

Abstract

論文の内容の要旨

論文題目 Theoretical study on the dynamics of the vortices and the Josephson junctions of superconductors

(超伝導体における渦糸およびジョセフソン接合のダイナミクスの理論的研究)

氏 名 三崎 航

The important effective degree of freedom inside the superconductor is the superconducting phase, which emerges because of the coherence of the wavefunction of cooper pairs established below the superconducting transition temperature. Although the superconducting phase is gauge dependent and therefore is not measurable in experiments, the difference of the phases between two superconductors is well-defined. In Josephson junctions where the two superconductors are separated by the normal state thin film, $I - V$ curve is determined by the dynamics of the superconducting phase difference, which is described by the Josephson relation, $\hbar\dot{\varphi} = 2eV$, where V is the voltage drop and φ is the phase difference. The fact that the experimentally obtained $I - V$ curve matches with the prediction of the theory of Josephson effect based on the dynamics of φ is an important experimental evidence of the coherence inside the superconductors.

Another important feature of the superconductor is the rigidity against the magnetic field, known as “generalized rigidity” à la P. W. Anderson. The magnetic field inside the superconductor obeys the London equation, $\Delta B = (n_s/m)B$, where B is the magnetic field, m is the electron mass, and n_s is the superfluid density. The left hand side of the London equation comes from the usual Maxwell term, while the right hand side is peculiar to the superconducting system, and comes from the generalized rigidity. In type I superconductor, from this equation, the magnetic field cannot penetrate into the bulk superconductor beyond the so-called London penetration depth $\lambda = \sqrt{m/n_s}$. In the type II superconductor, when we apply the magnetic field to the system, the magnetic field penetrates into the system as a $\Phi_0 = h/(2e)$ flux line with the characteristic size determined by the London penetration depth. The flux line is always quantized

to be the multiple of Φ_0 , and if we consider the circle surrounding the Φ_0 flux line, the superconducting phase grows by 2π along the circle because of the magnetic flux. The superconductivity is lost in the region near the flux line, and the superconducting gap approaches zero with the characteristic length called coherence length. This Φ_0 flux line with the core of the normal state is called a vortex. Since the motion of the vortex causes the time-dependent change of the superconducting phase, because of the Josephson relation, the motion of vortex leads to the finite voltage drop, i.e., the finite resistivity. Therefore, the resistivity of the superconductor under the magnetic field is determined by the dynamics of the vortices.

In this thesis, we will discuss the dynamics of the vortices in the superconductors and the superconducting phase degree of freedom. First, we will discuss the low temperature thermodynamic phase of superconductors in the presence of the finite magnetic field. In highly crystalline superconductors with finite magnetic field, experiments report the thermodynamic phase with very low resistivity ($R \ll R_q = h/(2e^2)$, where R_q is the quantum resistivity) down to the very low temperature. The theoretical understanding of this low temperature phase known as “the failed superconductor” remains unsettled. As we mentioned above, the motion of vortices leads to the resistivity, so we believe that the dynamics of the vortices is important in understanding the failed superconductors. The difficulty of the theoretical understanding of the failed superconductor lies in the fact that, since the vortices are known to behave as bosons, they exhibit the superfluidity at low temperature. The superfluid phase of vortices physically means that the system becomes insulator, so the resistivity cannot remain low at low temperature. However, we will argue that, although the vortices are bosons, they fail to exhibit superfluidity because of the low energy continuum degrees of freedom inside the normal core, which acts as the source of dissipation. We will show this suppression of superfluidity by dissipation both in the numerical and the field-theoretical calculation, in the first-quantized and the second-quantized formulation, respectively. The physical argument for the suppression of superfluidity, the importance of the Galilean invariance breaking, and the experimental consequences will be further discussed.

Secondly, we will discuss the theory of Josephson effect when the two bulk superconductors show different charge response property. In this case, the system lacks the inversion symmetry, and the shape of the $I - V$ curve is not antisymmetric under the sign change of the current bias I , i.e., $V(I) \neq -V(-I)$. This asymmetry of $I - V$ curve is called the nonreciprocity. The important example of the nonreciprocal system is the p-n junction, where the difference of the dopant of the two bulk semiconductors lead to the drastically different behavior for positive and negative bias case. The aim of our study is to extend this nonreciprocity caused by the difference of the bulk materials in normal junction system to the Josephson junctions. We will discuss the nonreciprocity both for the classical and quantum dynamics of the superconducting phase variable.

In the classical case, the nonreciprocity is realized for the relatively small junction where the dynamics of the superconducting phase variable is underdamped. In the absence of the thermal fluctuation, we analyze the dynamics using the methods developed in the dynamical systems. For finite temperature case, the nonreciprocity in the large deviation function will be discussed. For the quantum case, we will discuss the nonreciprocal $I - V$ curve caused by the nonreciprocal Bloch oscillation and the nonreciprocal Zener tunneling. The experimental detection of the nonreciprocity from the 2ω measurement will be further discussed.