopic ordering and beyond

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Excitons and Electron-Hole Plasma

**Exciton** – bound pair of electron and hole

\[ m_{\text{exciton}} = m_{\text{electron}} + m_{\text{hole}} \ll m_{\text{atom}} \]

**Exciton** – light bosonic particle in semiconductor

At high densities, excitons dissociate into plasma of free electrons and holes
how to get cold exciton gas?

- \( T_{lattice} << 1 \text{ K in He refrigerators} \)
- finite lifetime of excitons could result to high exciton temperature: \( T_X > T_{lattice} \)
- find excitons with lifetime \( \gg \) cooling time \( \Rightarrow T_X \sim T_{lattice} \)
- find materials with low e-h recombination rate

why it's interesting?
- exciton condensate is a new form of matter
- high \( T_c \) for exciton BEC due to light exciton mass: \( T_c^{\text{exciton}} \sim 1 \text{ K} \)
- possibility to study crossover from BEC to BCS-like state
- possibility of manipulating condensate in microscopic semiconductor devices

Kelvin for excitons
microKelvin for atoms
Condensation in 3D and 2D systems

**BEC → Macroscopic occupation of ground state**

quasi-condensate - macroscopic occupation of low energy states
difference between quasi-condensate and BEC is not essential for most experiments

**3D systems:** BEC is possible at finite \( T \)

\[
T_c = 0.527 \frac{2\pi\hbar^2}{M} \frac{n^{2/3}}{g^{2/3}}
\]

**2D systems:** BEC is possible at \( T=0 \) only

**Bogoliubov temperature**

\[
T_B \approx \frac{4\pi\hbar^2 n}{2Mg} \frac{1}{\ln[\ln(g/na^2)]}
\]

Onset of nonzero order parameter
= onset of local superfluidity

**Kosterlitz-Thouless temperature**

\[
T_{KT} = \frac{\pi^2 \hbar^2 n}{2Mg} \frac{(T=T_{KT}^-)}{n_s}
\]

pairing of vortexes = onset of macroscopic
superfluidity which is not destroyed by vortexes

**Finite 2D systems:** BEC is possible at finite \( T \)

\[
T_c = \frac{4\pi\hbar^2 n}{2Mg} \frac{1}{\ln(nS/g)}
\]

include 2D systems with in-plane (random) potential
in this case \( S \) - area of local potential minimum

D.S. Fisher, P.C. Hohenberg, PRB 37, 4936 (1988)
W. Ketterle, N.J. van Drutten, PRA 54, 656 (1996)
Materials with low e-h recombination rate

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<td>Ge, Si</td>
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**Novel systems**
- indirect excitons in coupled quantum wells
- polaritons in microcavities
- excitons in quantum-Hall bilayers
Why indirect excitons in CQWs?

long exciton lifetime due to separation between electron and hole layers
10^3 times shorter exciton cooling time than that in bulk semiconductors

coldest exciton gas: T_x << 1K < T_c

potential candidate for realization of exciton condensation

exciton energy relaxation by LA-phonon emission

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

E_0 = 2M \times \frac{v_s^2}{2} \sim 0.05 \text{ meV}
How to get cold exciton gas?

Excitons are generated hot and cool down to $T_{\text{lattice}}$ via phonon emission. $T_X$ drops down to 400 mK in 5 ns, $< T_c < \ll \text{lifetime}$.

Ways to overcome the obstacle of hot generation and study cold gases of indirect excitons with $T_X \sim T_{\text{lattice}}$

- Separation in time
  - Study indirect excitons a few ns after the end of photoexcitation pulse

- Separation in space
  - Study indirect excitons excitons beyond photoexcitation spot
Repulsive interaction between indirect excitons

Dipole-dipole repulsive interaction stabilizes exciton state against formation of metallic electron-hole droplets


the ground state of the system is excitonic

results in effective screening of in-plane disorder

R. Zimmermann

Repulsive interaction in experiment:
Exciton energy increases with density


energy shift: $\delta E \sim 4\pi n e^2 d/\varepsilon \rightarrow$ estimate for exciton density
Experiments on cold exciton gases in CQW nanostructures

effects indicating exciton condensate superradiance (macroscopic dipole), onset of exciton superfluidity, and fluctuations near phase transition

Butov et al. *J. de Physique* 3, 167 (1993)
PRL 73, 304 (1994)

bosonic stimulation of exciton scattering - signature of degenerate Bose-gas of excitons
Butov et al. PRL 86, 5608 (2001)
PRL 87, 216804 (2001)

shrinkage of spatially localized exciton cloud with reducing $T \rightarrow$ degenerate exciton gas

exciton rings macroscopically ordered exciton state
cond-mat/0308117 [PRL 92, 117404 (2004)]

SSC 127, 89 (2003)
http://physics.ucsd.edu/~lvbutov/
Bosonic stimulation of exciton scattering

Enhancement of exciton scattering rate to low energy states with increasing exciton concentration reveals bosonic stimulation of exciton scattering.

Signature of degenerate Bose-gas of excitons

scattering rate of bosons to a state $p$ is $\sim (1 + N_p)$

Experiment vs theory

\[ \frac{dN_{E=0}}{dt} = \Gamma_{ph} N_E (1 + N_{E=0}) (1 + n_{E}^{ph}) - \Gamma_{ph} (1 + N_{E}) N_{E=0} n_{E}^{ph} - N_{E=0} / \tau = \]
\[ = \Gamma_{ph} (N_E - n_{E}^{ph}) N_{E=0} + \Gamma_{ph} (1 + n_{E}^{ph}) N_E - N_{E=0} / \tau \]

at low \( T_{lattice} \) and in presence of generation of hot excitons \( N_E - n_{E}^{ph} > 0 \)

Frolich inversion condition
countertpart of population inversion condition for lasers

\[ N_{E=0} = e^{T_0/T_x} - 1 \]
\[ T_0 = \pi \hbar^2 n / 2gM_X k_B \]
temperature of quantum degeneracy
2D image of indirect exciton PL vs $P_{ex}$

L.V. Butov, A.C. Gossard, and D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]
Radial dependence of indirect exciton PL

- PL intensity vs. energy (eV)
  - Energy range: 1.54 to 1.57 eV
  - PL peak intensity
- Excitation spot profile
  - External ring center
  - Internal ring center
  - Bulk indirect exciton
  - Radial distance (µm): 3.7 µm
- PL peak intensity vs. radial distance (µm)
  - External ring
  - Internal ring
  - Excitation spot center
  - PL intensity vs. energy (eV)
    - Energy range: 1.54 to 1.58 eV
    - External ring (r = 0)
    - Internal ring center
    - Excitation spot center
    - Multiplication factor: x4
Ring structure of indirect exciton PL

at low densities:
spatial profile of indirect exciton PL intensity follows laser excitation intensity

at high densities:
spatial profile of indirect exciton PL intensity is characterized by ring structure

internal ring

e external ring can be remote from excitation spot by hundreds of microns
Temperature dependence of ring-shaped PL structure

PL peak intensity

PL intensity

Energy (eV)

r (µm)

T=2.4 K

T=14 K

ring structure of indirect exciton
PL is observed at low T
with increasing T rings wash out and spatial profile approaches monotonic bell-like shape
The external ring is fragmented into circular structures that form a periodic array over macroscopic lengths, up to ~1 mm. This exciton state exhibits spatial order on macroscopic lengths – macroscopically ordered exciton state.
Temperature dependence of ring fragmentation into spatially ordered array of beads

ring fragmentation into spatially ordered array of beads appears abruptly at low $T$
Ordered state

- Ordered state
- Ring onset
- Low-temperature state

Graph:
- Y-axis: Temperature (T) in Kelvin (K)
- X-axis: Excitation power in micro-Watts (µW)
- Ordered phase
- Ring onset
- Low-temperature state
Features in exciton PL pattern
- inner rings
- external rings
- localized bright spots
- macroscopically ordered exciton phase
moving excitons are optically inactive
$K > K_0 \Rightarrow v > v_s \Rightarrow$ shock

excitons can travel in a dark state after having been excited until slowed down to a velocity below photon emission threshold, where they can decay radiatively

$T_X$ drops outside of excitation spot
fraction of optically active excitons increases

L.V. Butov, A.C. Gossard, and D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]
simulations: A.L. Ivanov, unpublished
off-resonance laser excitation creates additional number of holes in CQW

electrons and holes have different collection efficiency to CQW

excess holes are photogenerated in the laser excitation spot
electron source is spread out over the entire plane due to current through the CQW from n-doped GaAs layers

holes created at the excitation spot diffuse out this depletes electrons in the vicinity of the laser spot creating electron-free and hole rich region

excitons are generated within the external ring formed at the interface between the hole rich region and the outer electron rich area

same for e ↔ h

Expansion of the ring with increasing $P_{ex}$

An increase of $P_{ex}$ increases hole density in CQW

$\dot{n} = D\Delta n - \gamma np + J(r)$

$\dot{p} = D'\Delta p - \gamma np + J'(r)$

$J(r) = I(r) - a(r)n(r)$

$J'(r) = P_{ex}\delta(r)$

$n_x \propto np$

Expansion of the ring with increasing $P_{ex}$

Optical control of the ring by excitation intensity

$T = 380$ mK

410 µm
Shrinkage of the ring with increasing gate voltage

an increase of gate voltage increases electron density in CQW

\[
\dot{n} = D\Delta n - \gamma np + J(r)
\]
\[
\dot{p} = D'\Delta p - \gamma np + J'(r)
\]
\[
J(r) = I(r) - a(r)n(r)
\]
\[
J'(r) = P_{ex} \delta(r)
\]
\[
n_x \propto np
\]
Interaction of two exciton rings

rings attract one another at large distances
the existence of “dark matter” outside the rings that mediates the interaction
electron flow outside each ring which is perturbed by the presence of another ring
electrons in the area between the rings are depleted more strongly
attraction of the rings
do not mix with attractive exciton-exciton interaction!
Collapse of rings to localized bright spots

collapse of exciton rings to localized bright spots ("stars") with increasing $P_{ex}$

2D image of indirect exciton PL vs $P_{ex}$

Localized bright spots are due to localized sources of electrons (at current filaments crossing CQW) embedded in the hole rich illuminated area.

direct excitons indicate hot cores at the collapsed rings
Ordered state

**indirect exciton PL**

**direct exciton PL**

aggregates on the ring have no hot cores contrary to bright spots generated by the pinholes

aggregates move in concert with the ring when the position of the source is adjusted showing further that in-plane potential fluctuations are not strong enough to destroy the ordering
excitons in external ring are formed from well-thermalized carriers
heating sources in the ring - the binding energy released at exciton formation
due to long lifetimes of indirect excitons the heating has little effect on their temperature
the rings represent a source of cold excitons with temperature close to $T_{\text{lattice}}$
in external ring exciton gas is the coldest

macroscopically ordered exciton state

macroscopically ordered phases can be both in quantum (e.g. atom BEC) and classical (e.g. Taylor vortices) systems

new state, not predicted
origin of ordered exciton state - ?

the macroscopically ordered phase appears abruptly at low temperatures

is observed in the same temperature range as bosonic stimulation of exciton scattering (coincidence?)

statistically degenerate Bose-gas of excitons

note that the experiments on pattern formation and PL kinetics were done at different geometries
direct comparison is not available yet
Similarities with known phenomena: Modulational instabilities

stationary solutions to 1D nonlinear Schrödinger equation under periodic boundary conditions

stationary soliton trains

on a ring

experimental example:
soliton train in atom BEC with attractive interaction

soliton train is observed below $T_c$ only
intrinsic property of atom BEC

repulsion between beads of soliton train is wave interference phenomenon

attractive interaction for indirect excitons? positive feedback?
Similarities in astrophysics

S. Chandrasekhar and E. Fermi (1953)

**gravitational instability** of an infinite cylinder:
the cylinder is unstable for all modes of deformation with wavelengths exceeding a certain critical value

for the mode of maximum instability $\lambda \sim \pi D$

fragmentation of gaseous slabs and filaments

step in star formation

attractive interaction for indirect excitons?
positive feedback?
origin of macroscopically ordered exciton state is, at present, unclear

low temperature state ← experiment

restriction for interpretations