Superconducting system with current in the ground state

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PACS numbers:

About the paper SUPERCONDUCTING SYSTEM WITH WEAK COUPLING TO CURRENT IN GROUND-STATE by BULAEVSKII L.N., KUZII V.V., SOBYANIN AA

In the paper Pis'ma Zh.Eksp. Teor. Fiz. 25, 314, 1977, Bulaevskii, Sobyanin and Kuzii (BSK) introduced conception of SIS π junction consisting two singlet s wave pairing superconductors S separated by the dielectric I with magnetic impurities. This advance was based on previous finding by Kulik (Zh. Eksper. Teor. Fiz. 49, 1211, 1965) that magnetic impurities inside dielectric I in SIS junctions diminish the superconducting critical current. The physical reason for that is that tunneling of Cooper pair with opposite spins of electrons gives negative contribution to the critical current (and thus to junction superconducting energy) as compared with contribution of tunneling via nonmagnetic atoms. BSK argued that if tunneling via magnetic atoms becomes dominant over nonmagnetic ones, critical current will be negative resulting in the junction ground state with the phase difference π instead of 0 as in ordinary junctions. In both cases, π or 0 junctions, supercurrent in the ground state vanishes. However, BSK showed that if one connects (shorts) the superconducting electrodes with the inductance L (e.g. superconducting wire), one may expect the spontaneous supercurrent circulating in the loop, passing through the junction and through inductance clockwise or counterclockwise. This supercurrent is spontaneous and direction of its circulation is chosen at random. Such a supercurrent will induce a magnetic field which can be detected experimentally. The magnetic flux passing through the loop will have the value in the range from 0 to a half of magnetic flux quanta, i.e. from 0 to $\Phi_0/2$, depending on the value of inductance L.

Four years later Bulaevskii, Buzdin and Panyukov (Pis'ma v Zh. Eksp. Teor. Fiz. 35, 147, 1981) showed that π junction may be realized in the system SFS with ferromagnet F because exchange field in F results in oscillating behavior of the junction phase difference on the thickness of F layer. Hence, thickness of F layer may be chosen in such a way that phase difference on opposite edges of this layer will be π while the critical current will be negative. Experimentally such a π junction was made 20 years later by Ryazanov *et al.* (Phys. Rev. Lett. 86, 2427, 2001).

In 1987 Geshkenbein, Larkin and Barone (Phys. Rev. B 36, 235, 1987) showed that the system SS'S with heavy fermion p wave superconductor S' may exhibit behavior similar to π junction because p wave superconducting order parameter changes sign on crystal edges with opposite orientations. This notion becomes very useful to identify high temperature superconductors as those with d wave pairing. In this case superconducting order parameter changes sign for orientations along ab plane which differ by 90 degrees. Indeed, Tsuei and Kirtley, (Rev. Mod. Phys. 72, 969, 2000) made first π junction in this way, as a corner junction in yttrium barium copper oxide crystal (d-wave) and Pb (s-wave) superconductors and proved unambiguously d wave pairing in that copper superconductors.

Later it was proved experimentally that SIS system with dielectric I containing magnetic impurities exhibits supercurrent in the ground state as 0 and π regions were induced by magnetic impurities inside junction, see O. Vavra *et al.* Phys. Rev. B 74, 020502, 2006.

Nawdays several other technologies are available to introduce π phase shift inside Josephson junctions, see Schulz, , *et al.* Appl. Phys. Lett., 76, 912, 2000; J. J. A. Baselmans, *et al.*, Nature, 397, 43, 1999; J-P. Cleuziou, *et al.*, Nature Nanotechnology, 1, 53, 2006. Finally, π junctions were proposed as an elements inside qubits capable to reduce noise in such quantum devices. This is a reason that they are in focus of recent activity in the fields of superconductivity and quantum computing.