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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 - IV

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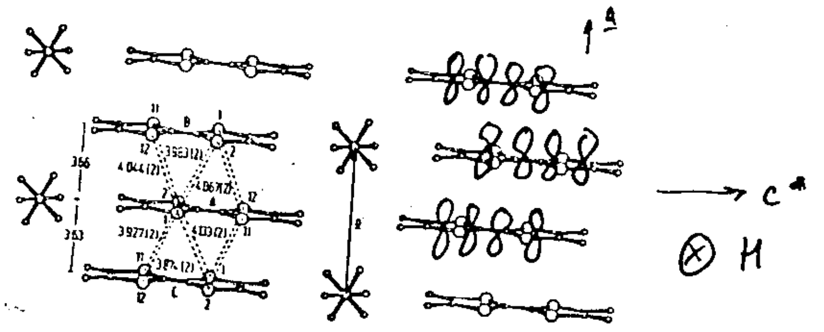


Question of contraction of wave f^n raised last time.

HLM } calculations of $\chi(\underline{Q})$ with $\underline{H} \parallel \underline{c}^*$ used substitution
GL }

$\underline{p} \to \underline{p} - \frac{e\underline{A}}{c}$ so any contraction of wave functions is included.

In the metallic state ($H < H_T$) magnetoresistance seems to be regular for geometry

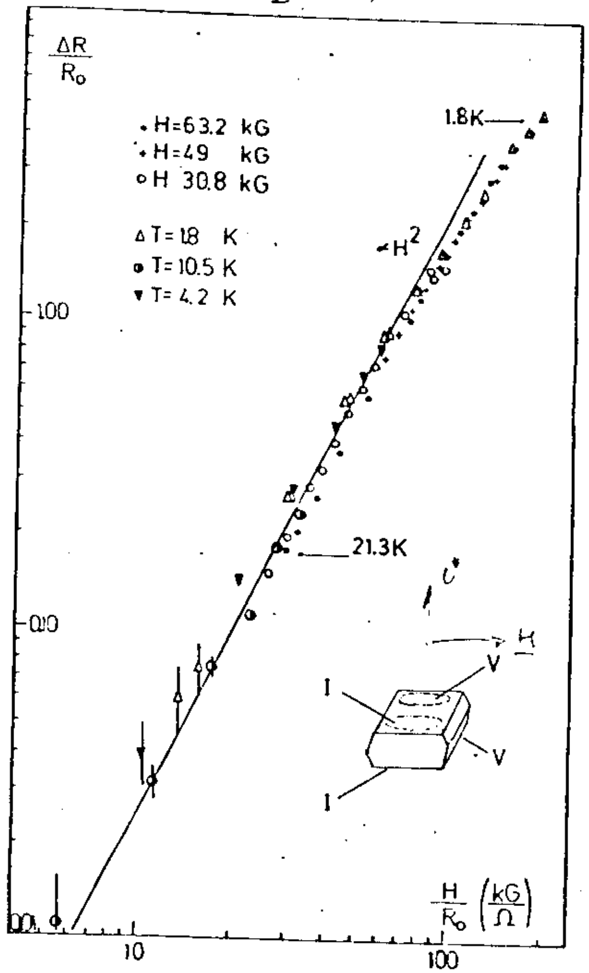
$\underline{j} \parallel \underline{c}^*$, $\underline{H} \parallel \underline{b}'$ ($\hat{\underline{b}}' \equiv \underline{a} \times \underline{c}^*$)
($\hat{\underline{c}}^* \equiv \underline{a} \times \underline{b}$)

and anomalously large for

$\underline{j} \parallel \underline{a}$, $\underline{H} \parallel \underline{c}^*$

so cannot see clear explanation in terms of contraction of wave f^n.

$TMTSF_2\ ClO_4$



J. R. Cooper, L. Forró and B. Korin-Hamzić, (1986)

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)]

Kohler's rule

$\frac{\Delta\rho}{\rho_0} = F(H/\rho_0)$

in Boltzmann eq^n.

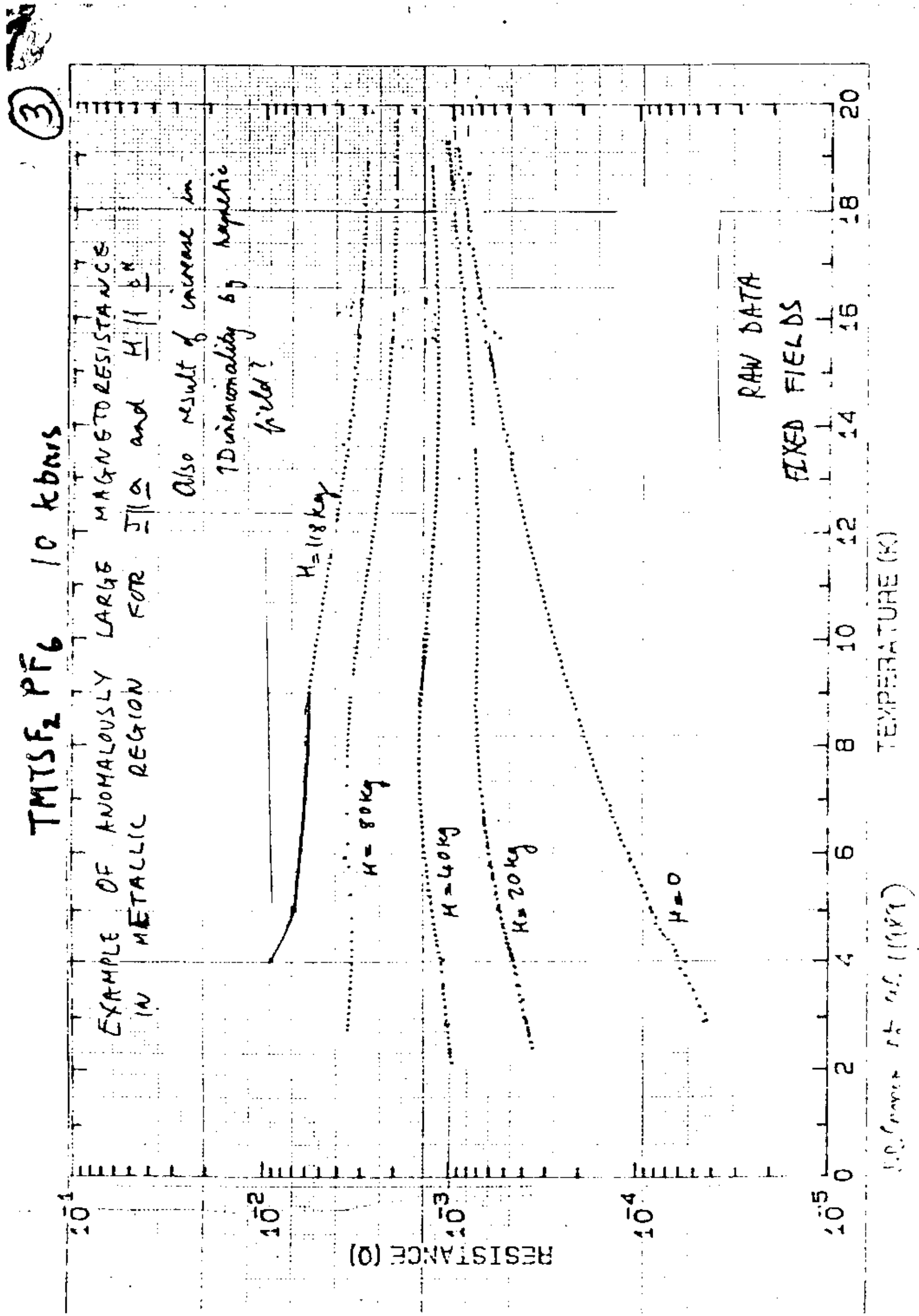
$\frac{d\underline{k}}{dt} = \frac{e}{c}\underline{v} \times \underline{H}$

so $\delta\underline{k} \propto H\tau$

τ is relaxation time

n fixed, m^* fixed

$\rho_0 \propto \tau^{-1}$



Classical magnetoresistance theory (Chambers 1956. Kubo, Nagamiya p 255)

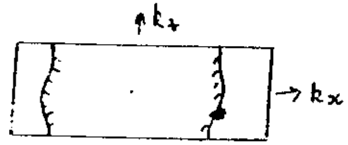
also Gottlieb et al ~ P Rev. 26, 0797 1982

$$\sigma_{ij} = \frac{-e^2}{4\pi^3} \int \frac{dS}{\hbar |V_k|} \int_0^\infty V_i(0)\, V_j(t)\, e^{-t/\tau} dt \qquad (1)$$

$V_j(t) = V_j(k(t))$ and $k(t)$ solⁿ of $\frac{dk}{dt} = \frac{e}{c\hbar}(V \times H)$

$$\mathcal{E} = -2t_{\parallel} \cos k_x a - 2t_{\perp}^{b} \cos(k_y b \cos 20 + k_x b \sin 20) - 2t_{\perp}^{c} \cos(k_z c)$$

(P. Grant 1983)



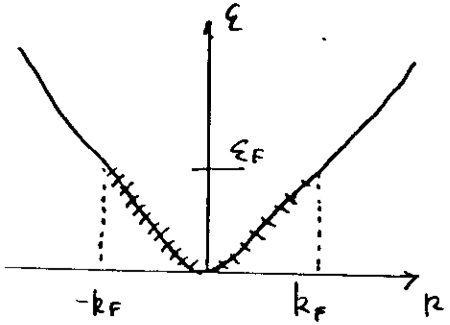
$H \parallel a \times c$

$$\sigma_{c^*c^*} \equiv \sigma_{zz} = \frac{2\pi}{b} \frac{e^2}{4\pi^3} 2 \int_{-\pi/c}^{+\pi/c} dk_z \frac{V_z(0)}{|V_x|} \left[V_z(0)\tau + \dot{V}_z(0)\tau^2 + \ddot{V}_z(0)\tau^3 + \cdots \right]$$

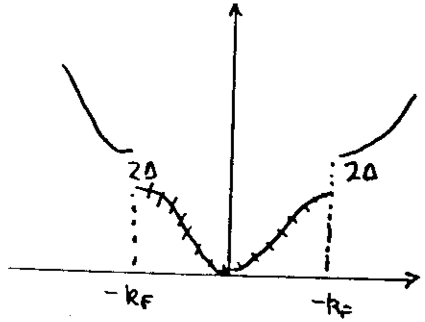
$$\ddot{V}_z = -V_z \left(\frac{ce}{c\hbar} V_x H \right)^2$$

$$\sigma_{c^*c^*}(H) = \sigma_{c^*c^*}(0) \left[1 - \Omega_c^2 \tau^2 \right]$$

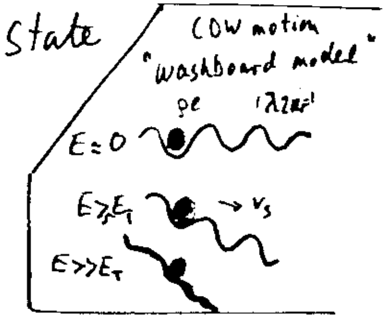
$$\Omega_c = \frac{ec}{c\hbar} V_{\parallel} H \qquad , \quad u_a = \frac{t_{\perp}^{c}}{t_{\parallel}}$$

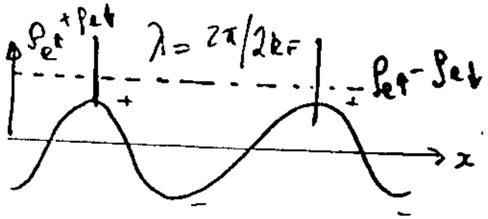


1 D Band

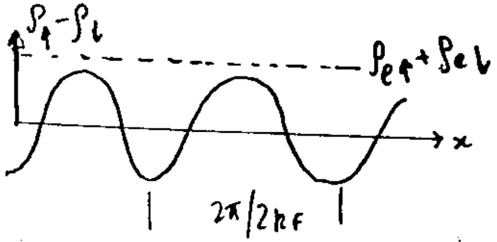


CDW or SDW State



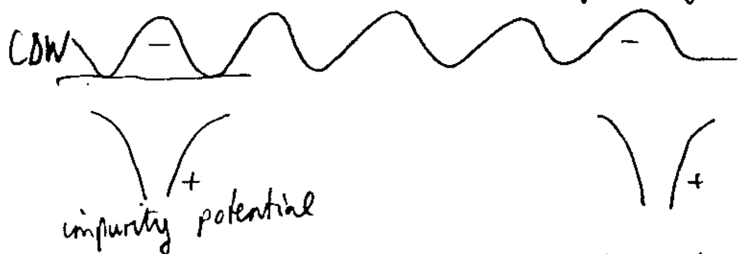


CDW uniform spin density
driven by el-phonon interaction or Coulomb forces between electrons



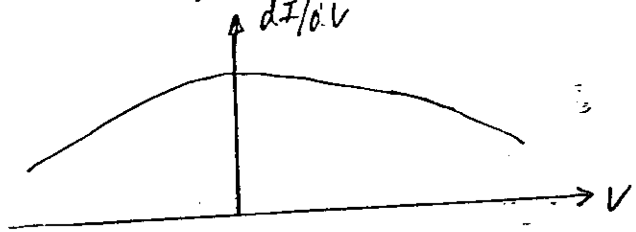
SDW uniform charge density
driven by spin dependent exchange interaction between electrons

Not so obvious that electric field will couple to SDW to give extra current nor that there will be pinning as for a CDW, nor large effective mass



CDW will be pinned and deformed by charged impurities.

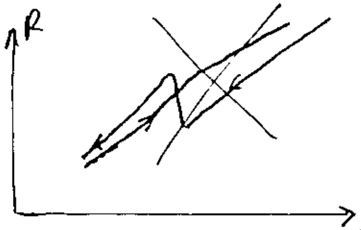
Early experiments (Grüner and colleagues) showed anomalous microwave conductivity for $(TMTSF)_2PF_6$ - ascribed to collective motion of SDW, but the non-linearity developed continuously from low electric fields (no threshold field)



Later concluded that it was probably due to heating - either at contacts or at microcracks within crystal.

However S. Tomić (Zeyher-Orsay) did the same sort of pulsed I-V experiments (as shown previously for TTF-TCNQ) on another Bechgaard salt $(TMTSF)_2NO_3$ — which also has a SDW phase transition at 12K — as well as an anion ordering phase transition at 40K.

Cooled extremely slowly 1-2K/hr (computer controlled) monitoring resistance continuously



no jumps (occasionally)

Important because in TTF-TCNQ sometimes had spurious non-linearity arising from jumps (microcracks), semiconductor-semiconductor tunneling, charging of capacitances by drive pulse?

Saw non-linear I-V characteristics and sharp threshold, $E_T \sim 30$ mV/cm, at lower end of range typically observed for CDW systems.

More recently re-investigated $(TMTSF)_2PF_6$. In meantime I. Kang developed method of contacting which avoids cracking — spring gold wires making contact to evaporated gold pads.

Crystal

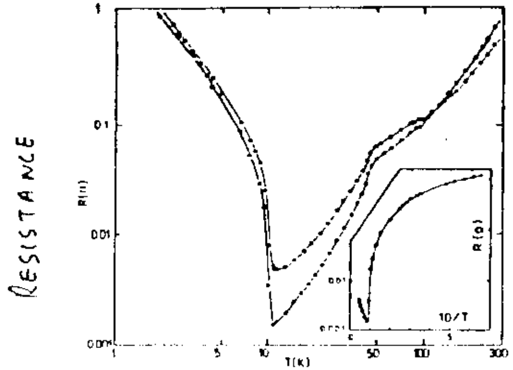
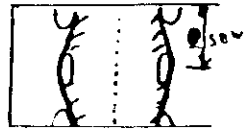


FIG. 1. Log-log plot of resistance vs temperature for two $(TMTSF)_2NO_3$ samples. Open and filled circles are for samples 1 and 2, respectively. Inset: plot of log$R$ vs $1/T$ for sample 1.

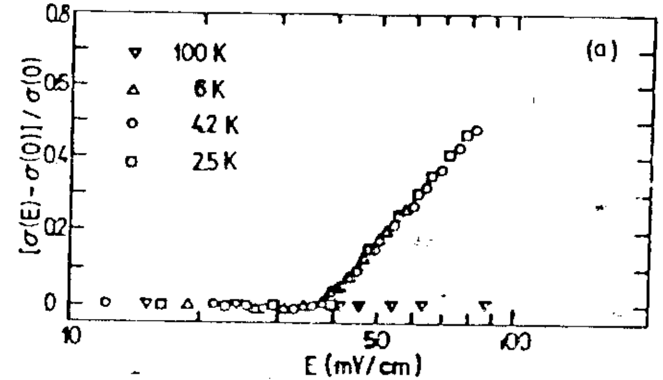
X-ray diffuse scattering

40K $(\frac{1}{2}, 0, 0)$ superlattice



T > 40K

T < 40K



Pulse method.

continuous method.

$I = I_0 + I_1 \sin\omega t$

sample directly immersed in superfluid helium

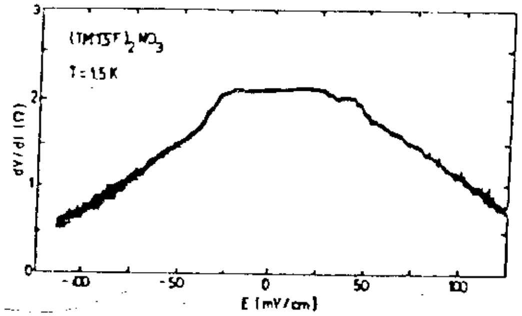
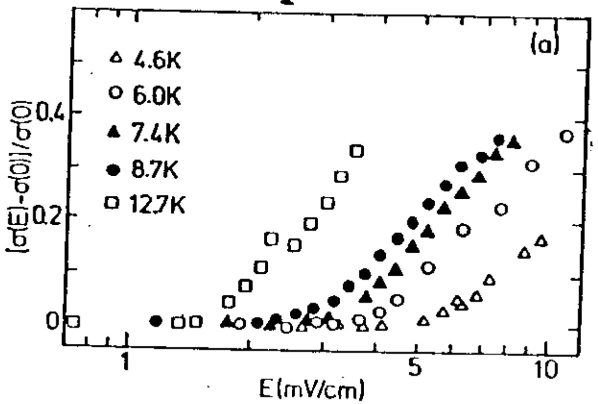


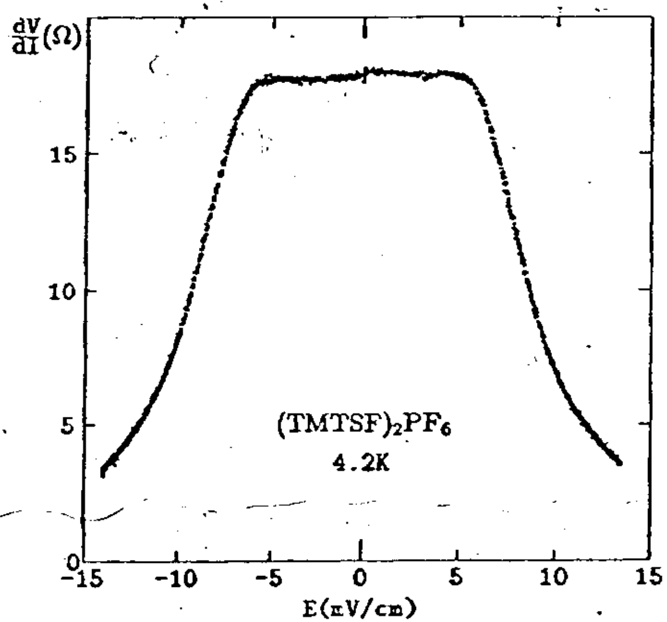
Fig.2. Dynamic resistance (dV/dI) versus electric field (E) for $(TMTSF)_2NO_3$.

S. Tomić et al PRL 62, 462 (1989)

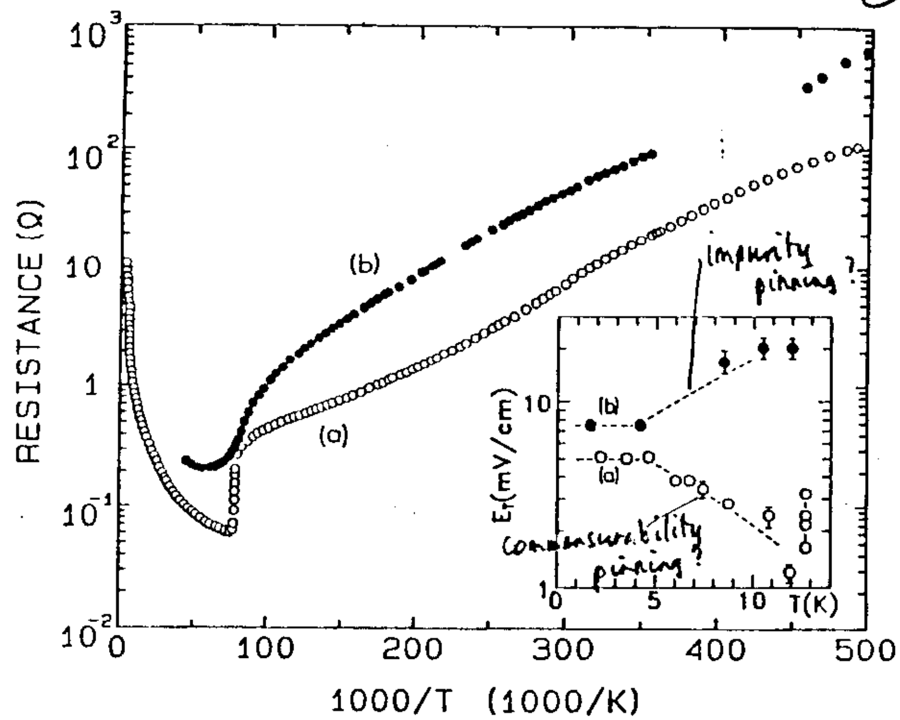
TMTSF$_2$ PF$_6$



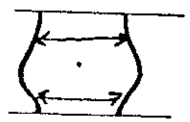
W. Kang, S. Tomić, J.R. Cooper and D. Jérome (1989)



W. Kang, S. Tomić and D. Jérome (1990)

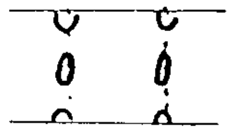


TMTSF$_2$ PF$_6$ W. Kang et al PR Rapid Commun. (1990)



TMTSF$_2$ PF6 T > 11 K

TMTSF$_2$ NO$_3$ T > 40 K

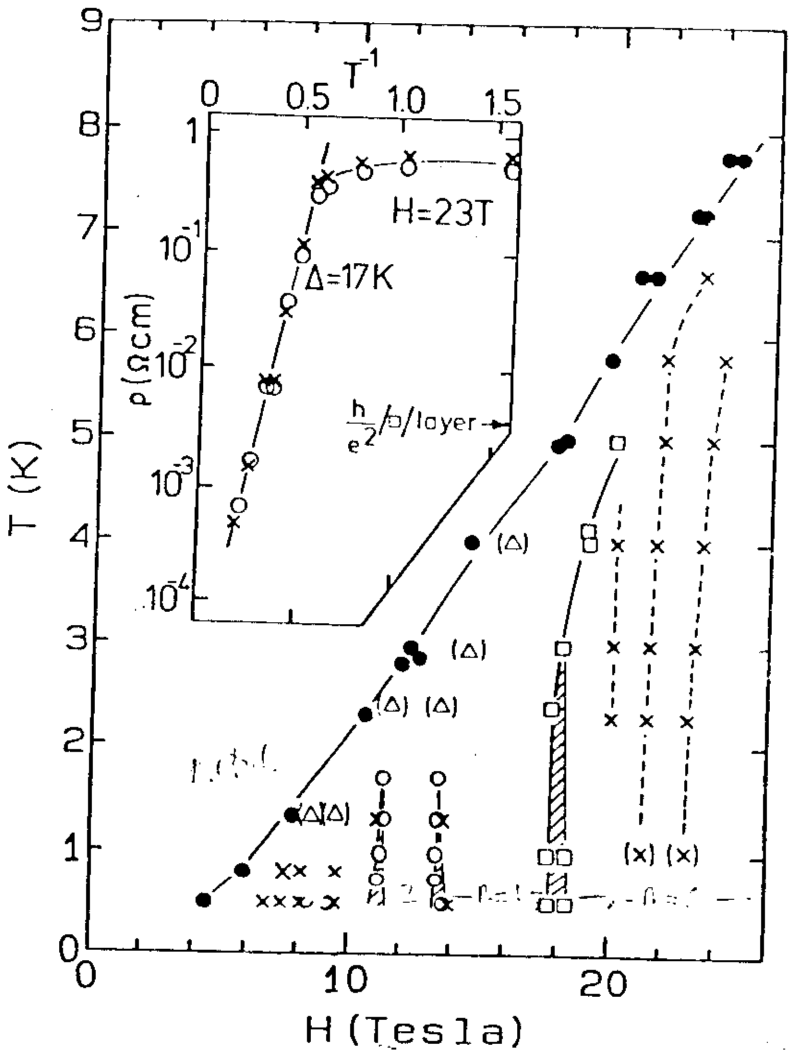


TMTSF$_2$ NO$_3$

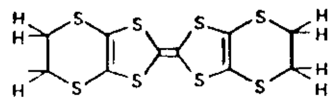
11K < T < 40K

Still much more to do. Increase defect concentration by electron irradiation (in progress) - look for narrow and broad band noise, metastability, relaxation effects as in CDW materials

$TMTSF_2 PF_6$

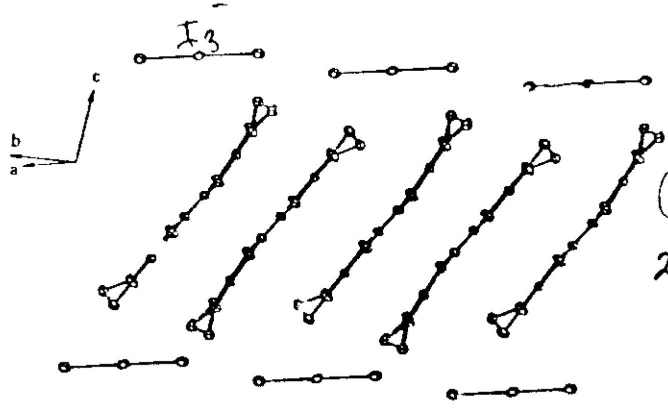


We also see non-linear behaviour and a threshold electric field E_T in the FISDW states e.g. in the n=0 state. E_T is in the range 1–10 mV/cm and decreases as T increases at



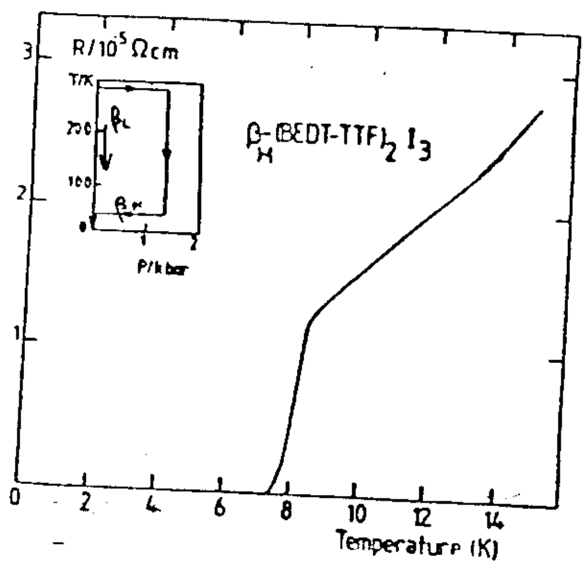
BEDT-TTF (ET)

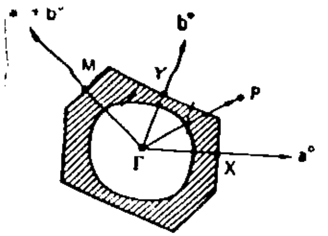
I_3

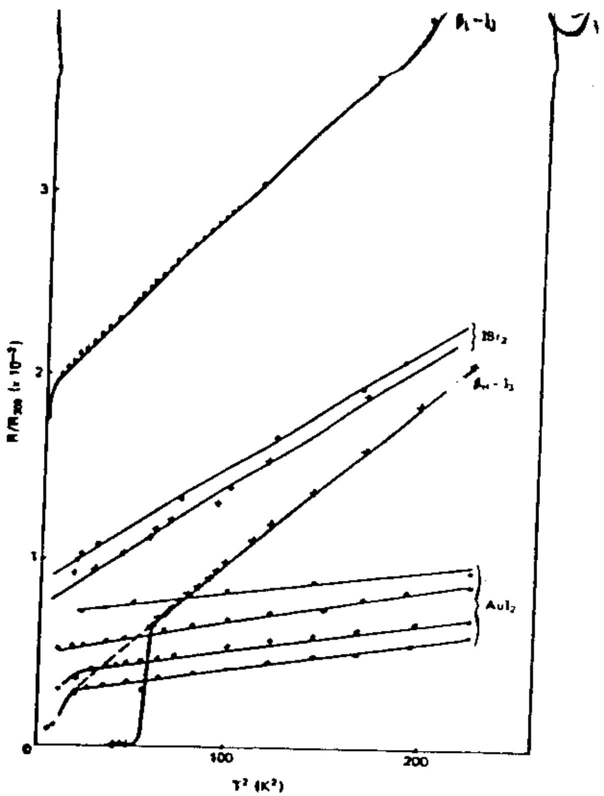


$(BEDT\text{-}TTF)_2 I_3$

2D metal







From L. N. Bulaevskii
"Organic layered superconductors"
Advances in Physics (1988)
Vol. 37 443-470

Because of overall momentum conservation Electron-electron scattering only gives a contribution to the resistivity if Umklapp processes are allowed (they are here because closed FS near to Brillouin zone face) or if there are states with different effective mass

- β_H phase of $(BEDT\text{-}TTF)_2 I_3$ has $T_c \simeq 8K$
- β_L phase has higher residual resistivity and t_c 25% smaller T_c only 1.5K — Why?

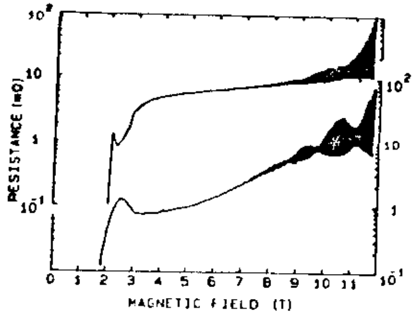


FIG. 1. The overall magnetoresistance behavior of two samples between 0 and 12 T at 380 mK.

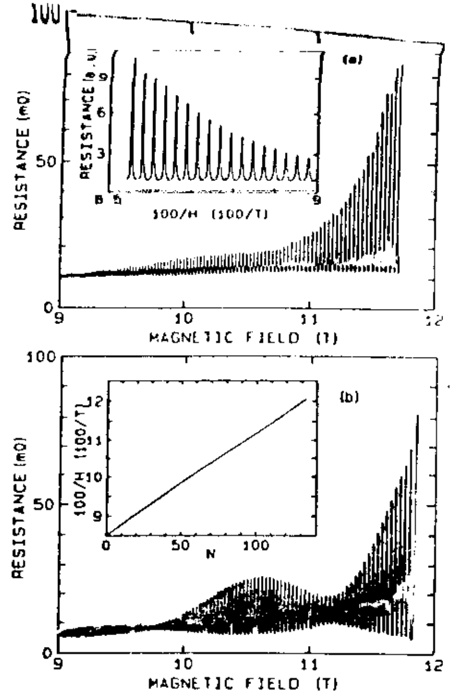


FIG. 2. Details of the magnetoresistance between 9 and 12 T at 380 mK: (a) sample 1, (b) sample 2. Insets: The anharmonicity of oscillations and the linearity of peak positions, respectively.

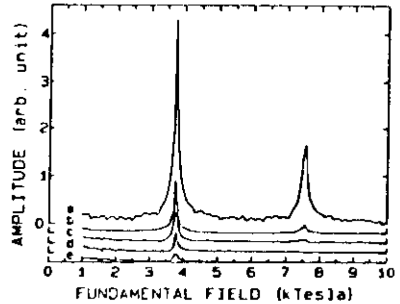


FIG. 3. Fourier transform of experimental data between 9 and 12 T at different temperatures: curve *a*, 380 mK; curve *b*, 550 mK; curve *c*, 700 mK; curve *d*, 800 mK; and curve *e*, 900 mK.

Evidence for cylindrical Fermi surface in $\beta\text{-}(BEDT\text{-}TTF)_2 I_3$ (high T_c phase)

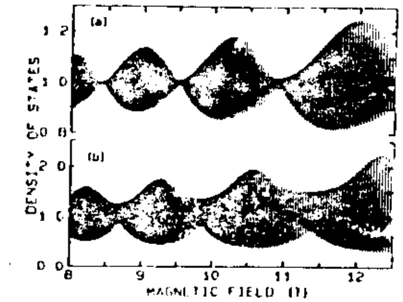
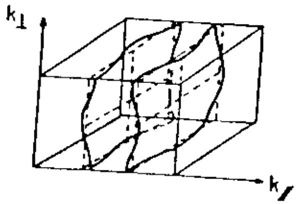


FIG. 4. DOS oscillation of (a) a single cylindrical Fermi surface with a small warping and (b) two perfect cylinders. ($T = 0.38$ K, $T_D = 0$ K, $\mu = 4$, $H_0 = 3700$ T, and $H_1 = 37$ T.)

β_H $ET_2 I_3$ $p = 1$ bar

W. Kang et al (1989)
PRL 62, 2559



$TMTSF_2\ X$

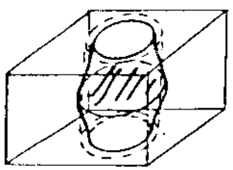
$T_c \leq 1.2\,K$

$\beta_H\ (BEDT\ TTF)_2\ I_3$

Area of central orbit $= 0.5\%_3$ of Brillouin Zone

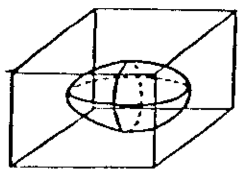
$t_c^* = 0.5\,meV$

25% lower in β_L phase



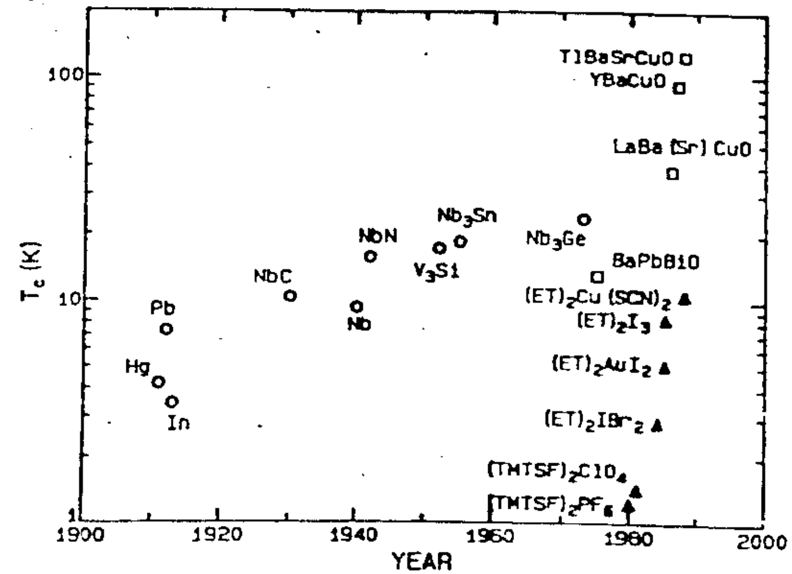
$(BEDT\text{-}TTF)_2\ X$

$T_c \leq 11\,K.$



anisotropic 3D metal

no known organic conductors.



D. Jerome (1989)

Conclusion

Research on low dimensional organic conductors has given some interesting results in condensed matter physics and there are likely to be more pleasant surprises in the future. It is an interdisciplinary research field, structural studies by X ray diffuse scattering have been particularly important. In general relatively simple measurement methods have been used on single crystals of different (but related) new materials. The equipment required for most of these techniques is on a rather small scale and is relatively inexpensive.