ECRYS-2022

Low-temperature magnetoresistance in o-TaS_3 and $(TaSe_4)_2I$ in nonlinear conduction regime

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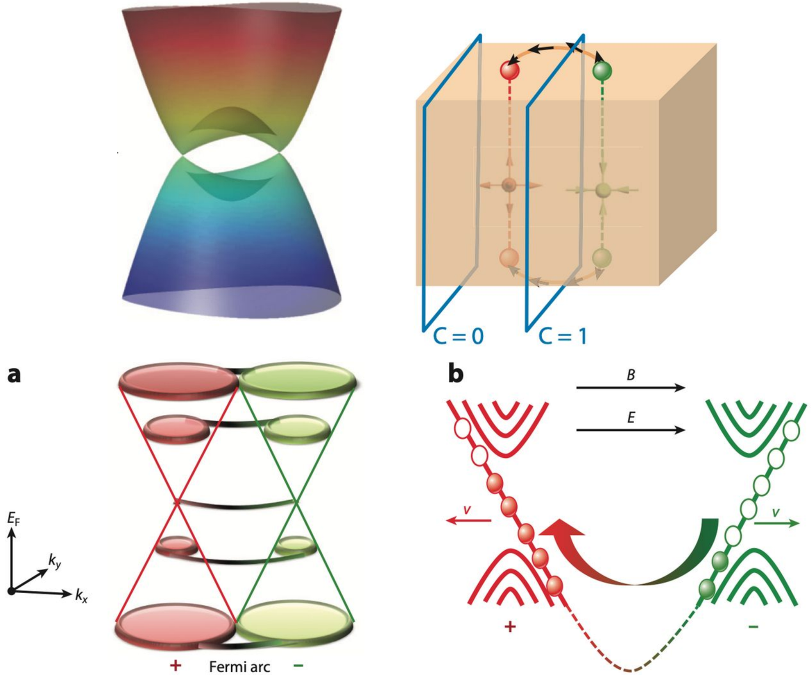
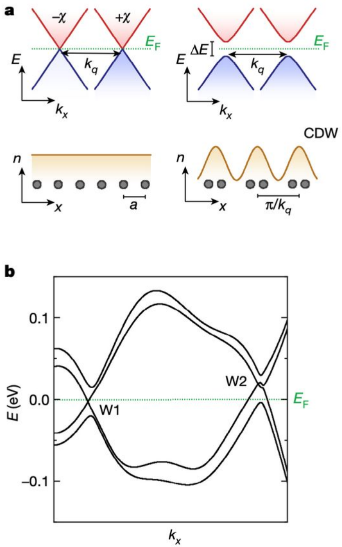
Outline

- Motivation
- Magnetoresistance in $(TaSe_4)_2I$
  - Thin crystals
  - Bulky crystals
  - Conclusion
- Magnetoresistance in *o*-TaS_3
  - Short crystals
  - Long crystals
  - Conclusion

Motivation: Magnetoresistance of quasi-1D Weyl semimetal $(TaSe_4)_2I$ in the CDW state



[D. Yan and C. Felser, Ann.Rev.Cond.Mat.Phys. 2017]

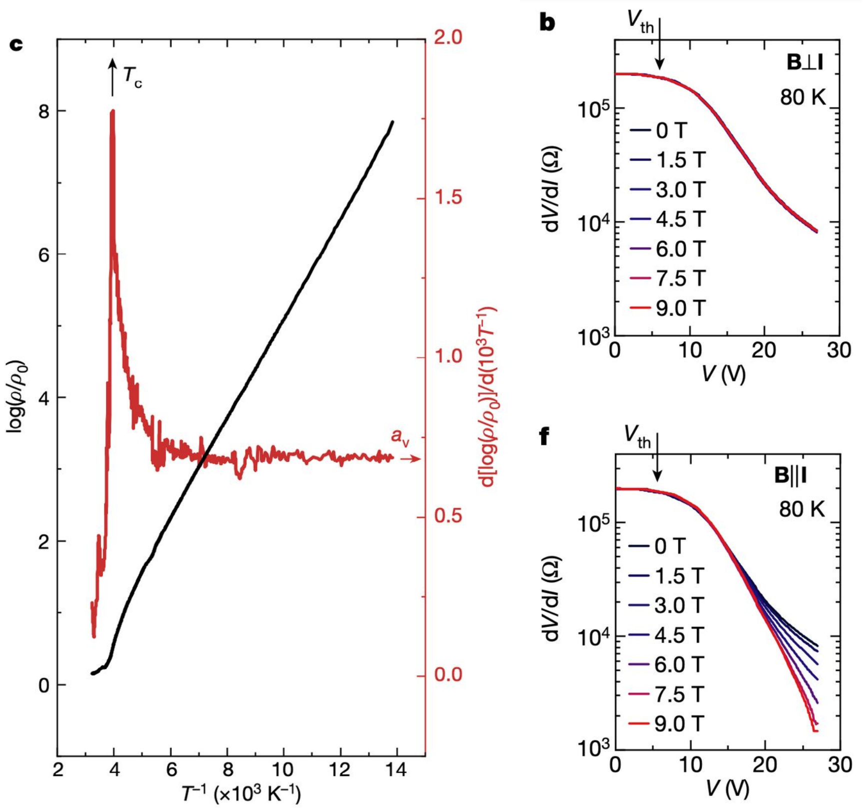


Weyl semimetals:

- The absence of inversion or time reverse symmetry
- Chiral electrons (not helical as in topological insulators)
- Negative longitude magnetoresistance as a feature of Weyl semimetals

[W. Shi *et al.*, A charge-density-wave topological semimetal, Nature Physics, **17**, 381 (2021);
J. Gooth, *et al.*, Axionic CDW in the Weyl semimetal $(TaSe_4)_2I$, Nature **575**, 315 (2019)]

Motivation: Magnetoresistance of quasi-1D Weyl semimetal $(TaSe_4)_2I$ in the CDW state



[J. Gooth, *et al.*, Axionic CDW in the Weyl semimetal $(TaSe_4)_2I$, Nature **575**, 315 (2019)]

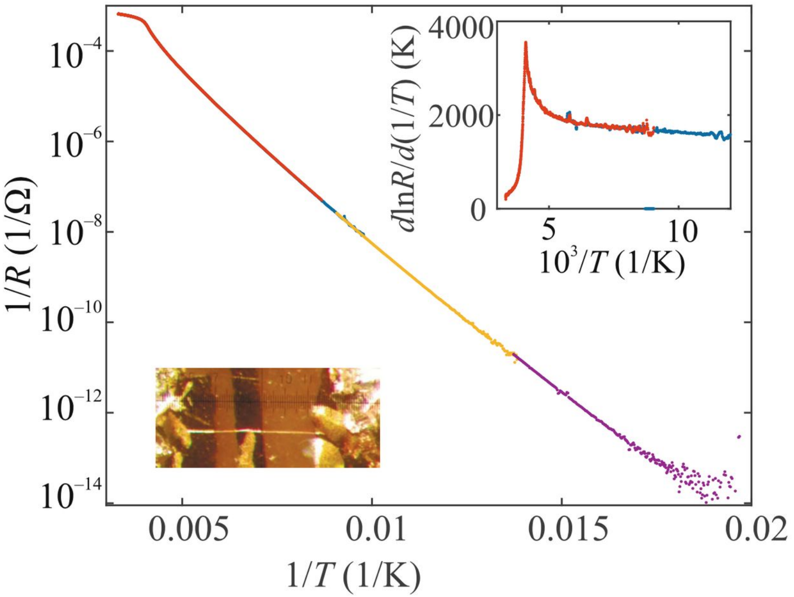
Our doubts:

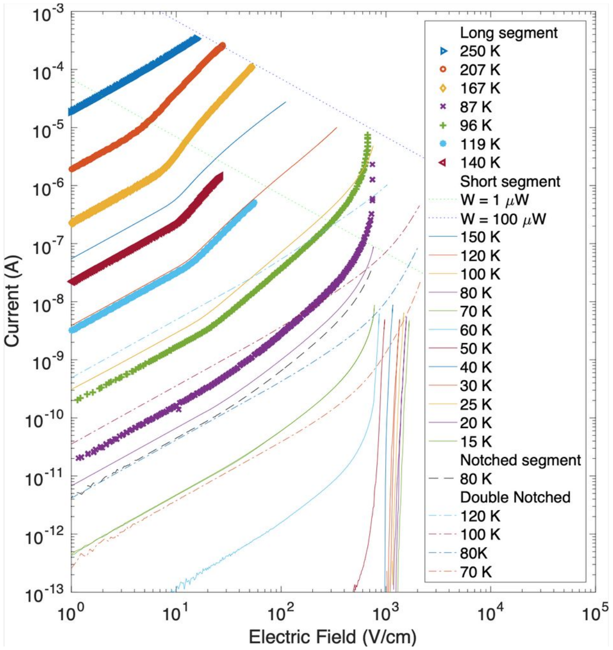
- There is the Peierls gap ~ 0.2 eV, so no Weyl semimetal features
- Too much Joulie heating (60 mW)
- One order magnetoresistance in the CDW without quasiparticle magnetoresistance breaks the scaling law!

Scaling law: $\sigma_{CDW}(T) \propto \sigma_q(T)$ [XJ Zhang, NP Ong PRL (1985); RM Fleming *et al*. PRB(1986)]

Our first attempt: Magnetoresistance of quasi-1D Weyl semimetal $(TaSe_4)_2I$ in various CDW motion regimes

Two-contact study. Joulie heating << 1 μW (almost 4 orders smaller)

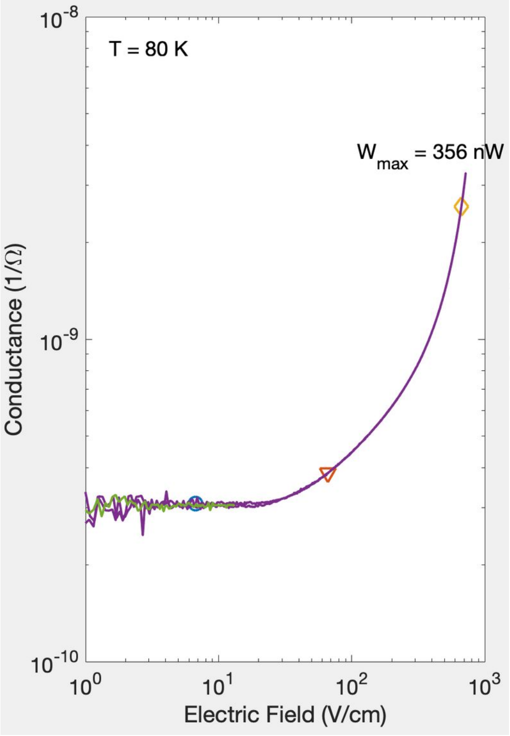


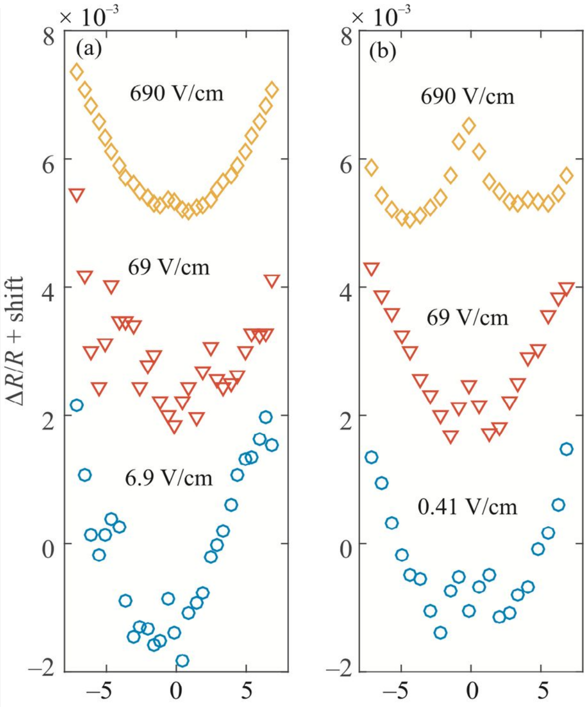


[IA Cohn, *et al.*, JETP Letters **112**, 88 (2020)]

Our first attempt: Magnetoresistance of quasi-1D Weyl semimetal $(TaSe_4)_2I$ in various CDW motion regimes

H || *J* *T* = 80 K *H* ⊥ *J*





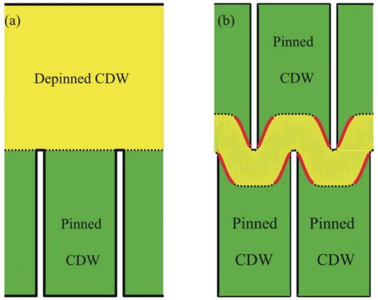
Two-contact study:

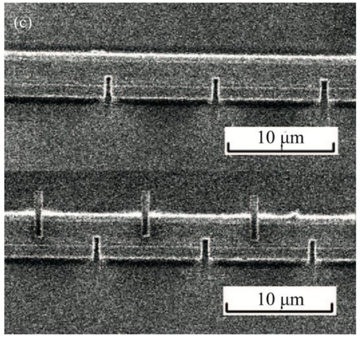
- Joulie heating << 1 μW
- No chiral anomaly (the absence of negative MR was also observed in [A. Sinchenko *et al.*, APL **120**, 063102 (2022)])
- Surprising weak localization like behavior in the CDW sliding regime (weak localization is not expected for the CDW)

[IA Cohn, *et al.*, JETP Letters **112**, 88 (2020)]

Our first attempt: Magnetoresistance of quasi-1D Weyl semimetal $(TaSe_4)_2I$ in various CDW motion regimes

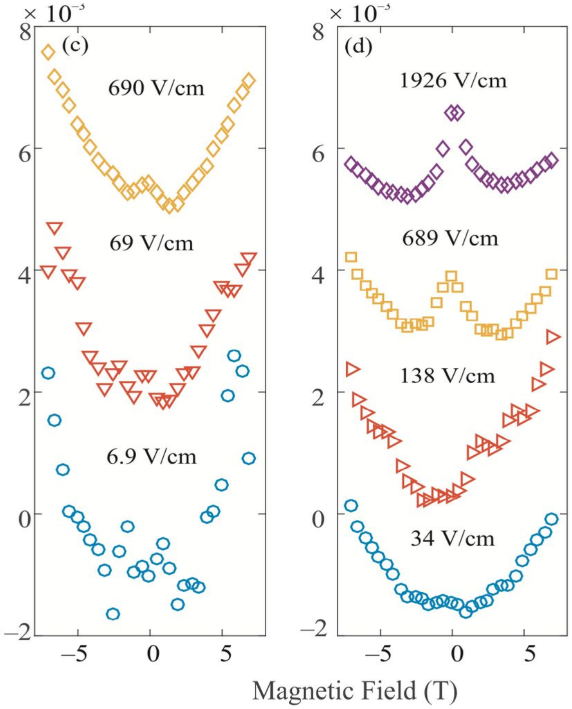
E-sample W-sample



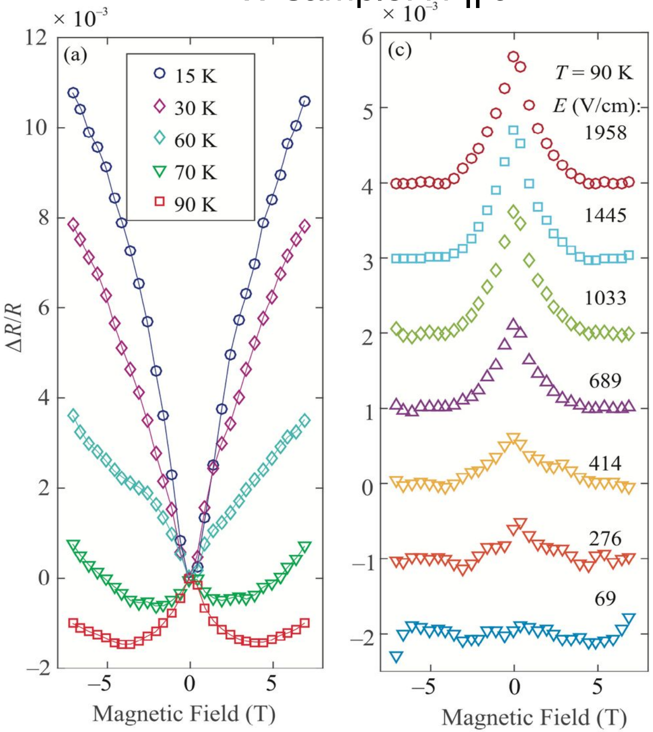


[IA Cohn, *et al*., JETP Letters **112**, 88 (2020)]

E-sample: $H \parallel J$ $T = 80$ K $H \perp J$



W-sample: $H \parallel J$

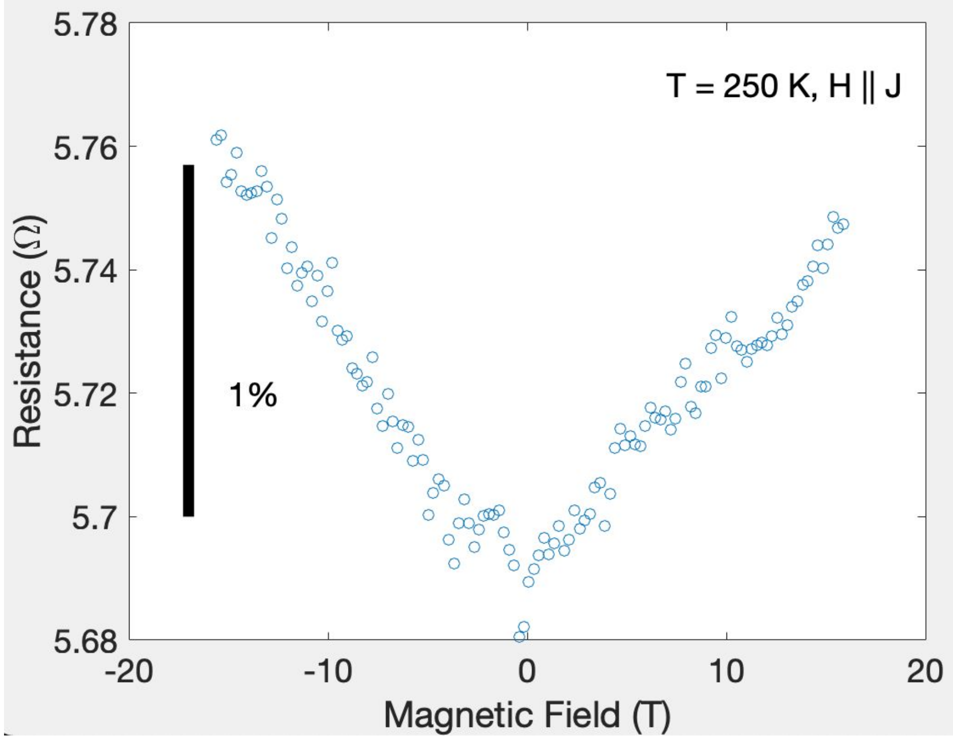


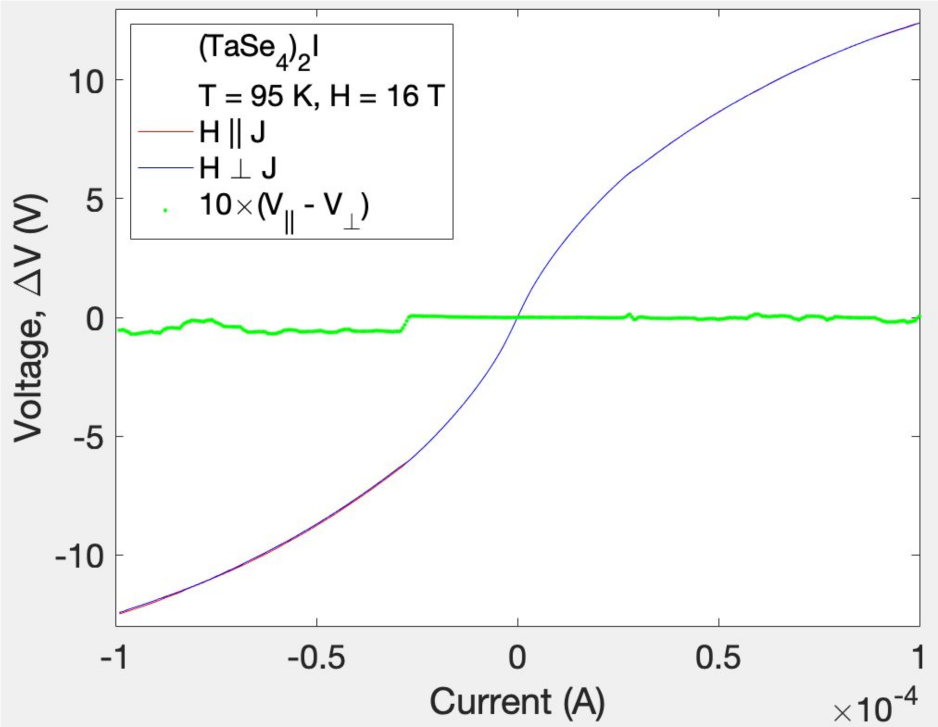
Preliminary summary

If no overheating:

- No giant negative longitudinal magnetoresistance
- Dislocations are not responsible for negative magnetoresistance
- Small magnetic-field effect on CDW conduction is present
- Combination of localization-like and positive parabolic magnetoresistance
- Orientation-independent positive parabolic magnetoresistance
- Orientation-dependent localization-like dependence

Second attempt: 4-probe measurements of bulk $(TaSe_4)_2I$ crystal in high magnetic fields





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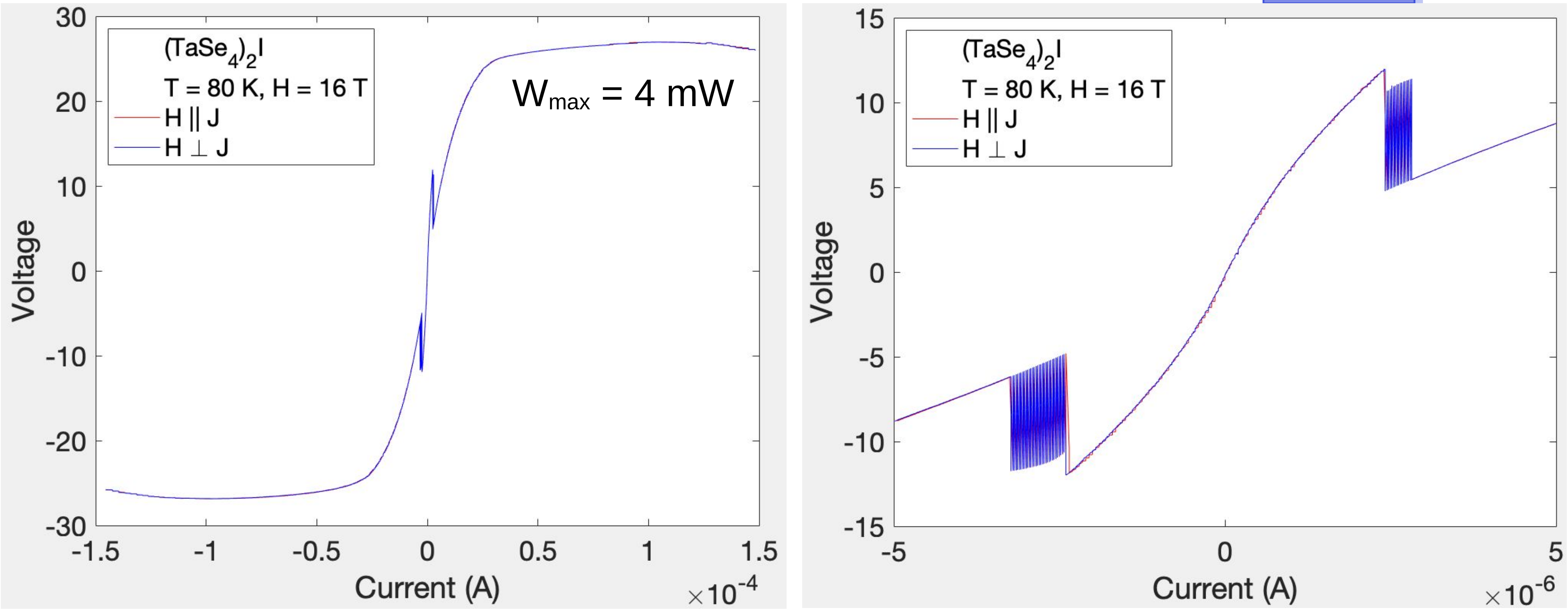
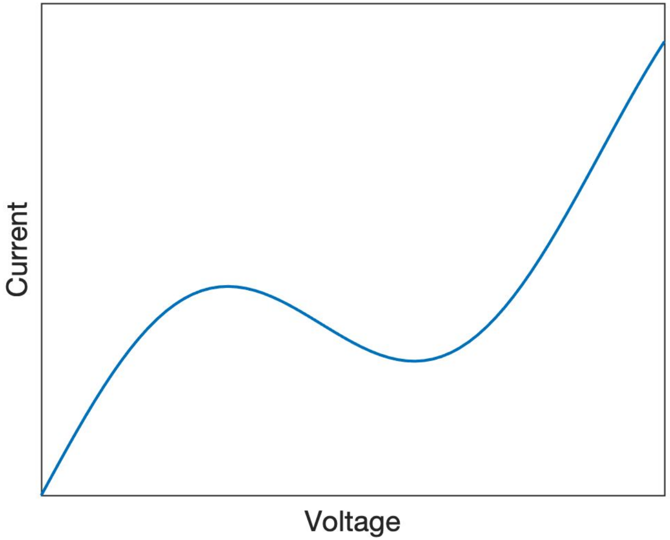


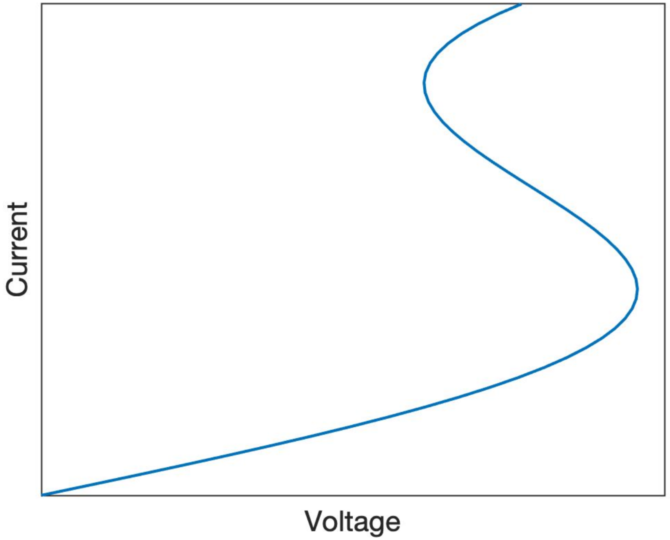
Instabilities in I-V curves

N-type



Strong field domains

S-type



Filamentary current

Filamentary current in systems with S-shaped I-V curve

Festkörperprobleme 30 (1990)

Current Filaments and Nonlinear Oscillations in n-GaAs

Albert Brandl and Wilhelm Prettl

Institut für Angewandte Physik, Universität Regensburg,
D–8400 Regensburg, Federal Republic of Germany

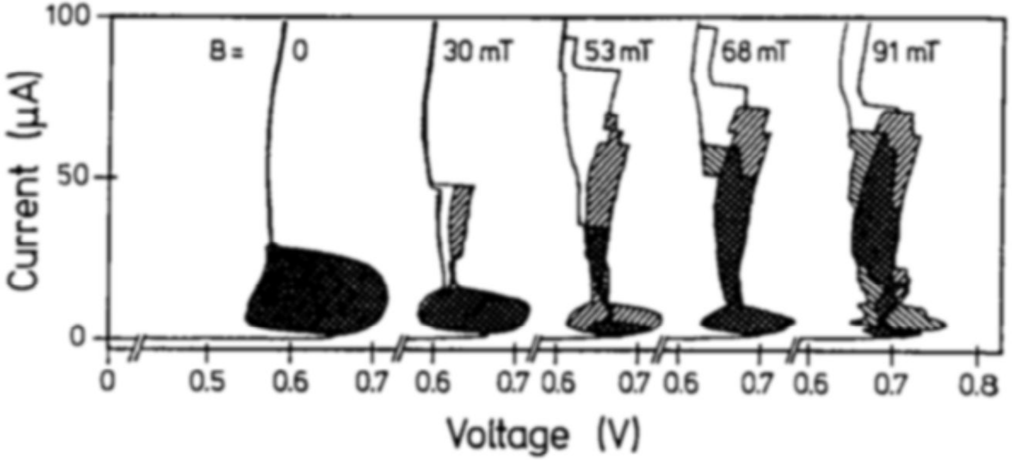
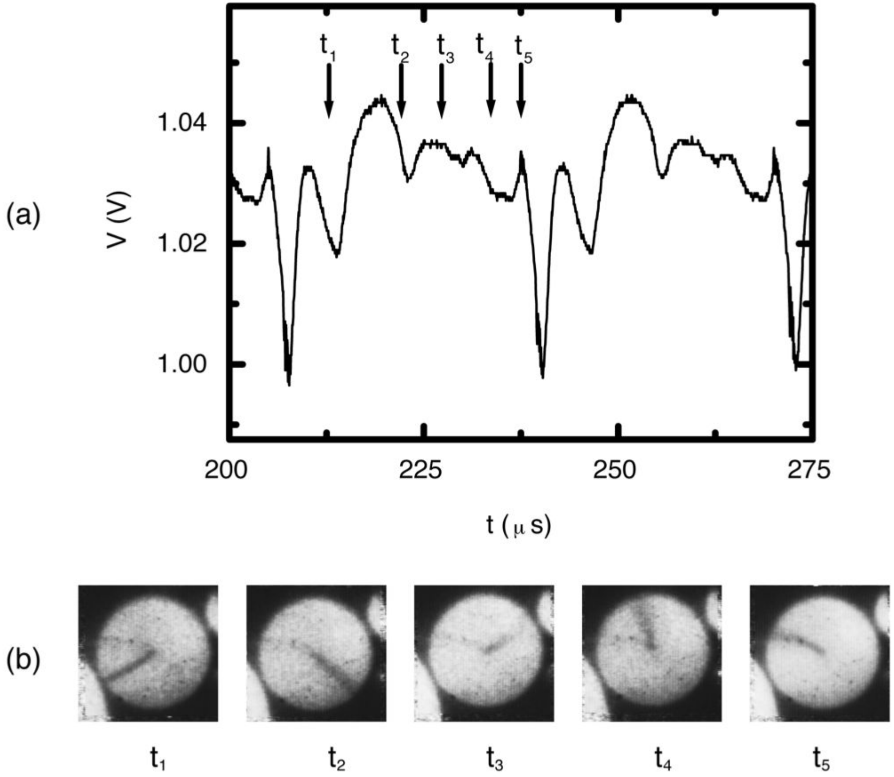


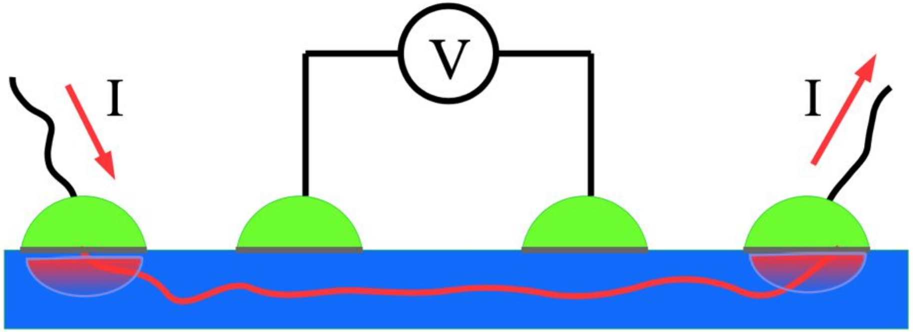
Fig. 2 Current-voltage characteristics for various applied magnetic fields B at a temperature T = 4.2 K. Hatched areas mark the extent of oscillatory regimes (from bottom-left to top-right inclined hatching denotes recording direction to increasing current, from top-left to bottom-right inclined hatching denotes decreasing current.

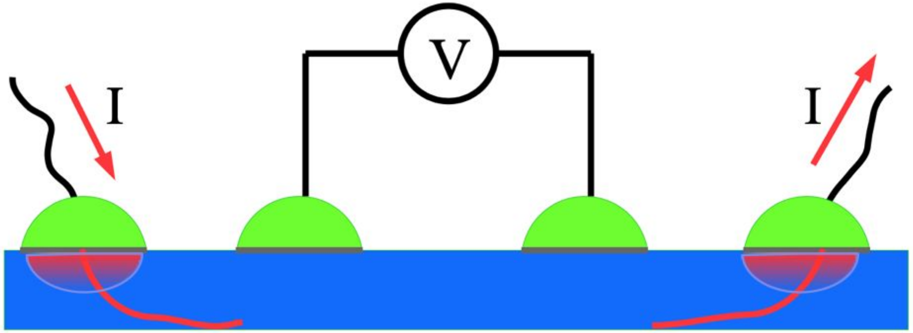
Filamentary current in systems with S-shaped I-V curve in transverse magnetic field



[F.-J. Niedernostheide, J. Hirschinger, W. Prettl, V. Nova´k, H. Kostial PRB (1998)]

Possible trivial explanation





Joule overheating in the contact area

- H || J   Magnetic field stabilizes the current filament inside the sample
- H ⊥ J Magnetic field press the current fiament to the sample surface
- Sample-dependent behavior

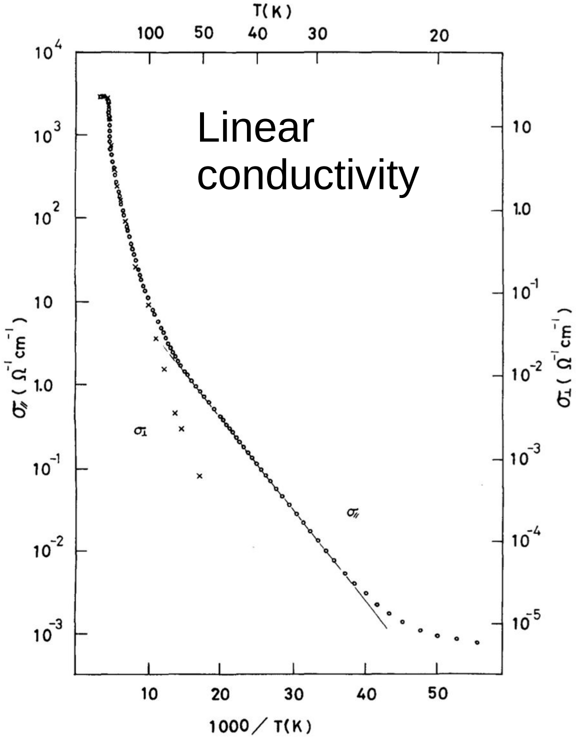
Summary for $(TaSe_4)_2I$

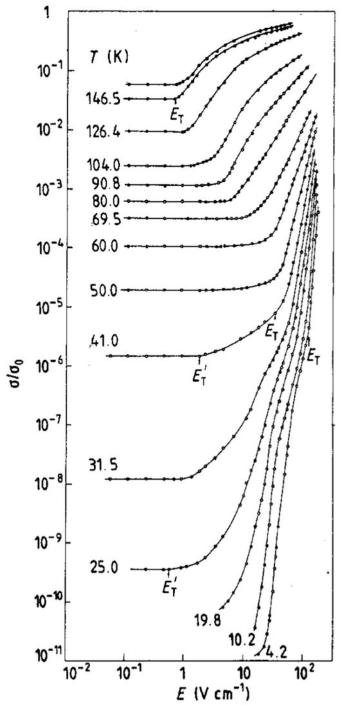
- Negative magnetoresistance may result from interaction of overheat-induced filamentary current with magnetic field (no direct evidence yet)

  In the absence of overheating:

- Small magnetoresistance (~ 1%)
- Sum of positive parabolic and negative/positive localization/antilocalization-like magnetoresistance

Our third attempt: study of topologically trivial material o-TaS_3

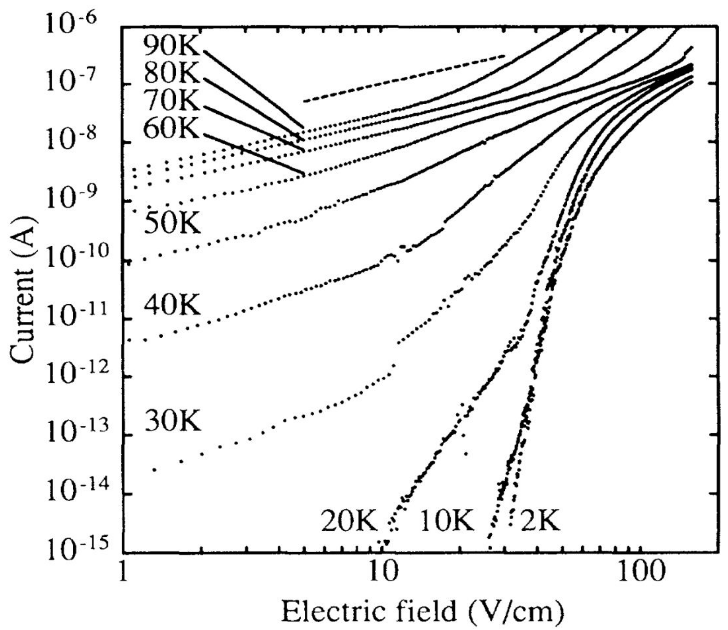


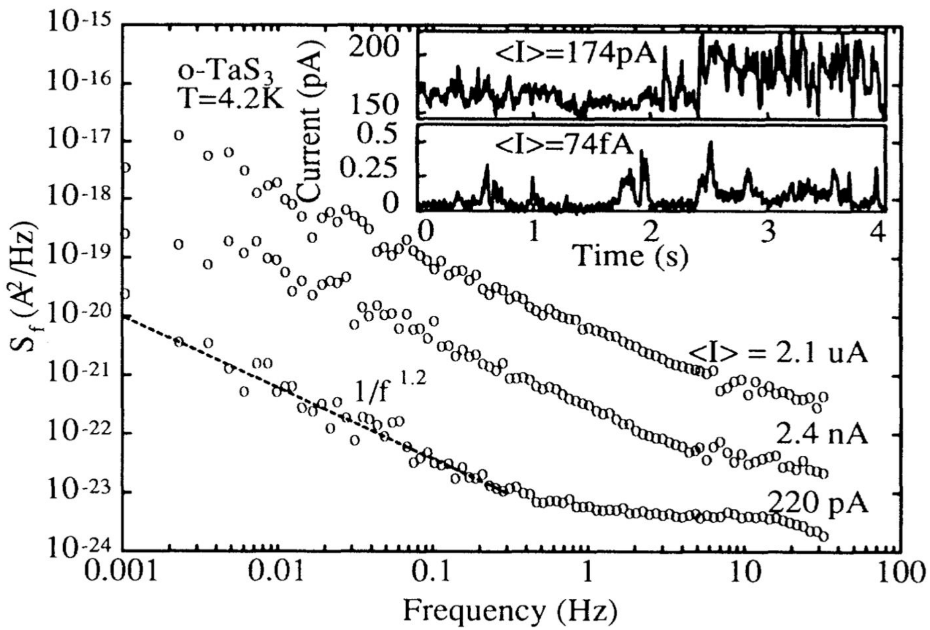


- Material with chain-like structure
- Metal-dielectric transition at T_P = 220 K
- Activation conduction with activation energy 800 K at 220 K < T < 100 K, 400 K at 100 K < T < 40 K, and hopping at T < 40 K

T. Takoshima et al., Solid State Commun. **35**, 911 (1980)   M.E. Itkis, F.Ya. Nad' 1990 J. Phys.: Cond. Mat. **2,** 8327 (1980)

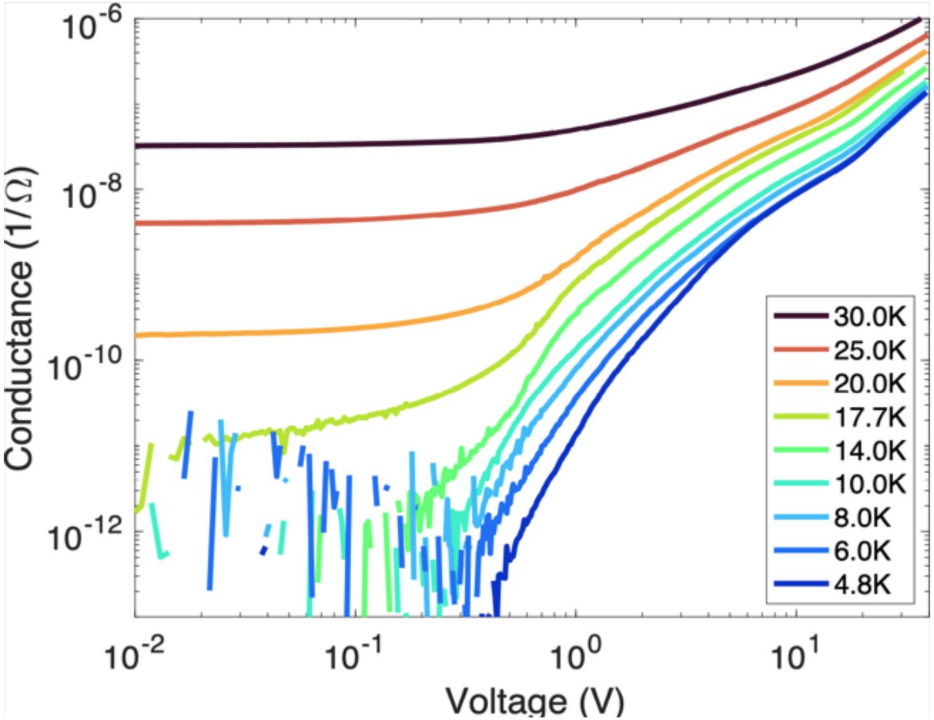
Low-temperature nonlinear conduction in *o*-TaS_3

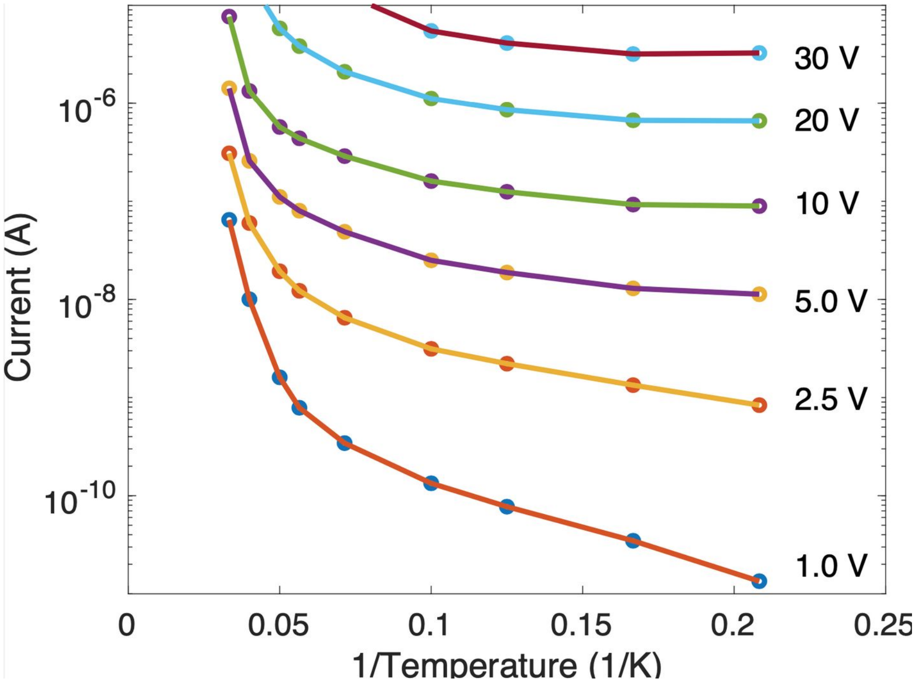




SVZZ, PRL **71**, 605 (1993)

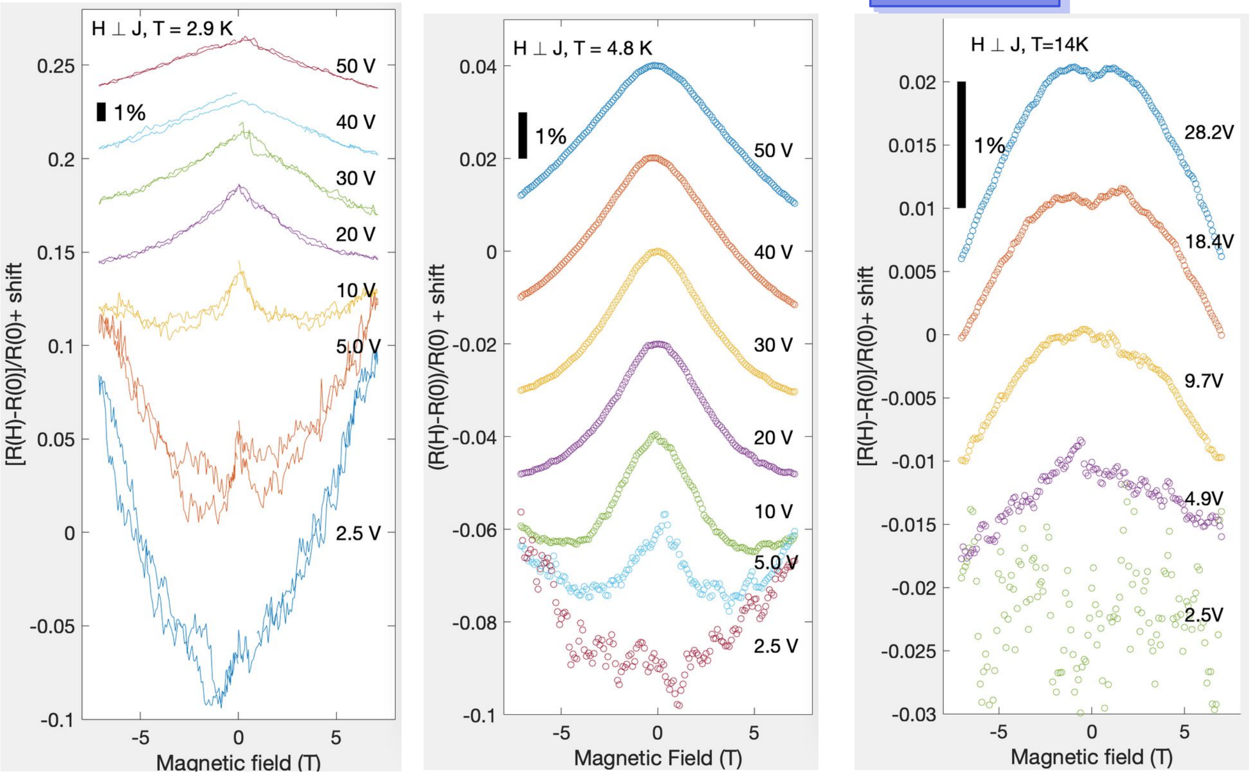
Zero magnetic field





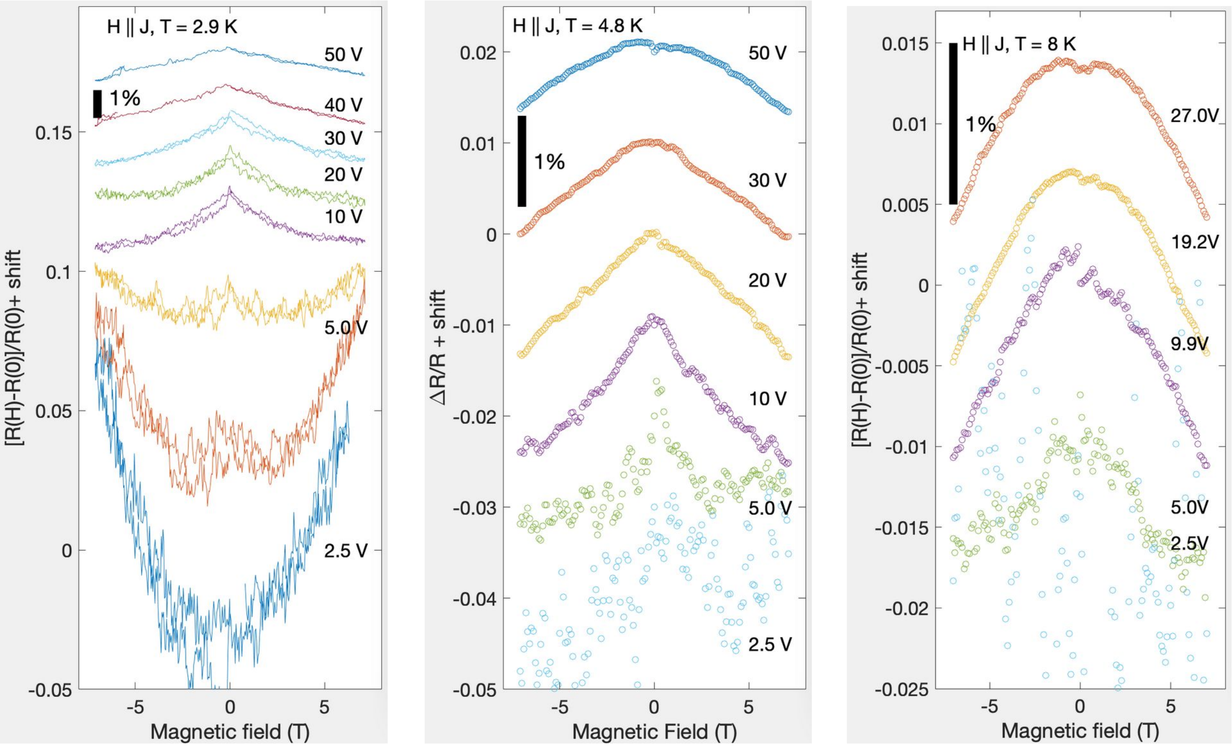
Magnetoresistance in *o*-TaS_3 (**H ⊥ J**)

- A few % negative MR at large voltage
  - Temperature dependence is weak
  - The linearity disappears at higher temperatures
- Positive low-field MR
  - Strong temperature dependence

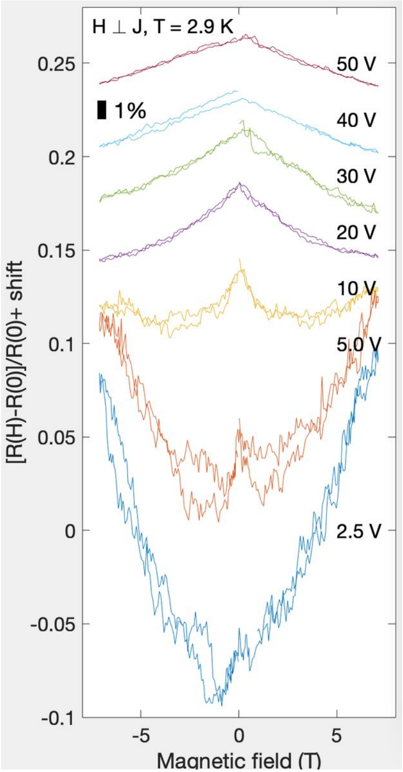


Magnetoresistance of *o*-TaS_3 (**H || J**)

- Smaller signal
- Negative MR at high *E*
- Positive MR at low *E* and *T*



Summary of experimental data



- High *V* region:
  - Negative MR close to linear at low *T*
  - Parabolic negative MR at high *T*
- Low *V* region:
  - Positive parabolic MR
  - Strong temperature dependence

Magnetoresistance in q-1D CDW conductors

$J_{tot} = \sigma_{lin}E + J_{BackFlow} + J_{CDW}$

$J_{cdw} >> J_{BackFlow} >> \sigma_{lin}E$ *at the lowest temperatures*

Quasiparticles: electric filed dependent potential relief

We see that conduction scenario depends on the electric field *E* and temperature *T*:

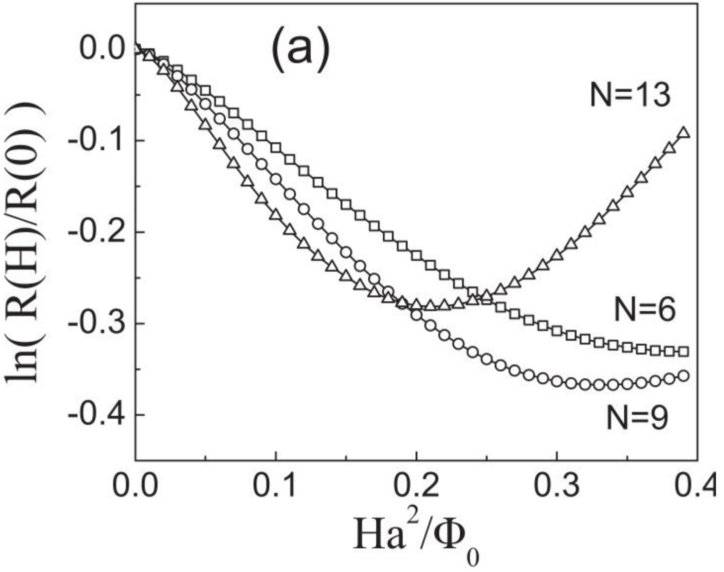
- **Low *T*:**
  - **Low *E*:** positive **parabolic** (exponential) magnetoresistance due to magnetic-field induced shrinking of the wave functions of localised states, $\ln(\delta\rho/\rho) \propto B^2$ [BI Shklovskii, AL Efros 1979]
  - **High E:** **linear** negative magnetoresistance (various possibilities)
- **High *T*: parabolic** negative MR - Zeeman splitting results in magnetic field induced suppression of the Peierls gap $\delta\Delta(B) \propto B^2$.

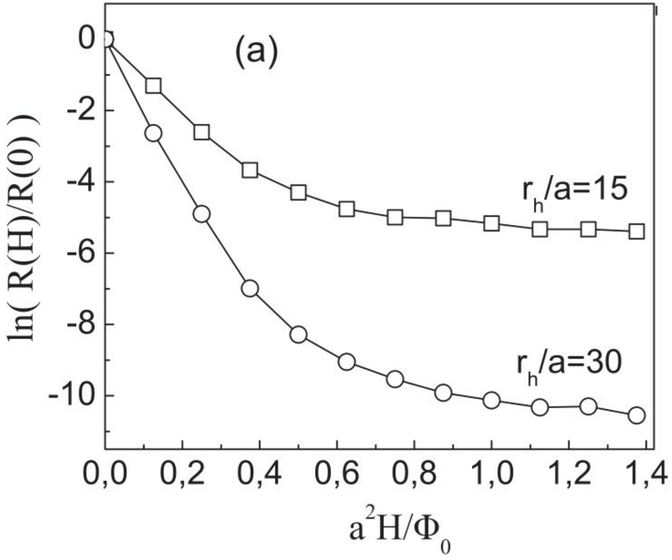
$$\frac{\delta\rho_\Delta}{\rho_q} = -\frac{1}{2}\left(\frac{\mu_B B}{kT}\right)^2 + O\left(\frac{\mu_B B}{kT}\right)^4$$

~ 5% @ 5 T, 10 K [T. Tiedje, *et al.*, Can. J. Phys **53**, 1593 (1975)]

Magnetoresistance in hopping regime

- Interference effects [VL Nguen, BZ Spivak, and BI Shklovski, JETP (1985); AV Shumilin and VI Kozub, PRB (2012)]





Magnetoresistance of sliding CDW

What we see:

- MR of the CDW looks like MR of hopping conduction of quasiparticles

What is strange:

- CDW contribution >> quasiparticle one, quasiparticle MR is shunted

What is known:

- Energy dissipation of **sliding** CDW is provided by quasiparticles. => MR of quasiparticles results in MR of sliding CDW

What we conclude:

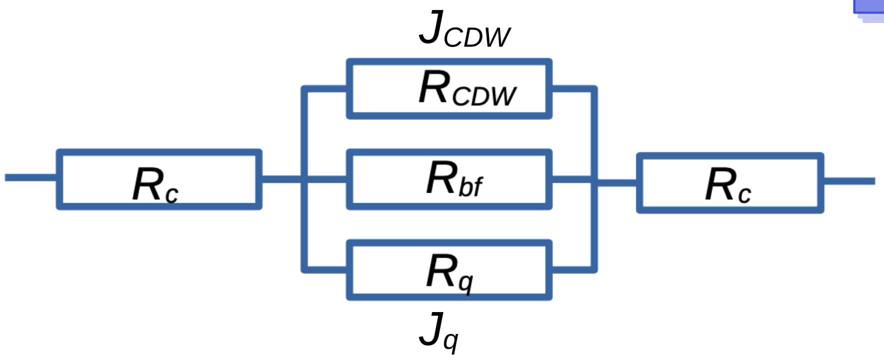
- The CDW “amplifies” magnetoresistance of quasiparticles

What is strange:

- Why such a scaling exists in the CDW creep regime?

Magnetoresistance in q-1D CDW conductors

Equivalent scheme

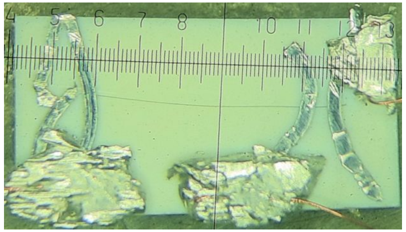


- R_c – contact resistance (possible dielectric barrier, phase-slip voltage, carrier injection)
- R_{CDW} – CDW channel (is described usually in terms of CDW current)
- R_{bf} – back-flow current will be neglecting ($J_{bf} \ll J_{CDW}$)
- R_q – quasiparticle resistance $R_q \gg R_{CDW}$ ($J_{bf} \ll J_{CDW}$)

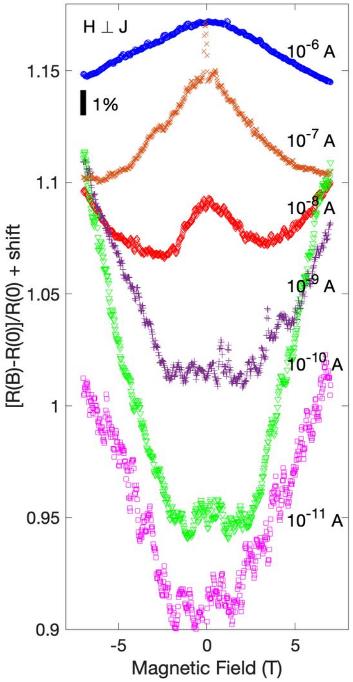
Contact contribution

T = 2.9 K

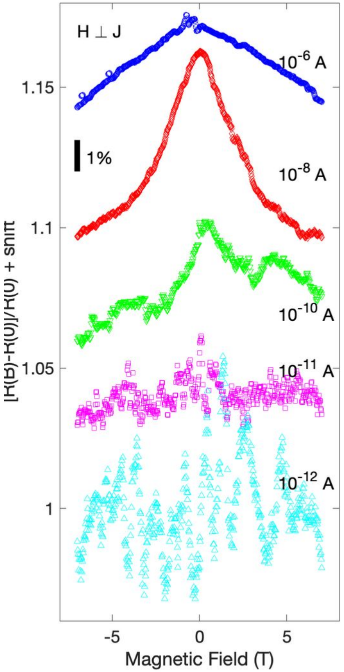
o-TaS_3
Two segments
- 0.5 mm (short)
- 5 mm (long)



Short segment



Long segment



- Positive MR is a contact effect
- There is negative MR in sliding regime
- There is no MR in creeping regime.

Thus MR is not a consequence of modification of the CDW by magnetic field but results from modification of its kinetic coefficients

Conclusion

- Positive parabolic MR is a contact phenomena
- Magnetoresistance in CDW sliding regime results from magnetoresistance of quasiparticles
- There is no MR in CDW creep regime

Thank you for attention!

Financial support from RSF (grant #21-72-20114) is acknowledged