Ballistic transport in bulk 1D electronic/magnetic systems

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an observation

approach linear response theory

theoretical/experimental status

Idea

Commonly used prototype models for the description of (quasi-) 1D materials exhibit ballistic transport at all temperatures.

Hubbard model (electronic/magnetic)

spin 1/2 Heisenberg (magnetic)

nonlinear $\sigma-$ model (magnetic - $S = 1$)

"$t - J$" $(t = J)$ (doped antiferromagnets)

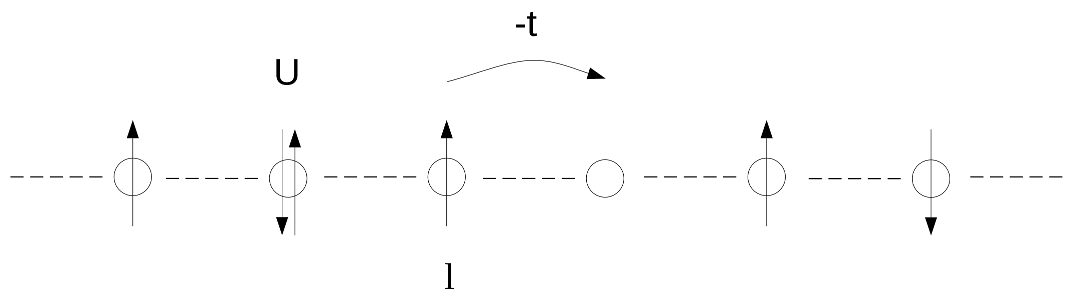
sine-Gordon (?)

1D integrable quantum models

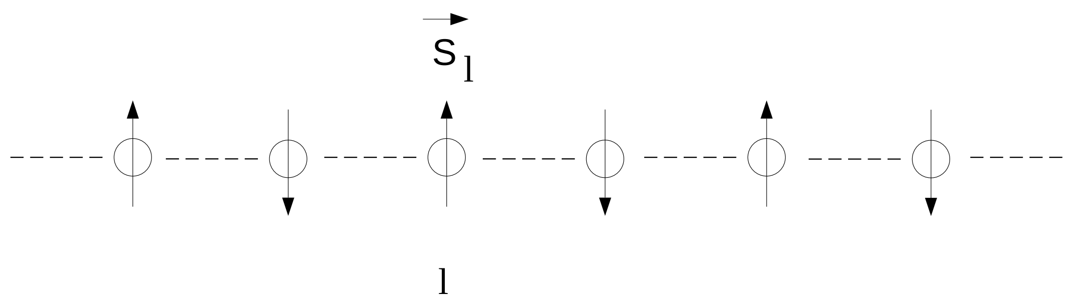
physics analogous to classical nonlinear integrable systems; widely studied in mathematics - physics (theory/ experiment) - for technological applications (e.g. optical fibers)

Approach

Hubbard model (electronic)



Heisenberg model, spin 1/2 (magnetic)



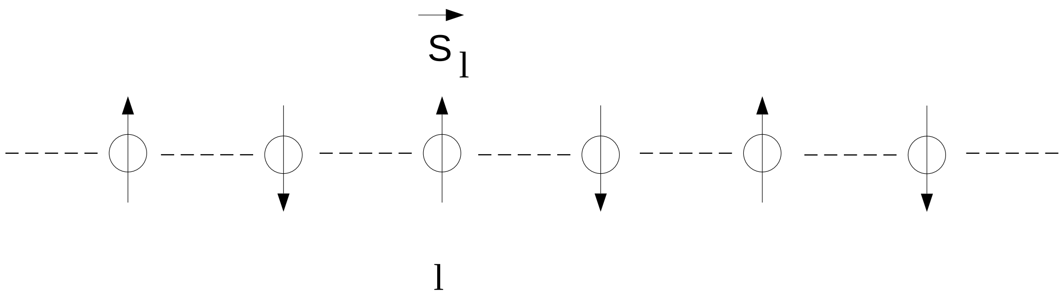
$$H_{Heis} = J \sum_l \vec{S}_l \cdot \vec{S}_{l+1}$$

integrable quantum systems

Bethe ansatz $\rightarrow$ thermodynamic properties

dynamic and transport properties ?

electrical/thermal/magnetic conductivity *spin 1/2 Heisenberg model (magnetic)*



$$H_{Heis} = \sum_l h_l = J \sum_{l=1}^{L} (S_l^x S_{l+1}^x + S_l^y S_{l+1}^y + \Delta S_l^z S_{l+1}^z)$$

$J > 0$, antiferromagnet, $S = 1/2$, p.b.c.

$\Delta > 1$ "easy axis", $\quad \Delta < 1$ "easy plane"

spin current j^z (continuity equation)

$$S^z = \sum_l S_l^z, \qquad [H, S^z] = 0, \qquad \frac{\partial S_l^z}{\partial t} + \nabla j_l^z = 0$$

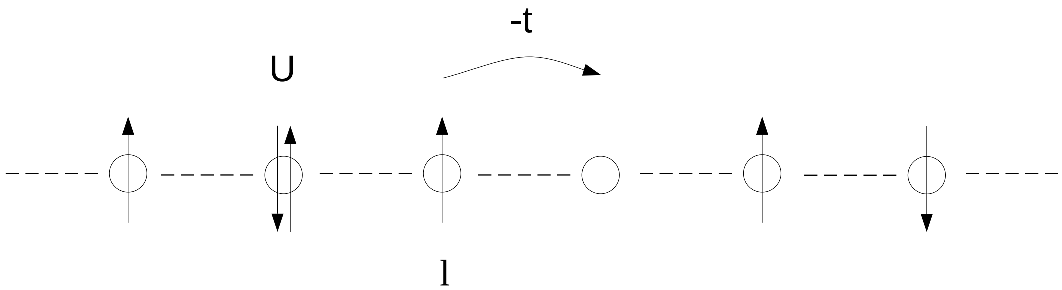
$$j^z = \sum_l (S_l^y S_{l+1}^x - S_l^x S_{l+1}^y), \qquad , [j^z, H] \neq 0$$

energy current j^E

$$\frac{\partial h_l}{\partial t} + \nabla j_l^E = 0$$

$$j^E = J \sum_l (S_{l-1}^x S_l^z S_{l+1}^y - S_{l-1}^y S_l^z S_{l+1}^x) + \Delta\, (perm. - x, y, z)$$

Hubbard model (electronic)



$$H = (-t) \sum_{\sigma,l} (c^\dagger_{l\sigma} c_{l+1\sigma} + h.c.) + U \sum_l n_{l\uparrow} n_{l\downarrow}$$

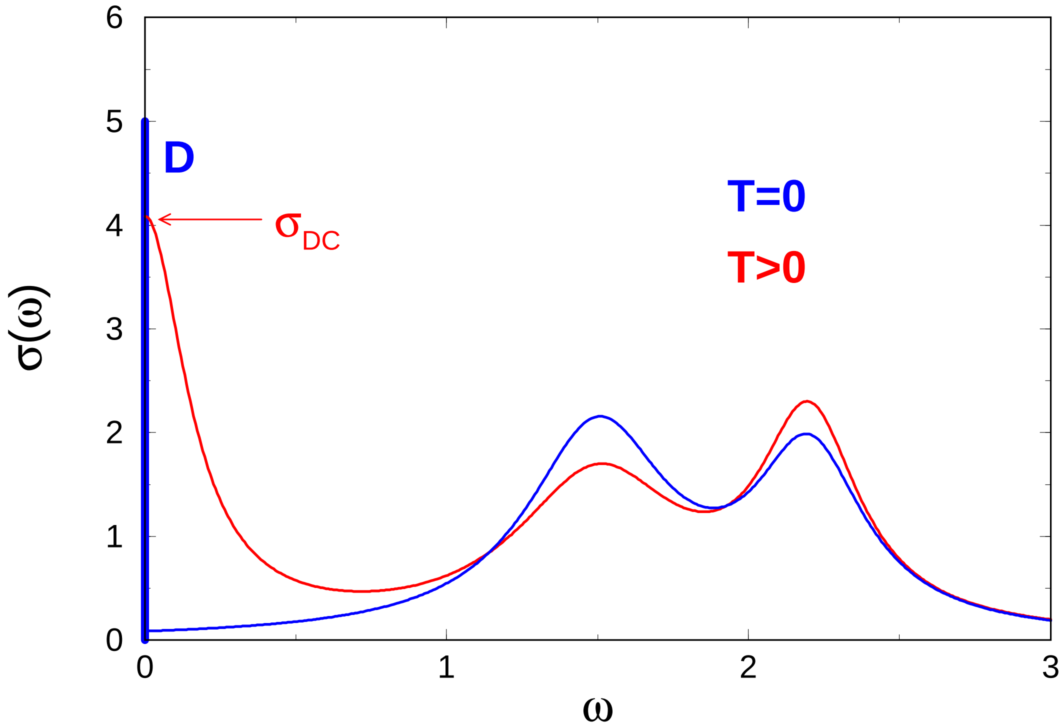
charge current j

$$\frac{\partial n_l}{\partial t} + \nabla j_l = 0$$

$$j = (-t) \sum_{\sigma,l} (i c^\dagger_{l\sigma} c_{l+1\sigma} + h.c.)$$

Finite temperature transport properties

"common sense"



conductivity

$$\sigma'(\omega) = 2\pi D\delta(\omega) + \sigma_{reg}(\omega > 0)$$

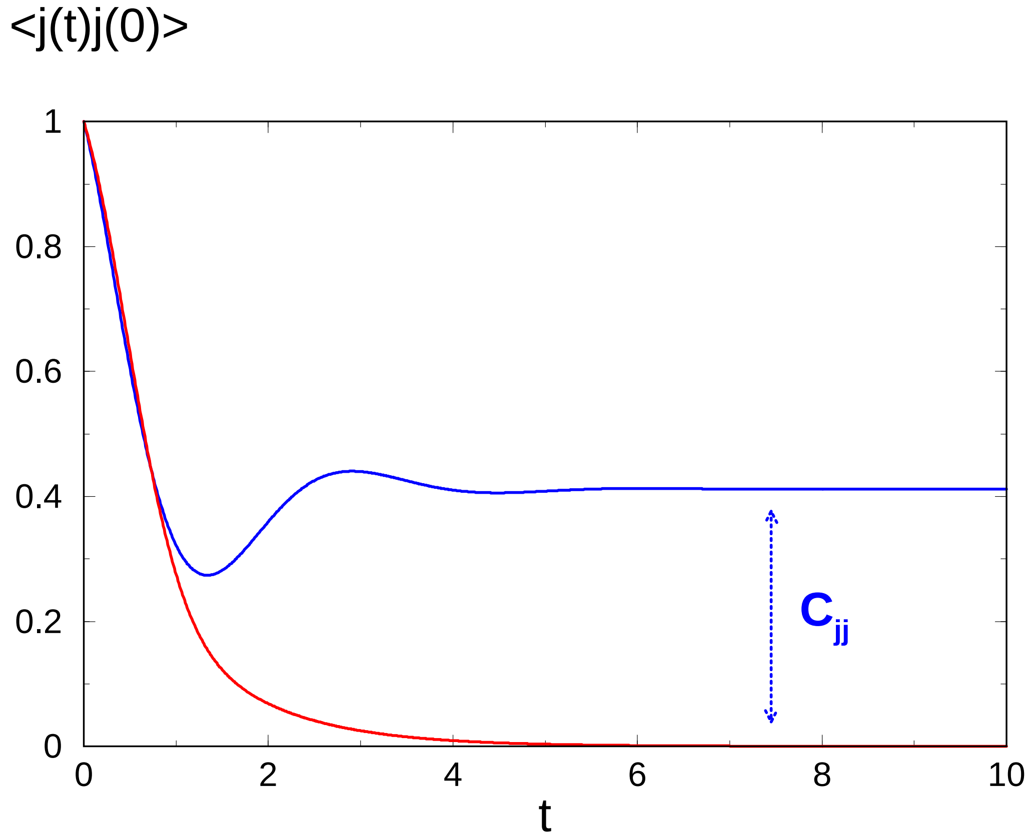
$$\sigma'_{reg}(\omega) = \frac{1 - e^{-\beta\omega}}{\omega\ L}\pi \sum_{n,m\neq n} p_n \mid \langle n \mid \hat{j} \mid m\rangle \mid^2 \delta(\omega - \epsilon_m + \epsilon_n)$$

$$\sigma''(\omega) = 2D/\omega|_{\omega\to 0}$$

D= "Drude weight"

$$\int_{-\infty}^{\infty} \sigma'(\omega) d\omega = \frac{\pi}{L}\langle -\hat{T}\rangle$$

$$D = \frac{1}{L}\sum_n p_n D_n = \frac{1}{L}\sum_n p_n \frac{1}{2}\frac{\partial^2 \epsilon_n(\phi)}{\partial \phi^2}|_{\phi\to 0},\quad (W.Kohn\ \ 1964)$$



$$D = \frac{\beta}{2L} < j(t)j(0) >_{t\to\infty} = \frac{\beta}{2L} C_{jj}$$

$$C_{jj} = \sum_n p_n | < n|j|n > |^2$$

generic behavior

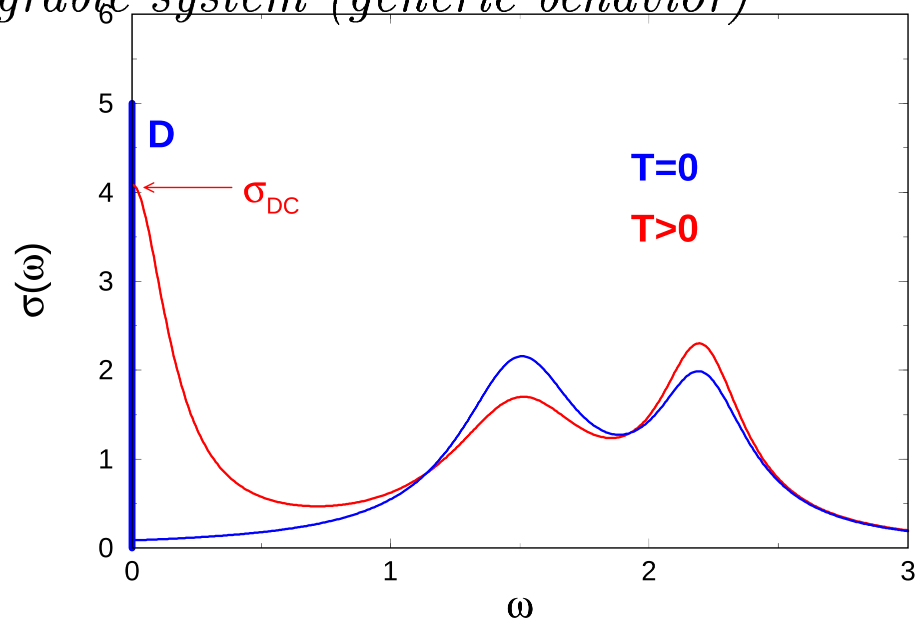
- $T > 0,\ D = 0 \rightarrow$ normal conductor (dissipation)
- $T = 0,\ D > 0 \rightarrow$ *ideal conductor*

Proposal (*Phys. Rev. Lett.* **74**, 972 (1995))

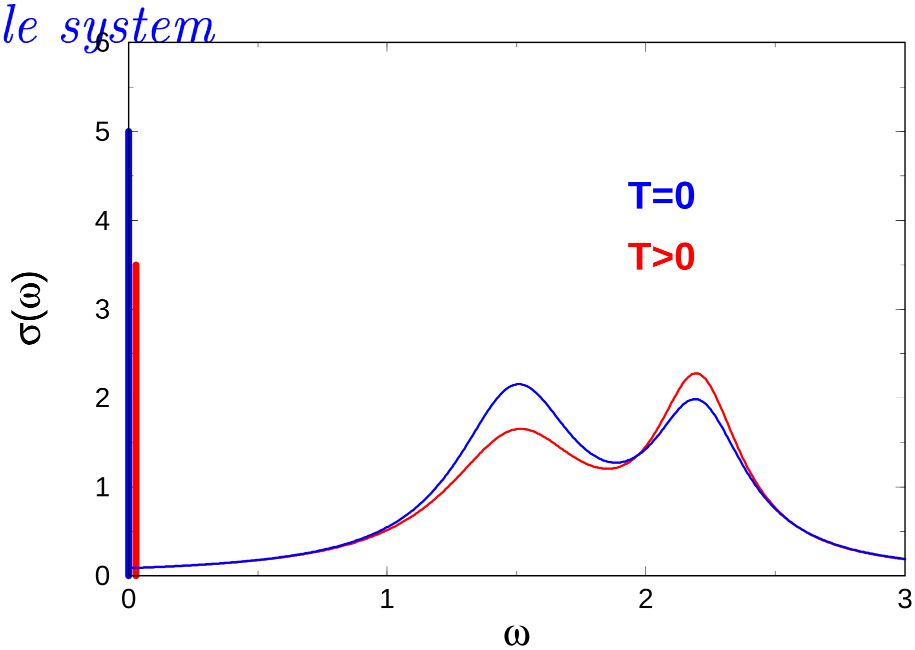
numerical simulation → analytical confirmation

integrable quantum systems present
ideal conduction (without dissipation)
at *all temperatures*.

nonintegrable system (generic behavior)



integrable system



Mazur inequality and conservation laws
(*Phys. Rev.* *B***55** 11029 (1997))

integrable system: macroscopic number of Q_n

$$[Q_n, Q_m] = 0, \qquad [Q_n, H] = 0$$

$$C_{AA} =< A(t)A >_{t\to\infty} \geq \sum_n \frac{< AQ_n >^2}{< Q_n^2 >}$$

$<>$ thermal average, $< Q_n Q_m >=< Q_n^2 > \delta_{n,m}$, $A^\dagger = A$, $< A >= 0$.

Heisenberg model

$Q_3 = j^E \rightarrow$ *ideal thermal conductivity*

$< j^E(t) j^E(0) >=$const.

$$D(T) \geq \frac{\beta}{2L} \frac{< j^z Q_3 >^2}{< Q_3^2 >}$$

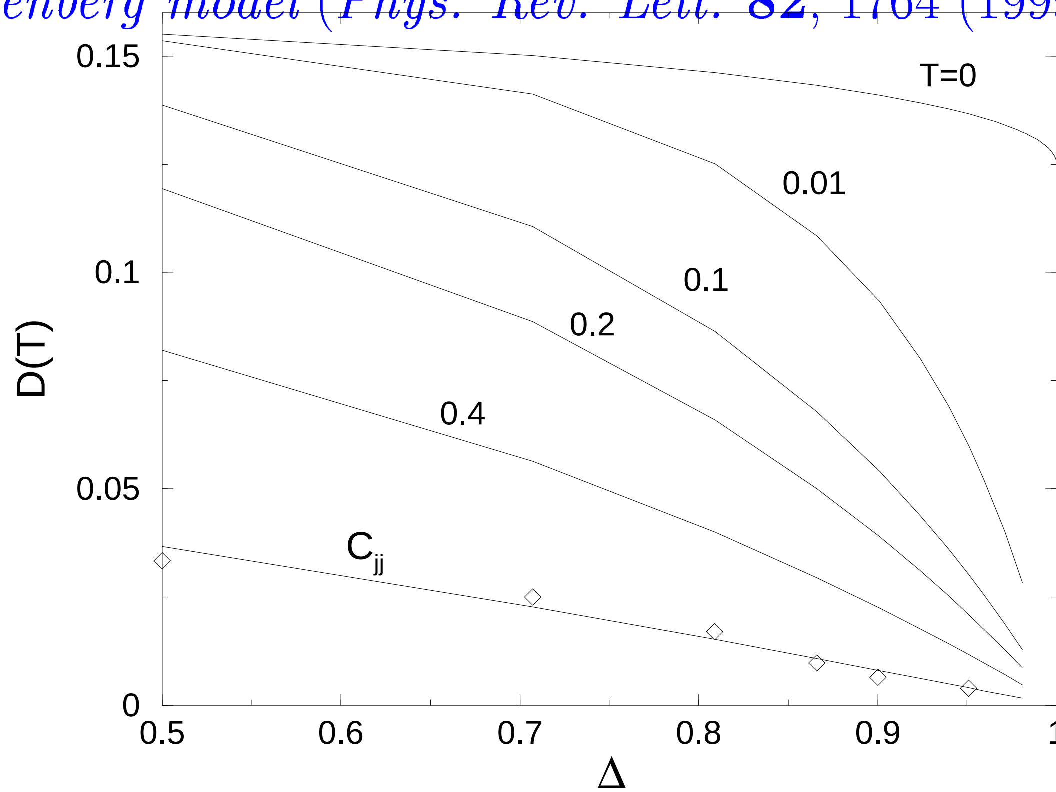
high temperature limit

$$D(T) \geq \frac{1}{2k_B T} \frac{8\Delta^2 m^2 (1/4 - m^2)}{1 + 8\Delta^2 (1/4 + m^2)}, \qquad m =< S_l^z >$$

BA calculation of D(T)

(Hubbard model: S. Fujimoto and N. Kawakami,
J. Phys. A. **31**, 465 (1998))

Heisenberg model (*Phys. Rev. Lett.* **82**, 1764 (1999))



$T \to 0$

$$D(T) = D(T=0) - const.T^{\alpha}$$

$$\alpha = \frac{2}{\nu - 1}, \quad \Delta = cos(\frac{\pi}{\nu})$$

Experimental developments

NMR

M. Takigawa et al. (IBM/Tokyo, 1996):

Sr_2CuO_3: S=1/2, $D^s_{exp} \simeq 10^3 D^s_{th-cl}$

$AgVP_2S_6$: S=1, diffusive behavior, nonlinear-σ model ?

thermal conductivity (magnetic materials)

H.R. Ott (ETHZ), Sr_2CuO_3, $SrCuO_2$, $(La, Sr, Ca)_{14}Cu_{24}O_{41}$

B. Büchner (Aachen), $(La, Ca)_{14}Cu_{24}O_{41}$

F. Steglich (MPI Dresden), Yb_4As_3

optical absorption ?

F. Degiorgi, G. Grüner (ETHZ, UCLA, 1996)

Bechgaard salts ("zero mode")

Perspectives

theory

- transport in integrable systems:
  quantum/classical systems
- conservation laws and finite frequency conductivity
- stability to perturbations:
  linear vs. nonlinear transport

experiment

- (quasi-) 1D magnetic materials
- (quasi-) 1D electronic materials
- superlattices
- self-assembled structures on surfaces

In collaboration with:

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