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SPRING COLLEGE IN CONDENSED MATTER
ON
'PHYSICS OF LOW-DIMENSIONAL SEMICONDUCTOR STRUCTURES'
(23 April - 15 June 1990)

ELECTRON PROPERTIES OF LOW-DIMENSIONAL ORGANIC CONDUCTORS - III

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Lecture 3: Electronic properties of low dimensional organic conductors

Field induced spin density waves (FISDW), QHE, reentrant metallic behaviour and anomalous magnetoresistance for $H \parallel c^*$ in the Bechgaard salts $(TMTSF)_2ClO_4$ and $(TMTSF)_2PF_6$

From Lecture 2:

$X = ClO_4$ $T_c = 1.2\,K$ atmospheric pressure

$X = PF_6$ $p \sim 8$ kbars suppresses SDW, s/c $T_c = 1.2\,K$.

PF_6 simpler than ClO_4 – no anion ordering and therefore no associated superlattice.

First experiments carried out on ClO_4 (with exception of Kwak et al)

$H \parallel c^*$ s/c rapidly destroyed

$T \sim 1K$ $H \sim 6T$ $\rho(H)$ changes slope – threshold field

then series of sharp anomalies often with hysteresis $H\uparrow, H\downarrow$.

Specific heat sharp peaks – series of phase transitions

NMR $T_1^{-1} \Rightarrow$ SDWs. but 'orbital' effect since

$H_T \sim \frac{1}{\cos\theta}$ θ angle between H and c^* axis.

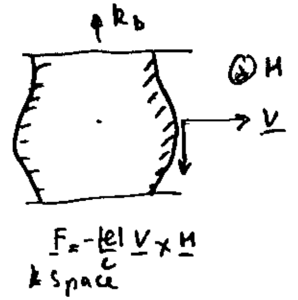
In 1984 Gor'kov and Lebed proposed a theory of FISDW in which $H \parallel c^*$ restored 1D of system

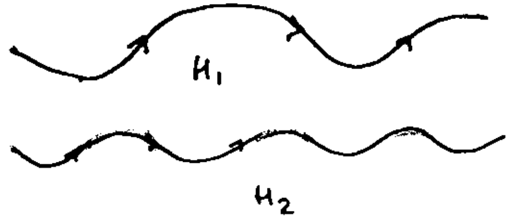
In other words SDW absent at $H = 0$ because t_b too large

(actually $t_b' = t_b^2/t_a$ remember $t_a > t_b > t_c$)

but $H \parallel c^*$ effectively reduces t_b'.

Roughly speaking



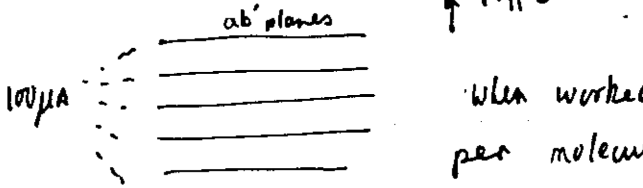


Gor'kov and Lebed actually calculated $\chi(Q)$

Showed $H \parallel c^*$ increased $\chi(Q) \rightarrow$ series phase transitions

However at about same time Ribault et al measured Hall effect in FISDW states

Series of plateaus – reminiscent of QHE



when worked out Hall voltage per molecular (ab) layer

$V_H \sim \frac{25}{n} \times 10^3$ ohms per layer n small integer 4–6

i.e. magnitude also not too far from QHE $\frac{h}{2e^2 j}$ $j = 1,2,3\ldots$

(1984) Héritier, Lederer and Montambaux worked out a theory of quantised nesting

- $\chi(q_1)$ – series of peaks
- V_H quantised
- physical reason – SDW Q such that un-nested pockets are filled Landau levels.

TMTSF$_2$ ClO$_4$ p = 1 bar

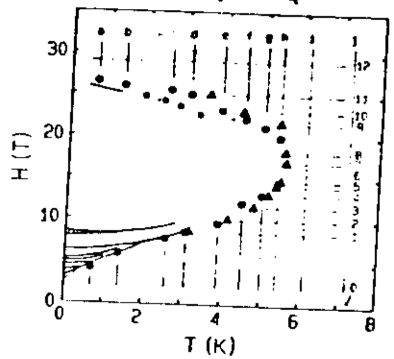
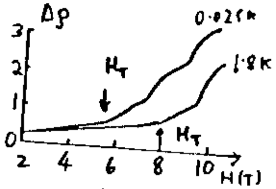
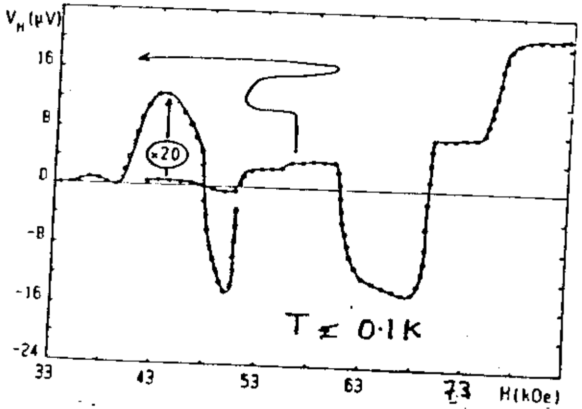


FIG. 3. Reentrant H-T phase diagram for (TMTSF)$_2$ClO$_4$ at high fields. Light horizontal and vertical lines represent the temperature and field excursions of Figs. 1 and 2. Solid symbols, present data; thick lines and other symbols, previous results.

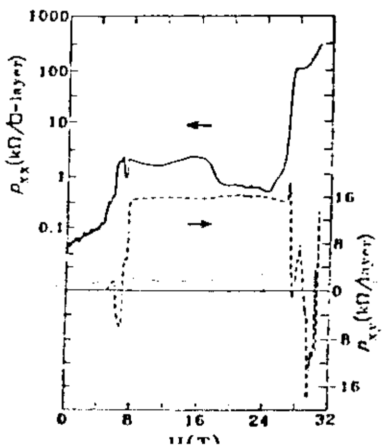
M.J. Naughton et al
PRL 61, 621 (1988)



Kajimura et Al (1983)



M. Ribault (1985)
Mol. Cryst. Liq. Cryst. 119, 91



R.V. Chamberlin et al
PRL 60, 1189 (1988)

$$\chi(q) = \sum_k \frac{f_{k+q} - f_k}{E_k - E_{k+q}}$$

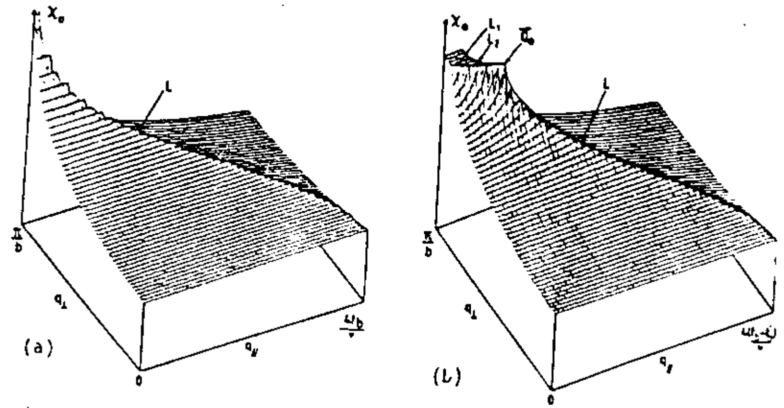


Fig. 4 : Susceptibility $\chi_o(\vec{Q})$ of the non interacting electron gas versus the two components of the nesting vector $\vec{Q} = (2k_F + q_\parallel, q_\perp)$ at zero temperature. a) $t_b' = 0$, there is a logarithmic divergence of χ_o at $\vec{Q}_c = (2k_F, \pi/b)$. b) $t_b' \neq 0$, due to imperfect nesting there is no divergence of χ_o. $\vec{Q}_o$ connects the inflexion points of the Fermi surface. The lines L, L_1, L_2 describe the sliding of the two sheets of the Fermi surface one onto another.

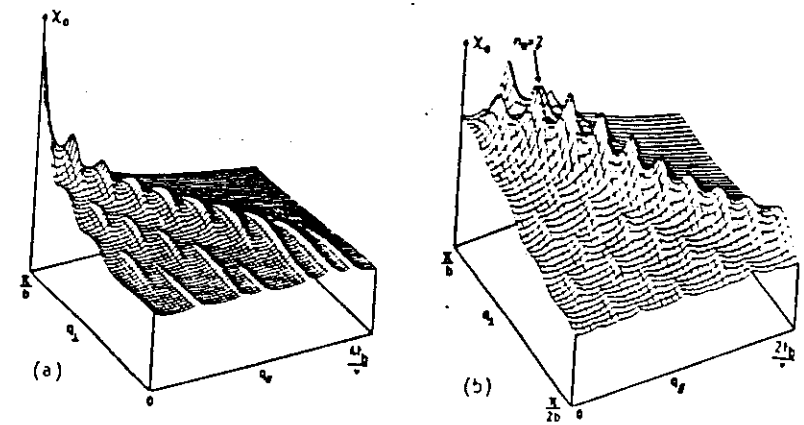
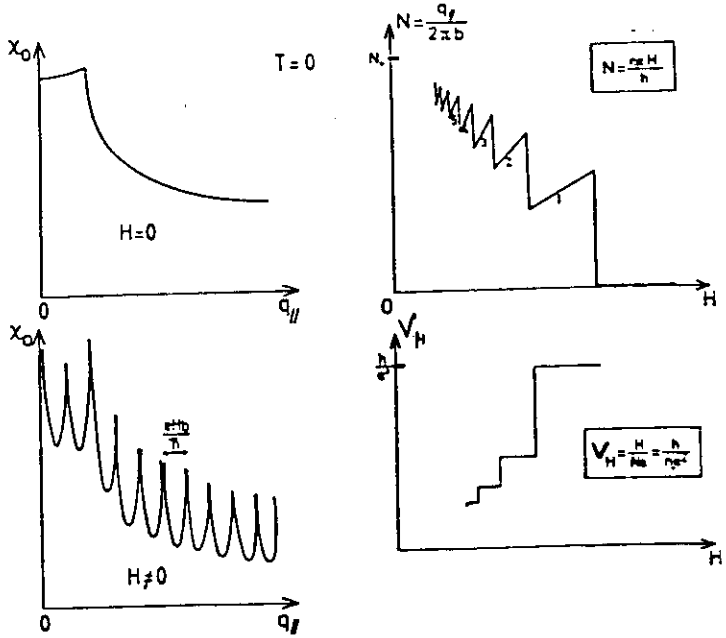


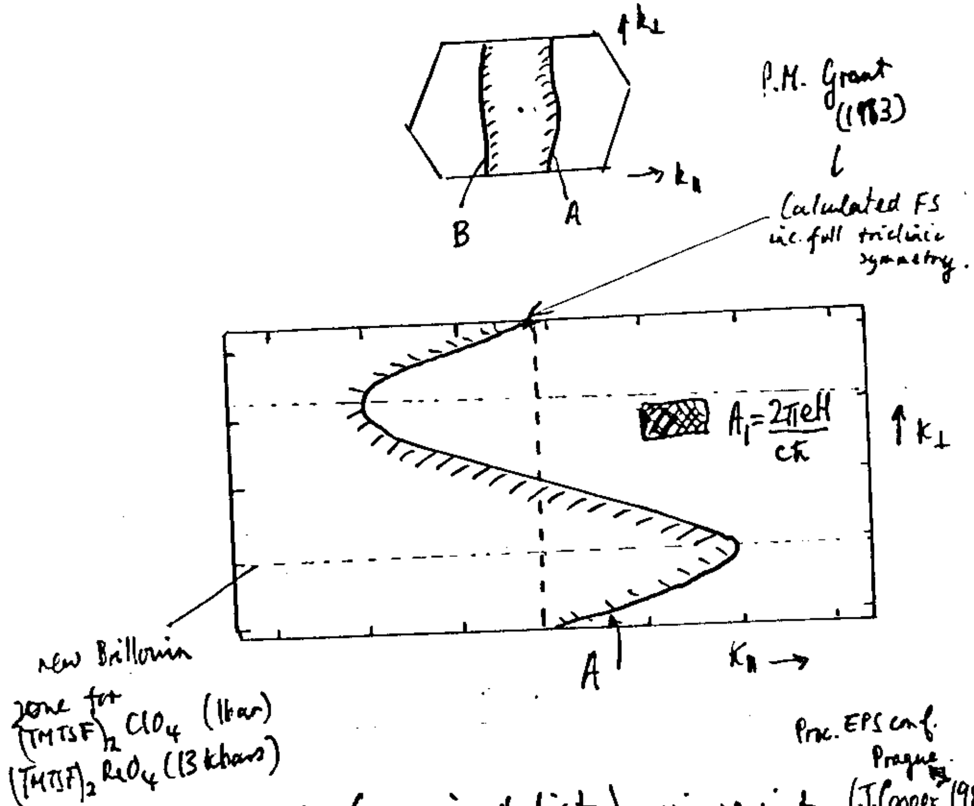
Fig. 5 : Susceptibility under magnetic field. a) $t_b' = 0$, the best nesting vector is the zero field one. b) $t_b' \neq 0$, the absolute maximum varies with the magnetic field. In this case, it is labelled by $n_o = 2$.

$$\rho_q = \chi(q)\, V(q)$$



From G. Montambaux Ph.D. Thesis

Orsay (1985)



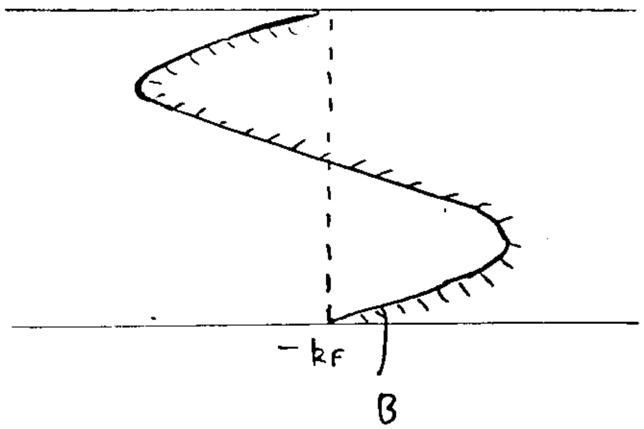
Proc. EPS conf. Prague 1984

Simple (experimentalists) viewpoint. (J. Cooper 1984)

SDW acts as 'reservoir' of electrons - allows Landau levels to remain full over extended field range.

- ...... $TMTSF_2ClO_4$ more complicated

than $TMTSF_2PF_6$ (if magnetic breakdown not complete)



By sliding transparency (7) over transparency (6) can see large nesting region and small electron[+] pockets. Area of pockets corresponds well to A_1 - area of lowest Landau level at 7 Tesla.

It ... with measured sign of V_H)

However still some problems

ClO_4 - two peaks dependent on cooling rate

Hall ratios not 'good', generally did not find $\rho_{xx} \to 0$ on Hall plateaus

no n = 0 state - what was long plateau in V_H from 8-24 T?

1988 New phase transition found at high fields for $(TMTSF)_2 ClO_4$ (Chaikin and colleagues)

Careful resistivity and Hall measurements showed that it was reentrance to metallic (but very high resistivity) state

Explanation by Yakovenko - system so 1D at high fields that fluctuations destroy SDW state.

But unusual metallic state $\frac{C_V}{T} = \gamma \to 0$ as $T \to 0$

Perhaps localisation induced by field or 1D CDW or SDW fluctuations without long range order (cf. KCP at 1 at. pressure - lecture ?)

1989. Looked at PF_6 salt under pressure at high fields (Hybrid magnet facility at C.N.R.S - Max Planck Laboratory, Grenoble)

Be Cu pressure clamp directly immersed in He^3 space of home made He^3 cryostat

J.R. Cooper, V. Kang, G. Montambaux, P. Auban, D. Jérome and K. Bechgaard

at same time similar experiments in U.S.A. by S.T. Hannahs, J.S. Brooks, L.Y. Chiang and P.M. Chaikin

published consecutively in PRL 63, 1984 (1989)

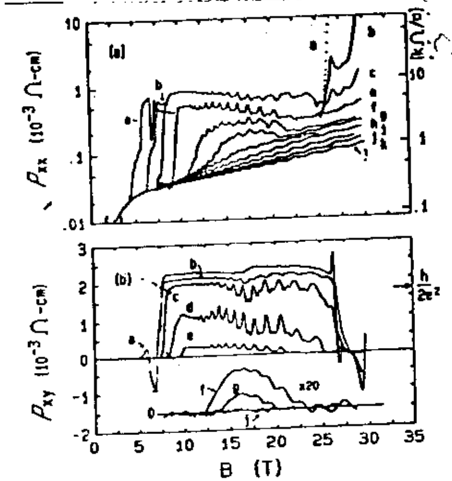


FIG. 1. (a) Magnetoresistance and (b) Hall resistance at several temperatures (note log scale for ρ_{xx}). Temperatures: trace *a*, 0.6 K; *b*, 1.4 K; *c*, 2.6 K; *d*, 3.1 K; *e*, 3.9 K; *f*, 4.5 K; *g*, 5.0 K; *h*, 5.4 K; *i*, 6.1 K; *j*, 7.2 K; *k*, 8.3 K; *l*, 9.3 K. ρ_{xx} for traces *a* and *b* decreases below 0.1 mΩ-cm between 10 and 20 T, and is not shown, while ρ_{xx} for trace *a* rises above 120 mΩ-cm at 30 T.

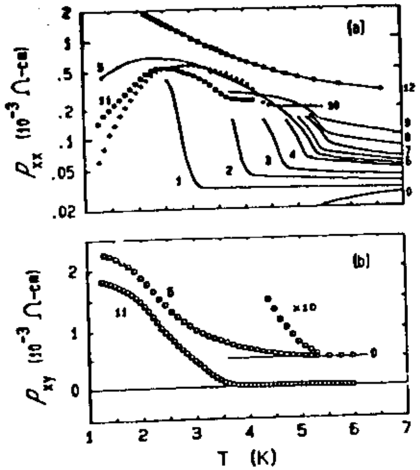


FIG. 2. Temperature sweeps at constant magnetic field, showing the FISDW-metal transition. Magnetic fields (T): trace 0, 0; 1, 8.5; 2, 10; 3, 11.4; 4, 13; 5, 14; 6, 14.6; 7, 16.9; 8, 18.1; 9, 21.6; 10, 23; 11, 25; 12, 29. ρ_{xx} in trace 0 is multiplied by 2, and in trace 12 rises smoothly to 120 mΩ-cm at 0.6 K.

M.J. Naughton et al (loc. cit)

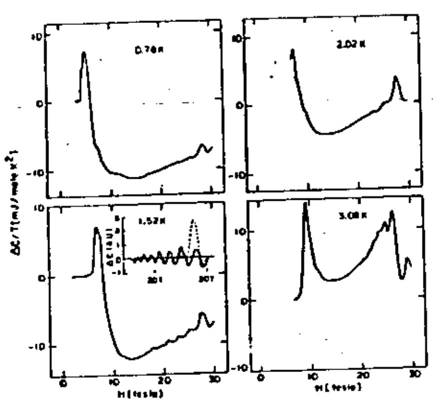
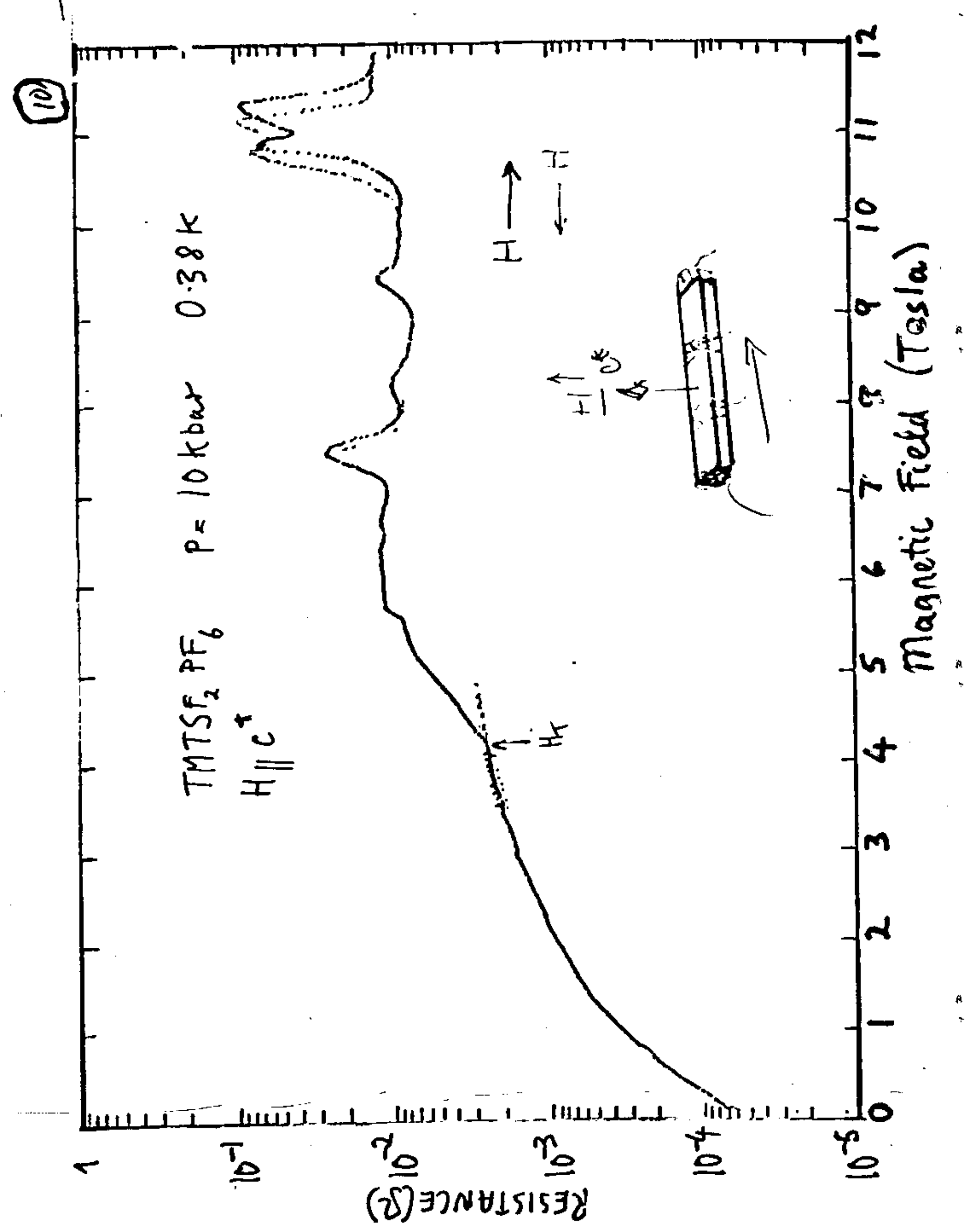
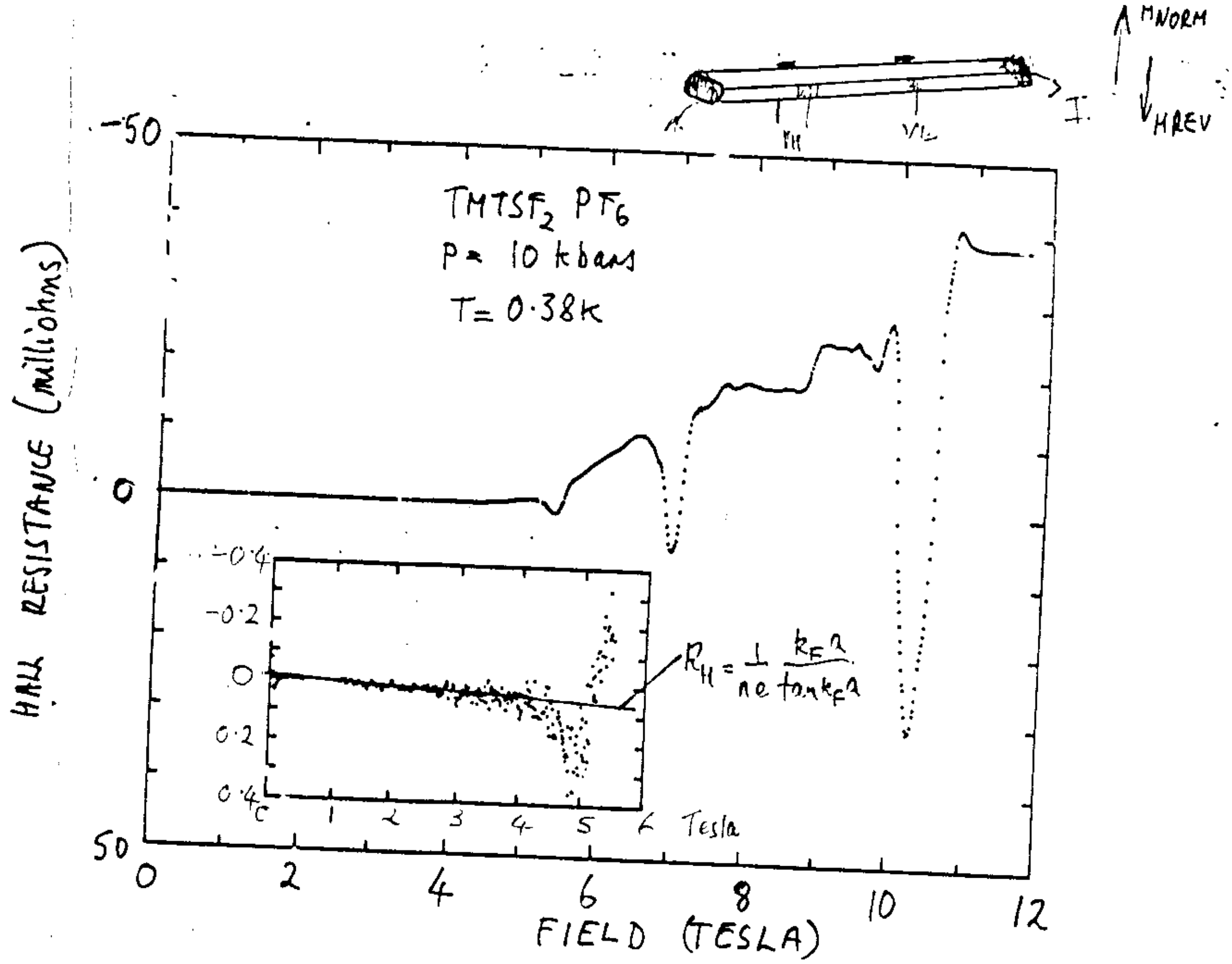


FIG. 2. Magnetic-field-dependent variation of the specific heat ($\Delta C/T$) of $(TMTSF)_2ClO_4$ at four temperatures from an FBNML hybrid run. Inset: Simple model of fast oscillations (solid line) compared to heat-capacity data at 1.52 K (dotted line) to show relative contributions of the reentrant jump and the coexisting oscillations.

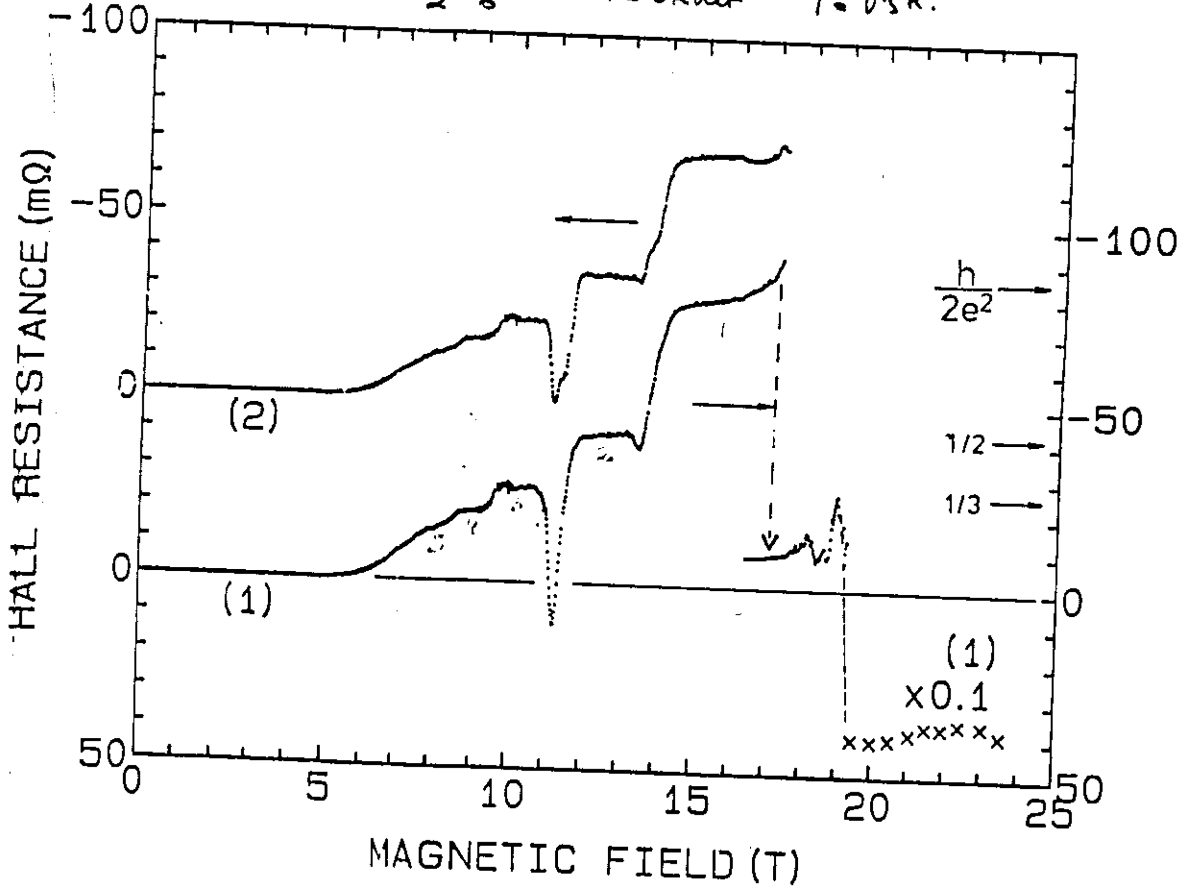
N.A. Fortune et al PRL 64, 2054 (1990)





J.R. Cooper, W. Kang et al PRL 63, 1984 (1989)

TMTSF$_2$ PF$_6$ P = 9kbar T = 0·5K.



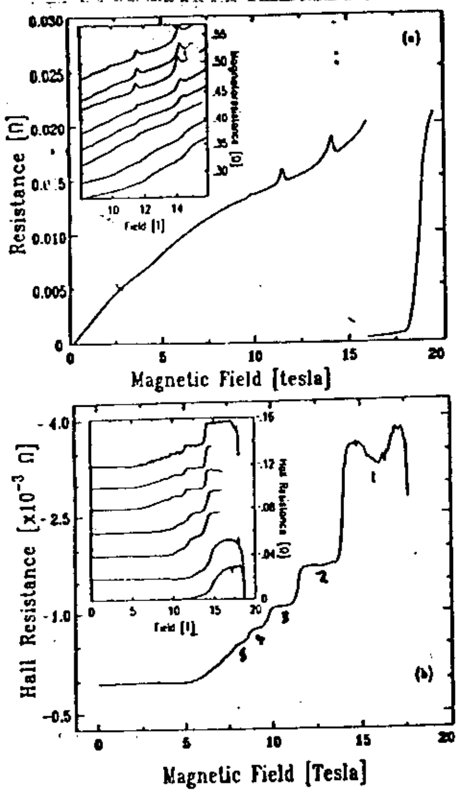
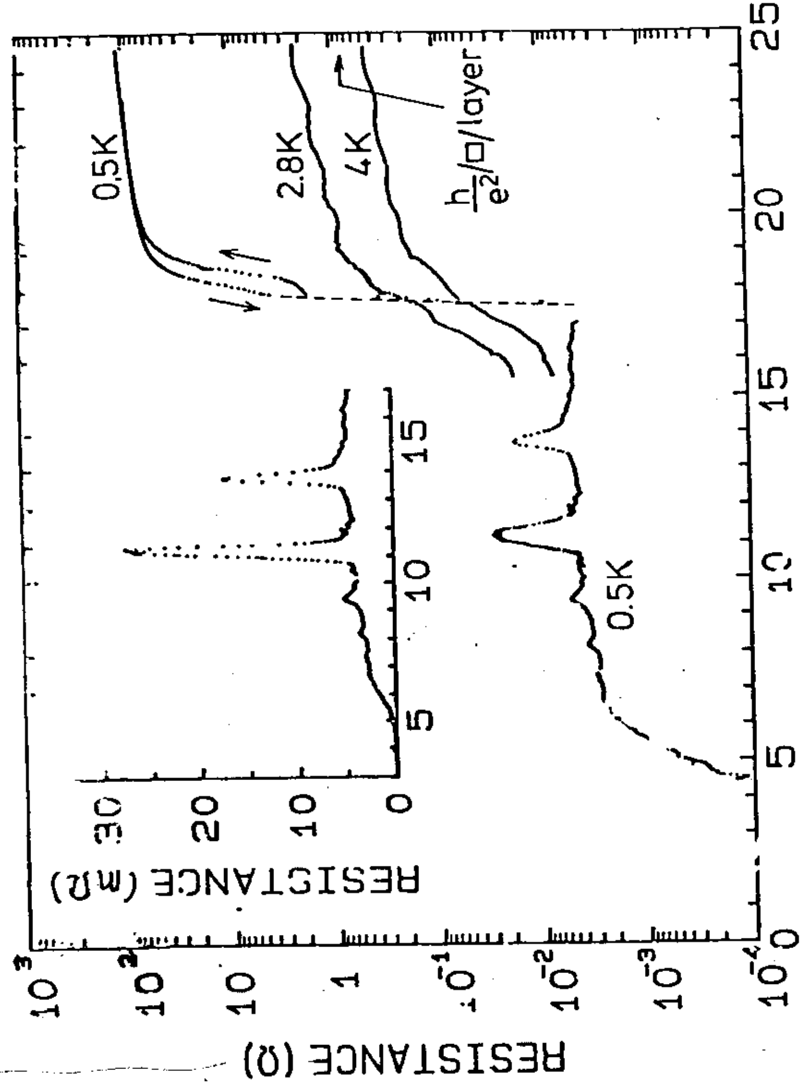


FIG. 1. Magnetoresistance and Hall resistance of $(TMTSF)_2PF_6$ vs magnetic field for different temperatures. (a) Original trace of mixed magnetoresistance and Hall signal at 0.1 K. Scale above 16 T is reduced by a factor of 50. Inset: Temperature evolution of the corrected magnetoresistance for (top to bottom) 0.1, 0.3, 0.33, 0.62, 1.01, 1.1, 1.5, and 2.0 K. (b) Hall signal at 0.1 K. Uncertainties above 15 T originate from errors in subtraction of digitized signals with low resolution and the rapidly increasing magnetoresistance terms. Inset: Similar traces for 0.1, 0.1, 0.33, 1.01, 1.1, 1.5, and 2.0 K. Note the negative sign of the Hall signal.

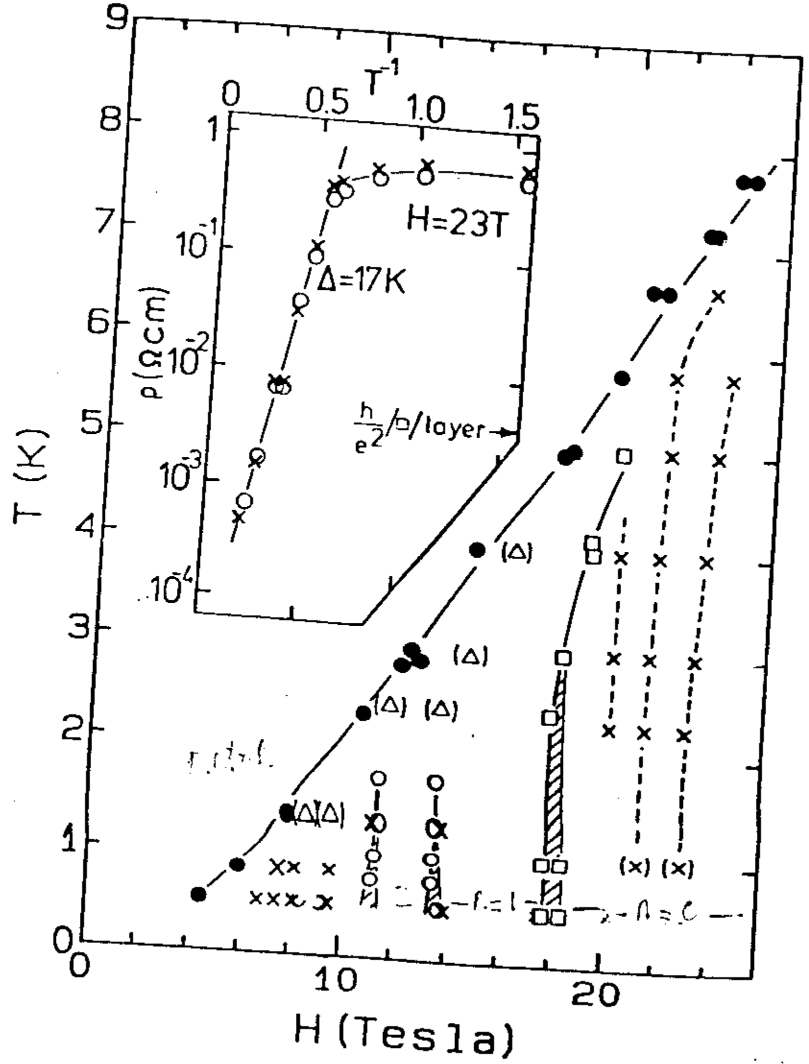
S.T. Hannahs et al

PRL. 63, 1988 (1989)

Figure 2



(14)



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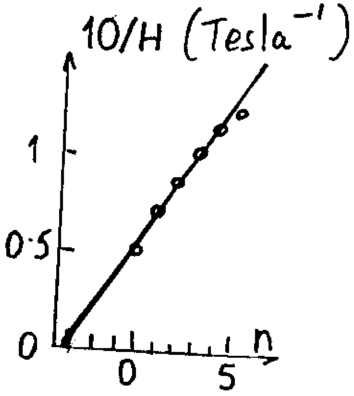
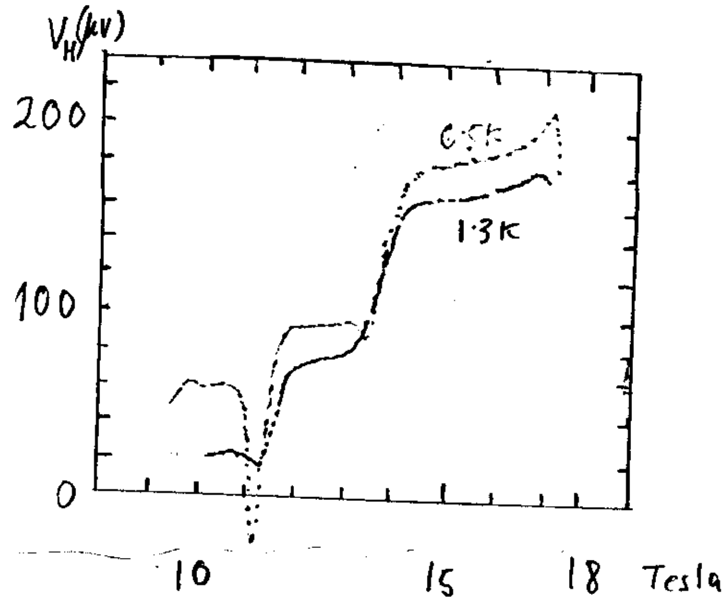




TMTSF₂PF₆ Cooper et al (loc. cit)

Summary of Main Points.

Present work $(TMTSF)_2PF_6$ • Hall plateaus in integer ratios

1 : 0·52 : 0·32 : 0·24 : (0·2)   both pairs contacts 25T exp.

Abs. values 11·6 ± 0·5, 10·2 ± 0·5 } kilohms per layer: close to $\frac{h}{2e^2}$ = 12·5 kΩ/layer

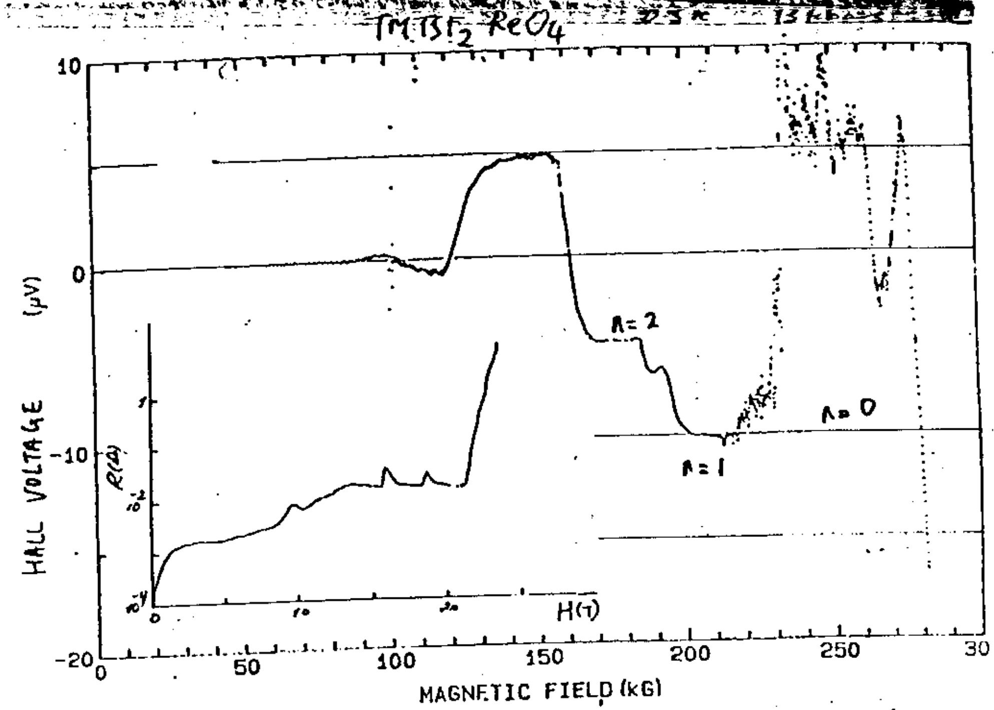
and 0·5 : 0·32 : 0·24 : 0·2   12T exp.

abs. values 14·4 ± 0·8, 8·6 ± 0·5 } kilohms per layer

- Minima in magnetoresistance 150 - 200 times less than h/e^2 /□/layer, i.e. $\rho_{xx} \ll \rho_{xy}$

  For $J = J_x$, $E_x \ll E_y$ } $E \perp J$ as in normal QHE.

- Transition to very resistive state above 18T
  Hall effect +ve there as in metallic state
  In contrast to re-entrant metallic state in $TMTSF_2ClO_4$ believe that this is $n = 0$ state predicted by HLM, because:
  1/ no sign of re-entrance to 25T
  2/ High field transition first order with hysteresis.
  3/ Only weakly T dependent
  4/ Onset field as expected for $n = 0$
  Not understood
- "Fast" oscillations in high field phase
- Saturation in high field resistance below 1·7K



W. Kang, J.R. Cooper, D. Jérome and K. Bechgaard (1990)

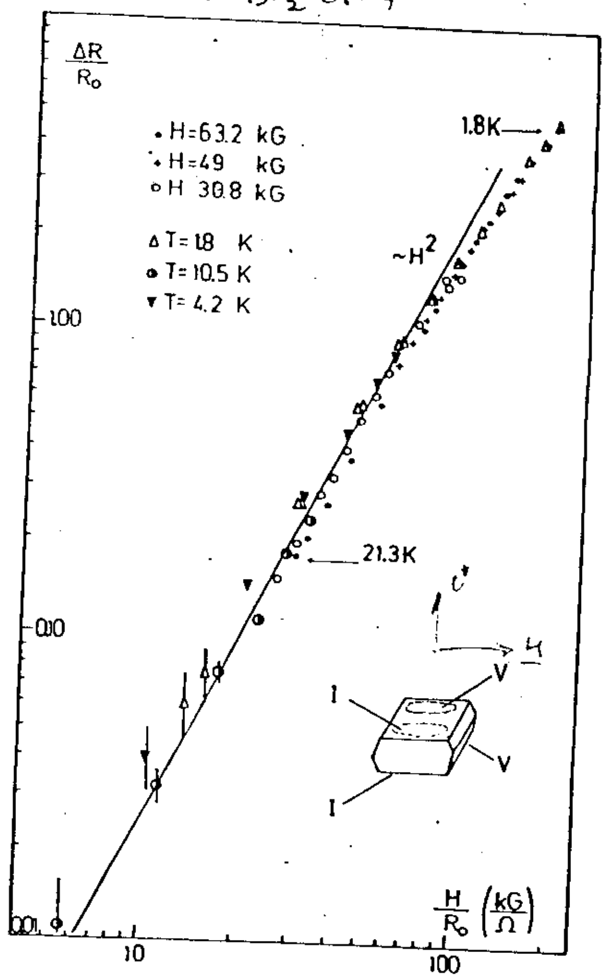
Example of recent results for $(TMTSF)_2ReO_4$

Have $(0, \frac{1}{2}, \frac{1}{2})$ superlattice as for $(TMTSF)_2ClO_4$

Above 15T very similar to PF_6 salt, n=0, 1, 2.

below 15T +ve peak in V_H reminiscent of that in ClO_4 near 7 Tesla.

$TMTSF_2\ ClO_4$



R. Cooper, L. Forró and B. Korin-Hamzić, (1984)

Example showing 'regular' magnetoresistance for $TMTSF_2\ ClO_4$ with $\underline{I} \parallel \underline{c}^*$, $\underline{H} \parallel \underline{b}'$

Kohler's rule is obeyed as in ordinary metals [in field and temperature range studied (3 to 6.3 Tesla, 1.8 to 22 K)]