Spin Currents in a Coherent Exciton Gas

University of California San Diego

M. Vladimirova T. Ostatnický, A.V. Kavokin
Universite Montpellier 2, CNRS University of Southampton

K.L. Campman, M. Hanson, A.C. Gossard
University of California Santa Barbara

- Cold exciton gas
- Indirect excitons
- Exciton rings
- Spontaneous coherence
- Spin currents
**exciton** – bound pair of electron and hole

light bosonic particle in semiconductor

cold excitons

thermal de Broglie wavelength is comparable to separation between excitons

\[ \lambda_{db} = \left( \frac{2\pi \hbar^2}{mk_B T} \right)^{1/2} \]

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

excitons in GaAs QW

\( n = 10^{10} \text{ cm}^{-2}, m_{\text{exciton}} = 0.2 m_e \rightarrow T_{dB} \sim 3 \text{ K} \)

how to realize cold exciton gas?

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

finite lifetime of excitons can result to high exciton temperature: \( T_{\text{exciton}} > T_{lattice} \)

find excitons with **lifetime** >> **cooling time** \( T_{\text{exciton}} \sim T_{lattice} \)
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)

$T_X \sim 100 \text{ mK} \ll T_{dB}$
is realized for indirect excitons

A.L. Ivanov et al.
in PRL 86, 5608 (2001)
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$T_X$ ~ 100 mK << $T_{dB}$ is realized for indirect excitons

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$\sim 100$ ns to cool to 100 mK

http://physics.ucsd.edu/~lvbutov/
Exciton rings and macroscopically ordered exciton state

**external ring**

**inner ring**

ordered array of exciton beads

localized bright spots (LBS)

410 µm

spatial order on macroscopic lengths

macroscopically ordered exciton state (MOES)

Position on the ring (µm)

Bead number

Amplitude of the Fourier Transform

MOES emerges at low $T$


model of

- **inner ring:** A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, EPL 73, 920 (2006)


- **MOES:** L.S. Levitov, B.D. Simons, L.V. Butov, PRL 94, 176404 (2005)
laser excitation creates excitons in CQW

inner ring forms due to transport and cooling of optically generated excitons

emission of indirect excitons
above barrier laser excitation creates excitons + holes in CQW

excitons are generated in external ring and LBS rings at ring shaped interface between electron-rich and hole-rich regions

external rings and LBS rings form sources of cold excitons

exciton gas is hot in LBS centers is cold in external ring and LBS rings
spontaneous coherence
and
spin polarization textures

measured by
shift-interferometry

measured by
polarization resolved imaging
First order coherence function $g_1(\delta x)$

Pattern of $g_1(\delta x)$ is measured by shift-interferometry

$$g(t, r) = \frac{\langle E(t' + t, r' + r)E(t', r') \rangle}{\langle E^2(t', r') \rangle}$$

Images produced by arm 1 and 2 of MZ interferometer are shifted to measure interference between emission of excitons separated by $\delta x$.

Contrast of interference fringes $A_{\text{interf}}(\delta x) \rightarrow g_1(\delta x)$

Contrast of interference fringes

$${I_{\text{interf}}} = \frac{(I_{12} - I_1 - I_2)}{2\sqrt{I_1I_2}}$$
Emission, interference, coherence degree, and polarization patterns

<table>
<thead>
<tr>
<th>Emission pattern</th>
<th>Interference pattern</th>
<th>Pattern of amplitude of interference fringes</th>
<th>Pattern of linear polarization</th>
<th>Pattern of circular polarization</th>
</tr>
</thead>
</table>

$I_{PL}$ (a.u.)

$A_{Interf}$

$P_{lin}$

$P_{circ}$

map of coherence degree

coherence is not induced by pumping light and, instead, is spontaneous


First order coherence function $g_1(\delta \chi)$

**Distribution in $q$-space $n_q$**

- With and without optics PSF deconvolution

**Fourier transform**

$g_1(r) \overset{\text{Fourier transform}}{\rightarrow} n_q$

- Coherence length

**Classical gas:** narrow $g_1(r)$ and broad $n_q$

- $\xi_{\text{classical}} \sim \frac{\lambda_{\text{DB}}}{\pi^{1/2}} \sim 0.3 \, \mu m$ at $0.1 \, K$

**Quantum gas:** extended $g_1(r)$ and narrow $n_q$

- $\xi >> \xi_{\text{classical}}$
- $\delta q << \delta q_{\text{classical}}$

**Characteristic of a condensate**

- $\xi \sim \xi_0 = \sqrt{\frac{n_0}{4\pi}} \lambda_{\text{DB}}$

- $g_1(r) \sim \int d^2q e^{iqr} n_q$

- Resolution of optics and exciton cloud geometry matter

- $\xi, l_{\text{sys}}, l_{\text{res}}$
Exciton coherence and spin texture around LBS-ring

Emergence of
- Spontaneous coherence
- Spin polarization vortex
at low $T$ at $r > r_0$

vortex of linear polarization
ring of linear polarization
Exciton coherence and spin texture around external ring

Emergence of
- Spontaneous coherence
- Periodic spin texture

at low $T$ at $r > r_0^*$
Pattern of coherence length $\xi(x, y)$

spontaneous coherence of excitons emerges
- in region of MOES
- in region of vortices of linear polarization

$\xi >> \xi_{\text{classical}}$

$\delta q << \delta q_{\text{classical}}$

directional property of exciton coherence:

extension of $g_1(r)$ is higher when exciton propagation direction is along vector $r$
## Pattern formation and coherence: Experiment

<table>
<thead>
<tr>
<th>inner ring</th>
<th>LBS</th>
<th>external ring</th>
<th>fragmentation / ordering</th>
<th>coherence</th>
</tr>
</thead>
</table>
What we know about the macroscopically ordered exciton state

**MOES is a state with:**
- macroscopic spatial ordering

- spontaneous coherence (coherence length >> classical)
  \[ \rightarrow \text{a condensate in } k\text{-space} \]

**observed in a cold exciton gas**
- at low temperatures below a few K
- in a system of indirect excitons
- in the external ring far from hot excitation spot

**observed in external ring**
- on interface between hole-rich region and electron-rich region

  \[ \text{not observed in inner ring} \]

A.L. Ivanov et al., EPL 73, 920 (2006)

**characterized by repulsive interaction**
\( \rightarrow \) not driven by attractive interaction

MOES: Sen Yang et al., PRB 75, 033311 (2007)

IX: L.V. Butov et al., PRL 73, 304 (1994)

dipolar matter
Theoretical model for MOES consistent with experimental data

instability requires positive feedback to density variations

\[ \frac{\partial n_e}{\partial t} = D_e \nabla^2 n_e - wn_e n_h + J_e \]

\[ \frac{\partial n_h}{\partial t} = D_h \nabla^2 n_h - wn_e n_h + J_h \]

\[ \frac{\partial n_X}{\partial t} = D_X \nabla^2 n_X + wn_e n_h - n_X/\tau_{opt} \]

\[ w \sim 1 + N_{E=0} = e^{\frac{\tau_{th}}{\tau}} = e^{\frac{2\pi h^2}{mgk_B n_x}} \]

L.S. Levitov et al., PRL 94, 176404 (2005)
spin textures and spin currents
Spin polarization texture around LBS – radial source of cold excitons

exciton spin states

optically active states

\[ S_z = -1 \]

\[ + \frac{1}{2} e, -\frac{3}{2} h \]

\[ S_z = +1 \]

\[ - \frac{1}{2} e, +\frac{3}{2} h \]

dark states

\[ S_z = -2 \]

\[ - \frac{1}{2} e, -\frac{3}{2} h \]

\[ S_z = +2 \]

\[ + \frac{1}{2} e, +\frac{3}{2} h \]

ballistic exciton transport with coherent spin precession

vortex of linear polarization

due to SO interaction, splitting of exciton states, and Zeeman effect

theory of Alexey Kavokin:
in the basis of 4 exciton states with spins \( J_z = +1, -1, +2, -2 \) the coherent spin dynamics is governed by

\[
\hat{H} = \begin{bmatrix}
E_b - (g_h - g_e)\mu_B B/2 & -\delta_b & k_e\beta e^{-i\phi} & k_h\beta e^{i\phi} \\
-\delta_b & E_b + (g_h - g_e)\mu_B B/2 & k_h\beta e^{-i\phi} & k_e\beta e^{i\phi} \\
k_e\beta e^{i\phi} & k_h\beta e^{-i\phi} & E_d - (g_h + g_e)\mu_B B/2 & -\delta_d \\
k_h\beta e^{-i\phi} & k_e\beta e^{i\phi} & -\delta_d & E_d + (g_h + g_e)\mu_B B/2
\end{bmatrix}
\]
condensation of indirect excitons → suppression of exciton scattering → suppression of Dyakonov-Perel and Elliott-Yafet mechanisms of spin relaxation

exp: strong enhancement of coherence length

separation between electron and hole → strong enhancement of the spin relaxation time in a condensate of indirect excitons

while the spin relaxation times of free electrons and holes can be short, the formation of a coherent gas of their bosonic pairs results in a strong enhancement of their spin relaxation times → long-range spin currents
control of spin currents

measured by polarization resolved imaging

by magnetic field
radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons

radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons

measured polarization pattern

spin currents carried by electrons and holes bound to excitons

electron and hole spin tend to align along the effective magnetic fields given by the Dresselhaus SO interaction

theory of Alexey Kavokin

radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons

$B = 1\text{T}$

applied magnetic fields bend spin current trajectories

$\downarrow$

spiral patterns of linear polarization

$P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y}$
$B=2\text{T}$

Experimental $P_{\text{lin}}$

Simulated $P_{\text{lin}}$

\[ P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y} \]

applied magnetic fields bend spin current trajectories

\[ \Phi \]

spiral patterns of linear polarization

Simulated in-plane exciton polarization

\[ +\pi/2 \]

\[ -\pi/2 \]
B=3T

Experimental $P_{\text{lin}}$

Simulated $P_{\text{lin}}$

$P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y}$

applied magnetic fields bend spin current trajectories

⇒ spiral patterns of linear polarization
B=4T

Experimental $P_{\text{lin}}$

Simulated $P_{\text{lin}}$

\[ P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y} \]

applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization
B=5T

Experimental $P_{\text{lin}}$

Simulated $P_{\text{lin}}$

$P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y}$

applied magnetic fields bend spin current trajectories

$\uparrow$

spiral patterns of linear polarization

Simulated in-plane exciton polarization
$B=6\,T$

- Applied magnetic fields bend spin current trajectories.
- Spiral patterns of linear polarization.

Experimental $P_{\text{lin}}$  
Simulated $P_{\text{lin}}$  

$$P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y}$$
$B = 7T$

Experimental $P_{\text{lin}}$  

Simulated $P_{\text{lin}}$

$P_{\text{lin}} = \frac{I_x - I_y}{I_x + I_y}$

applied magnetic fields bend spin current trajectories  

$\downarrow$

spiral patterns of linear polarization

spiral direction of exciton polarization current  

$\neq$

radial direction of exciton density current
radial source of excitons with hedgehog momentum distribution generates

<table>
<thead>
<tr>
<th>$B$</th>
<th>Linear Polarization</th>
<th>Circular Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Helical (vortex) pattern</td>
<td>Four-leaf pattern</td>
</tr>
<tr>
<td>Finite $B$</td>
<td>Spiral pattern</td>
<td>Bell-like with inversion pattern</td>
</tr>
</tbody>
</table>
The vortex of linear polarization vanishes with increasing temperature.

The four-leaf pattern of circular polarization vanishes with increasing temperature.

A periodic array of beads in the MOES creates periodic polarization textures.

The periodic polarization textures vanish above the critical temperature of the MOES.
Summary

- **Spontaneous coherence in a cold exciton gas**
  

- **Spin currents and spin textures in a coherent exciton gas**
  