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Aharonov–Bohm interferometry based on helical edge states[1)] (Mini-review)

R. A. Niyazov[+*2)], D. N. Aristov[+*], V. Yu. Kachorovskii[×]

[+]Department of Physics, St. Petersburg State University, 198504 St. Petersburg, Russia

[*]National Research Centre "Kurchatov Institute", Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia

[×]Ioffe Institute, 194021 St. Petersburg, Russia

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The Aharonov–Bohm interferometers (ABI) made of quantum wires with single or few ballistic quantum channels are very attractive as prime devices to probe quantum coherent phenomena and in view of possible applications as miniature and very sensitive sensors of magnetic field. The underlying physics is related to Aharonov–Bohm (AB) oscillations of conductance. The shape and amplitude of these oscillations depend essentially on the strength of the tunneling coupling and on the relation between temperature, T, and level spacing, Δ. For $T \ll \Delta$ and weak tunneling coupling there are narrow resonant peaks in the dependence of conductance, G, on the magnetic flux Φ [1–3]. The positions of the peaks depend on the electron Fermi energy [1] and on the strength of the electron-electron interaction [4]. Remarkably, the interference effects are not entirely suppressed with increasing the temperature, and the resonant behavior of $G(\Phi)$ survives for the case $T \gg \Delta$. Specifically, the high-temperature conductance of the noninteracting ring weakly coupled to the contacts exhibits sharp antiresonances at $\phi = \Phi/\Phi_0 = 1/2 + n$, where $\Phi_0 = hc/e$ is the flux quantum and n is an arbitrary integer number [5, 6]. The antiresonances acquire a fine structure due to the electron-electron interaction [5–8] and are broadened by the weak disorder [9].

The complexity of creating ballistic single- or few-channel interferometers based on conventional semiconductors, such as GaAs or Si, is connected with technological problems of manufacturing one-dimensional clean systems. The efficiency of practically used quantum electronic interferometers is limited by rather stringent requirements, for example, very low temperature for interferometers based on superconducting SQUIDs or the requirement of very strong magnetic fields for interferometers based on the edge states of Quantum Hall Effect systems. Moreover, the antiresonances arising in the usual ABIs at $T \gg \Delta$, are very sensitive to the geometry of the problem [6–9].

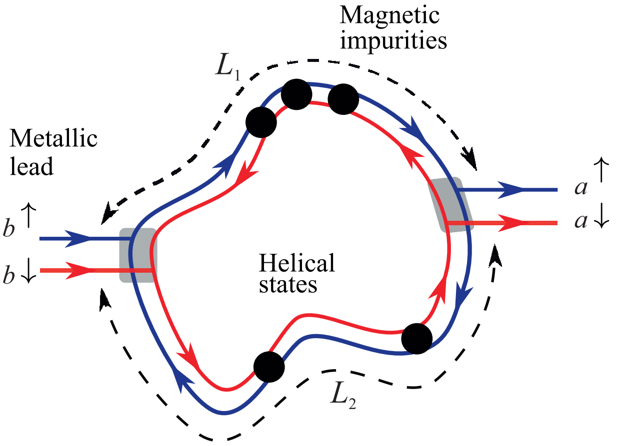

Fig. 1. (Color online) Helical ABI with the magnetic impurities

A promising opportunity for a technological breakthrough in this direction is associated with the discovery of topological insulators, which are materials insulating in the bulk, but exhibiting conducting one-dimensional helical channels at the surface or at the boundaries (see Fig. 1).

The electron transport via helical edge states is ideal, in the sense that electrons do not experience backscattering from conventional non-magnetic impurities. Hence, in the absence of magnetic disorder, the boundary states are ballistic and the intereferometers constructed on such states are topologically protected from external perturbations. Due to this key advantage the helical edge states (HES) are very promising candi-

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[2)] e-mail: r.niyazov@spbu.ru

dates for building blocks in quantum spin-sensitive interferometry. HES-based interferometers were already studied theoretically at zero temperature for normal [10–12] and ferromagnetic [13] leads.

In this review, we focus on the case of relatively high temperature, $T \gg \Delta$. We discuss recent studies of spin dependent transport through HES-based ABI (see Fig. 1) and formulate essential steps towards solving several critical problems of quantum information processing: spin filtering, long-distance spin transfer, and effective spin manipulation. We start by discussing the tunneling conductance of the interferometer. We show that G is structureless in ballistic case but reveals sharp antiresonances, as a function of dimensionless flux ϕ in the presence of magnetic impurities. Although similar antiresonances are known to arise in the single-channel rings made of conventional materials, the helical ABI shows essentially different behavior due to specific properties of the HES. Most importantly, the effect is more universal and robust to details of the setup, in particular, to relation between L_1 and L_2 and the position of the magnetic impurity. Another difference concerns the periodicity of the function $G(\phi)$, which obeys $G(\phi + 1/2) = G(\phi)$, while for interferometers made of conventional materials, this function is periodic with the period 1.

Another property of helical interferometer of key significance for quantum computations is the possibility to operate as a spin filter. Physically, the spin filter blocks transmission of particles with one spin orientation, say spin-down, so that the outgoing current acquires spin-up polarization. Spin transport in HES was already discussed at zero temperature (see [14–17] and references therein). A finite spin polarization arises at high temperature, even in the fully classical regime and is therefore dephasing-insensitive. Even for a nonmagnetic lead the incoming electron beam splits into two parts: right-moving electrons with spin up and left-moving electrons with spin down. If the transmission over one of the shoulders of the system is blocked, say, by inserting a strong magnetic impurity into the upper shoulder, then only the down shoulder remains active and the spin polarization of outgoing electrons can achieve 100 %. Remarkably, this mechanism is robust to dephasing and, therefore, works at high temperatures. The quantum contribution to polarization shows AB oscillations with the magnetic flux piercing the area encompassed by HES and is therefore tunable by external magnetic field. A very sharp dependence of the conductance and the spin polarization on ϕ is very promising for applications for tunable spin filtering and in the area of extremely sensitive detectors of magnetic fields.

Importantly, the tunneling interferometer can be described in terms of ensemble of flux-tunable qubits giving equal contributions both to conductance and spin polarization. The number of active qubits participating in the charge and spin transport is given by the ratio of the temperature to the level spacing. Such an ensemble of qubits can effectively operate at high temperature and can be used for quantum calculations [18]. This opens a wide avenue for high-temperature quantum computing.

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