

Quantificando $\omega_c \tau = \mu B$: é pequeno?

$$\omega_c = \frac{e \cdot B}{m^*}$$

$$\mu_e = \frac{e \tau}{m^*}$$

■ B em Tesla: 1 Tesla = 1 kg/(s² A) = 1 kg/(s Coulomb)

■ μ em cm²/(V s): 1 Volt = 1 N m/ Coulomb = m² kg/(s² Coul)

$$1 [\text{cm}^2/(\text{V s})] = 10^{-4} [\text{Tesla}^{-1}]$$

$e = 1.6 \times 10^{-19}$ Coulomb

$m_0 = 9.11 \times 10^{-31}$ kg

$$\omega_c \tau = \mu_e B = 10^{-4} \left(\frac{B}{1 \text{ Tesla}} \right) \left(\frac{\mu_e}{1 \text{ cm}^2/(\text{Vs})} \right)$$

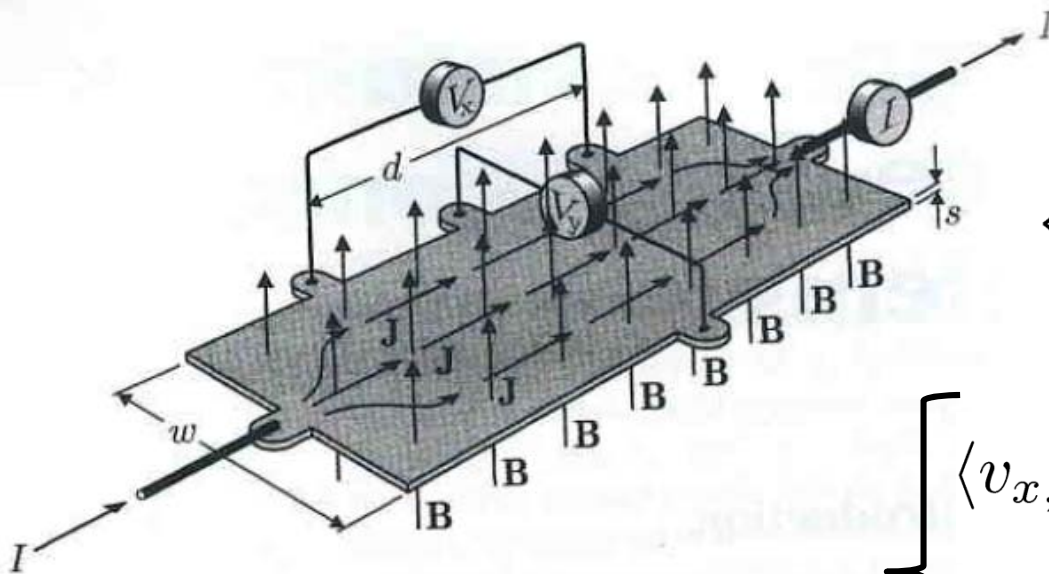
Exemplo: Para uma mobilidade de $\mu_e = 10000$ cm²/(Vs) e um campo de 1 Tesla, $\omega_c \tau = 1!!$)

Mobilidades típicas em metais

Element	Diffusion coefficient D , $\text{cm}^2\text{-s}$	Drift mobility μ_{amb} , cm^2/Vs	Electron velocity v_F , 10^7 cm/s	Fermi energy E_F , eV	Ratio E_F/kT	Wave vector k_F , 10^8 cm^{-1}	Free pass length $l_F = v_F \tau_F$, Å	$n_e = \frac{1}{ eR_D }$, 10^{22} cm^{-3}
Li	20.9	820	4.9	0.68	26.9	0.42	128	3.68
Na	88.4	3470	10.1	2.90	114	0.87	263	2.98
K	74.1	2910	9.3	2.43	95.7	0.80	240	1.49
Rb	45.3	1780	7.2	1.49	58.5	0.63	188	1.49
Cs	26.7	1050	5.6	0.88	34.5	0.48	144	0.80
Cu	147	5770	13.0	4.81	189	1.12	338	11.6
Ag	241	9490	16.7	7.92	312	1.44	434	6.94
Au	156	6120	13.4	5.11	201	1.16	349	8.56
Be	216	8480	15.8	7.08	279	1.36	410	2.57
Mg	61.2	2410	8.4	2.01	79.1	0.73	219	7.53
Ca	61.0	2400	8.4	2.00	78.8	0.73	218	16.0
Sr	10.6	418	3.5	0.35	13.7	0.30	91	
Ba	8.86	348	3.2	0.29	11.4	0.28	83	
Zn	59.2	2330	8.3	1.94	76.5	0.71	215	6.01
Cd	63.7	2510	8.6	2.09	82.3	0.74	223	11.8
Al	66.1	2600	8.7	2.17	85.3	0.76	227	18.9
Ga	32.4	1270	6.1	1.06	41.9	0.53	159	9.92
In	25.9	1020	5.5	0.85	33.5	0.47	142	89.3
Tl	17.5	688	4.5	0.57	22.6	0.39	117	
Sn	20.4	800	4.9	0.67	26.3	0.42	126	313
Pb	7.20	283	2.9	0.24	9.30	0.25	75	104

V. Palenskis, "Drift Mobility, Diffusion Coefficient of Randomly Moving Charge Carriers in Metals and Other Materials with Degenerated Electron Gas," *World Journal of Condensed Matter Physics*, Vol. 3 No. 1, 2013, pp. 73-81. doi: [10.4236/wjcmp.2013.31013](https://doi.org/10.4236/wjcmp.2013.31013).

E se mantivermos os termos $(\omega_c \tau)^2$?



Metais: considerando apenas portadores tipo n

$$\mu_e = \frac{e\tau_e}{m_e^*}$$

$$\omega_c^e = \frac{e \cdot B}{m_e^*}$$

Aprox. tempo de relaxação, estado estacionário:

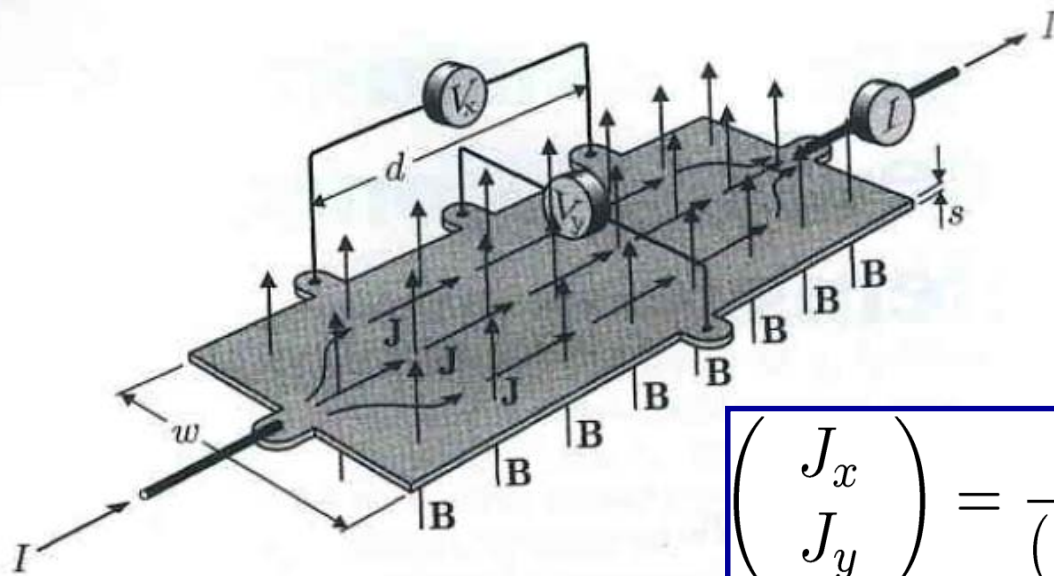
$$\begin{cases} \frac{m_e^*}{e\tau_e} \langle v_{x,e} \rangle = -E_x - \langle v_{y,e} \rangle B \\ \frac{m_e^*}{e\tau_e} \langle v_{y,e} \rangle = -E_y + \langle v_{x,e} \rangle B \end{cases}$$

$$\begin{cases} \langle v_{x,e} \rangle = \frac{\mu_e}{(1 + (\omega_c^e)^2 \tau_e^2)} (-E_x + \omega_c^e \tau_e E_y) \\ \langle v_{y,e} \rangle = \frac{\mu_e}{(1 + (\omega_c^e)^2 \tau_e^2)} (-E_y - \omega_c^e \tau_e E_x) \end{cases}$$

Velocidade em x será afetada por campos magnéticos fortes!

Magnetoresistência

Tensor de condutividade



$$\mathbf{J} = (-e)n\langle \mathbf{v}_e \rangle$$

$$\mathbf{J} = \boldsymbol{\sigma} \cdot \mathbf{E}$$

$$\sigma_0 = en\mu_e$$

$$\begin{pmatrix} J_x \\ J_y \end{pmatrix} = \frac{\sigma_0}{(1 + (\omega_c^e)^2 \tau_e^2)} \begin{pmatrix} 1 & -\omega_c^e \tau_e \\ +\omega_c^e \tau_e & 1 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

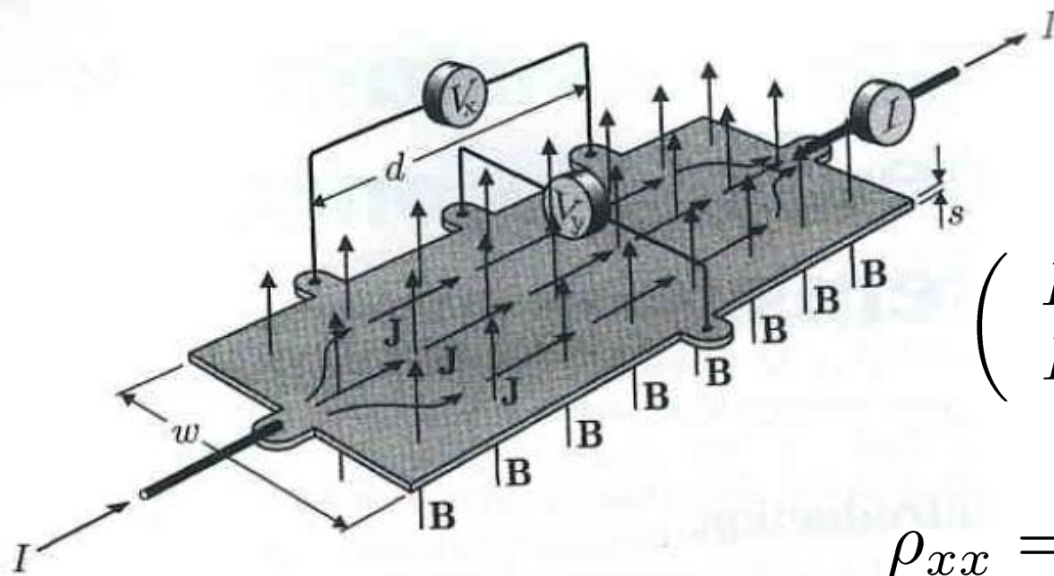
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$$\mu_e = \frac{e\tau_e}{m_e^*}$$

$$\omega_c^e = \frac{e \cdot B}{m_e^*}$$

$$\sigma_{xx} = \frac{\sigma_0}{(1 + (\omega_c^e)^2 \tau_e^2)} \quad \sigma_{yx} = \frac{\sigma_0 \omega_c^e \tau_e}{(1 + (\omega_c^e)^2 \tau_e^2)}$$

Tensor de resistividade



$$\mathbf{E} = \rho \cdot \mathbf{J}$$

Invertendo as equações, temos:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \frac{1}{\sigma_0} \begin{pmatrix} 1 & +\omega_c^e \tau_e \\ -\omega_c^e \tau_e & 1 \end{pmatrix} \begin{pmatrix} J_x \\ J_y \end{pmatrix}$$

$$\rho_{xx} = \rho_0$$

Os termos $(\omega_c \tau)^2$ cancelam!(*)

Metais: considerando apenas portadores tipo n

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Resistividade Hall:

$$\rho_{yx} = -\rho_0 \omega_c^e \tau_e = \frac{B}{(-e)n}$$

No caso $J_y = 0$ recuperamos $\rho_{xx} = \frac{E_x}{J_x}$ $\rho_{yx} = \frac{E_y}{J_x}$

(* Em metais reais há mais de um tipo de portador e este cancelamento não é perfeito, o que leva a uma magnetoresistência em ρ_{xx} .

Medindo a superfície de Fermi (Lista 4)

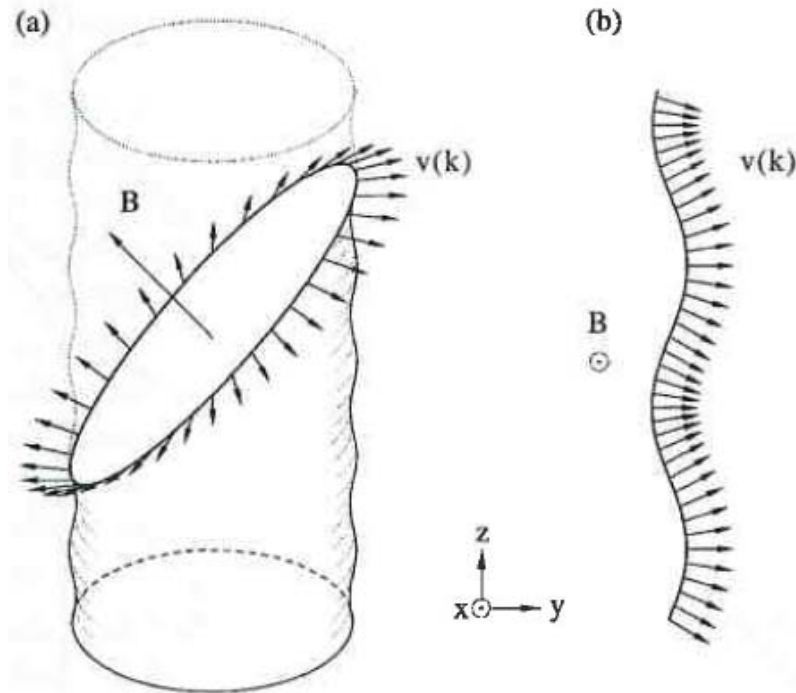
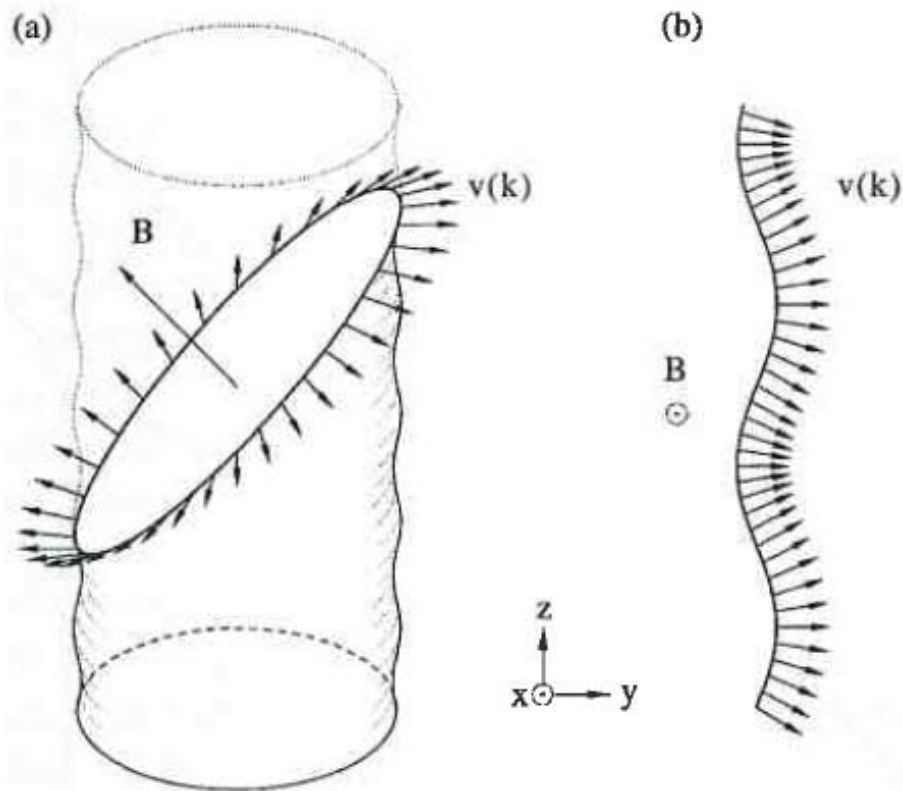


Fig. 10.5 (a) Schematic of electron motion on a closed section of Fermi surface in a magnetic field. The arrows indicate the velocities of an electron following a closed orbit about the Fermi surface in a plane perpendicular to the magnetic field \mathbf{B} . (b) An open orbit on the Fermi surface. In an in-plane magnetic field, electrons will be driven across the Fermi surface, so that their velocities (shown by arrows) will rock from side to side.

Direções com **órbitas fechadas**: $\langle v \rangle = 0$ e ρ_{xx} satura a campos altos.
Direções com **órbitas abertas**: $\langle v_y \rangle \neq 0$ e $\rho_{xx} \sim B^2$ para $B \rightarrow \infty$.

Lista 4.

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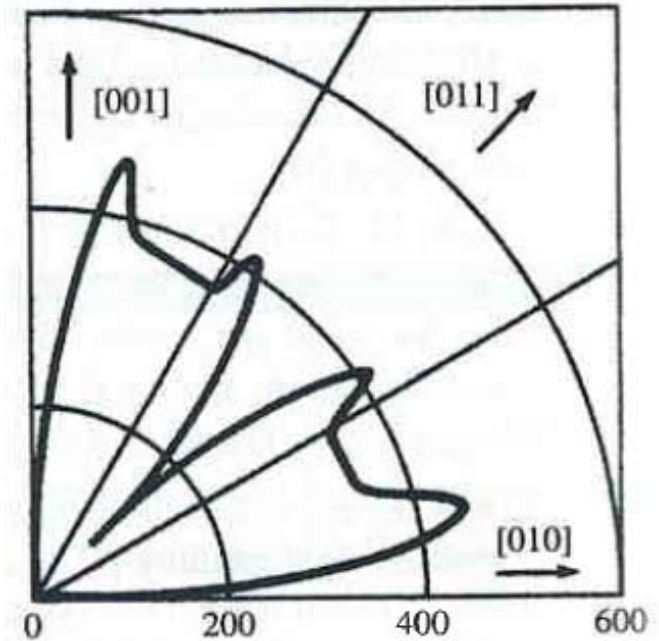


Fig. 10.9 Magnetoresistance of copper at a temperature of 4.2 K and a fixed magnetic field of 1.8 T; the current has been applied in the [100] direction (perpendicular to the plane of the page) and the magnetic field has been rotated from the [100] direction to the [010] direction. The magnetoresistance has been plotted radially as $(\rho(B) - \rho(B = 0)) / \rho(B = 0)$. (Data from J.R. Klauder and J.E. Kunzler, *The Fermi surface*, edited by Harrison (Wiley, New York, 1960).)

Lista 4.