Dipolar exciton condensation

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1. Introduction

2. Disorder in 2D exciton condensation

3. Exciton condensation in 1D
Introduction
The fundamental idea

- System with two layers
- One doped with electrons, one with holes
- Mutual attractive Coulomb interaction
- Bosonic bound states form
- Bosons condense

This is the true many-body ground state of the system
A new mechanism for superconductivity: pairing between spatially separated electrons and holes

Yu. E. Lozovik and V. I. Yudson

Spectroscopy Institute, USSR Academy of Sciences
(Submitted March 2, 1976)

A new mechanism for superconductivity, based on the pairing of spatially separated electrons and holes that arises from their Coulomb attraction, is proposed. A gap in the single-particle excitation spectrum is found. The roles of interband transitions, the electron-phonon interaction, scattering by impurities, spin-orbit interaction, etc. are analyzed. The critical current is calculated. Possible experiments are discussed.

PACS numbers: 74.30.—e

The maximum value of the gap $\Delta$, equal in order of magnitude to the binding energy $E_0 = m^* e^4 / \varepsilon^2$ of an isolated pair, is attained when $m_e \sim m_h \sim m^*$ and $D \leq a^* \sim l$ (the strong-interaction regime, in which (8) has only the character of an estimate; $a^* = \varepsilon / m^* e^2$). If, e.g., $m^* = 0.03 m_0$ ($m_0$ is the electron mass) and $\varepsilon = 3$, then $a^* \approx 50$ Å and for $D \sim l \sim 50$ Å we have $\Delta \sim 300$ K.

Prediction was formation of 'superconductivity' with gap of the order of room temperature.
Drag measurement

Su et al., Nat. Phys. 4, 799 (2008)

Inter-layer current measurement


Figure 4 | Coulomb drag current ratio, $I_2/I_1$ at $v_f = 1$. a, $I_2/I_1$ versus d.c. voltage $V_{dc}$ at $v_f = 1$ for $d/l = 1.5$ at various temperatures. Filled circles are estimates based on measurements of $\sigma_{||}$ at $V_{dc} = 0$, as described in text. b, $I_2/I_1$ versus $V_{dc}$ at $v_f = 1$ and $T = 17$ mK for various $d/l$. All data taken at $\theta = 26^\circ$. Dashed lines indicate perfect drag limit.

Device applications

Transistor

Bilayer PseudoSpin Field-Effect Transistor (BiSFET): A Proposed New Logic Device
Sanjay K. Banerjee, Fellow, IEEE, Leonard F. Register, Senior Member, IEEE,
Emanuel Tutuc, Member, IEEE, Dharmendar Reddy, and Allan H. MacDonald

(a) $V_{\text{clock}}(t)$

$V_{G,1}$

$V_{G,2}$

$V_{G,n}$

$V_{n}$

$V_{p}$

Output $\bar{A}$

$-25 \text{ mV}$

(b)

Time (ps)

0 10 20 30 40 50

0 25

Input (mV)

Output (mV)


Thermoelectrics


Theoretical claim for $zT \sim 60$ for TI-based bilayer excitons.
Dipolar excitons in 2D – the role of disorder
The condensate has yet to be observed despite several experimental attempts. Question is: Why?

Possibility 1: Excitonic gap is too small.

The form of the inter-layer screening used in the calculation of the gap is crucial:

For SiO$_2$ or BN substrates, $\alpha = \frac{e^2}{\kappa \hbar v_F} \approx 0.5$.

For vacuum (suspended graphene), $\alpha = 2.2$.

- Unscreened interaction $\Rightarrow$ room temperature condensate!!!
- Static screening $\Rightarrow$ vanishing gap.
- Dynamic screening $\Rightarrow$ ???

Possibility 2: Disorder

Disorder in graphene systems

STM can reveal disorder in graphene

Monolayer graphene:


Scale bar is 8nm.


STM can reveal disorder in graphene

Monolayer graphene:


Scale bar is 8nm.


Upper layer

Lower layer
Disorder in graphene systems

STM can reveal disorder in graphene

Monolayer graphene:


Scale bar is 8nm.


D.S.L. Abergel
There are three stages to the calculation:

1. **Theory for homogeneous unbalanced system.**
   - Temporarily ignore inhomogeneity, calculate effect of imperfectly nested Fermi surfaces.

2. **Analysis of realistic inhomogeneity.**
   - Calculate statistics for density distribution in situations corresponding to contemporary experiments.

3. **Combine these two results to assess impact of inhomogeneity on condensate formation.**
Mean field theory – $T_c$ with finite $\delta\mu$

\[
\bar{\mu} = \frac{\mu_u + \mu_l}{2}
\]

$\delta\mu = \mu_u - \mu_l$

We do mean-field BCS theory

\[
\Delta_k(T) = \sum_{k'} V(k' - k) \frac{\Delta_{k'}(T) f(k, k') N(k', T)}{\sqrt{\left(v_F k' - \bar{\mu}\right)^2 + \Delta_{k'}(T)^2}}
\]

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\]


At zero temperature:

\[
\delta \mu = \Delta
\]
Mean field theory – $T_c$ with finite $\delta \mu$

We do mean-field BCS theory

\[ \Delta_k(T) = \sum_{k'} V(k' - k) \frac{\Delta_{k'}(T) f(k, k') N(k', T)}{\sqrt{(v_F k' - \bar{\mu})^2 + \Delta_{k'}(T)^2}} \]

At zero temperature:

\[ \delta \mu = \mu_u - \mu_l \]

\[ \bar{\mu} = \frac{\mu_u + \mu_l}{2} \]


Mean field theory – $T_c$ with finite $\delta \mu$

\[ \bar{\mu} = \frac{\mu_u + \mu_l}{2} \]

\[ \delta \mu = \mu_u - \mu_l \]

We do mean-field BCS theory

\[ \Delta_k(T) = \sum_{k'} V(k' - k) \frac{\Delta_{k'}(T) f(k, k') N(k', T)}{\sqrt{(v_F k' - \bar{\mu})^2 + \Delta_{k'}(T)^2}} \]

Use a numerical Thomas Fermi Theory.

Total energy functional is:

$$E[n_u, n_l] = E_u[n_u(r)] + E_l[n_l(r)] + \frac{e^2}{2\kappa} \int \int d^2r d^2r' \frac{n_u(r)n_l(r')}{\sqrt{|r - r'|^2 + d^2}}$$

Single layer functional is:

$$E[n] = E_K[n(r)] + \frac{e^2}{2\kappa} \int dr' \int dr \frac{n(r)n(r')}{|r - r'|} + \frac{e^2}{\kappa} \int dr V_D(r)n(r) - \mu \int dr n(r).$$

Step 3: Links back to BCS theory

- We can perform this calculation for many ($\approx 600$) disorder realizations and collect statistics for the distribution of $\delta \mu$.

- This distribution characterized by its root-mean-square (rms) value.

If $\delta \mu_{\text{rms}} < 2\Delta$ then condensate is stable.

Predictions for $\Delta$ from BCS theory:
- Unscreened: $\Delta \sim 30\text{meV}$,
- Static screening: $\Delta \sim 0.01\text{meV}$,
- Dynamic screening: $\Delta \sim 1\text{meV}$.

Dipolar excitons in 1D
The issue: Mermin-Wagner states that long-range order cannot exist in 1D.

Single particle tunneling term:

\[ H_T = t_\perp \sum_n c_{1,n}^{\dagger} d_{2,n}^{\dagger} + \text{h.c.} \]

This term breaks charge conservation symmetry.

A. Kantian and D.S.L. Abergel, in preparation
Experimental detection

Inter-layer tunneling:

Current–current correlator is

$$\sigma_{\text{inter}}(\omega) = \left\langle c_{1,0} d_{2,0} \frac{1}{\hbar \omega - \hat{H} + i \eta} c_{1,0}^{\dagger} d_{2,0}^{\dagger} \right\rangle$$

A. Kantian and D.S.L. Abergel, in preparation
Mean field theory for core-shell nanowires

\[ m_1^* > 0 \]

\[ m_2^* < 0 \]

\[ \mu = \mu_c \]

\[ \mu_{\text{crit}} = \mu_c \pm 2\Delta_{\text{max}} \sqrt{|m_1^*||m_2^*|} / |m_1^* - m_2^*| \]


Dipolar exciton condensates exist in reduced dimensions.

In 2D, disorder a very important factor – maybe on cusp of experimental detection?

in 1D, condensate stabilized by inter-layer tunneling.

Slides available at www.nordita.org/~dabergel/talks.php