Equilibrium current temperature quasi-oscillations in a ferromagnetic loop

R.G. Mints

School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel

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 magnetization.

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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 \( \phi \) threading the loop \[ \phi \phi_0 = \frac{hc}{e} \text{ and exist if the electron phase coherence is preserved. The Josephson-type magnetic response of an isolated normal-metal loop subjected to a static external magnetic field was predicted theoretically} \]

\[ \text{ and studied experimentally for a variety of mesoscopic systems: an array of about 10}^7 \text{ isolated mesoscopic cooper rings \[ \text{; a single, isolated micron-size gold loop \[ \text{; a GaAs-AlGaAs single mesoscopic ring \[ \text{; an array of about 10}^5 \text{ GaAs-AlGaAs single mesoscopic rings \[ \text{; and an array of 30 gold mesoscopic rings \[ \text{.} \]

In this paper we consider an equilibrium persistent current carried by an isolated ferromagnet-metal ring in the absence of an external magnetic field. We show that at low temperatures this persistent current is quasi-periodic in temperature. The quasi-period \( \delta T \) 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 Curie temperature. Suppose that the external magnetic field is equal to zero. In this case the electrons of a ferromagnet metal are subjected to the internal magnetic field \( \text{B = } 4\pi M \), where \( M \) is the magnetization. In a small ferromagnet sample \( M \) is uniform as the formation of magnetic domains increases the free energy \[ \text{. Therefore, a magnetic flux } \phi \text{ is threading a small ferromagnet-metal ring even in the absence of an external magnetic field.}

A monotonic variation of the magnetic field \( 4\pi M \) results in a periodic in the flux \( \phi \) equilibrium persistent current oscillations in a ferromagnet-metal ring. This effect is similar to the oscillations in a normal-metal ring subjected to an external magnetic field. The flux \( \phi \) induced by the field \( B = 4\pi M \) can be presented as \( \phi = 4\pi MA_{\text{eff}} \), where \( A_{\text{eff}} \) is an effective area of the ring. The value of \( A_{\text{eff}} \) depends on the orientation of the magnetization \( M \) and the specific geometry of the ring. In particular, if \( M \) is parallel to the axis of symmetry, then \( A_{\text{eff}} \sim \pi d D \), where \( d \) is the thickness and \( D \) is the diameter of the ring.

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

$$\delta T = \frac{\phi_0}{4\pi A_{\text{eff}} \left| \frac{dM}{dT} \right|}.$$  \hspace{1cm} (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:

$$M = M_0 \left[ 1 - \alpha \left( \frac{T}{T_c} \right)^{3/2} \right],$$  \hspace{1cm} (2)

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

$$\left| \frac{dM}{dT} \right| = \frac{3\alpha M_0}{2T_c} \left( \frac{T}{T_c} \right)^{1/2}.$$  \hspace{1cm} (3)

Combining the Eqs. (1) and (3) we find for the quasi-period $\delta T$ the final expression

$$\delta T = \frac{\phi_0 T_c}{6\pi \alpha A_{\text{eff}} M_0} \left( \frac{T_c}{T} \right)^{1/2}.$$  \hspace{1cm} (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 $\delta T$ let us consider a small dysprosium ring. Suppose the temperature $T = 4.2$ K and effective area $A_{\text{eff}} = 3 \times 10^{-8}$ cm$^2$. Using for dysprosium the data $T_c = 89$ 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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