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Equilibrium current temperature quasi-oscillations in a mesoscopic ferromagnetic loop

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Abstract

Equilibrium persistent current carried by a small ferromagnet-metal loop is considered. This current is shown to be quasi-periodic in temperature at low temperatures. The quasi-period is determined mainly by the temperature dependence of the equilibrium magnetization of the ferromagnet.

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1. Introduction

An equilibrium persistent current arising in a static magnetic field in a single normal-metal loop results in a magnetic response, which periodically oscillates with the magnetic flux ϕ threading the loop [1,2]. These oscillations have a fundamental period given by the flux quantum $\phi_0 = hc/e$ and exist if the electron phase coherence is preserved [2]. The Josephson-type magnetic response of an isolated normal-metal loop subjected to a static applied magnetic field was predicted theoretically [1] and studied experimentally for a variety of mesoscopic systems: an array of about 10^7 isolated mesoscopic cooper rings [3]; a single, isolated micron-size gold loop [4]; a GaAs–AlGaAs single mesoscopic ring [5]; an array of about 10^5 GaAs–AlGaAs single mesoscopic rings [6]; and an array of 30 gold mesoscopic rings [7].

In this paper we consider an equilibrium persistent current carried by an isolated ferromagnet-metal ring in the absence of an applied magnetic field. We show that at low temperatures this persistent current is quasi-periodic in temperature. The quasi-period δT is determined mainly by the temperature dependence of the equilibrium magnetization of the ferromagnet.

2. Ferromagnet-metal ring

Consider a ferromagnet-metal ring at a certain temperature $T \ll T_c$, where T_c is the Courie temperature. Suppose also that there is no applied magnetic field. In this case the electrons of a ferromagnet-metal are subjected to the internal magnetic field $\mathbf{B} = 4\pi\,\mathbf{M}$, where $\mathbf{M}$ is the magnetization. In a small ferromagnet sample $\mathbf{M}$ is uniform as the formation of magnetic domains increases the free energy [8]. Therefore, a magnetic flux ϕ is threading a small ferromagnet-metal ring even in the absence of an applied magnetic field.

A monotonic variation of the internal magnetic field $\mathbf{B} = 4\pi\,\mathbf{M}$ results in a periodic in the flux ϕ equilibrium persistent current oscillations in a ferromagnet-metal ring. This effect is similar to the oscillations in a normal-metal ring subjected to a static magnetic field. The flux ϕ induced by the field $\mathbf{B} = 4\pi\mathbf{M}$ can be presented as $\phi = 4\pi M A_{\rm eff}$, where $A_{\rm eff}$ is an effective area of the ring. The value of $A_{\rm eff}$ depends on the orientation of the magnetization $\mathbf{M}$ and the specific geometry of the ring. In particular, if $\mathbf{M}$ is parallel to the axis of symmetry,

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then $A_{\mathrm{eff}} \sim \pi d D$, where d is the thickness and D is the diameter of the ring.

The equilibrium magnetization of a ferromagnet $M(T)$ is a nonlinear function of the temperature T. A small variation of the temperature $\Delta T \ll T$ results in a flux variation $\Delta\phi = 4\pi A_{\mathrm{eff}}|\mathrm{d}M/\mathrm{d}T|\Delta T$. The equilibrium persistent current is periodic in ϕ with the period given by the flux quantum ϕ_0. Therefore, the nonlinear dependence $M(T)$ results in an equilibrium current which is quasi-periodic in temperature. The quasi-period δT follows from the relation $\Delta\phi = \phi_0$, which leads to the expression

$$\delta T = \frac{\phi_0}{4\pi A_{\mathrm{eff}}\left|\dfrac{\mathrm{d}M}{\mathrm{d}T}\right|}. \tag{1}$$

It is worth noting that Eq. (1) is valid if $\delta T \ll T$.

At low temperatures the dependence $M(T)$ is given by the Bloch law

$$M = M_0\left[1 - \alpha\left(\frac{T}{T_{\mathrm{c}}}\right)^{3/2}\right], \tag{2}$$

where M_0 is the saturation magnetization and the constant $\alpha = 0.2$–0.5 depending on the ferromagnet. It follows from Eq. (2) that

$$\left|\frac{\mathrm{d}M}{\mathrm{d}T}\right| = \frac{3\alpha M_0}{2T_{\mathrm{c}}}\left(\frac{T}{T_{\mathrm{c}}}\right)^{1/2}. \tag{3}$$

Combining Eqs. (1) and (3) we find for the quasi-period δT the final expression

$$\delta T = \frac{\phi_0 T_{\mathrm{c}}}{6\pi\alpha A_{\mathrm{eff}} M_0}\left(\frac{T_{\mathrm{c}}}{T}\right)^{1/2}. \tag{4}$$

3. Summary

To summarize, we demonstrate that the magnetic response of a single one-domain ring of a ferromagnet-metal is quasi-periodic in temperature even in the absence of an applied magnetic field. To estimate the quasi-period δT let us consider a small dysprosium ring. Suppose the temperature $T = 4.2$ K and effective area $A_{\mathrm{eff}} = 3 \times 10^{-8}$ cm^2. Using for dysprosium [9] the data $T_{\mathrm{c}} = 89$ K and $M_0 = 0.29$ T and estimating $\alpha \approx 0.3$ we find $\delta T = 0.3$ K. This value seems to be reasonable for an experimental observation.

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