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PERSISTENT CURRENT, INDUCED BY MAGNETIC IMPURITIES

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Abstract: We calculate the averaged persistent current in mesoscopic normal metal rings (diffusive limit). In the presence of magnetic impurities, we identify a contribution to the persistent current which is related to fluctuations in the electron spin density. Assuming low temperatures ($kT < E_c$) and a spin-flip scattering rate which is comparable in size to the Thouless energy E_c, this new contribution to the persistent current is of the order $I \sim E_c^2/(kT\phi_0)$. This is larger than the persistent current due to the electron-electron interaction.

Weak Spin Scattering: It is known that the persistent current is sensitive with respect to magnetic scattering, but in previous investigations the magnetic impurities were considered as a static, spin-dependent scattering potential and an enhancement of the persistent current due to magnetic scattering was never predicted.

In the present study, we take into account the inner degrees of freedom of the impurity spins. The spins are coupled to the conduction electrons, where we assume the usual local exchange Hamiltonian $H = -J\mathbf{s}(\mathbf{R}) \cdot \mathbf{S}$; $\mathbf{s}(\mathbf{R})$ is the spin density of the conduction electrons at the impurity site. To first order in J, this coupling is equivalent to an additional magnetic field for the impurity spin: $2\mu_B H \to 2\mu_B H + Js^z(\mathbf{R})$. For electrons on a ring, the local spin density depends on the magnetic flux ϕ penetrating the ring. As a consequence the grand potential, Ω, of the impurity is flux dependent, and there exists a persistent current $I = -\partial_\phi \Omega$.

For the explicit calculation, we decompose the electron spin density in its flux independent mean value plus the fluctuations, $s^z(\mathbf{R}) = \langle s^z(\mathbf{R})\rangle + \delta s^z$; then we expand Ω with respect to δs^z and average, with the result

$$\langle \Omega(s^z) \rangle = \Omega(\langle s^z \rangle) - \frac{1}{8\mu_B^2}\chi^{zz} J^2 \langle \delta s^z(\mathbf{R}) \delta s^z(\mathbf{R}) \rangle + \cdots , \tag{1}$$

where $\chi^{zz} = -\partial_H^2 \Omega$ is the bare (longitudinal) susceptibility of the impurity. These rather simple considerations already lead to a new contribution to the persistent current.

We evaluate the fluctuations of the local spin-density using Green's functions. In averaging over impurity configurations, we keep only the diagrams with one particle-particle ladder, i.e. one cooperon. Details of the calculation will be published elsewhere [1,2]. The spin fluctuations and consequently the free energy are periodic in ϕ with periodicity $h/2e$. The Fourier components of the persistent current are found immediately from the Fourier components of the free energy: $\langle I_m \rangle = me\langle \Omega_m \rangle / \hbar$. Note that only the even Fourier components are non-zero.

Strong Spin Scattering: In the case of strong spin-orbit scattering or strong spin-flip scattering, we find a significantly enhanced persistent current.

Let us first assume strong spin-orbit scattering, but rather weak spin-flip scattering. In this case it is straightforward to generalize the calculation described above. We take into account fluctuations in the electron spin density not only in z-direction, but also in x- and y-direction. Eq. (1) generalizes to

$$\langle \Omega(\mathbf{s}) \rangle = \Omega(\langle s^z \rangle) - \frac{1}{8\mu_B^2} J^2 \left(\chi^{zz} \langle \delta s^z \delta s^z \rangle + 4\chi^{+-} \langle \delta s^- \delta s^+ \rangle \right) \tag{2}$$

where χ^{+-} is the *transverse* spin susceptibility. Fig. 1 shows the first non-vanishing Fourier component, i.e. $\langle\Omega_2\rangle$, in units of the Thouless energy $E_c = \hbar D/L^2$. For a low concentration of paramagnetic impurities we have to multiply the results with the number of impurities. We choose the concentration such that the spin-flip scattering rate equals the Thouless energy, i.e. $\hbar/\tau_s = E_c$. For the temperature range in the figure, the temperature dependence of $\langle\Omega_2\rangle$ is mainly determined by the temperature dependence of the susceptibilities χ^{zz} and χ^{+-}: The second harmonic of the free energy is proportional $1/kT$ for $\mu_B H \ll kT$, and proportional to $1/(\mu_B H)$ for a strong magnetic field, i.e. $\mu_B H \gg kT$.

Note that the electron-electron interaction induces an additional contribution to $\langle\Omega_2\rangle$ which is at low temperature (and without magnetic impurities) given by [3] $\langle\Omega_2\rangle = 4\mu^* E_c/\pi$. The dimensionless constant μ^* characterizes the strength of the interaction. However its precise value for copper, the material of which the averaged persistent current has been measured [4], is not known.

The second harmonic of the free energy, $\langle\Omega_2\rangle$, for higher concentrations of magnetic impurities is shown in Fig. 2. Here we consider the low temperature and weak magnetic field limit, where $\langle\Omega_2\rangle \propto 1/kT$. Without spin-orbit scattering (broken line), the persistent current is diamagnetic for small magnetic flux, whereas we find a paramagnetic persistent current in the case of strong spin-orbit scattering (full line).

In conclusion we have shown that magnetic impurities contribute significantly to the persistent current. Thus a future experimental study of persistent currents in the presence of magnetic impurities promises to yield interesting results.

[1] P. Schwab and U. Eckern, in preparation; preliminary results were discussed in Ann. Phys. **5**, 57 (1996).
[2] P. Schwab, Ph.D. thesis, Universität Augsburg, March 1996, unpublished;
see: http://www.physik.uni-augsburg.de/~schwab
[3] V. Ambegaokar and U. Eckern, Phys. Rev. Lett. **65**, 381 (1990).
[4] L. P. Lévy, G. Dolan, J. Dunsmuir, and H. Bouchiat, Phys. Rev. Lett. **64**, 2074 (1990);
L. P. Lévy, Physica B **169**, 245 (1991).

Figure 1:

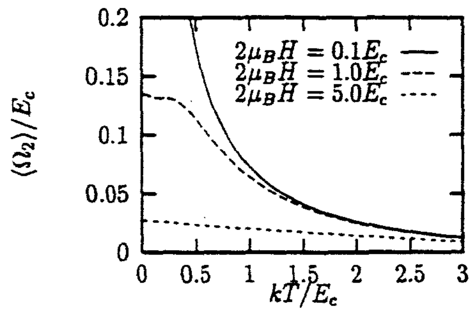

Figure 2: