COHERENT INTERLAYER AND INTERCHAIN TRANSPORT IN NbSe$_3$ AMD GRAPHITE UNDER HIGH MAGNETIC FIELDS

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OUTLINE

1. Introduction to intrinsic Josephson effects in HTS and interlayer tunneling gap spectroscopy.

2. CDW gap spectroscopy. Intragap states.

3. Field induced CDW state in NbSe$_3$ and graphite.

4. Coherent nonlinear transport across the chains in NbSe$_3$ under perpendicular magnetic fields.

5. Conclusions.
1. Introduction to intrinsic Josephson effects in HTS.
IJE - Josephson effects on naturally layered crystalline structure of layered superconductors

Early ideas in 70-s: W.E.Lawrence, S.Doniach 1971
L.N. Bulaevskii 1973

Further development in 90-s, after discovery of HTS
L.Bulaevskii, J.Clem, L.Glazman 1992

stationary IJE for short stacks $L < 2\lambda_j$

\[ \lambda_j = s \lambda_c / \lambda_{ab} \sim 1 \mu m \text{ in Bi-2212} \]

\[ I_c (H) = I_{c0} \left| \frac{\sin(\frac{\pi sLH}{\Phi_0})}{\pi sLH} \right| \Phi_0 = \frac{hc}{2e} \]
DC Intrinsic Josephson effect

Yu.I. Latyshev, N. Pavlenko, S-J. Kim, T. Yamashita ISS-99, Morioka

Physica C, 2001

\[ I_c(H) = I_c(0) \left| \frac{\sin x}{x} \right| \]

\[ x = \frac{\pi s L H}{\Phi_0} \]

\[ \Phi_0 = \frac{hc}{2e} \]

FIB fabricated Bi-2212 mesa, \( L=1.4 \, \mu m \), \( s=1.5 \, nm \), \( \Delta H=1 \, T \)
AC Intrinsic Josephson effect

H.B. Wang, T. Yamashita, P.H. Wu, PRL 2001
Quasiparticle tunneling
Quasiparticle tunneling over a gap: multibranched IVs, gap/pseudogap spectroscopy

2. CDW gap spectroscopy. Intragap states.
CDW state
Peierls transition. CDW state.

The gap is opened at the Fermi-surface. Condensed electron density is spatially modulated.

The order parameter in the ground state is

$$\Delta_0 = A \cos (Qx + \phi)$$

with $Q$ the CDW wave vector $Q = 2k_F$ and $\phi$ the arbitrary phase in the ICDW state.
$\sigma_b/\sigma_{a^*}=10^3-10^4$

$\sigma_b/\sigma_c=10-20$
The elementary prisms are assembled in elementary conducting layers with higher density of conducting chains (shaded layers in a figure) separated by a double barrier of insulating prism bases. That results in a very high interlayer conductivity anisotropy $\sigma_{a^*}/\sigma_b \sim 10^{-3}$ at low temperatures compared with intralayer anisotropy $\sigma_c/\sigma_b \sim 10^{-1}$.

That provides the ground for interlayer tunneling spectroscopy of CDW layered materials.
Mesa fabrication by double sided etching with focused ion beam (FIB)

FIB machine

Seiko Instruments Corp. SMI-3050
Ga+ ions 15-30 kV
Beam current: 0.3 pA – 50 nA
Minimal beam diameter: 4 nm

Stages of the double sided FIB processing technique for fabrication of the stacked structure; (d) SEM image of the structure. The structure sizes are 1µ x 1µ x 0.01 - 0.3µ

Determination of the energy gap from tunneling measurements

Tunneling junction S-I-S,

\[ N(E) \]

\[ E_F \]

\[ 2\Delta \]

\[ eV < 2\Delta \]

Tunneling I-V characteristic

\[ I \]

\[ V \]

\[ V_g = 2\Delta/e \]

Tunneling junction S-I-S at \( eV \approx 2\Delta \)

\[ N(E) \]

\[ E_F \]

\[ 2\Delta \]

\[ eV \]

\[ eV \approx 2\Delta \]
Temperature evolution of the spectra

Point contact spectra NbSe$_3$-NbSe$_3$ along the $a^*$-axis A.A. Sinchenko et al., 2003

Stacked junction behaves as a single junction. We consider that as the weakest junction in the stack.
CDW gap spectroscopy in NbSe$_3$

At low temperatures there are two CDWs $q_1 = (0, 241, 0)$, $q_2 = (0.5, 0.261, 0.5)$ in reciprocal unit length

$$2(q_1 + q_2) \approx (1, 1, 1)$$

In accordance to

R. Bruinsma and S.E. Trulinger PRB 1980 this phase coupling should be accompanied by small enhancement of $\Delta_1$ below $T_{p2}$

$$2\Delta_2 = 60 \text{ mV}, \quad 2\Delta_1 = 130\text{mV}$$

Comparison with other techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Temperature</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM</td>
<td>70</td>
<td>Z.Dai et al. PRB 92, D.Roditchev et al. PRB 98</td>
</tr>
<tr>
<td>Optics</td>
<td>70</td>
<td>A. Perucci et al. PRB 2004</td>
</tr>
<tr>
<td>ARPES</td>
<td>90</td>
<td>J. Schafer et al. PRL 2003</td>
</tr>
<tr>
<td>Microcon</td>
<td>60</td>
<td>A.A. Sinchenko and P. Monceau PRB 2007</td>
</tr>
</tbody>
</table>
Intragap states: \( \text{NbSe}_3 \)


There are two new features inside the CDW gap with characteristic energies \( V_s \sim 2\Delta/3 \) and \( V_t \sim 2\Delta/10 \) which has been identified as the amplitude and phase excitations of CDW.
Temperature evolution of the spectra under high field

Intragap peak in strong parallel field was observed in the wide temperature range up to 30 K.

Intragap peak in strong parallel field was observed in the wide temperature range up to 30 K.
CDW amplitude solitons

($\pi$-solitons)
Amplitude solitons in the incommensurate CDW (ICDW)

The order parameter in the ground state is $\Delta_0 = A \cos(Qx + \varphi)$ with $Q$ the CDW wave vector $Q = 2k_F$ and $\varphi$ the arbitrary phase in the ICDW state and $A=\text{const}$. That means that ground state is degenerated with respect to $A \leftrightarrow -A$.

That leads to the possibility of configuration with accepting of one electron and formation of new ground state with $A = \tanh(x/\xi_0)$ called amplitude soliton (AS).

AS is a self-localized state with an energy $E_s = 2\Delta_0/\pi$ S.A. Brazovskii, Sov. Phys.-JETP, 1980

This state is more preferable since its energy is smaller than the lowest energy $\Delta_0$ of the free band electron by $\approx \Delta_0/3$.

**CDW π-soliton is a kind of atomic scale π-junction**

The existence of ASs has not been reliably demonstrated yet.
CDW phase solitons

($2\pi$- solitons)
CDW phase solitons

CDW excitation when one CDW period is put into or taken out of one chain, excess phase changes within phase soliton by $2\pi$

local breaking of interchain phase coherency

Interchain phase decoupling

Interchain phase decoupling happens with creation of $2\pi$ solitons

Interplain phase decoupling happens with formation of CDW dislocation lines, or CDW vortices, that can be induced by electric fields across the layers

The energy of creation of CDW dislocation line is $\sim kTp$
Threshold voltage scaling with $T_p$


$eV_{th} \approx 0.2 \Delta \approx 1.3\ kT_p$

Theory S. Brazovskii, S.I. Matveenko, cond-mat 2007

$E_{ps} \approx kT_p$ per chain
Threshold and staircase structure

When dislocation cores start to overlap at high voltage bias all the voltage drops on a single elementary junction. That can explain puzzling equivalence of the behaviour of the stacked junction and point contact containing one junction.
Duality of phase topological defects in layered HTS and CDW systems

<table>
<thead>
<tr>
<th>HTS</th>
<th>CDW</th>
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</thead>
<tbody>
<tr>
<td>J-vortex</td>
<td>2πsoliton</td>
</tr>
<tr>
<td>flux</td>
<td>Charge</td>
</tr>
<tr>
<td>$Φ_0=\frac{hc}{2e}$</td>
<td>$Q_0=2e$</td>
</tr>
<tr>
<td>H // layers</td>
<td>$E⊥$ layers</td>
</tr>
<tr>
<td>$H_{c1}$</td>
<td>$E_t$</td>
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Analogy of DL array with AC Josephson effect

Josephson junction at $I>I_c$

$2eV = h \frac{d\phi}{dt}$

Phase difference changes in time. Period of Josephson oscillations is inversely proportional to $V$

CDW coupled junction at $V>V_t$

$2eV = h v_F \frac{d\phi}{dx}$

Phase difference changes in space. Period of CDW DL array also is inversely proportional to $V$

3. Magnetic field induced CDW state in NbSe$_3$ and graphite
Anomalously high magnetoresistance in NbSe$_3$

C.A. Balseiro and L.M. Falikov PR B 1986 magnetic field may increase CDW gap

L.P. Gor’kov and A. Lebed, 1984 mechanism is related with improvement of CDW nesting by magnetic field

A. Bjelis, D. Zanchi, G. Montambeaux PR B 1996, cond-mat /1999 also have shown the possibility to increase $T_p$ by magnetic field.
However, until recently there were no tunneling experiments on spectroscopy of CDW gap in high magnetic field and especially in the vicinity of Peierls transition temperature.
Interlayer tunneling spectra at pulsed magnetic field

LNCMP, Toulouse

Field start ~60 ms

Field finish ~350 ms

Full measurement time 500 ms

Sweep current

Start DAC, 3 ADC

Stop DAC, 3 ADC

H max

I max

~50 ms

0.5 ms

1000 IV

F m=2 MHz

1000 points in IV for H k

High speed acquisition system
Interlayer tunneling spectra of NbSe$_3$ in high magnetic fields $H/\parallel a^*$ near Peierls transition temperature $T_{p2}$.

Enhancement and induction of lower CDW gap by magnetic field

Phase diagram. Interplay of orbital and Pauli effects.

Non-monotonic behaviour of $T_p(H)$ is defined by interplay between orbital and Pauli effects on CDW pairing. Orbital effect is realized in improving of nesting condition and, thus, in increase of $\Delta$ and $T_p$, while Zeeman shift tends to destroy CDW pairing.

Experimental crossover field corresponds to $H \approx 30T$, $2\mu_B H_0 \approx kT_p$

That is consistent with calculations of Zanchi, Bjelis, Montambeau PRB 1996 for the case of moderate imperfection parameter (valid for NbSe$_3$)

$$\frac{\mu_B H_0}{(2\pi T_p)} \geq 0.1 \quad \text{or}$$

For $T_p = 61$ K that corresponds to $H_0 \approx 30T$
Why does eventually $T_p$ drop down with field?

In a zero field the CDW state is degenerated with respect to spin up $\uparrow\uparrow$ and spin down $\downarrow\downarrow$ configurations.

Magnetic field releases degeneration due to Zeeman splitting. As a result $Q_{\uparrow\uparrow}$, CDW vector increases with field while $Q_{\downarrow\downarrow}$ decreases $Q_{\uparrow\uparrow} > Q_0 > Q_{\downarrow\downarrow}$

Therefore, a CDW state with a fixed $Q_0$ tends to be destroyed with field.

Super. CDW
charge $e$-$e$ or $h$-$h$
momentum $P=0$
spin $\uparrow\downarrow$

$e$-$h$

$P=2p_F$
$\uparrow\uparrow$ or $\downarrow\downarrow$
Influence of field orientation

H⊥ layers

No effect at parallel fields
Field induced CDW (?) gap in graphite
Graphite at strong fields


Explanation was related with the CDW formation along the field axis

We attempted to find CDW gap above 30 T

Effect nearly disappears for 20 graphene layers
That means that it does not relate with individual graphene layers
Field induced CDW? 

graphite 

NbSe₃ 

dl/dV (S) 

4m 
3.5m 
3m 
2.5m 
2m 
1.5m 

The pictures for both compounds look very similar as well as the values of field induced gap are close 50-70 mV
Field and temperature dependences of the field induced CDW state in graphite

(a) Field and temperature dependences of the field induced CDW state in graphite for $T = 1.4K$.

(b) Field and temperature dependences of the field induced CDW state in graphite for $B = 55T$. 

The graphs show the change in $dI/dV$ with respect to voltage $V$ for different temperatures and magnetic fields.
Phase diagram of the field induced CDW state in graphite

$2\Delta/\text{To} = 3.1-3.5$ close to the BCS value as in field induced CDW state in NbSe$_3$.

The data are consistent with recent Hall effect data in graphite A. Kumar et al., J. Phys.: Condens. Matter 22(2010) 436004.

4. Coherent nonlinear transport across the chains in NbSe$_3$ under perpendicular magnetic fields.
NbSe$_3$

$T_{p2}=59$K $T_{p1}=145$K

$\sigma_b/\sigma_{a^*}=10^3-10^4$

$\sigma_b/\sigma_c=10-20$

Crystalline structure
Sliding CDW along the chains in NbSe₃ at high temperatures

CDW depinning above threshold fields.

Sliding CDW contribution to the conductivity

NBN with frequency proportional to CDW current

\[ J_{\text{CDW}} = N_e \Lambda f \]

For NbSe₃

\[ \Lambda = 4b \]

Shapiro steps of constant \( J_{\text{CDW}} \)

Different from Shapiro steps in Josephson effect \( V = hf/2e \)

Structures

Simple structure

More advanced 6-probes structure with different distances between potential probes and containing the Hall probes.

I //c
Results. Nonlinear transport under magnetic fields

- Threshold type of nonlinearity. Opposite sign to the nonlinearity along the chains: dI/dV drops down above threshold current.
- Nonlinearity appears at low temperatures and at high magnetic fields.
Threshold current does not depend on the length and is proportional to the width of the sample. Also that is inversely proportional to the value of magnetic field.
Coherent response to the RF-field. Shapiro steps

Shapiro steps appear as peaks on $\frac{dI}{dV}(V)$ dependences. They appear at low temperatures and under high magnetic fields, i.e. at the same conditions as a threshold nonlinearity without RF-field. Peaks position is nearly independent on magnetic field at high fields.
Shapiro steps 2

$\Delta V$ is proportional to the frequency and to the sample length.
Shapiro steps are observable at least up to 3 GHz
Analysis. Critical current

The basic idea is that the threshold is determined by the critical Hall electric field $E_{Hc}$ that induces critical deformation of CDW for the formation of phase dislocation (or excess CDW period) that reduces the number of pocket carriers.

$$E_H = V_H / w = R_H I H/dw$$

From where

$$I_t = E_{Hc} w d / (R_H H) \propto w / H$$

as that is observed in the experiment

Experimentally measured value of $E_{Hc} \approx 10 \text{ B/cm}$ $V_t \approx 1 \text{ mV}$

That is close to the energy of formation of phase slip center $V_{ps}$ in NbSe$_3$
Bloch oscillations

In 1928 Bloch demonstrated that electrons in a periodic lattice potential with period \( a \) subject to a dc electric field \( E_{dc} \) undergo oscillations with characteristic frequency

\[
\omega_B = \frac{eaE_{dc}}{\hbar}
\]

If one consider a charge soliton moving in periodic potential the Bloch equation mimics Josephson relationship \( 2eV = \hbar \omega \).
Analysis 2. Shapiro steps.

Mechanism of coherent emission is not clear. One can consider that this is related with motion of CDW dislocations along the bridge.

**Estimation of voltage to frequency relation.** Experiment gives 12.5 mV/ GHz on 1 micron. 1 micron corresponds to $5 \times 10^3$ chains, i.e. for one chain that gives $2.5 \, \mu V/\text{GHz}$. That is close to Josephson relation $2eV/ hf$, which produces $2 \, \mu V/\text{GHz}$

**Oversimplified model**

Phase vortex appear at $E_H > E_{tc} = E_{c1}$ with charge $2e$ and moves in periodic potential along the channel providing Bloch oscillations with Josephson frequency $f = 2eV_0 /h$
1. The interlayer tunneling spectroscopy has been developed on a number of layered materials as Bi-2212, NbSe$_3$ and graphite.

3. We found intra gap states in NbSe$_3$ associated with excitation of amplitude and phase CDW solitons in NbSe$_3$.

4. We found and studied field induced CDW states in NbSe$_3$ and graphite predicted long time ago.

5. We found a new threshold type non-linearity in magnetotransport across the chains in NbSe$_3$, which is accompanied by coherent emission in MHz-GHz frequency range with a frequency proportional to the voltage on the junction as in Josephson relation.

6. We proposed qualitative model of both phenomena.