Flux expulsion and flux trapping in mesoscopic cylinder and carbon nanotubes

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Flux expulsion and flux trapping are one of the main features characterizing the superconducting state being a hallmark of a phase coherence. There is a question whether these phenomena can be obtained in non-superconducting structures such as metallic or semiconducting mesoscopic systems.

As we consider the systems without electron pairing it is challenging to see what are the replacement conditions which have to be imposed to get the required coherent behaviour.

We consider a mesoscopic cylinder of lengh L and wall thickness d,

$$d = R_2 - R_1 , \tag{1}$$

(R_2, R_1 are its outer and inner radii respectively) in the presence of a magnetic field H parallel to the cylinder axis. Persistent currents which run in the circumferential direction can shield the external magnetic field leading to interesting collective effects.

Solving the differential equation [1] for the magnetic flux $\phi(r)$ one can formulate the conditions under which the mesoscopic system can exhibit flux expulsion and trapping of the quantized flux. The properties of the system are studied as a function of the shape of the Fermi Surface (FS). We have shown that to get a desired coherent behaviour one has to impose strong geometry and material requirements – the system has to exhibit quasi-1D or quasi-2D conduction. For circular FS the system exhibits a very weak reaction to ϕ followed by flux penetration and the absence of quantization.

We then considered system whose FS has flat regions on its opposite sides. Such FSs are often met in low dimensional systems, *e.g.* in high-T_c superconductors, in organic materials, *bcc* and body centered tetragonal crystals close to half filling and in hole-doped carbon nanotubes. We have shown that systems with d >> 2λ (λ is the penetration depth) exhibit full flux and field expulsion (see Fig. l) and trapping of the quantized flux in Φ_0 units. These coherent phenomena decrease with decreasing the thickness d of the cylinder, leading to partial flux and field expulsion and trapping of the quantized flux, but the effective magnitude of the flux quantum is then less than its full value. In Fig. 2 we show the field expulsion for multiwall carbon nanotubes [2] for different outer radii R_2.

The presented model calculations are valid for temperatures

$$T < T^* = \hbar \upsilon_F / 2\pi^2 R_2 \tag{2}$$

for which persistent currents can be created in mesoscopic systems. Taking, *e.g.* $\upsilon_F = 1.57*10^8$cm/s and $R_2 = 1\mu$m we get T* = 0.6K.

One can also estimate the upper magnetic field H* for which the above considerations are valid. If we equate the energy loss due to flux expulsion and the energy gain due to quantized flux (per single cylindrical sheet) we get

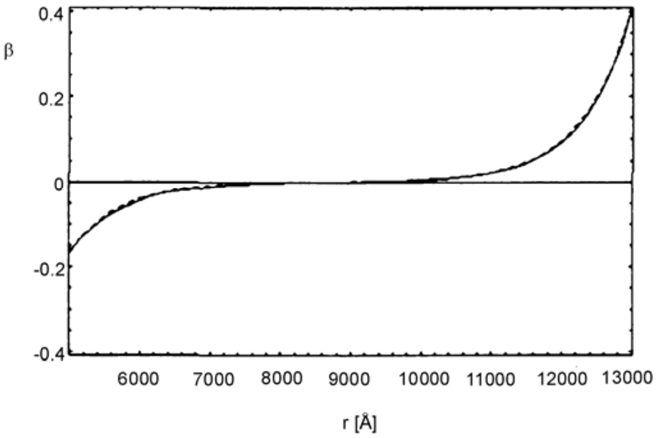
$$H^* = \frac{\phi_0}{4\pi R_2 \lambda}. \tag{3}$$

Assuming, *e.g.* $R_2 = 1\mu m$, $\lambda = 694Å$, one finds H* = 48Gs.

Notice that both T* and H* decrease with increasing R_2 and tend to zero in the macroscopic samples. Thus the presented phenomena can occur in samples of mesoscopic size.

In conclusions we have presented a model considerations which exhibit some features of a superconducting state on a mesoscopic scale, such as the flux expulsion and trapping of the quantized flux although electron pairing was not invoked.

The flux unit in the model is $\phi_0 = h/e.$.



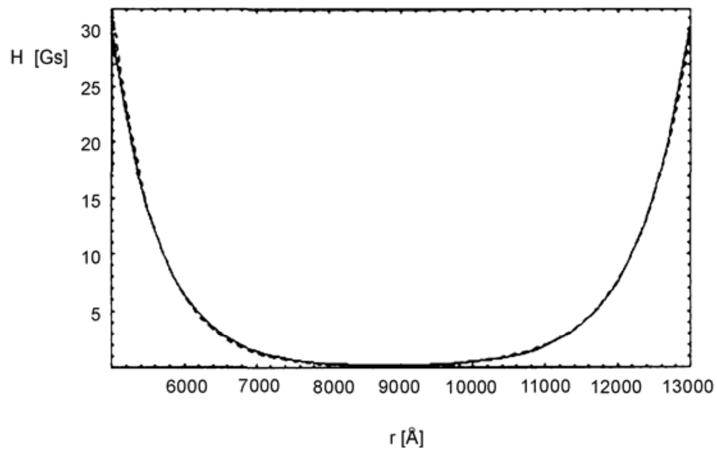


Fig. 1. Magnetic flux β ($\beta(r) = \Phi(r)/\Phi - l$, l integer) and magnetic field H as a function of r for $R_1 = 5 * 10^3Å$, $R_2 = 13 * 10^4Å$, $\lambda = 694Å$.

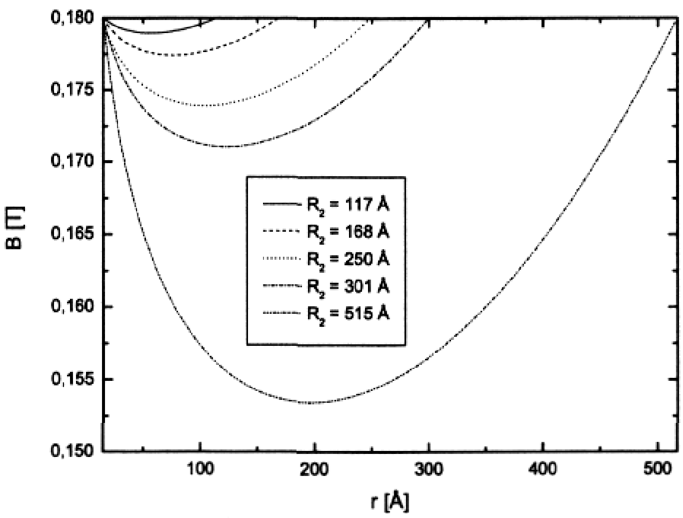


Fig. 2. The field expulsion in the multiwall nanotube as a function of the distance from the nanotube axis, for several outer radii R_2.

Quantum coherence is related here to both the small size of the sample (quantization due to the **Q**uantum **S**ize **E**ffect) and electron correlations coming from the magnetostatic interactions.

[1] M. Czechowska, M. Lisowski, M. Szopa, E. Zipper, Phys. Rev. B 68, (2003) 0353201.
[2] M. Szopa, M. Margańska, E. Zipper, M. Lisowski, submitted for publication.

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