Эффект Ааронова-Бома в системе квантовых точек

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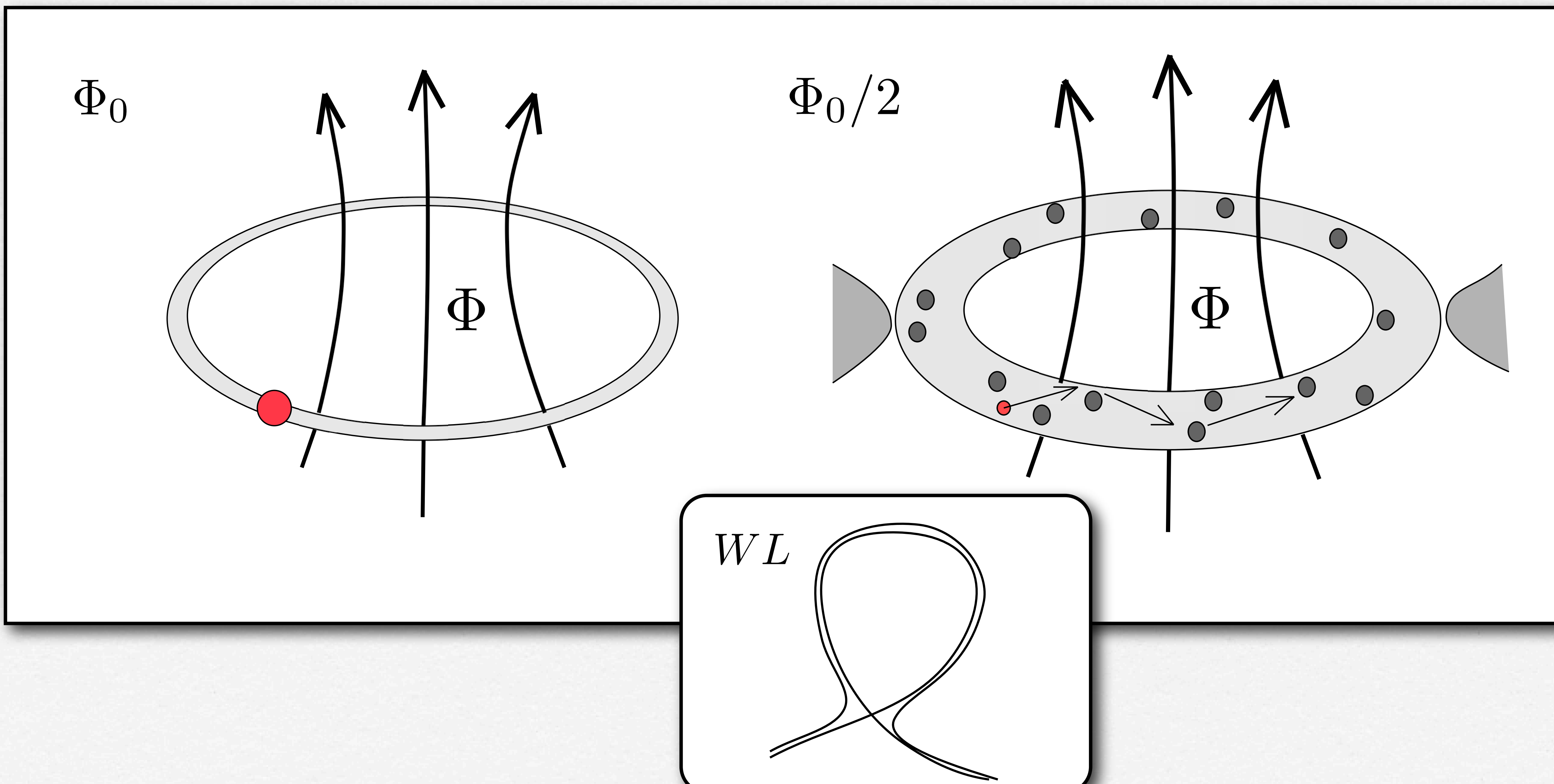
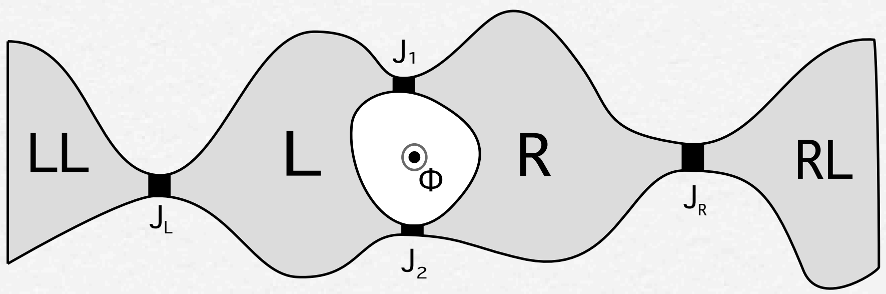
ОТФ ФИАН

Φ_0 и $\Phi_0/2$ эффект Ааронова-Бома



Две квантовые точки



$$\hat{\mathbf{H}} = \hat{\mathbf{H}}_{\mathbf{R}} + \hat{\mathbf{H}}_{\mathbf{L}} + \hat{\mathbf{H}}_{\mathbf{LL}} + \hat{\mathbf{H}}_{\mathbf{RL}} + \hat{\mathbf{T}} + \hat{\mathbf{T}}_{\mathbf{L}} + \hat{\mathbf{T}}_{\mathbf{R}} + \hat{\mathbf{H}}_{\mathbf{int}}$$

$$\hat{\mathbf{H}}_j = \sum_{\alpha=\uparrow,\downarrow} \int_j d^3r \hat{\Psi}^\dagger_{\alpha,j}(r)(\hat{H}_j - eV_j)\hat{\Psi}_{\alpha,j}(r) \qquad j = \mathbf{RL}, \mathbf{LL}$$

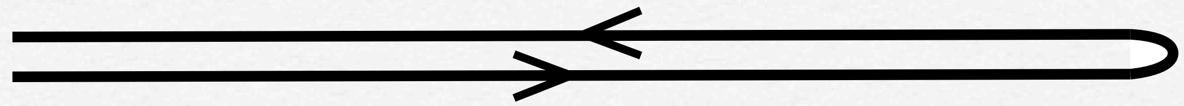
$$\hat{\mathbf{H}}_j = \sum_{\alpha=\uparrow,\downarrow} \int_j d^3r \hat{\Psi}^\dagger_{\alpha,j}(r)\hat{H}_j\hat{\Psi}_{\alpha,j}(r) \qquad j = \mathbf{R}, \mathbf{L}$$

$$\hat{\mathbf{T}} = \sum_{\alpha=\uparrow,\downarrow} \int_{J_1+J_2} d^2\mathbf{r} \left[t(\mathbf{r})\hat{\Psi}^\dagger_{\alpha,L}(\mathbf{r})\hat{\Psi}_{\alpha,R}(\mathbf{r}) + \text{c.c.}\right].$$

$$\hat{\mathbf{H}}_{\mathbf{int}} = \frac{e^2}{2} \sum_{i,j=L,R} \hat{N}_i [C^{-1}]_{ij} \hat{N}_j \qquad N_j = \sum_{\alpha=\uparrow,\downarrow} \int_j d^3r \hat{\Psi}^\dagger_{\alpha,j}(r)\hat{\Psi}_{\alpha,j}(r)$$

Функциональный интеграл на контуре Келдыша

$$\hat{\rho}(t) = e^{-i\hat{H}t}\hat{\rho}_0\, e^{i\hat{H}t},$$



$$\begin{aligned} e^{-i\hat{H}t} &= \int DV_j^F \;\mathrm{T}\,\exp\left\{-i\int_0^t dt'\,\hat{H}\left[V_j^F(t')\right]\right\}, \\ e^{i\hat{H}t} &= \int DV_j^B \;\tilde{\mathrm{T}}\,\exp\left\{i\int_0^t dt'\,\hat{H}\left[V_j^B(t')\right]\right\}. \end{aligned}$$

$$\begin{aligned} iS[V^F, V^B] &= \ln\Bigg(\mathrm{tr}\Bigg[\mathrm{T}\,\exp\left\{-i\int_0^t dt'\,\hat{H}\left[V_j^F(t')\right]\right\} \\ &\quad \times\; \hat{\rho}_0\tilde{\mathrm{T}}\,\exp\left\{i\int_0^t dt'\,\hat{H}\left[V_j^B(t')\right]\right\}\Bigg]\Bigg). \end{aligned}$$

Эффективное действие

$$iS = iS_C + iS_{ext} + 2\mathbf{Tr}\ln\left[\check{\mathbf{G}}^{-1}\right]$$

$$\check{\mathbf{G}}^{-1} = \begin{pmatrix} \hat{G}_{LL}^{-1} & \hat{T}_L & 0 & 0 \\ \hat{T}_L^{\dagger} & \hat{G}_L^{-1} & \hat{T} & 0 \\ 0 & \hat{T}^{\dagger} & \hat{G}_R^{-1} & \hat{T}_R \\ 0 & 0 & \hat{T}_R^{\dagger} & \hat{G}_{RL}^{-1} \end{pmatrix}.$$

$$\psi_{F,B}^{(j)} \to \psi_{F,B}^{(j)} e^{i(\varphi_{F,B}^{(j)} + \varphi_g^{(j)})}$$

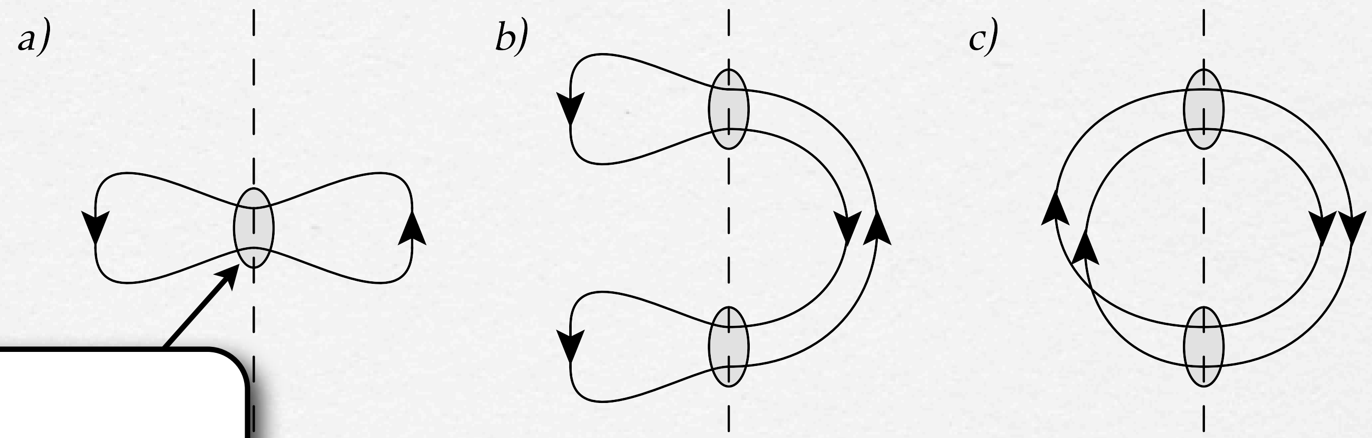
$$\varphi_{F,B}(t) = e\int^t d\tau (V_R^{F,B}(\tau) - V_L^{F,B}(\tau))$$

$$\varphi_g^{(1,2)} = \frac{e}{c}\int\limits_L^R dx_\mu A_\mu(x),$$

Эффективное действие

$$iS \approx iS_C + iS_{ext} + iS_L + iS_R - 2\mathbf{tr}\left[\hat{G}_L \hat{T} \hat{G}_R \hat{T}^\dagger\right] -$$

$$-\mathbf{tr}\left[\hat{G}_L \hat{T} \hat{G}_R \hat{T}^\dagger \hat{G}_L \hat{T} \hat{G}_R \hat{T}^\dagger\right] + \ldots$$



$$\overline{t(\mathbf{x})t(\mathbf{y})} = \frac{g_t(\mathbf{x})}{8\pi^2 N_L N_R}\delta(\mathbf{x}-\mathbf{y})$$

$$iS^{AES} = -\int dt_1 dt_2 \int\limits_{J_1+J_2} d\mathbf{x}\frac{g_t(\mathbf{x})}{4\pi^2 N_L N_R}\sum_{i,j=F,B}\hat{G}_L^{ij}(\mathbf{x}t_1;\mathbf{x}t_2)(-1)^j e^{i\varphi_j(t_2)}\hat{G}_R^{ji}(\mathbf{x}t_2;\mathbf{x}t_1)(-1)^i e^{-i\varphi_i(t_1)},$$

Эффективное действие

$$iS_\Phi = -\sum_{m,n=1,2} e^{2i(\varphi_g^{(n)}-\varphi_g^{(m)})}\int dt_1dt_2dt_3dt_4\int_{J_n} d\mathbf{x}\int_{J_m} d\mathbf{y}\,\frac{g_t(\mathbf{x})g_t(\mathbf{y})}{64\pi^4N_L^2N_R^2}\times$$

$$\times\sum_{i,j,k,l=F,B}\hat{G}_L^{ij}(\mathbf{x}t_1;\mathbf{y}t_2)(-1)^je^{i\varphi_j(t_2)}\hat{G}_R^{jk}(\mathbf{y}t_2;\mathbf{x}t_3)(-1)^ke^{-i\varphi_k(t_3)}\times$$

$$\times\hat{G}_L^{kl}(\mathbf{x}t_3;\mathbf{y}t_4)(-1)^le^{i\varphi_l(t_4)}\hat{G}_R^{li}(\mathbf{y}t_4;\mathbf{x}t_1)(-1)^ie^{-i\varphi_i(t_1)}.$$

$$\hat{G}_{L,R}(\mathbf{x_1}t_1;\mathbf{x_2}t_2)=\int dt(G^R_{L,R}(\mathbf{x_1}t_1;\mathbf{x_2}t)\hat{F}_1(t-t_2)-\hat{F}_2(t_1-t)G^A_{L,R}(\mathbf{x_1}t;\mathbf{x_2}t_2)),$$

$$\hat{F}_1(t)=\begin{pmatrix} h(t) & -f(t)\\ h(t) & -f(t)\end{pmatrix},\qquad \hat{F}_2(t)=\begin{pmatrix} -f(t) & -f(t)\\ h(t) & h(t)\end{pmatrix}$$

Эффективное действие

$$iS_\Phi^{WL} = -i \sum_{m,n=1,2} e^{2i(\varphi_g^{(n)} - \varphi_g^{(m)})} \int d\tau_1 d\tau_2 \int dt_1 dt_2 dt_3 dt_4 \int_{J_n} d\mathbf{x} \int_{J_m} d\mathbf{y} \frac{g_t(\mathbf{x}) g_t(\mathbf{y})}{4\pi^2 N_L N_R} \times$$

$$\times \mathcal{C}_L(\tau_1; \mathbf{y}, \mathbf{x}) \mathcal{C}_R(\tau_2; \mathbf{x}, \mathbf{y}) e^{i(\varphi^+(t_2) - \varphi^+(t_3) + \varphi^+(t_4) - \varphi^+(t_1))} \sin \frac{\varphi^-(t_1)}{2} \times$$

$$\times \left[h(t_1 - t_2 - \tau_1) e^{i\frac{\varphi^-(t_2)}{2}} + f(t_1 - t_2 - \tau_1) e^{-i\frac{\varphi^-(t_2)}{2}} \right] \times$$

$$\times \left[h(t_2 - t_3 - \tau_2) e^{-i\frac{\varphi^-(t_3)}{2}} f(t_3 - t_4 + \tau_1) - \right.$$

$$\left. - f(t_2 - t_3 - \tau_2) e^{i\frac{\varphi^-(t_3)}{2}} h(t_3 - t_4 + \tau_1) \right] \times$$

$$\times \left[e^{i\frac{\varphi^-(t_4)}{2}} f(t_4 - t_1 + \tau_2) + e^{-i\frac{\varphi^-(t_4)}{2}} h(t_4 - t_1 + \tau_2) \right] +$$

$$+ \{L \leftrightarrow R, \varphi^\pm \to -\varphi^\pm\},$$

$$\varphi^+(t) = \frac{\varphi_F(t) + \varphi_B(t)}{2}, \qquad \varphi^-(t) = \varphi_F(t) - \varphi_B(t)$$

Осцилляции тока

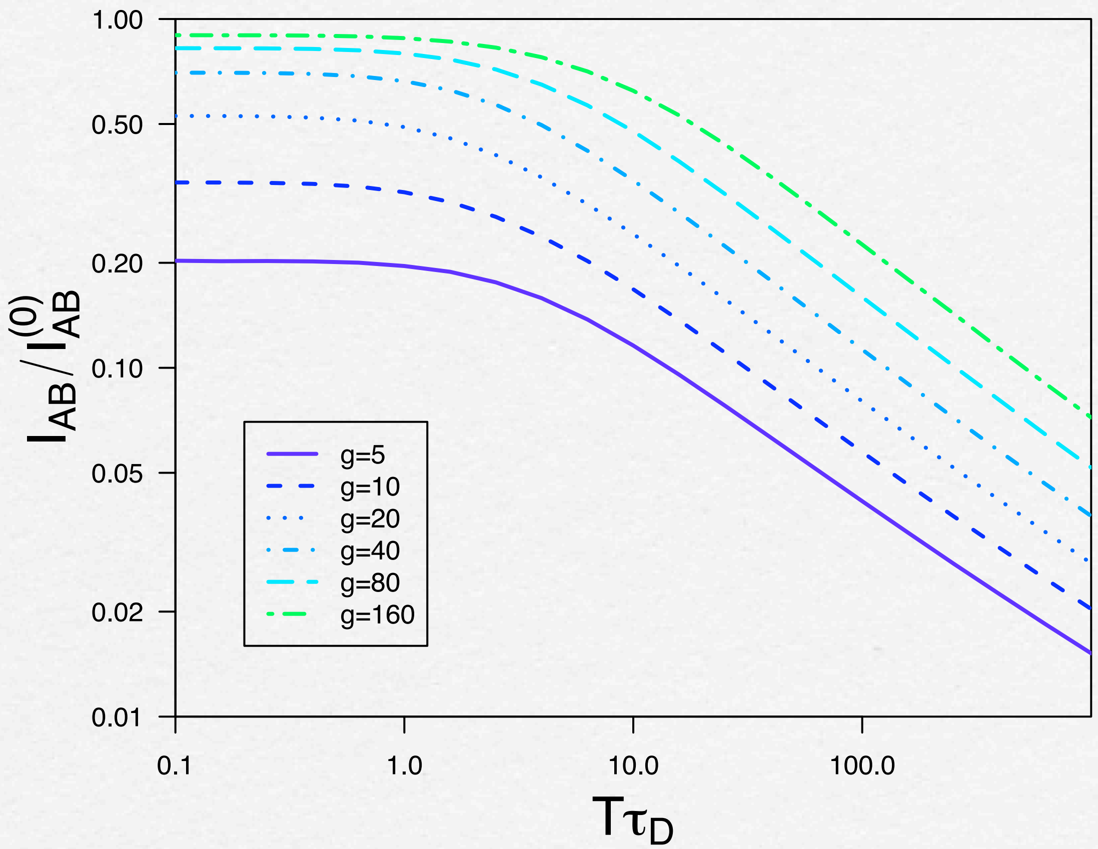
$$\delta I = -e \int \mathcal{D}^2\varphi^{\pm} \frac{\delta S_{\Phi}^{WL}[\varphi^+, \varphi^-]}{\delta\varphi^-(t)} e^{iS[\varphi^+,\varphi^-]}$$

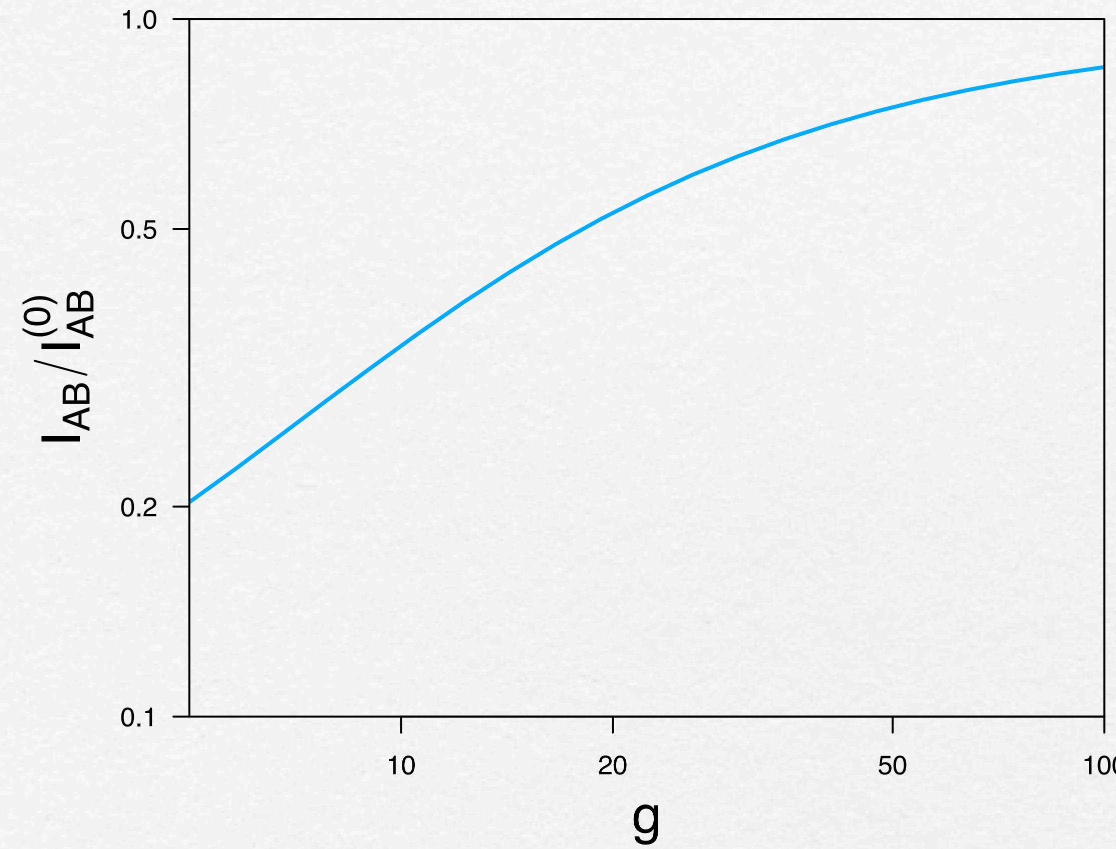
$$\delta I(\Phi) = -\sum_{m,n=L,R} \frac{e^2 V e^{2i(\varphi_g^{(n)}-\varphi_g^{(m)})}}{8\pi^3 N_L N_R} \int d\tau_1 d\tau_2 \int_{J_n} d\mathbf{x} \int_{J_m} d\mathbf{y}\, g_t(\mathbf{x}) g_t(\mathbf{y}) \times$$

$$\times \mathcal{C}_L(\tau_1; \mathbf{y}, \mathbf{x}) \mathcal{C}_R(\tau_2; \mathbf{x}, \mathbf{y}) e^{-2F(\tau_1)-2F(\tau_2)+F(\tau_1-\tau_2)+F(\tau_1+\tau_2)}$$

$$I_{AB}(\Phi) = I_{AB} \cos(4\pi\Phi/\Phi_0)$$

Осцилляции тока



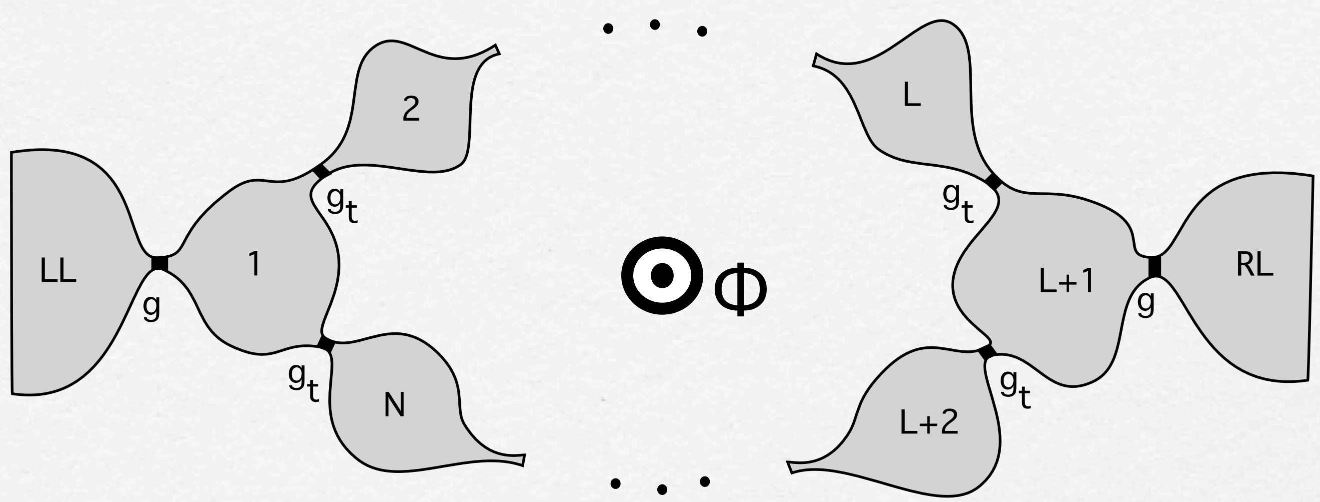


$$I_{AB} = \frac{e^2 g_{t1} g_{t2} \delta^2 V}{4\pi^3} \int\limits_0^\infty d\tau_1 d\tau_2 e^{-\frac{\tau_1+\tau_2}{\tau_D} - 2F(\tau_1) - 2F(\tau_2) + F(\tau_1-\tau_2) + F(\tau_1+\tau_2)}$$

$$\frac{I_{AB}}{I_{AB}^{(0)}} = \begin{cases} e^{-\frac{8\gamma}{g}} \frac{(2\pi T \tau_{RC})^{8/g}}{1+4\pi T\tau_D/g}, & \tau_D^{-1} \lesssim T \lesssim \tau_{RC}^{-1}, \\ \frac{1}{2\tau_D}\left(\frac{g\tau_{RC}}{T}\right)^{1/2}, & \tau_{RC}^{-1} \lesssim T, \end{cases}$$

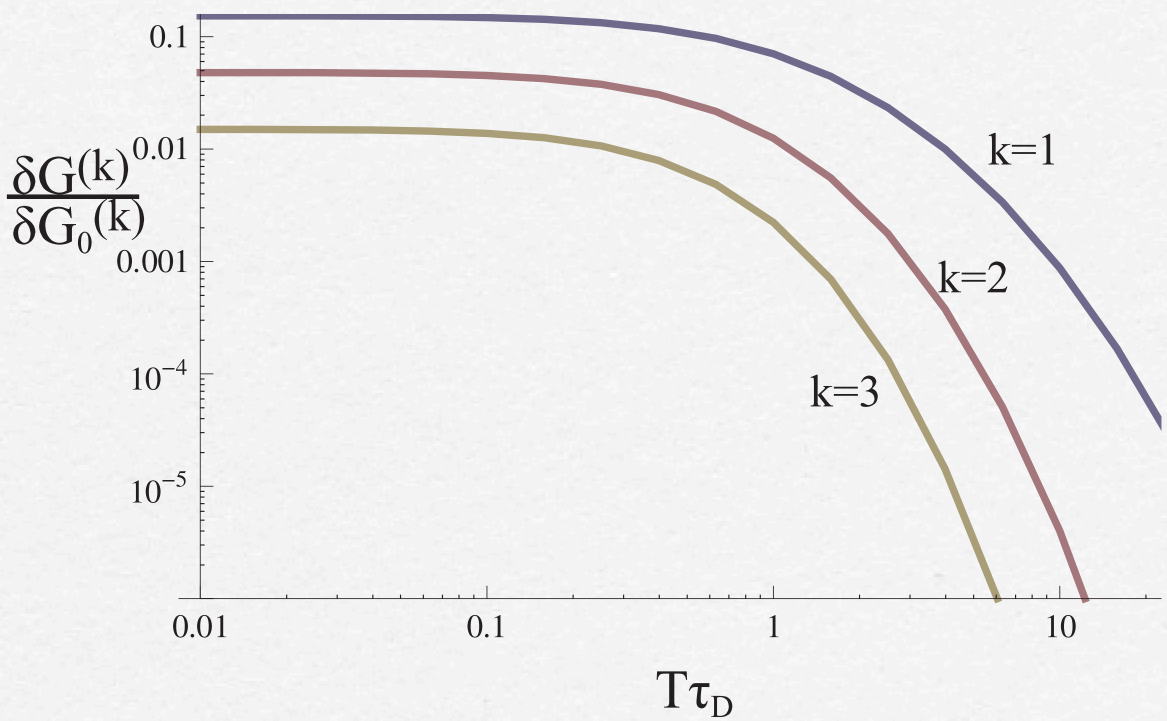
$$\frac{I_{AB}}{I_{AB}^{(0)}} = e^{-\frac{8\gamma}{g}} \left(\frac{2\tau_{RC}}{\tau_D}\right)^{8/g}, \qquad T \lesssim \tau_D^{-1}$$

Система квантовых точек



$$\delta G^{AB} = \frac{e^2 L(N-L)g^2}{2\pi N g_t^2}$$
$$\times \frac{(\beta_t \alpha + 1 - \beta_t)(z^{-N} - \cos(4\pi\Phi/\Phi_0))}{\sqrt{\alpha^2 - 1}(z^N + z^{-N} - 2\cos(4\pi\Phi/\Phi_0))},$$

Система квантовых точек



$$\delta G^{(k)} = -\frac{e^2 L(N-L) g^2 (\beta_t \alpha + 1 - \beta_t)}{2\pi N g_t^2 \sqrt{\alpha^2 - 1}} z^{-N|k|}$$

$$\delta G^{AB} = \sum_{k=1}^{\infty} \delta G^{(k)} \cos\left(4\pi k \Phi / \Phi_0\right)$$

$$\delta G^{(k)} \sim \begin{cases} e^{-|k|(\mathcal{L}/\mathcal{L}_\phi)} & T \ll D/(\mathcal{L}d), \\ e^{-|k|(\mathcal{L}/\mathcal{L}_\phi)^{3/2}} & T \gg D/(\mathcal{L}d). \end{cases}$$

$$\mathcal{L}_\phi = \begin{cases} \left(\frac{\pi \nu d^3 D}{\ln \frac{4E_c}{\delta}}\right)^{1/2} & T \ll D/(\mathcal{L}d), \\ \left(\frac{12 \nu d^2 D^2}{T}\right)^{1/3} & T \gg D/(\mathcal{L}d). \end{cases}$$

Thank you for your attention