Condensation and pattern formation in cold exciton gases

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exciton condensation

dilute exciton gas \((n_{a_B}^d << 1)\)
excitons are weakly interacting Bose particles
exciton condensation is analogous to Bose-Einstein condensation

dense electron-hole system \((n_{a_B}^d >> 1)\)
excitons are formed at Fermi level like Cooper pairs
exciton condensate called excitonic insulator
is analogous to BCS superconductor state

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

how to get cold exciton gas?
\(T_{\text{lattice}} < 1\) K in He refrigerators
finite lifetime of excitons could result in high exciton temperature: \(T_x > T_{\text{lattice}}\)
\(T_x\) is determined by the ratio of the exciton lifetime and cooling time

Kelvin for excitons
microKelvin for atoms
Why indirect excitons in CQWs?

**GaAs/AlGaAs CQW**
- GaAs/AlGaAs CQW
- 

**AlAs/GaAs CQW**
- 

**potential candidate for realization of exciton condensation**

**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:** \( T_x << 1K < T_c \)

**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**

\[ E_0 = 2M \frac{v_s^2}{s} \sim 0.05 \text{ meV} \]

- \( E \leftrightarrow K \)
- \( h \leftrightarrow e \)
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

$< T_c$ $<<$ lifetime

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

discrimination in time
study indirect excitons a few ns after the end of photoexcitation pulse

discrimination in space
study indirect excitons excitons beyond photoexcitation spot
Repulsive interaction between indirect excitons

Indirect excitons are oriented dipoles

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


results in effective screening of in-plane disorder

the ground state of the system is excitonic
Experiments on exciton condensation 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
degenerate exciton gas


macroscopically ordered exciton state


http://www.lbl.gov/~butov/
http://www.issp.ac.ru/butov/

difference between quasi-condensate – macroscopic occupation of low energy states and BEC – macroscopic occupation of ground state – is not essential for most experiments [V.N. Popov (1972)] and unambiguous distinguishing between them in experiments is hard (if possible)
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 \( T_{\text{lattice}} \) and in presence of generation of hot excitons \( N_{E} - n_{E}^{ph} > 0 \)

Frolich inversion condition

counterpart of population inversion condition for lasers

\[ N_{E=0} = e^{T_0/T_x} - 1 \]

\[ T_0 = \frac{\pi h^2 n}{2M_X k_B} \]

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

Energy (eV)

1.54 1.55 1.56 1.57

D

r=0

bulk indirect exciton

PL peak intensity

r (µm)

0 40 80 120

external ring center

internal ring center

excitation spot center

r=0

excitation spot profile

3.7 µm

PL intensity

Energy (eV)

1.54 1.55 1.56 1.57

D

x4

I

internal ring center

excitation spot center

r=0
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 nontrivial — ring structure
Temperature dependence of ring-shaped PL structure

PL intensity vs. Energy (eV) for $T=2.4$ K and $T=14$ K.

- **T=2.4 K**: Nontrivial spatial profile of indirect exciton PL intensity is observed at low $T$ only.
- **T=14 K**: With increasing $T$, rings wash out and spatial profile approaches monotonic bell-like shape.

For $T$ values of 4.4, 7, 10, and 14 K, there are also plots showing the peak intensity vs. radius ($r$ in µm).
external ring is fragmented into circular-shaped structures that form periodic array over macroscopic lengths, up to ~1 mm
2D image of indirect exciton PL vs temperature

T=0.38-20 K
Temperature dependence of ring fragmentation into spatially ordered array of beads appears abruptly at low T
Ordered phase

Ordered phase

T (K) versus excitation power ($\mu W$)

Ring onset

Ordered phase
Discussion

origin of the rings

on origin of the macroscopically ordered exciton phase

Similarities in astrophysics: ring structure of expanding matter

Ring structures are generic for systems with centrally symmetric mass flow.

A planetary nebula - represents the final stage in the evolution of a Sun-like star.

The nebular shells with textures are formed by the wind of material ejected by the star.

Rayleigh-Taylor instability?

“...head-on collision between two galaxies.”

“Like a rock tossed into a lake, the collision sent a ripple of energy into space, plowing gas and dust in front of it ... this cosmic tsunami leaves in its wake a firestorm of new star creation ... in large fragmented gas clouds.”

From http://hubblesite.org
PL pattern $\leftrightarrow$ spatial distribution of optically active low energy excitons

continuous flow of excitons out of excitation spot due to exciton drift, diffusion, phonon wind, carrier wind etc.

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
Excitons are generated within the external ring

off-resonance laser excitation creates charge imbalance in CQW

electrons and holes have different collection efficiency to CQW

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 interface between the hole rich region and the outer electron rich area

\[ \delta \gamma \]

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

expansion of the ring with decreasing gate voltage

a reduction of transverse electric field, and hence of the current $I(r)$, depletes electrons in CQWs

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

At large distances, the interaction of two exciton rings attract one another.

The existence of "dark matter" outside the rings 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.

The attraction of the rings at T = 380 mK.

Dimensions: 520 µm.
Collapsing rings to localized spots

around the localized spots, small rings appear which shrink at increasing $P_{ex}$ localized sources of electrons (due to pinholes) embedded in the hole rich illuminated area

direct exciton emission indicates hot cores at the center of the collapsed rings
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
the rings represent a source of cold excitons with a temperature close to that of the lattice in external ring heating sources vanish → 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

microscopic nature 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

statistically degenerate Bose-gas of excitons

the macroscopic ordering is an intrinsic property of exciton condensate?
Similarities with known phenomena: Modulational instabilities
stationary solutions to 1D nonlinear Schrödinger
equation under periodic boundary conditions
stationary soliton trains

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?

the macroscopic ordering is an intrinsic property of exciton condensate?
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

- **λ** 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?
The attractive interaction? 

Soliton train in atom BEC appears when the interaction is switched from repulsive to attractive.


- Repulsive interaction: 
  \[ U \sim \frac{d^2}{r^3} (1 - 3\cos^2 \theta) \]

- Attractive interaction (for \( \cos^2 \theta < 1/3 \))

When in-plane electric field exceeds the threshold the interaction switches from repulsive to attractive?
indirect excitons with spatially separated electrons and holes, $d_{eh} \sim 10$ nm

- strong dipole-dipole interaction
- large in-plane polarizability

- spontaneous in plane dipole alignment at $T<T_c$

- instability due to attractive interaction

?