Point contact spectroscopy of hopping transport : effects of magnetic field

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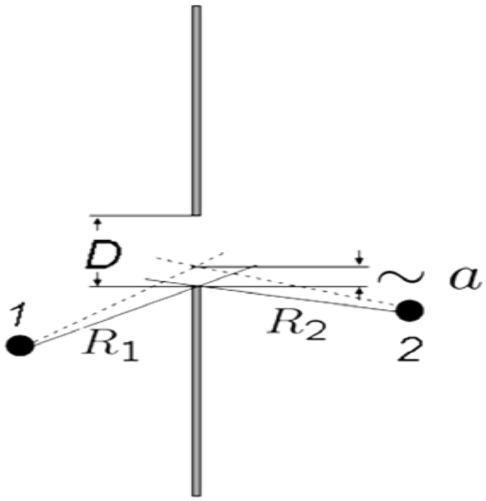


Hopping transport through a constriction (Kozub, Zyuzin, 2004):
It is dominated by a single hop since the corresponding tunneling trajectory is systematically longer than typical hopping length in the bulk

Effect of external magnetic field - ?
We will consider 2D geometry (allowing in particular to change the sites configuration varying the gate voltage).

1. Magnetoresistance.

$$\Psi_1(\mathbf{r},\mathbf{R}) = \frac{1}{\sqrt{\mathcal{N}}} e^{-A(\mathbf{r},\mathbf{R})}, \quad \mathcal{N} = \int d^3r\, e^{-2A(\mathbf{r},0)},$$
$$A(\mathbf{r},\mathbf{R}) = \frac{|\mathbf{r}-\mathbf{R}|}{a} + \frac{|\mathbf{r}-\mathbf{R}|^3 a}{24\lambda^4} - i\frac{[\mathbf{HR}]\,\mathbf{r}}{24\lambda^2}.$$

-> Overlap integral $V_{12} \sim V_0\, e^{-(R_1+R_2)/a}\, e^{-a\left(R_1^3+R_2^3\right)/24\lambda^4}, \quad V_0 \sim \frac{e^2}{\kappa a}$

Magnetoconductance $g(H) \equiv G(H)/G(0) = e^{-a(R_1^3+R_2^3)/12\lambda^4}$

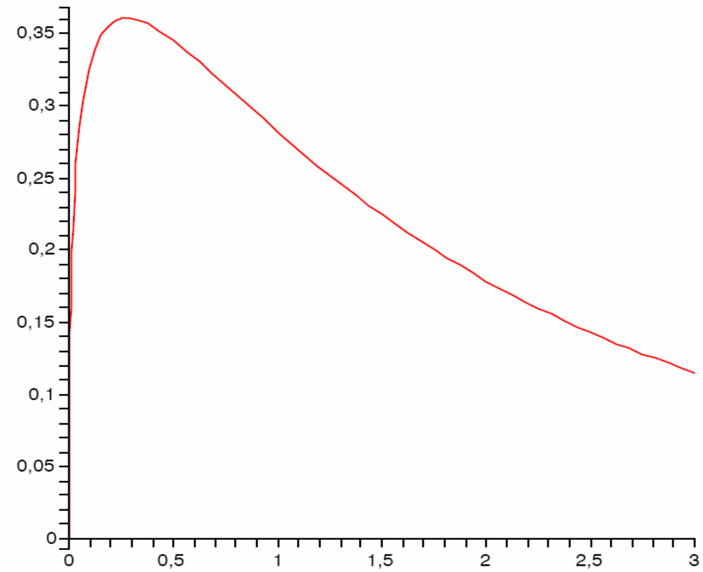
Magnetoresistance $\rho \equiv G(0)/G(H) - 1 = 1 - g(H)$

$\bar{\rho}(H) \equiv= a\bar{R}^3/6\lambda^4 \ll 1$

Distribution function : $\mathcal{P}(\rho) = \bar{\rho}^{-1}\mathcal{F}(\rho/\bar{\rho})$ $\mathcal{F}(z) = \frac{4z^{1/3}}{9}\int_0^1 \frac{d\xi\, e^{-z^{2/3}[\xi^{2/3}+(1-\xi)^{2/3}]}}{\xi^{1/3}(1-\xi)^{1/3}}$

At small g

$$\mathcal{P}(g) \propto g^{\bar{\rho}-1}\ln^3(1/g)$$



$\mathcal{F}(z)$

-Statistics of magnetoresistance
-Strongly differs from that of the resistance

At $\bar{\rho}(H)$ *>> 1 (strong magnetic fields) -*

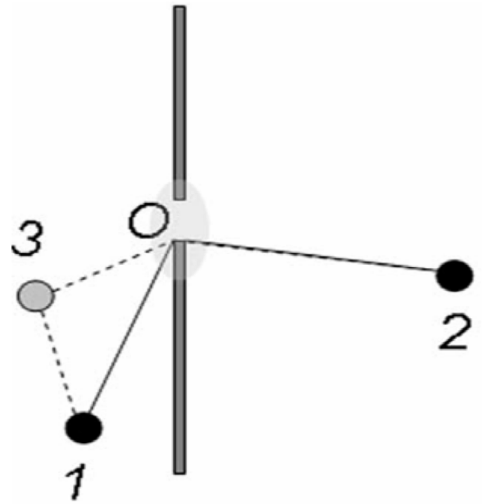
-Giant mesoscopic fluctuations of magnetoresistance due to switching on of the closer pairs of sites with smaller intersite distances

$$F\left(\log\frac{G}{G_0}\right)=\frac{T}{T_0}\left(\log\frac{G}{G_0}\right)^4\exp\left(\frac{T}{T_0}\left(\log\frac{G}{G_0}\right)^4\right)$$

- 2.Aharonov-Bohm effect

$$G \propto \frac{|V_{12}\left(1+Je^{i\varphi}\right)|^2}{\varepsilon_1-\varepsilon_2} = \frac{|V_{12}|^2(1+J^2+2J\cos\varphi)}{\varepsilon_1-\varepsilon_2}$$

$$V_{ij}=V_0 e^{-r_{ij}/a},\ J=\frac{V_{13}V_{32}}{V_{12}(\varepsilon_3-\varepsilon_1)},\ \varphi=2\pi\frac{HS}{\Phi_0}.$$



r_{ij} *- Distance between the sites along the tunneling trajectory*

S is the area of the interference triangle $1-3-O$ $\bar{S} \sim \bar{R}^{3/2}a^{1/2}$

The sites 1 and 2 are within the hopping band while the scattering site 3 can be of any energy, thus

$|\varepsilon_3| \geq |\varepsilon_{1,2}|$ *Consequently the phase of the oscillations can be any depending whether the site 3 is occupied or empty*

The characteristic field for the oscillations is $H_c = \Phi_0/\bar{S} \sim \Phi_0/\bar{R}^{3/2}a^{1/2}$

which is of the same order as the critical field for the magnetoresistance

In the bulk – the interference give rise to negative magnetoresistance (NMR)

(Shklovskii, Spivak, 1991)

Contribution of configurations with smallest hopping probabilities is emphasized – “logarithmic” averaging

Calculations for “strong” (Coulomb) scattering potentials (Raikh et al., 1993) –

Prediction of “universal” behavior of NMR

Experiments – non-universal NMR

Observations of a suppression of NMR at small T in Coulomb-gap regime

(Agrinskaya et al., 1994)

- “weak” scattering” (as considered by Shklovskii and Spivak)?

For “strong” (Coulomb) scattering $V_0 \sim e^2/\kappa a$ the oscillations amplitude $2J/(1+J^2)$ can be of the order of unity. For the weak scattering case $V_0 = \frac{e^2 a}{r}$ the amplitude decreases with a temperature increase. Thus the information concerning the scattering can be obtained.

Then, the phase of the oscillations depend on $sign J$

The Aharonov-Bohm effect depends on a configuration of the sites spins. The modulation depth of the oscillation is given as

$$\mathcal{M} \equiv \frac{\mathcal{G}_{\max} - \mathcal{G}_{\min}}{\mathcal{G}_{\max} + \mathcal{G}_{\min}} = \frac{2|J|}{1+J^2} [n_{1\uparrow} n_{3\uparrow} + n_{1\downarrow} n_{3\downarrow} + n_1(1-n_3)] (1-n_2) = \frac{|J|}{1+J^2} (s_1 s_3 n_3 - n_3 + 2)$$

For the unpolarized spins $< s_1 s_3 >= 0$

If there is a source of spin accumulation or depletion, it affects the modulation depth

In general, for the spin-dependent contribution to the contact conductance one has

$$\frac{\delta G}{G} = \frac{2J}{1+J^2} n_3 < s_1 s_3 >$$

In the equilibrium a relatively weak magnetic field $H_p \approx 2mcT/e\hbar g$

would polarize spins at both sites and one obtains for the corresponding magnetoresistance (Spivak et al., 1991)

$$\frac{\delta G}{G} = \frac{2J}{1+J^2} n_3 \frac{2\tanh^2(H/H_p)}{1+\tanh^2(H/H_p)}$$

Since Hp is well defined, studies of magnetoresistance in weak fields can help to calibrate the device (to measure n3 and J)
Note that the product s1s3, so if the spins are polarized in the same direction, the effect does not depend on the sign of the polarization –
A possibility to observe AC spin accumulation
(Entin-Wohlman,Aharony, Galperin, Kozub, Vinokur, Phys. Rev. Lett. **95**, (2005)

c) Spin-orbital scattering.

For a given tunneling path the scattering can be described by S-matrix

$$S_l = \begin{pmatrix} \alpha_l & \beta_l \\ -\beta_l^* & \alpha_l^* \end{pmatrix}$$

where the matrix elements are related to the spin rotations angles θ, ϕ and ψ as $\alpha = e^{i(\phi+\psi)} \cos(\theta/2)$, $\beta = ie^{i(\phi-\psi)} \sin(\theta/2)$.

Keeping only rotations by θ one concludes that the factors J should be multiplied by $\cos(\theta_a - \theta_b)$

-The spin-orbital interaction can even reverse the phase of Aharonov-Bohm -oscillations

The spin alignment suppresses spin-orbital interactions recovering original A-B oscillations – a unique possibility to quantitative study of spin-orbital effects In hopping conductivity!

d) Mesoscopic Hall effect

A set of 3 sites serves as an elemental “Hall generator”.

While the most of the applied voltage V is concentrated on the pair (1,2), the Hall voltage is generated on the sites (1,3).

If $J \sim 1$ then $V_H \sim (H/H_c)V$

Since this voltage is redistributed over $W_H/\mathcal{L}$ branches, the measured Hall voltage is

$$\frac{V_H}{V} = J \cdot \frac{HS}{\Phi_0} \cdot \frac{\mathcal{L}}{W_H}$$

$\mathcal{L} = \xi r_h$ Is the percolation cluster correlation length, $\xi = (T_0/T)^\nu$ is the hopping exponent.

The comparison to the bulk contribution:

$$\frac{V_H}{V_H^{(\mathrm{bulk})}} \approx \frac{\mathcal{L}\mathcal{L}_H}{W r_h} \approx \frac{\xi}{\eta} \frac{\mathcal{L}_H}{W}$$

where η *V is the (exponentially small) part of the bias dropped* within the lead

Conclusions

1. The point contact allows to obtain a unique information concerning the hopping transport which is not distorted by the averaging procedure:
2. Statistics of magnetoresistance gives information concerning spatial distribution of the hopping sites.
3. Aharonov-Bohm effect allows to study efficiency of the under-barrier scattering and spin-orbital interactions.
4. Aharonov-Bohm effect and magnetoresistance allows to study spin effects including AC spin accumulations
5. Mesoscopic Hall effect gives an information about structure of the percolation cluster.