3/4 Experimental Observation of Majorana Fermions in Kitaev Materials

Background

- Kitaev Model

Electron (Dirac fermion) spinor
complex

Majorana fermion real

$\Downarrow$

1 Majorana fermion carries half the degrees of freedom of an electron

• Finite Temperature

$\exists$ Z_2 flux excitations $\Rightarrow$

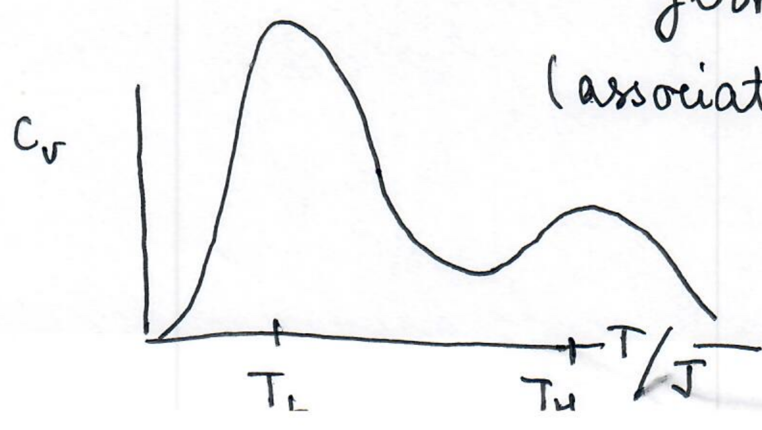
no exact solution

Must be studied numerically

Two energy scales

$T = T_L$ excitation gap of Z_2 fluxes

$T = T_H$ itinerant Majorana fermions (associated w/ DOS)



- Finite Magnetic Field $(K_x = K_y = K_z)$

$$H_{total} = H_{Kitaev} - \vec{h} \cdot \sum S_i$$

Flux Operator No Longer Conserved.

Kitaev: Perturbation in $\frac{h}{K}$

$\Downarrow$ (lowest relevant term)

$$H' \propto - \frac{h_x h_y h_z}{J^2} \sum_{\langle ijk \rangle} S_i^x S_j^y S_k^z$$

Flux configurations identical in initial/final states

$\Downarrow$

complex next-neighbor hopping!

Magnetic field opens gap

$$\Delta_h \propto h_x h_y h_z$$

Note: Δ_f (flux gap) independent of field

Model w/ nnn hopping $\Longleftrightarrow$ Haldane's model for spontaneous Hall effect

formally equivalent

$\Downarrow$

Gapped fermion band <u>topologically nontrivial</u>

$\Downarrow$

Chern # $= \pm 1$

Gapless chiral edge modes

In Kitaev system edge modes <u>cannot</u> be detected by electromagnetic measurements

(no charge)

$\Downarrow$ BUT

Can be observed by thermal measure-ments as they carry <u>heat</u>

$\Downarrow$

Thermal Hall Measurements (more soon..)

Kitaev model with Finite Temperature and Field Difficult even Numerically

- Thermal Hall Effect

Thermal Conductance

Metals = good heat conductor

$$\sigma \propto \frac{\kappa}{T}$$

$\downarrow$

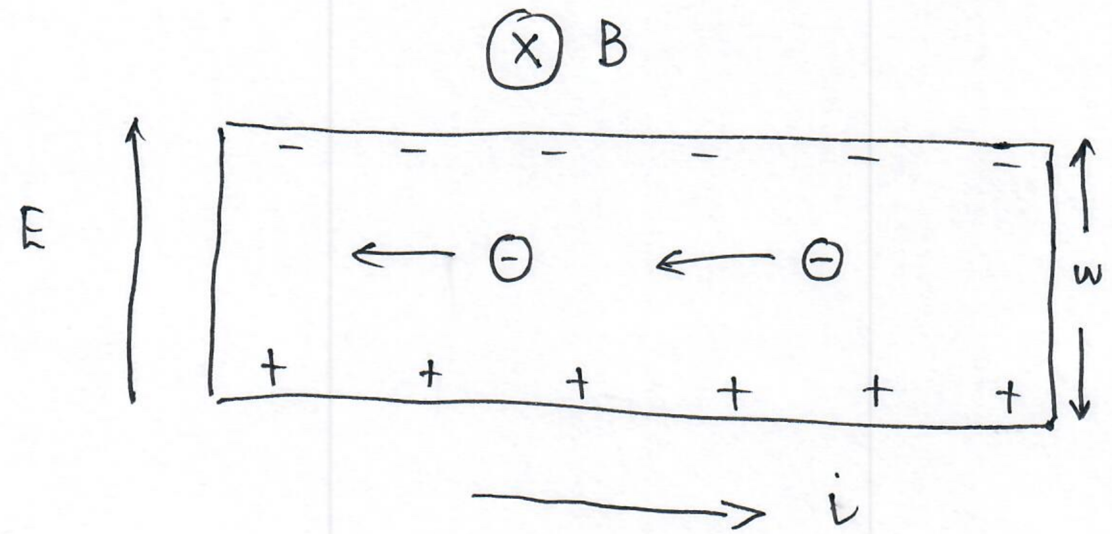
non-universal scattering

If motion of the carriers is ballistic (effectively no scattering)

$\sigma, \kappa \propto$ # propagating modes (conduction channel) electron $\rightarrow$ 1 "unit" of thermal conductance.

Majorana $\rightarrow$ $\frac{1}{2}$ " "

- Recall the conventional Hall effect



In steady state

$$qE_y = \frac{qV_H}{w} = qv_d B_z$$

$$\Downarrow$$

$$V_H = v_d w B.$$

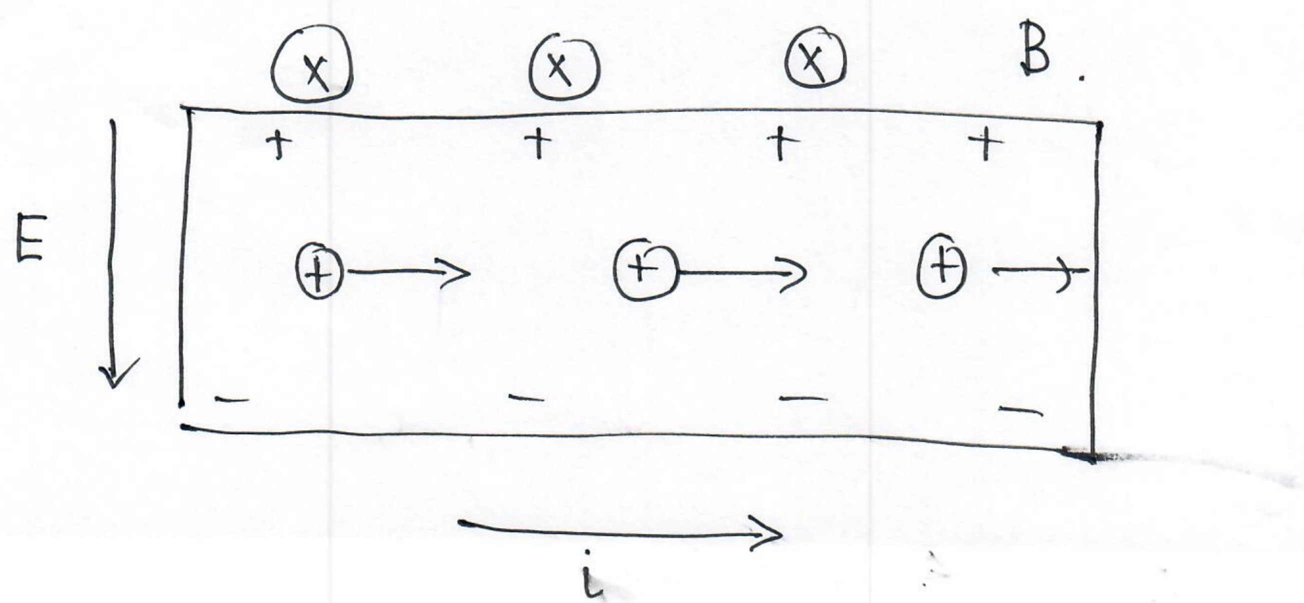
$$i_x = q n w d v_d$$

$$\Downarrow$$

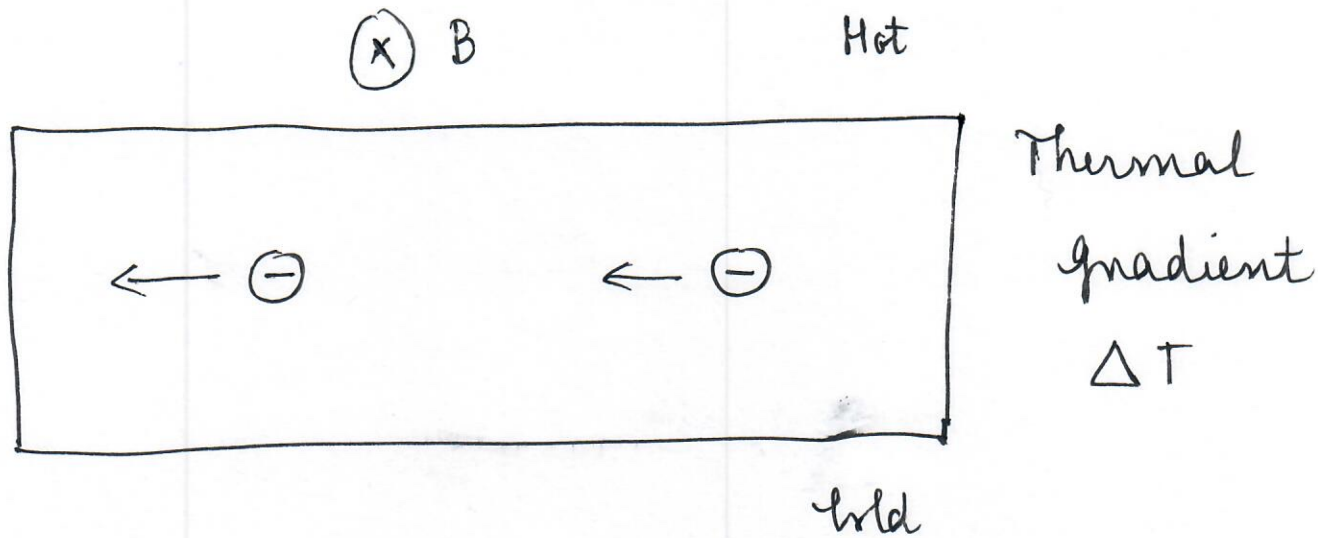
$$V_H = \frac{i_x B_z}{q n d} = \frac{j_x w B_z}{n q}.$$

$$R_H \equiv \frac{E_y}{j_x B_z} = \frac{1}{nq}.$$

$$\boxed{R_H = \frac{1}{nq}}$$



Thermal Hall Effect



- Kyoto Nature Paper

Kitaev model in B field

$$\Downarrow$$

Topological Spin Liquid + Majorana fermion edge states

Heat current carried by edge state

$$\underline{I}_Q = \sum_{k>0} v \times \hbar v k \; \frac{f(\hbar v k)}{L}$$

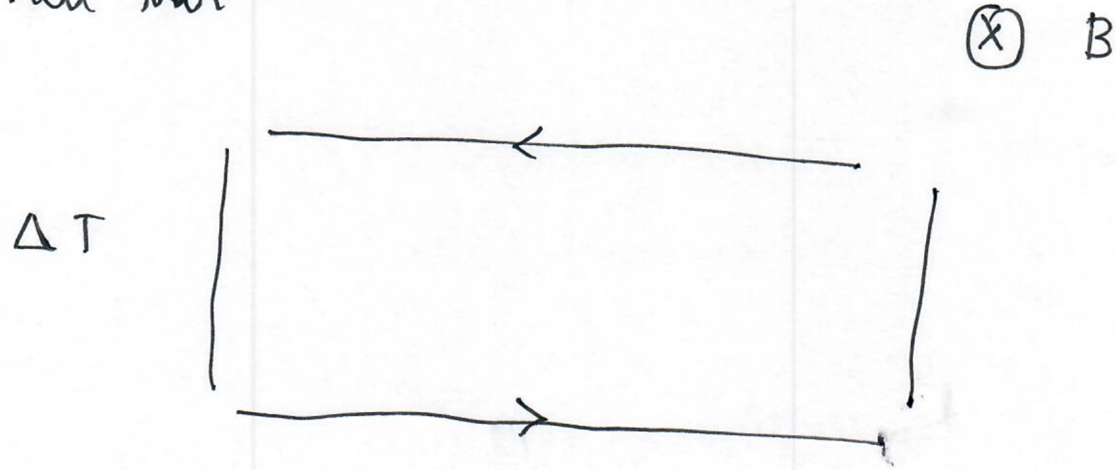
Fermi function

$$I_Q = c \, \frac{\pi}{12} \, \frac{(k_B T)^2}{\hbar}$$

$c = 1/2$

chiral central charge
of Majorana fermion

Hall bar



assume no heat current in
the bulk

QHE
c integer
values.

$$\frac{K_{xy}}{T} = c \, \frac{\pi}{6} \, \frac{k_B^2}{\hbar}$$

$c < 1$ Non-abelian anyons.