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Letters to the Editor

On the possibility of the Aharonov–Bohm effect observation in transport measurements in charge-density-wave conductor

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We have studied the conditions for the observation of the Aharonov–Bohm oscillatory magnetic flux-dependent component in the transport charge-density-wave (CDW) current in a thin film with columnar defects placed in a strong magnetic field. The flux through an isolated defect exceeds the magnetic flux quantum Φ_0, the defect serves as a solenoid. We predict the percolation and instanton contributions to the oscillatory CDW current. It has been shown that even at moderate temperatures at high enough concentration of columnar defects the amplitude of the ABE produced oscillatory current may reach of order of 10^{-4} of the transport current. The period of the oscillations over the magnetic flux is $\Phi_0/2$.

As it is known, there exist two ways of the experimental observation of the Aharonov–Bohm Effect (ABE) in conductors. In thermodynamic measurements, one studies oscillations of a magnetic moment in a thin conducting loop placed in a magnetic field. In transport geometry, the oscillations of conductance are measured in a circuit containing loop. The mesoscopic Aharonov-Bohm oscillations are periodic in magnetic flux Φ with a period $\Phi_0 = hc/e$ and they appear as a consequence of a topological phase shift $\exp(\pm 2\pi i\Phi/\Phi_0)$ which acquires the wave function of a conducting electron that encircles the flux along the closed loop.

In normal conductors, the mesoscopic ABE is the single-electron effect. It was first predicted in the paper of Krive and author [1] that the mesoscopic ABE existed in a system with a collective conduction — in quasi-one-dimensional Peierls–Fröhlich conductors, in which the charge transfer occurred via the movement of a CDW condensate along the maximum conducting chains. The toy model of a ring-shaped chain was investigated, and it was shown that the CDW excitations contributed to the magnetic moment oscillations. The CDW persistent currents can be observed below the Peierls transition temperature where the single-electron excitations are frozen out. The ideas of the Ref. 1 have been put forward in a series of publications [2–5] in which the novel instanton ABE in CDW conductors, i.e. the persistent currents produced by the topologically nontrivial tunnel fluctuations, had been predicted.

The instanton ABE does not imply the movement of a charge in a real time and thus it is insensitive to a structural disorder, it is ideologically similar to the tunnel-state ABE in dielectrics [4,6]. The collective CDW-produced ABE results in the oscillations with the period $\Phi_0/2$ that is dictated by an order parameter symmetry.

The experimental observation of the collective mesoscopic CDW (and Spin Density Wave) ABE would raise up our knowledge of the coherent phenomena in solid state to a qualitatively new level. Unfortunately, it is impossible yet to grow ring-shaped chain crystals for thermodynamic measurements, and it is worthy to discuss the manifestations of the collective ABE in transport experiments. This is the subject of our communication.

There exist submicron $NbSe_3$ films irradiated by high energy ions which create columnar defects of about 50–100 Å in diameter (by Latishev and Monceau, private communication). These holes may serve as solenoids (Fig. 1). If the average «intersolenoid» distance is much less than the typical coherence lengths in $NbSe_3$ $\xi_{\perp,\parallel} \approx 1\,\mu$m, the flux-dependent current is proportional to the number of holes N. It means that the ABE is most strongly pronounced in electric fields just over the threshold field E_{th}.

One can imagine two scenarios of the CDW-produced ABE: the percolation and the instanton ones. As a result of local destruction of the $NbSe_3$ lattice the percolation one-dimensional trajectories encircling

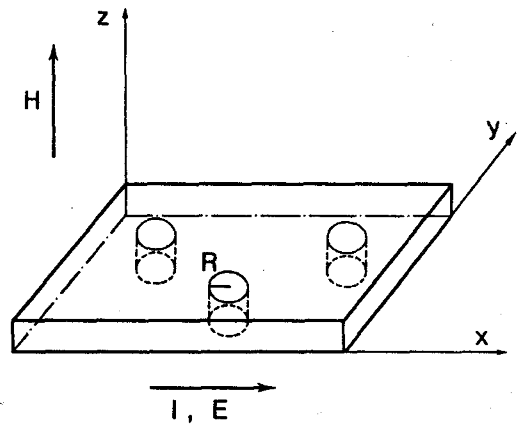

Fig. 1. Geometry of the experiment. Magnetic field H is oriented along the axis of columnar defects (z axis), the transport current I flows along the electric field E (x axis).

the columnar defect can be created. The CDW current flow along such a trajectory acquires the correction which oscillates with the period $\Phi_0/2$. The instanton ABE arises due to the CDW-interchain tunneling along the path which encircles the «solenoid», it also produces $\Phi_0/2$-periodic oscillations. One should distinguish between the transport and the thermodynamic instanton ABEs: in the former each tunneling act occurs under the potential barrier of order of the transition temperature T_c, and in the latter — of order of much smaller energies (weak pinning and commensurability potentials), and correspondingly, the former effect exists at temperatures much higher than the latter one.

The magnitude of the oscillatory term in the percolation ABE can be estimated as

$$I_{CDW}^{\text{osc. perc.}} \approx I \sum_{j=1}^{N^*} \exp\left(-\frac{k_B T\, l_j}{\hbar v_{\parallel}}\right) \cos\left(4\pi \frac{\Phi_j}{\Phi_0}\right) \quad (1)$$

where I is the transport current; l_j is the percolation loop perimeter; Φ_j the flux through the jth hole; $v_{\parallel}$ is the CDW velocity along the conducting chain; N^* is the number of loops.

It is plausible to assume $\Phi_j \sim \pi R^2 H$; R is a columnar defect radius. At l_j being of order of several hundred Angström and $v_{\parallel} \sim 10^6$ cm/s, the exponential factor is of order of $-(pT/10)$, $p \approx 1$.

The instanton ABE is actually much less pronounced because the macrotunneling takes place in three dimensions. At $T \ll T_c \hbar\omega/\Delta$, where ω is of order of the Debye frequency and Δ is the dielectric gap in a single-electron spectrum (in $NbSe_3$ $T_c < \hbar\omega < \Delta$), the probability of the macrotunneling is of order of

$$W \approx \exp\left(-\alpha \frac{L}{\xi_0} \frac{k_B T_c}{\hbar\omega} n\right), \quad (2)$$

where $\alpha \sim 1$; $L = 2\pi R$; $\xi_0 = \hbar v_F/\Delta$; n is of order of the number of layers in the film. In $NbSe_3$, the exponential factor is of order of $-10n$. At present, it is technologically possible to create films containing few layers in which one can expect to observe the instanton ABE. At $T \gg T_c \hbar\omega/\Delta$, the tunnel exponent has the universal form [3] independent of the specific shape of the barrier:

$$W \approx \exp\left(-\gamma \frac{k_B T\Delta}{(\hbar\omega)^2} \frac{L}{\xi_0} n\right), \quad \gamma \sim 1 . \quad (3)$$

The instanton contribution to the current takes the form

$$I_{CDW}^{\text{osc. inst}} \approx I \sum_{j=1}^{N} W_j \cos\left(4\pi \frac{\Phi_j}{\Phi_0}\right), \quad (4)$$

and it is again plausible to put $\Phi_j = \pi R^2 H$.

Estimations show that it is possible, in principle, to observe the CDW ABE in very thin films with many tiny holes. At temperatures of order of several tens Kelvin and at $N \sim 10^6$, the amplitude of the oscillating current can reach $10^{-4} I$.

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