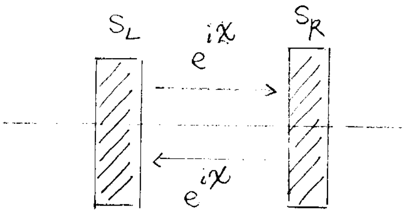
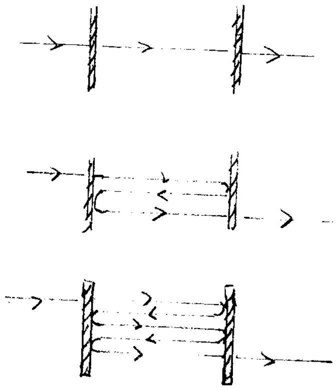
Dupla junção





$$A_1 = t_L e^{i\chi} t_R$$

$$A_2 = t_L e^{i\chi}\left(r_R e^{i\chi} r_L' e^{i\chi}\right) t_R$$

$$A_3 = t_L e^{i\chi}\left(r_R e^{+i\chi} r_L' e^{i\chi}\right)^2 t_R$$

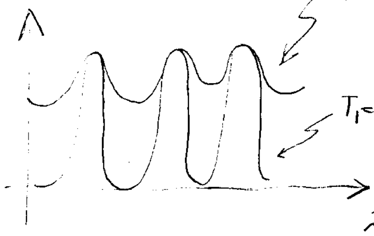
$$S_L = \begin{pmatrix} r_L & t_L' \\ t_L & r_L' \end{pmatrix}$$

$$S_R = \begin{pmatrix} r_R & t_R' \\ t_R & r_R' \end{pmatrix}$$

$$A_n = t_L t_R (r_L' r_R)^{n-1} e^{i(2n-1)\chi}$$

$$t = \sum_{n=1}^{\infty} A_n = t_L t_R e^{i\chi} \sum_{m=0}^{\infty}\left(r_L' r_R e^{i2\chi}\right)^m$$

$$t = \frac{t_R t_L e^{i\chi}}{1 - r_L' r_R e^{i2\chi}}$$



Transmissão

$$T = \left|\frac{t_R t_L e^{i\chi}}{1 - r_L' r_R e^{i2\chi}}\right|^2 = \frac{T_R T_L}{1 + R_L R_R - 2\sqrt{R_L R_L}\cos 2\chi}$$

$\hookrightarrow 2\chi \to 2\chi + \arg(r_L' r_R)$

"pequeno roubo"

$$T_{min} = \frac{T_R T_L}{(1+\sqrt{R_L R_R})^2} \leq T(\chi) \leq \frac{T_R T_L}{(1-\sqrt{R_L R_R})^2} = T_{max}$$

se $T_{LR} \ll 1$ $\quad R_{L,R} = 1 - T_{L,R}$

$$T_{min} \approx T_R T_L \ll 1 \quad \text{e} \quad T_{max} = \frac{T_R T_L}{\left[1-\sqrt{(1-T_L)(1-T_R)}\right]^2} \approx \frac{T_R T_R}{\left[1-\sqrt{1-(T_L+T_R)+T_R T_L}\right]^2}$$

$$T_{max} \approx \frac{4 T_R T_L}{(T_L + T_R)^2}$$

Fabre-Perot

Vamos supor que T_{max} ocorre para $E=E_0$, onde a transmissão tem ressonância.

$$\cos[2\chi(E)] = \cos[2\chi(E_0)] + \frac{d}{dE}\cos[2\chi(E)]\Big|_{E=E_0}(E-E_0) + \frac{d^2}{dE^2}\cos[2\chi(E)]\Big|_{E=E_0}\frac{(E-E_0)^2}{2} + O(E^3)$$

$$\cos[2\chi(E_0)] \equiv \cos 2\chi_0 = 1 \quad \therefore \quad \chi_0 = n\pi$$

$$\frac{d}{dE}\cos[2\chi(E)] = -\sin 2\chi_0 \frac{d\chi}{dE}\Big|_{E=E_0} = 0$$

$$\frac{d^2}{dE^2}\cos[2\chi(E)] = -\cos 2\chi_0 \frac{d^2\chi}{dE^2}\Big|_{E=E_0} \equiv -\frac{1}{W^2}$$

$$\sqrt{(1-T_L)(1-T_R)} \approx 1 - \frac{T_L+T_R}{2} \qquad \text{onde usamos } T_{L,R} \ll 1$$

$$T \cong \frac{T_R T_L}{1+R_L R_R - 2\sqrt{R_L R_R}\left[1-\frac{1}{2}\left(\frac{E-E_0}{W}\right)^2\right]} \cong \frac{T_R T_L}{\left(\frac{T_R+T_L}{2}\right)^2 + \left(\frac{E-E_0}{W}\right)^2}, \quad \text{onde usamos } T_{L,R} \ll 1$$

Definindo,

$$\Gamma_{R,L} = W\, T_{R,L} \quad \therefore \text{ largura de decaimento}$$

$$\boxed{T = \frac{\Gamma_R \Gamma_L}{(E-E_0)^2 + \left(\frac{\Gamma_R+\Gamma_L}{2}\right)^2}} \qquad \text{forma Lorentziana, ressonância de Breit-Wigner}$$

$$\Gamma = \Gamma_R + \Gamma_L \ll \Delta \; \cdots \text{ espaçamento de ressonâncias}$$

Processo incoerente

$$T_{cl} = \sum_{m=0}^{\infty} |A_m|^2 = T_L T_R \sum_{m=0}^{\infty} (R_L R_R)^m = \frac{T_L T_R}{1-R_L R_R} \qquad \text{não depende de } \chi$$

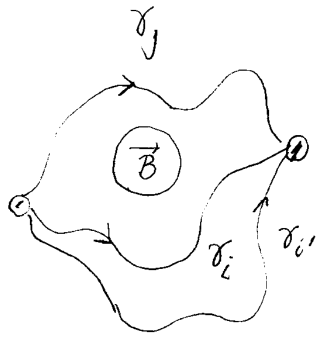
para $T_L, T_R \ll 1$, $\quad R_L R_R \approx 1 - (T_L + T_R)$

$$T_{cl} \approx \frac{T_L T_R}{T_L + T_R}, \qquad \text{lembrando que } g_{L,R} = g_Q T_{L,R}$$

$$g_{cl} = g_Q T_{cl} = \frac{g_R g_L}{g_R + g_L} \qquad \frac{1}{g_{cl}} = \frac{1}{g_R} + \frac{1}{g_L}$$

lei de Ohm para dois resistores $1/g_R$ e $1/g_L$ em série

Fase de Aharonov-Bohm



Usando a substituição mínima

$$\vec{p} \to \vec{p} - q\vec{A}$$

para uma dada trajetoria γ_i

$$\varphi_i(\vec{B}) = \varphi_i(0) + \frac{e}{\hbar}\int_{\gamma_i} d\vec{s}\cdot\vec{A}$$

como resultado, a diferença de fases

$$\Delta\varphi_{ii'}(\vec{B}) = \varphi_i(\vec{B}) - \varphi_{i'}(\vec{B}) = \Delta\varphi_{ii'}(0)$$

$$\Delta\varphi_{ij}(\vec{B}) = \varphi_i(\vec{B}) - \varphi_j(\vec{B}) = \frac{e}{\hbar}\int_{\gamma_i-\gamma_j} d\vec{s}\cdot\vec{A} + \Delta\varphi_{ij}(0) = \Delta\varphi_{ij}(0) + 2\pi\frac{\Phi}{\Phi_0}$$

Movimento circular (em 2D)

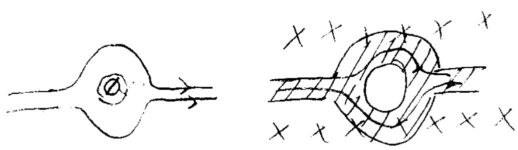
$$H = \frac{1}{2m}(\vec{p} + e\vec{A})^2 + V(r)$$

$$\vec{A} = \hat{e}_\varphi \frac{\phi}{2\pi r} \quad \text{dá} \quad \vec{B} = \vec{\nabla}\times\vec{A} = 0 \text{ para } r > 0$$

mas $\oint d\vec{s}\cdot\vec{A} = \phi$ se o contorno envolver orgem

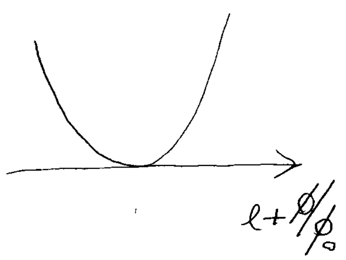
$$\vec{p} = \hbar\left(i\frac{\partial}{\partial r}, i\frac{1}{r}\frac{\partial}{\partial\theta}\right)$$

para simplificar vamos considerar movimento unidimensional



$$H = \frac{\hbar^2}{2mr_0^2}\left(i\frac{\partial}{\partial\theta} - \frac{\phi}{\phi_0}\right)^2$$

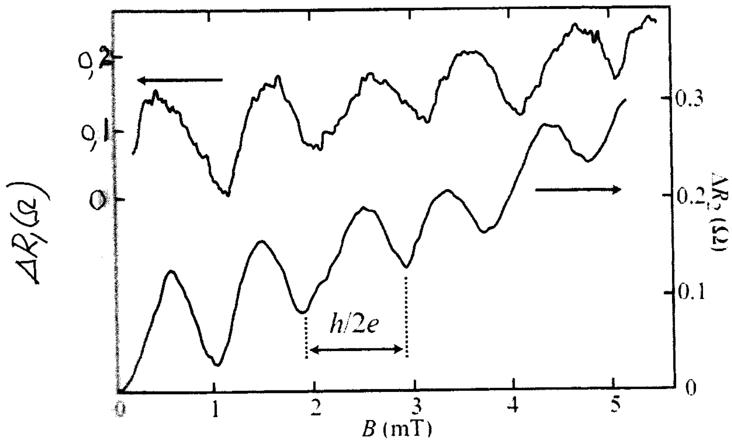
$$\psi(\theta) = \frac{1}{\sqrt{2\pi}}e^{il\theta} \qquad E_l = \frac{\hbar^2}{2mr_0^2}\left(l + \frac{\phi}{\phi_0}\right)^2$$

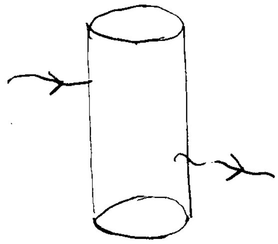


$$v_g(l) = \frac{r_0^2}{\hbar}\frac{\partial E_l}{\partial l} = \frac{\hbar}{mr_0}\left(l + \frac{\phi}{\phi_0}\right)$$

Experimentos de Aharonov-Bohm

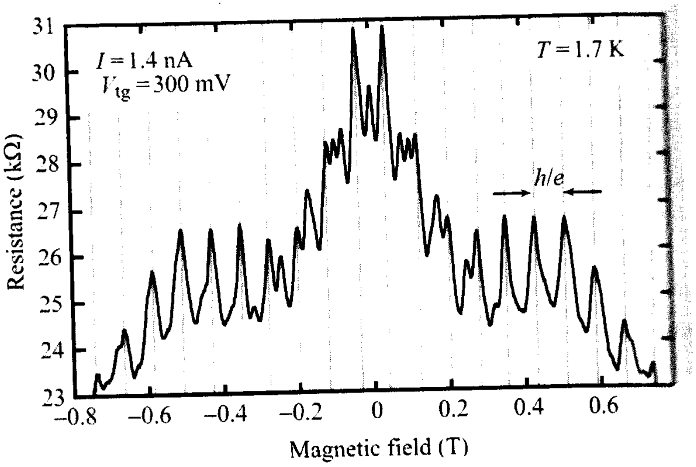
Sharvin & Sharvin, gold cilinders (1981)



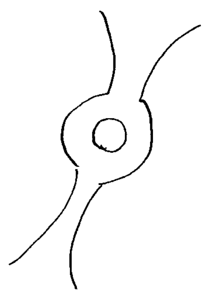


Oscilações AAS
Altshuler-Aronov-Spivak

Fuhrer (2001)



anel quântico

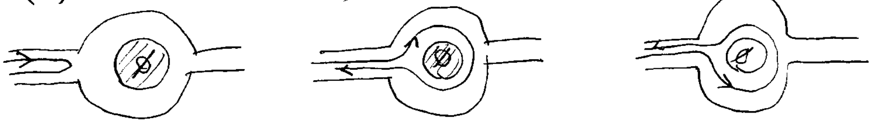


reciprocidade

$$G(B) = G(-B)$$

Interpretação

(a) (b) (c)



$$G = \frac{2e^2}{h}\, T(E_F) = \frac{2e^2}{h}\left[\, 1 - R(E_F)\right]$$

$$\mathcal{R} = \left| r_0 + r_1 e^{i 2\pi \phi/\phi_0} + r_1 e^{-i 2\pi \phi/\phi_0} + \dots \right|$$

$$= |r_0|^2 + 2|r_1|^2 + \dots$$

$$+ 4|r_0||r_1| \cos\delta \cos\left(2\pi \frac{\phi}{\phi_0}\right) + \dots$$

$$+ 2|r_1|^2 \cos\left(4\pi \phi/\phi_0\right)$$

independe de B, "clássica"

período h/e ... efeito AB
δ é a fase entre r_0 e r_1 (orbital)
$B=0$ pode ser máximo ou mínimo dependendo de δ

média sobre muitos anéis
↳ desaparece

período $h/2e$, AAS
interferência de trajetórias
com reversão temporal

Discutir: (i) Rigidez de fase
(ii) Efeito de temperatura