VARIABLE RANGE HOPPING

→ definition of VHR

- → movement of charge carriers, such as electrons or holes
  - → move by hopping between localized states
    - ↳ hopping depends on spatial distances btw states/energy difference

* at low temperatures, VRH is impactful since less thermal energy = carriers more freely

→ conductivity (σ) in VRH

* temp dependence

$$\sigma = \sigma_0 \exp\left(-\left(\frac{T_0}{T}\right)^{1/n}\right)$$

T = temp

σ_0 = preexponential factor

T_0 = characteristic temp based on density of states/localization length

n = exponent depending on dimensionality of sys.

↳ 3D system → $n = 4$

energy states → holes don't have enough energy to reach continuous energy states of the valence band

localized charge traps → moving by "hopping" between localized charge trap states that are in the band gap above the valence band

Hopping mechanism → allows for charge transport @ lower temp where thermal energy is insufficient for promoting holes in valence band

LINEARIZING VRH equation

describes how conductivity of disordered material depends on TEMP

VRH eq → $\sigma = \sigma_0 \exp\left(-\left(\frac{T_0}{T}\right)^{1/n}\right)$

$\ln\sigma = \ln\left(\sigma_0 \exp\left(-\left(\frac{T_0}{T}\right)^{1/n}\right)\right)$ ← natural log

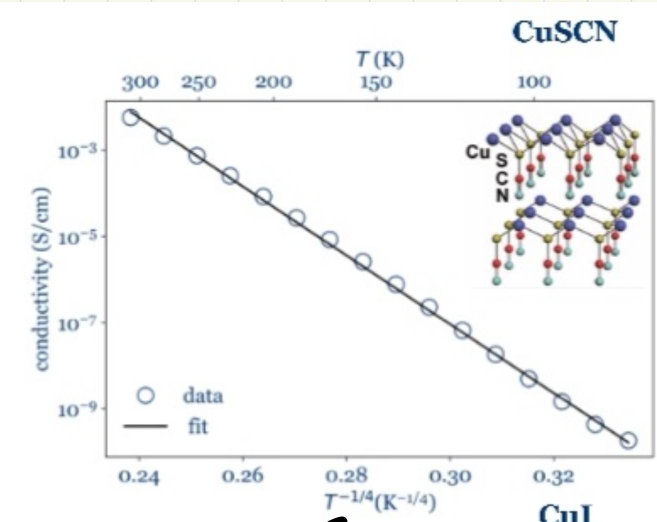
$\exp(x) = e^x$

$\ln\sigma = \ln\sigma_0 + \cancel{\ln} e^{(-(T_0/T)^{1/n})}$

$\ln\sigma = (\ln\sigma_0) - \left(\frac{T_0}{T}\right)^{1/n}$

$y = \ln\sigma$ $\quad b = \ln\sigma_0$ $\quad x = T^{-1/n}$ $\quad m = T_0^{1/n}$

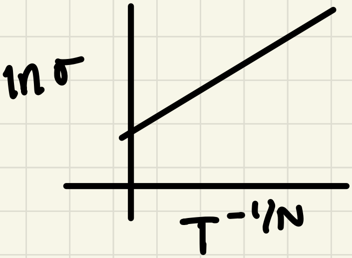
plot $T^{-1/n}$ against $\ln(\sigma)$



Copper thiocyanate (CuSC
is a transparent and air sta
hole transport materi
prominent due to its sim
and cheap fabricati
processes. **Fig 5** (left) sho
that the log of t
conductivity of CuSCN
proportional to $T^{-1/4}$, which
consistent with VRH

here $x = T^{-1/4}$

where $N = 4$ meaning 3D system



$$\ln \sigma = (\ln \sigma_0) - (T_0)^{1/N} (T)^{-1/N}$$

$$y = b + m x$$

this should give us a straight line that describes material's conductivity

↓

slope / y intercept gives us info on material's properties

→ linearization (natural log)

takes a complex exponential relation & makes in a simple linear one

x exponential functions are harder to analyze the data

→ ln(   ) of the equation linearizes

↳ we can use lin. regression / simplifies analyzing data

slope = $-T_0^{1/n}$ helps us find T_0

intercept = $\ln(\sigma_0)$ gives us pre exponential factor σ_0

VHR & conductivity

more simply

it is like hopping across stepping stones

" charge carriers need to move from one place

→ importance to conductivity

conductivity = how easily electricity can flow through material

→ MOTT'S Law

$$\sigma \propto \exp\left(-\left(\frac{T_0}{T}\right)^{1/4}\right)$$

conductivity

proportional to

T_0 = characteristic temp

T = absolute temp

σ and T

→ conductivity dependends on sensitivity to temp → esp. where variable range hopping is dominant

↓ change in temp = change in σ

* you can linearize Mott's law by taking the natural log of both sides

→ TEMP dependence

$T^{-1/4}$ is the temp dependence of σ

* highlights electron hopping between localized states & the influence of disorder on electronic transport properties