

Collective oscillations of plasma and order parameter in graphene counterflow superconductors.

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It is known [1] that in systems with Cooper pairing a specific collective excitations can exist, such as: the Anderson–Bogoliubov mode (oscillations of the phase of the order parameter), the Schmid mode (oscillations of the modulus of the order parameter), and the Carlson–Goldman mode (coupled oscillations of the phase of the order parameter and the scalar potential). These modes can exist under certain conditions. A genuine Anderson–Bogoliubov mode can appear in neutral superfluids, and the Carlson–Goldman mode exists in a very narrow temperature range near T_c .

We consider [4] a possibility of these modes existence in a double layer graphene system with electron-hole pairing. Such a system consists of two parallel graphene layers, which are spatially separated. If one layer has an electron conductivity and the other layer has a hole conductivity, then electrons and holes from the opposite layers can form pairs, which are similar to the Cooper pairs. This system is an example of a so-called counterflow superconductor [2,3].

The influence of electron-hole pairing in the double layer graphene system on collective plasma excitations is investigated under accounting for the order parameter fluctuations. It is established that out-of-phase oscillations of the order parameters of two spin subsystems are uncoupled from electromagnetic field oscillations. The spectrum of these oscillations splits into two branches: a low-energy (weakly damped, $\hbar\omega < 2\Delta$) and high-energy (strongly damped, $\hbar\omega > 2\Delta$) ones. Here 2Δ is the gap in the electron spectrum caused by the pairing. The low-energy branch can be considered as an analog of Anderson–Bogoliubov mode and the high-energy—as an analog of Schmid mode. At small wave vectors q the Anderson–Bogoliubov mode has an acoustic dispersion $\omega \approx qv_F/\sqrt{2}$ (v_F is the Fermi velocity), and its frequency saturates at $\hbar\omega = 2\Delta$ at large q . The Schmid mode exists only at small q .

It is shown that in-phase oscillations of the order parameters of two spin subsystems are hybridized with out-of-phase oscillations of scalar potentials in layers. The spectrum of these oscillations also splits into two branches: a low-energy (weakly damped, $\hbar\omega < 2\Delta$) and high-energy (strongly damped, $\hbar\omega > 2\Delta$). The low-energy mode can be interpreted as Carlson–Goldman mode and the high-energy—as a strongly damped acoustic plasmon mode. The Carlson–Goldman mode exists at all temperatures below the critical one, in contrast with conventional superconductors in which this mode appears only near the critical temperature. Similarly to the Anderson–Bogoliubov mode, the Carlson–Goldman mode demonstrates an acoustic dispersion at small q and its frequency saturates at $\hbar\omega = 2\Delta$ at large q .

It is established [4,5] the existence of two symmetric (optical) plasmon modes in counterflow superconductors, which correspond to in-phase oscillations of the scalar potentials in the layers. These modes are uncoupled from order parameter oscillations.

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