Summary of thesis:
Edelstein effect and diode effect
in noncentrosymmetric superconductors

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In this thesis, I report a theoretical investigation of various transport response phenomena in noncentrosymmetric superconductors. Inversion symmetry breaking affects electronic states in the form of spin-orbit interactions. As a result, phenomena called Fermi surface splitting (Rashba splitting) and spin-momentum locking occurs. In the superconducting state, a peculiar quantum state also appears. This paper aims to investigate the effect of such a peculiar quantum state on the transport response quantities.

In this thesis, I describe the following two main results.

Discovery of an enhancement of the Edelstein effect (magneto-electric effect) on the surface of d-wave topological superconductors (Chap.2).

Discovery of sign reversal and efficiency enhancement of the superconducting diode effect under weak impurity scattering (Chap.3).

In Chapter 2, we discuss the Edelstein effect in superconductors. In systems with inversion symmetry braking, the spin and momentum of electrons are coupled due to the spin-orbit coupling and the Fermi surface splits, as described above. It is known that applying an electric current to such a system induces spin magnetization. In the field of spintronics, this phenomenon is called the Edelstein effect. Switching of magnetization domains by electric current using this phenomenon has been reported and is attracting particular attention in terms of applications. However, it is known that domain switching using this effect usually requires a huge current density, and the Joule heating created by the dissipative current is problematic. Therefore, spintronics using dissipation-free superconducting currents is a solution to the problem. On the other hand, in the field of superconductors, it has been reported that there exists a surface state protected by topological invariants in d-wave superconductors with spatial inversion symmetry breaking. This surface state is called the surface Majorana state due to its similarity. This surface localized state is known to have a peak near zero energy due to particle-hole symmetry. I have calculated the Edelstein effect using this surface Majorana state, noting that it is an ideal stage for obtaining giant transport response phenomena. I found that the Edelstein effect is enhanced by about two orders of magnitude at the

surface of the d-wave superconductor. Furthermore, it is found that the enhancement at the surface is caused by the surface Majorana state.

In Chapter 3, we discuss the superconducting diode effect. Nonreciprocal transport phenomena are one of the central research topics in modern condensed matter physics. Nonreciprocal transport refers to the inequivalence of transport response quantities in one and opposite directions. A concrete example is the rectification effect of an ideal diode, i.e., a phenomenon with finite resistance in one direction and infinite resistance in the opposite direction. Recently, a non-equivalence in the superconducting critical current was discovered in the superconductor Nb/V/Ta. By appropriately adjusting the magnetic field and applied current, it is possible to create a situation in which a non-dissipative supercurrent flows in one direction and a dissipative current flows in the opposite direction. This is called the superconducting diode effect. Since the diode is one of the fundamental devices of modern electronics, energy-saving circuits based on it are expected to be developed, and it is essential to further research and development. Microscopic theoretical calculations in the deparing mechanism have revealed that the superconducting diode effect increases beyond the scaling law near the superconducting transition temperature and that the sign of the diode effect reverses in the low-temperature high-field region. Interestingly, the magnetic field region where the sign of the diode effect reverses roughly coincides with the crossover region of the superconducting state called helical superconductivity. Most of the above studies assume a pure superconductor, but impurity effects are an unavoidable problem in real superconductors. The diode effect at low temperatures exhibits interesting features, but the impurity effect in this regime has not been clarified. I formulate a microscopic theory for the intrinsic superconducting diode effect with disorder and find that the sign reversal of the diode effect is preserved under weak impurity effects. Furthermore, the peak position of the diode effect was found to capture the precursor of the helical crossover. This indicates that the superconducting diode effect has the potential to be an experimental probe of helical superconductivity. It was also found that the efficiency of the diode effect can be increased from about 15% to 20%.

Both of the above results clarify transport phenomena unique to noncentrosymmetric superconductors and are expected to lead to the development of properties of thin-film superconductors.