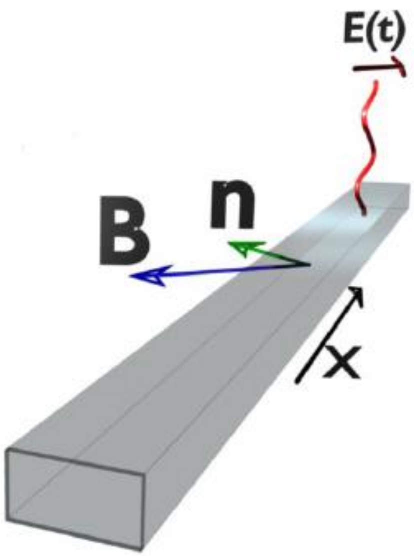
Spin flip resonance in spin-orbit split quantum wires



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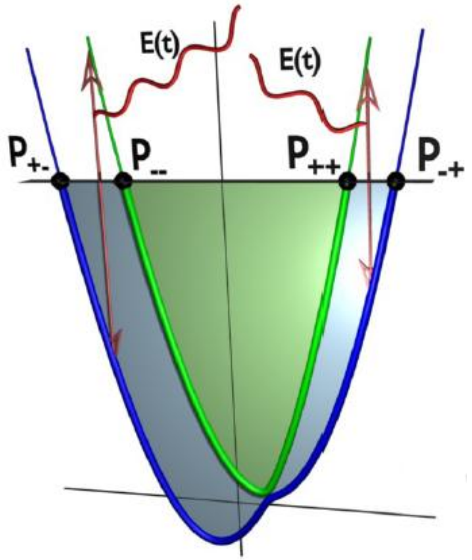
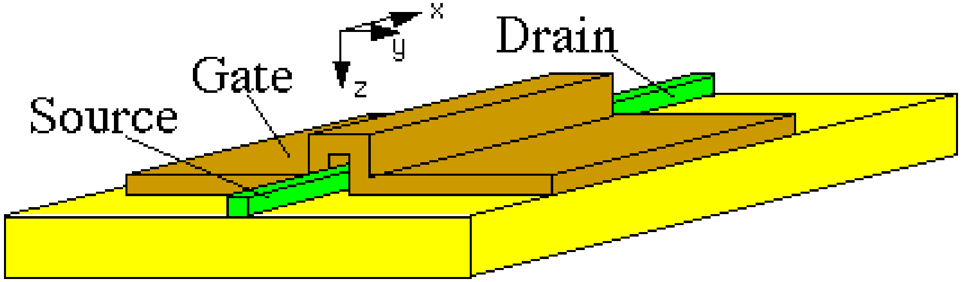


Collaborators: K. S. Tikhonov, V. L. Pokrovsky (Texas A&M University and Landau Institute)

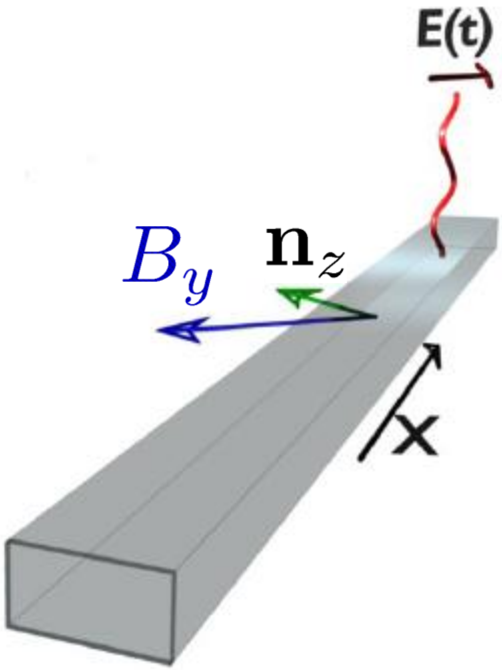
KITP, UC, Santa Barbara, CA; December 6, 2013

Outline

- Motivation: generation of spin currents
- Electron spin resonance (ESR)
- Spin current in a quantum wire with spin-orbit interaction
- Effect of strong e-e interactions
- Line shape of ESR in quantum wires



Quantum wire with spin-orbit interaction



InGaAs

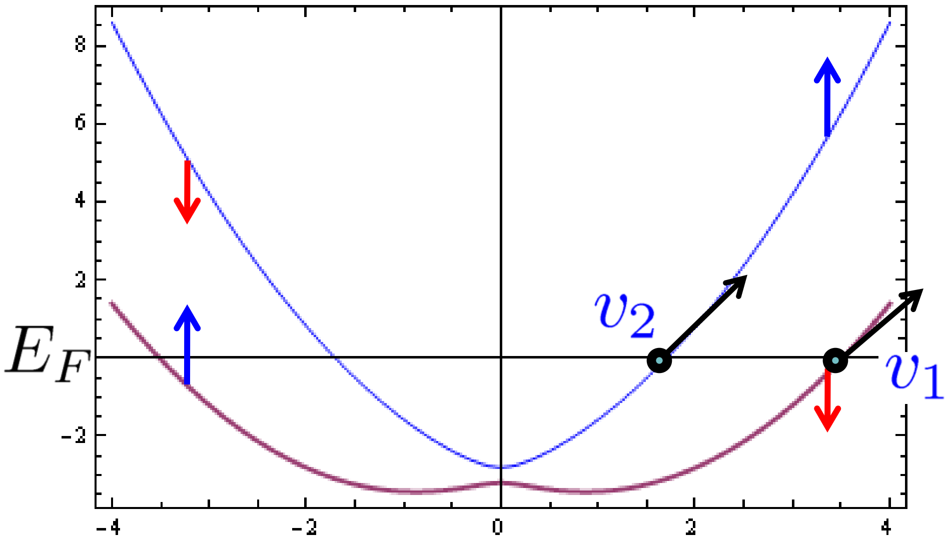
magnetic field splits the bands.

Rashba spin-orbit Hamiltonian with magn. field:

$$\mathcal{H} = \frac{p_x^2}{2m} + \alpha p_x \sigma_z + B_y \sigma_y$$

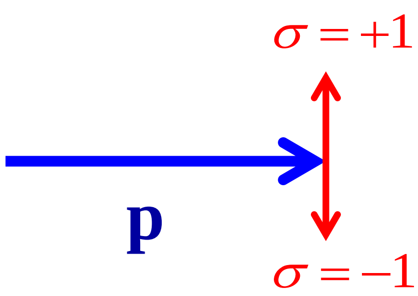
$$\alpha \ll v_F, \quad g\mu_B B \ll \alpha p_F$$

Energy spectrum:

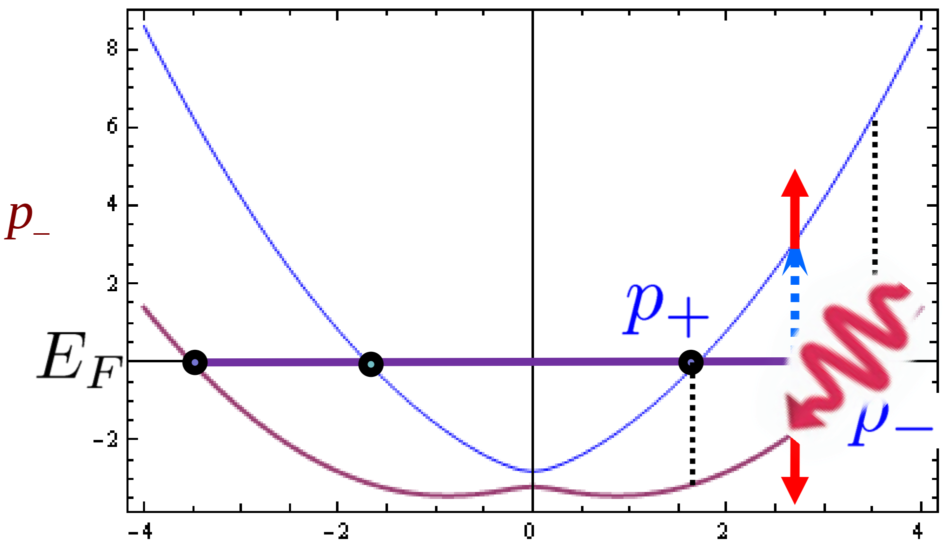


Spin flip and spin resonance

Energy spectrum: $\varepsilon_{\mathbf{p},\sigma} = \dfrac{p^2}{2m} + \alpha p \sigma; \;\; \sigma = \pm 1 -$ **Chirality**



4 Fermi points in 1D: $\dfrac{p_+^2}{2m} + \alpha p_+ = \dfrac{p_-^2}{2m} - \alpha p_-$

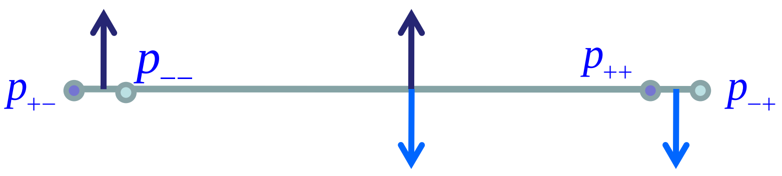


$$p_- - p_+ = 2\alpha m$$

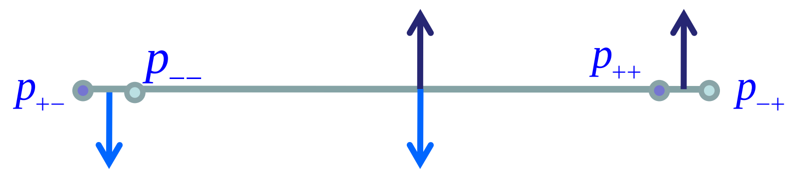
Resonant frequency: $\omega_s = \dfrac{2\alpha p_F}{\hbar}$

Spin current in 1D wire

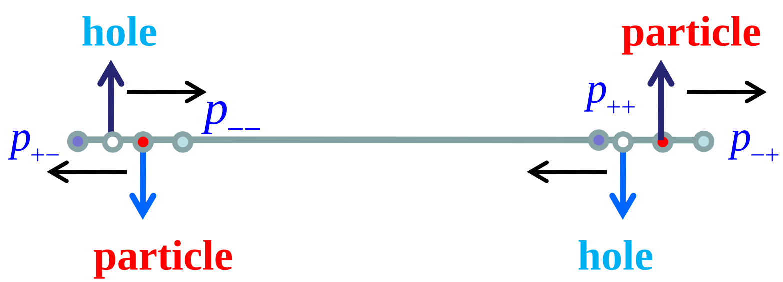
Linearly polarized ac electric field (along x-axis): $\mathcal{H}_{EM} = \frac{e}{c} A_x j_x$



Ground state



Excited state



Excitations

Velocity of the hole is opposite to the velocity of electron.

Spins up move right, spins down move left → **No electric current**

Permanent spin current!

Effect of electron-electron interaction

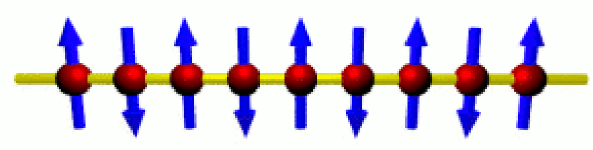
In 1D e-e interaction is strong:

free fermions $\Rightarrow$ bosonic collective excitations

$\Downarrow$

Luttinger liquid description

Two types of excitations: holons and spinons



ESR $\longrightarrow$ excitation of spinon (spin wave) with ω_s

Combined effect of SO and e-e interaction

bosonization technique:

$$\psi_{\tau,\sigma} \propto e^{-\frac{i}{\sqrt{2}}[\tau\phi_c(x)-\theta_c(x)+\tau\sigma\phi_s(x)-\sigma\theta_s(x)]}$$

charge spin

$\tau = \pm 1$ correspond to left and right movers

Spin-orbit interaction mixes spin and charge modes

For free fermions shape of resonance is Lorentzian:

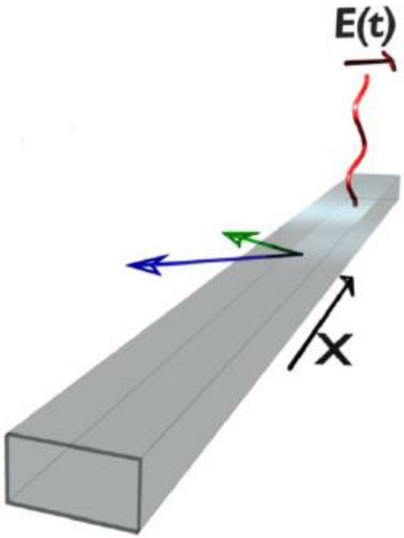
$$\frac{\gamma}{[(\omega-\omega_s)^2+\gamma^2]}$$

result for the spin-flip resonance lineshape:

$$\frac{\gamma}{[(\omega-\omega_s)^2+\gamma^2]^{1\pm\Delta_s}\,[(\omega-\omega_c)^2+\gamma^2]^{\Delta_c}}$$

Interacting Hamiltonian

Hamiltonian with the linearized dispersion:



$$H_0 = -iv_F \sum_\sigma \int dx \, (\psi^\dagger_{R,\sigma} \partial_x \psi_{R,\sigma} - \psi^\dagger_{L,\sigma} \partial_x \psi_{L,\sigma}) + H_{int} + H_R$$

The interaction part of Hamiltonian, H_{int}, contains terms

$\rho_{R(L)}(q)\rho_{R(L)}(q)$ and $:\psi^\dagger_{R,\uparrow}(x)\psi_{L,\uparrow}(x)::\psi^\dagger_{L,\downarrow}(x')\psi_{R,\downarrow}(x'):$

Rashba spin-orbit Hamiltonian:

$$H_R = \alpha \int \psi^\dagger p_x \sigma_z \psi \, dx$$

Interacting Hamiltonian (cont.)

Zeeman Hamiltonian:

$$H_Z = -\frac{g\mu_B B_\perp}{2} \sum_{\tau,\sigma,\sigma'} \int dx \psi^\dagger_{\tau\sigma} (\sigma_x)_{\sigma\sigma'} \psi_{\tau\sigma'}$$

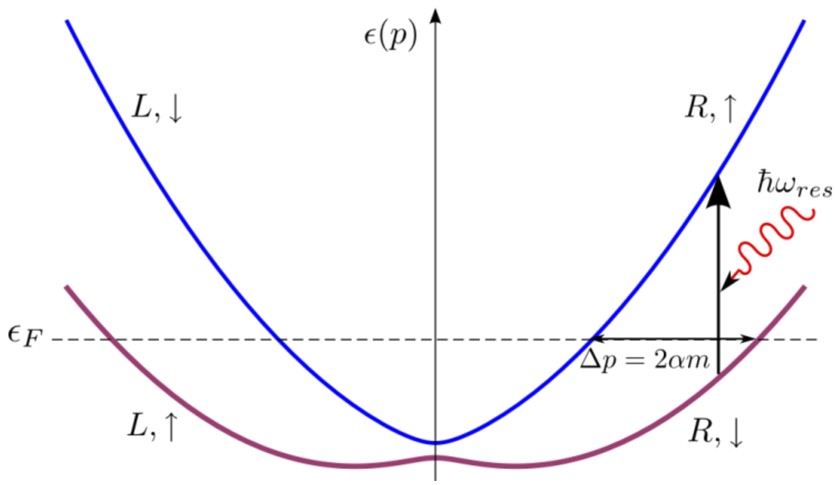
We assume that the magnetic field is weak: $g\mu_B B_\perp \ll \alpha p_F$

Electromagnetic field Hamiltonian:

$$H_{em} = -\frac{1}{c} \int j A_x dx$$

current $j = e\psi^\dagger(x)\hat{v}\psi(x)$

with velocity operator $\hat{v} = \hat{p}/m + \alpha\sigma_z$



Kubo Formula for Conductivity

The part of the current responsible for spin-flip processes:

$$j_s(x) = e\alpha\psi^\dagger(x)\sigma_z\psi(x)$$

Absorption power of EM radiation is $\mathrm{Re}\,\sigma_\omega|E_\omega|^2$

Kubo formula for the conductivity:

$$\sigma_\omega \propto \int_0^l dx \int_0^l dx' \int_{-\infty}^{\infty} dt\, \theta(t-t')\, e^{i\omega(t-t')} \langle [j_s(x,t), j_s(x',t')] \rangle$$

In terms of second quantized fermionic operators:

$$\sigma_\omega \propto \int_0^l dx \int_0^l dx' \int_{-\infty}^{\infty} dt'\, \theta(t-t')\, e^{i\omega(t-t')} e^{-2i\alpha m(x-x')/\hbar}$$
$$\times \langle [\psi^\dagger_{R,\uparrow}(x,t)\psi_{R,\downarrow}(x,t), \psi^\dagger_{R,\downarrow}(x',t')\psi_{R,\uparrow}(x',t')] \rangle$$

$$I^R(x,t)$$

Bosonization

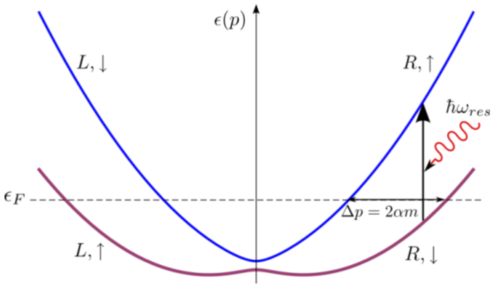
Transformation from fermions to bosons:

$$\psi_\sigma = \psi_{R,\sigma} + \psi_{L,\sigma}$$

$$\psi_{\tau,\sigma} = U_{\tau,\sigma} \frac{e^{i\tau k_F x}}{\sqrt{2\pi a_0}} e^{-i[\tau\phi_c(x) - \theta_c(x) + \tau\sigma\phi_s(x) - \sigma\theta_s(x)]/\sqrt{2}}$$

Density operators become linear in bosonic fields:

$$\rho_{c,s}(x) = -\frac{\sqrt{2}}{\pi} \partial_x \phi_{c,s}(x)$$



Fermionic Hamiltonian:

$$\begin{aligned} H &= -iv_1 \int dx \, (\psi^\dagger_{R,\uparrow} \partial_x \psi_{R,\uparrow} - \psi^\dagger_{L,\downarrow} \partial_x \psi_{L,\downarrow}) \\ &\quad -iv_2 \int dx \, (\psi^\dagger_{R,\downarrow} \partial_x \psi_{R,\downarrow} - \psi^\dagger_{L,\uparrow} \partial_x \psi_{L,\uparrow}) \end{aligned}$$

$\delta v = v_1 - v_2$ is due to SOI, magn. field, and dispersion curvature

Correlator in bosonic fields

After bosonization:

$$H = \int \frac{dx}{2\pi} \Big[v_c K_c \left(\partial_x \theta_c\right)^2 + \frac{v_c}{K_c} \left(\partial_x \phi_c\right)^2 + v_s K_s \left(\partial_x \theta_s\right)^2 + \frac{v_s}{K_s} \left(\partial_x \phi_s\right)^2 + \delta v \left(\partial_x \phi_c \partial_x \theta_s + \partial_x \phi_s \partial_x \theta_c\right) \Big]$$

Moroz et al., PRB (2000)

$v_s (v_c)$ is the spinon (holon) velocity

$$I^T_{\uparrow\downarrow,\downarrow\uparrow}(x,\tau) = -\langle T_\tau \psi^\dagger_{R\uparrow}(x,\tau) \psi_{R\downarrow}(x,\tau) \psi^\dagger_{R\downarrow}(0,0) \psi_{R\uparrow}(0,0) \rangle$$

4-fermion correlator in bosonized form:

$$I^T_{\uparrow\downarrow,\downarrow\uparrow}(x,\tau) \propto -\frac{e^{g(x,\tau)}}{(2\pi a_0)^2},$$

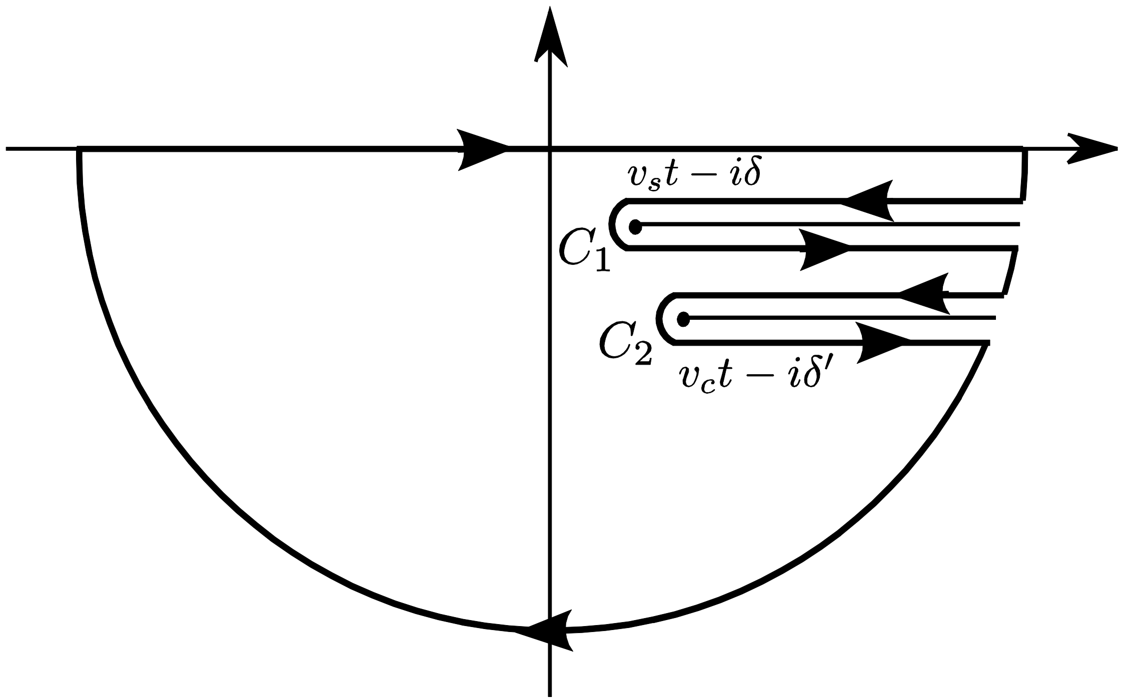
$$I^R_{\uparrow\downarrow,\downarrow\uparrow}(t) = -2\theta(t) I^T_{\uparrow\downarrow,\downarrow\uparrow}(t)$$

$$g(x,\tau) = \sum_{q,\omega} [1 - e^{i(\omega\tau - qx)}] \langle Y(q,\omega) Y(-q,-\omega) \rangle , \quad Y(x,\tau) = i\sqrt{2}[\phi_s(x,\tau) - \theta_s(x,\tau)]$$

Evaluation of Conductivity

Conductivity: $\sigma_\omega = \mathcal{A}\int_{-\infty}^{\infty} dx \int_0^{\infty} e^{i(\omega t - qx)}[K(t+i\delta) - K(t-i\delta)]dt,$

$$K(t) = \frac{1}{(x - v_c t)^\lambda (x + v_c t)^\mu (x - v_s t)^\nu},$$



Conductivity

Conductivity: $\sigma_\omega = \mathcal{A} \int_{-\infty}^{\infty} dx \int_0^{\infty} \frac{e^{i(\omega t - qx)} dt}{(x - v_c t)^\lambda (x + v_c t)^\mu (x - v_s t)^\nu}$

where $\mathcal{A} \propto B_\perp^2 / \alpha$

$$\lambda = (\delta v)^2 \frac{(1+K_c)^2}{8K_c (v_c - v_s)^2},$$

$$\mu = (\delta v)^2 \frac{(K_c - 1)^2}{8K_c (v_c + v_s)^2},$$

$$\nu = 2 - (\delta v)^2 \frac{K_c v_c^2 + (K_c^2 + 1) v_c v_s + K_c v_s^2}{2K_c (v_c^2 - v_s^2)^2}$$

$\delta v \sim \alpha$

strong e-e interaction: $K_c \to 0$

Case of Non-interacting Electrons

Absorption power of EM radiation is $\mathrm{Re}\,\sigma_\omega |E_\omega|^2$

$$\sigma_\omega = \mathcal{A}\int_{-\infty}^{\infty} dx \int_0^{\infty} e^{i(\omega t - qx)} \frac{1}{(x - v_s t + i\delta)^2} dt$$

$$\mathrm{Re}\,\sigma_\omega \simeq \mathcal{A} q \frac{\gamma}{(\omega - \omega_s)^2 + \gamma^2}$$

In the limit $\gamma \to 0$

$$\mathrm{Re}\,\sigma_\omega = 2\pi^2 \mathcal{A} q \delta\left(\omega - v_s q\right)$$

Abanov *et al*, PRB (2012)

$$\mathcal{A} = \frac{2(eg\mu_B B_\perp)^2}{\pi^2 p_F^3 \alpha}$$

Results for interacting wire

Spinon resonance:

$$\mathrm{Re}\,\sigma_\omega \propto \frac{\gamma}{[(\omega-\omega_s)^2+\gamma^2]^{1-\frac{\lambda+\mu}{2}}}$$

$$\lambda+\mu \sim \frac{(\delta v)^2}{K_c}$$

Holon peak:

$$\mathrm{Re}\,\sigma_\omega \propto \frac{\gamma}{[(\omega-\omega_c)^2+\gamma^2]^{1-\frac{\mu+\nu}{2}}}$$

$$\frac{\mu+\nu}{2} \sim 1-\frac{(\delta v)^2}{K_c}$$

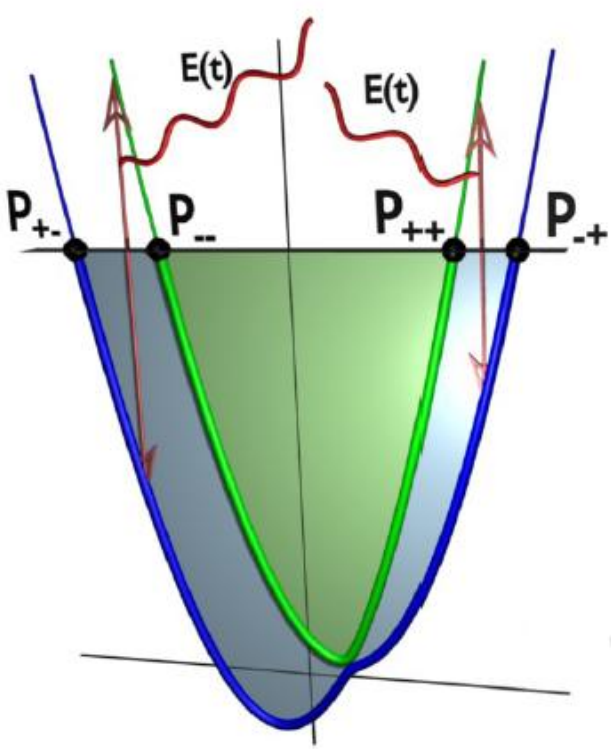
Two resonances

EM absorption power: $\mathrm{Re}\,\sigma_\omega \;\propto\; \dfrac{\gamma}{\left[(\omega-\omega_s)^2+\gamma^2\right]^{1+\Delta_s\frac{(\delta v)^2}{K_c}}} + \dfrac{\gamma}{\left[(\omega-\omega_c)^2+\gamma^2\right]^{\Delta_c\frac{(\delta v)^2}{K_c}}}$

(efficiency of spin flip)

spinon resonance

satellite peak at holon frequency



$\delta v = v_1 - v_2 \sim \alpha$

strong interaction: $K_c \to 0$

Resonant frequency ~ 1 THz

$\hbar\omega_s = 2\alpha m v_s$

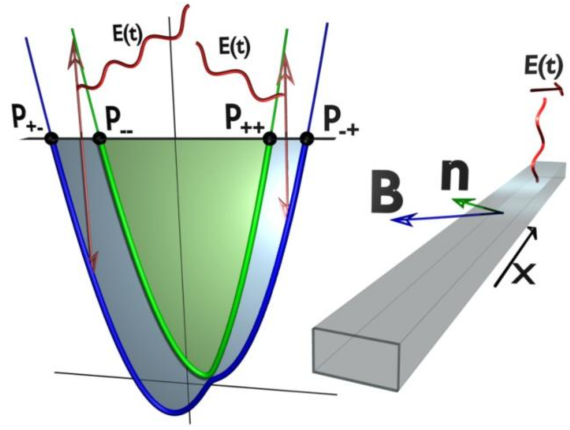
Tretiakov *et al*., PRB 88, 125143 (2013)

Summary

➢ The spin resonance *persists* in Luttinger liquid even though the excitations are bosonic (rather then being fermionic as in the absence of e-e interaction).

➢ The ESR resonance in Luttinger liquid is an excitation of a *spin wave*.

➢Because of spin-orbit interaction, the spin and charge channels are mixed and as a result an additional pick emerges at the *plasmon* frequency.



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