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Chapter

Introductory Chapter: Superconductivity in Progress

Heshmatollah Yavari

1. Introduction

Describing the behavior of strongly correlated systems is a challenge for every area of physics. The many-body ground state that emerges in these systems can have exotic and unexpected properties. As a remarkable of these correlated systems was the discovery of superconductivity by Onnes in 1911 [1], which opens active areas of study in the field of condensed matter physics.

This state is a quantum phenomenon that is displayed by certain materials under particular magnetic and temperature regimes. The Meissner effect discovered in 1933 shows that superconductivity is more than just the disappearance of resistance and it is a true thermodynamic state of matter because it leads to the superconductors as perfect diamagnetism materials [2]. This effect distinguishes a superconductor from a perfect conductor.

To describe these phenomena, a lot of theoretical works were proposed. The first phenomenological theory which is known as London theory was proposed by the London brothers [3]. This theory described well the magnetic properties and magnetic penetration depth of Type I superconductors in weak magnetic fields. By extending the London theory, Ginzburg and Landau proposed a phenomenological theory, which enables the study of Type II superconductors in a strong magnetic field [4]. By assuming the second-order phase using physical intuition and using variational principle of quantum mechanics, the Ginzburg-Landau (GL) theory allowed the calculation of macroscopic quantities of the material in the superconducting state. The most beautiful and successful theory in condensed matter physics, i.e. the microscopic theory of superconductivity which is known as BCS theory was formulated by Bardeen et al. [5].

The starting point of this theory was an effective Hamiltonian of fermionic quasiparticle excitations that interact via a weak phonon-mediated potential close to the Fermi surface. This attractive interaction leads to bound electron pair states known as Cooper pairs. While the single electrons are fermions, not being able to occupy the same state due to Pauli exclusion principle, Cooper pairs are no longer obliged to obey the Fermi-Dirac statistics, and like bosons, they can enter the same state. Superconductors that can be described by the BCS theory are known as conventional superconductors.

The discovery of high-temperature superconductors (HTS) in 1986 [6] presented another challenge for theoretical physicist. Their superconductivity mechanism remains one of the most challenging problems in physics. It is believed that the BCS theory alone cannot explain properties of these classes of superconductors and new theoretical concepts will be required. This unexpected discovery opened a new area in the history of superconductivity, and experimental researchers started trying to find new compounds in this class of superconductors. In the following years, many different HTS compounds with high transition temperatures were found [7–9]. Unfortunately, most HTS compounds are ceramic in nature and thus their industrial application (e.g., cables and conductors) is difficult. The symmetry of the Cooper pairs in exotic superconductors like cuprates, heavy-fermion [10, 11], organic superconductors [12], and Sr_2RuO_4 [13] is different from conventional superconductors. Since the pairing symmetry of these superconductors is no longer s-wave, they are known as unconventional superconductors and the study of them has become a central issue in condensed matter physics. These superconductors are often characterized by the anisotropic character in the superconducting gap function with nodes along a certain direction in the momentum space [14, 15]. Since the pairing interaction has an important role in the superconducting gap structure, its determination is very important to explain the basic pairing mechanism. The experimental techniques for the determination of the nodal structure such as phase-sensitive experiments [16] and angle-resolved photoemission spectroscopy (ARPES) [17] are suitable for HTC cuprates but are difficult to apply to other unconventional superconductors with low transition temperature T_c. Therefore, the superconducting gap structure of most unconventional superconductors is still unclear.

The classification of the superconducting order parameter is determined by its behavior under symmetry transformations. From the viewpoint of symmetry, the full symmetry group of the crystal includes the gauge $U(1)$, crystal point G, spin rotation $SU(2)$, and time reversal symmetry T groups, and has the following form:

$$\mathfrak{R} = U(1) \otimes G \otimes SU(2) \otimes T \quad (1)$$

Below the transition temperature, the $U(1)$ symmetry is broken automatically by the phase coherence in the superconducting state. If symmetries other than $U(1)$ are kept, the superconducting state becomes conventional.

Superconductors that yield due to breaking additional symmetries besides the $U(1)$ symmetry [14] are unconventional superconductors. Thus, unconventional superconductors can be classified by determining the symmetry properties of the order parameter besides gauge symmetry.

By using the parity state in space of Cooper pairs, we can classify superconductors as those with even (spin singlet) and odd (spin-triplet) parities. The discovery of superconductors without inversion symmetry (noncentrosymmetric superconductors) such as $CePt_3Si$, UIr, $CeRhSi_3$, and $CeIrSi_3$ [18–21] has opened a new field to the theoretical study of superconductivity. The induced Rashba-type spin-orbit coupling due to absence of inversion symmetry leads to the superconducting state with mixed parity [22–25].

Motivated by new symmetry classes that appear in disordered superconductors, they have also gained great attention for theoretical studies [26–28]. In these systems, the single particle momentum is no longer a good quantum number and plain-wave eigenfunctions with momentum k should be replaced by position-dependent functions and pairing is between time-reversed states.

To find these functions, the generalized Hartree-Fock equations including the pairing potential of the superconducting state can be used, which leads to Bogoliubov-de Gennes (BdG) equations. The BdG equations are mostly used to describe the behavior of elementary excitation or quasiparticles that are created by Cooper pair breaking in the superconductors. Simultaneously, the properties and classification of the dirty superconductor can be determined by the BdG equations, where pairing symmetry is reflected.

When we apply magnetic field on the superconductor, depending on the strength of the magnetic field, the spin-polarized (strong magnetic field) or BCS states (weak magnetic field) will be favored. In the intermediate region of magnetic field, the Cooper pairs with opposite spins and net momentum are formed and Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state is realized [29, 30]. In this state, both translational and rotational symmetries are broken. This state is attractive for particle and nuclear physicists, because it is realized in high-density quark matter, nuclear matter, and cold fermionic atom systems [31]. In addition to FFLO states, there are other types of fascinating superconductors with multiple broken symmetry, such as ferromagnetic superconductors. According to the BCS theory, Cooper pairs in s-wave superconductors could be destroyed by an exchange field, which is known as paramagnetic effect, and it can be observed within a specific temperature interval with the maximum paramagnetic Meissner temperature.

Although, ferromagnetism and superconductivity have opposed order much attention has been paid due to nontrivial phenomena which predicted theoretically or found experimentally [32–34]. Ferromagnetic superconductors are expected to have triplet pairings since triplet pairings and ferromagnetism can coexist. So far, several ferromagnetic superconductors in bulk materials, for example, UGe 2 [35], ZrZn 2 [36], and URhGe [37], have been identified.

As mentioned earlier, symmetry is a cornerstone in the theory of superconductivity, and the properties of the Cooper pairs, that is, the basic constituents of superconductors, are determined by symmetry. Mathematically, correlation of two electrons to make Cooper pair depends on the position, spin, and time coordinate of these electrons. In BCS theory, the time coordinate is usually ignored but the symmetry property of a paired state allows for the interesting possibility that the two electrons are not correlated at equal times and that they are instead correlated as the time separation grows. In fact, this is realized if the correlation function is odd in time. This novel type of superconducting correlation that is odd in relative time or frequency is known as odd-frequency pairing and it has attracted a lot of attention. The pairing mechanism of odd-frequency superconductors had been theoretically introduced by Berezinskii in the context of superfluid ^{3}He [38]. This pairing mechanism was also predicted in ferromagnet/conventional superconductor junctions due to the breakdown of symmetry in spin space [33, 34]. The experimental results show that odd-frequency pairing exists near the interface in normal metal/superconductor junctions due to the violation of translational symmetry [39]. Consequently, the symmetry breaking more than U(1) is important for existence odd-frequency pairing. The emerging field of complexity in strongly correlated electronic systems may be connected to multiple symmetry breaking systems [40].

Quite analogously with noncentrosymmetric superconductors without inversion symmetry, where even- and odd-parity components are mixed, a mixing of even- and odd-frequency components should occur in principle, when the time reversal symmetry is broken, which affects many superconducting properties [41]. For example, the mixing of the conventional s-wave singlet with the odd-frequency triplet component in the presence of uniform magnetic fields, which may also be related to superconductivity coexisting with ferromagnetism, was proposed [42].

In last few years, technological advancement allowed to build superconductors of mesoscopic size like single electron transistors, quantum wires, quantum dots, quantum Hall systems, normal metal-superconductor-ferromagnet hybrid structures, magnetic multilayer systems, carbon nanotubes, graphene, small metallic nanoparticles, and nanomechanical systems, which are considered for both experimental and theoretical investigations [43–45]. In comparing with natural systems, artificial systems are of more interest for investigations because their transport properties can be measured in a more controllable way.

The superconducting properties of mesoscopic superconductors, in which one or more dimensions are comparable with the coherence length, differ remarkably from those of bulk superconductors and their properties such as the critical temperature and the critical fields are affected by the size of the sample. On the other hand, thermal and quantum fluctuations, which are strongly enhanced in these systems, cause dissipation and prevent the formation of the long-range-ordered state.

The study of emergent phases, phase competition, phase transitions, interactions between particles, and dimensional confinement in superconductors, which are of basic interest in the fundamental physics of magnetism, superconductivity, magnetoelectric and spin-dependent transport, is the central goal of the researchers. Their activities may produce new intuition on several related and persistent open questions in condensed matter physics and the results of these studies may also have practical implications for potential applications in spintronics and superconducting micro- or nano-electronics devices. The surface states of topological insulators have attracted strong interest in the past few years. The unique properties of the surface states provide a favorable field to explore emergent phenomenon, such as Majorana fermion-like excitations and quantum anomalous Hall effect. They are also considered attractive candidates for spintronic devices with pure spin current that can be controlled by electric field.

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