

SUPERCONDUCTIVITY

A FASCINATING

STATE OF MATTER



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Ladies and Gentlemen,

It is a great honor for me to be awarded the Latsis Prize. I would like to express my sincere gratitude to the family Latsis and their foundation. It is my pleasure to introduce my working field, the theoretical study of superconductivity, to you.

Superconductivity is one of the most intriguing phenomena in solid state physics. A large number of metals undergo a transition to this peculiar state at a low enough temperature. The commonly known signs of superconductivity are vanishing electrical resistance and the complete expulsion of the magnetic field, the Meissner-Ochsenfeld effect. The former serves for loss-free transport of electrical power, while the latter provides the basis for the technology of levitation trains. These two phenomena do not, however, by any means exhaust the spectrum of phenomena in the superconducting state. A variety of other properties, no less intriguing, make superconductivity one of the most active research fields in physics.

In the past 20 years we have seen the discovery of several new classes of superconductors which distinguish themselves strikingly from the previously known ones. There are superconductors among the low-dimensional organic compounds, the mostly uranium-based heavy fermion systems, but probably the best-known are the high-temperature (copper-oxide) superconductors discovered in Switzerland in 1986 by G. Bednorz and K.A. Müller. Although these superconductors are in many respects different from each other, most of them have the common feature that they belong to the class of so-called unconventional superconductors. In this context unconventional refers to the symmetry of the superconducting state as I will explain below [1].

Cooper pairing symmetry

In the microscopic view superconductivity is explained as a condensate in which electrons form pairs, so-called Cooper pairs. The paired electrons no longer act individually as in normal metals, but, for some deep reason, enter into a cooperative - we say macroscopically coherent - state. In this state the dissipation of energy is impossible, resulting in zero electrical resistance. In recent years it became clear that the form (internal symmetry) of Cooper pairs has very important implications on the physical properties of superconductors [1]. In standard superconductors, the Cooper pairs, described by a quantum mechanical wave function, have the highest possible symmetry and are consequently rather structureless, and in some respects dull. Unconventional superconductors, however, possess for various reasons Cooper pairs of lower symmetry leading to an interesting internal structure of the condensate.

The symmetry of the superconducting state is by no means an obvious, easily observable property of a superconductor. Indeed it is a long way from the first hint of unconventionality to the final experimental proof. Nevertheless, there are a few examples of compounds where we can be quite confident today that their superconducting state has lower symmetry. Those are the heavy fermion superconductors UPt_3 , UPt_3 and Sr_2RuO_4 [1] and, at least, some of the high-temperature superconductors [2]. In the last case the issue of symmetry led for some time to a large controversy, but could finally be resolved by experiments which I will introduce in the following section.

Tell-tale features of unconventional superconductivity

Many experiments were proposed from the theoretical side to identify the symmetry of the superconducting state. So far the most successful proposal, realized experimentally for the first time only

about four years ago, is based on the Josephson effect. This effect occurs if two superconductors are weakly connected with each other. Then the condensates in the two superconductors are no longer independent, but show macroscopic quantum coherence via mutual exchange of Cooper pairs. It is the geometrical aspect of the Josephson contacts which allows us to probe the superconducting state selectively in certain directions of the crystal lattice [3].

The coherence in the Josephson effect is most obvious in interference patterns of the maximal current which can pass through the contact when a magnetic field is applied. The aim is to create a device which probes simultaneously various directions of the superconductor and would via distinctive interference feature reveal the internal symmetry of the superconductor. For high-temperature superconductors such devices were proposed to compare the superconducting state in two orthogonal directions [4,5]. The experimental result shows that in contrast to standard superconductors, the Cooper pair wave function has an internal structure which alters the interference pattern drastically and in an unambiguous way [6]. This symmetry is called "d-wave" in connection with the internal angular momentum of Cooper pair.

Another aspect of the low pairing symmetry is the possibility of "frustration" effects in superconducting loops. This is another coherence effect which can give rise to spontaneous currents and a resulting magnetic moment of the loop [4]. It is a general feature of superconducting loops that the threading magnetic flux - the total amount of the magnetic field - is quantized in a universal way. In standard superconductors the flux is quantized in units of $\Phi_0 = hc/2e$ and the smallest flux in a loop is zero. On the other hand, in high-temperature superconductors, we find special conditions under which the smallest flux is finite, more precisely $\Phi_0/2$ [4]. This theoretical prediction was verified in one of the most beautiful experiments in this field [7]. In particular, it was found that a loop consisting of several superconducting pieces can generate a sponta-

neous magnetic moment depending on the geometrical structure.

The presence of spontaneous magnetic moments of this origin is the key to the interpretation of the peculiar magnetic response of some granular high temperature superconductors. The response of a standard superconductor is usually diamagnetic, i.e. the internal magnetic field is diminished compared to the applied one as a consequence of the Meissner-Ochsenfeld effect. However, in granular high-temperature superconductors, spontaneous magnetic moments of the above type exist. They are aligned with an external field and create an internal magnetic field - a paramagnetic signal [4]. This type of effect has been observed and studied in detail in granular $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ [8]

Superconductivity with broken time-reversal symmetry

Surfaces of the material do not have a very big influence on standard superconductors. In unconventional superconductors, however, they introduce a severe disturbance suppressing superconductivity close to the surface. The reason is again the low symmetry of the Cooper pairs. Based on phenomenological arguments it can be shown that under certain conditions the superconductor can recover in a rather unexpected way by generating a superconducting state with new properties in the surface region [9]. Among the most surprising aspects of such a state is the presence of spontaneous currents flowing along the surface [10]. This effect is a manifestation of broken time reversal symmetry. (If we reversed the flow of time then these currents would run in the opposite direction corresponding to another state.) Indeed some experimental evidence for such surface states has been found in tunneling conductance measurements for high-temperature superconductors [11].

States of broken time reversal symmetry have also been proposed for some heavy fermion superconductors where they would not only

appear at the surface, but throughout the whole material [12]. These states have significant magnetic properties which have been observed in muon spin rotation measurements [13]. Therefore it is very likely that in both systems, the heavy fermion and the high-temperature superconductors, this exotic type of state is realized which gives rise to a number of unusual properties.

Microscopic mechanisms of unconventional superconductivity

Superconductivity is one of a variety of low-temperature phases which occur in a system of many interacting electrons. Systems with strong repulsive interaction among the electrons - we talk about strongly correlated electron systems - tend actually to favor magnetism. Although superconductivity and magnetism are like oil and water avoiding each other, the two phenomena are intimately connected in strongly correlated electron systems. In virtually all heavy fermion and in high-temperature superconductors, the tendency towards magnetic behavior seems to play a vital role for superconductivity. In particular, high-temperature superconductivity emerges from an antiferromagnetic insulator upon doping charge carriers. It is one of the most challenging problems of present solid state physics to understand the interplay between the two phenomena, magnetism and superconductivity.

A promising and tractable way to address such questions for high-temperature superconductors is the theoretical study of low-dimensional systems with rather well-defined magnetic behavior. One class of very suitable systems investigated over the past few years are so-called ladder systems [14]. Strong interaction among electrons residing on a lattice with a ladder structure yields a distinct magnetic state which is known as resonating valence bond state. It has been shown that this magnetic state is the origin of superconductivity in these ladders [15]. A particularly important aspect of

Cooper pairing in these systems is that the symmetry of the resulting superconducting state is identical to the one found in experiments on high-temperature superconductors.

The properties of the quasi one-dimensional ladders shed light on various aspects of the high-temperature superconductors which are quasi two dimensional electron systems [14]. Ladder systems are, however, not only toys of theorists, half way to the real high-temperature superconductors. Nowadays we know a number of real compounds which contain ladder structures [16]. It is one of the ongoing efforts in material research to push such systems to the limits where they are predicted to be superconducting. A probably successful attempt was recently reported in Japan where superconductivity was discovered below 12 K (-265 C) in $\text{Sr}_{0.4}\text{Ca}_{13.6}\text{Cu}_{24}\text{O}_{41.85}$ [17]. This subject is under very intense investigation now because it might allow us to design new superconductors with a higher transition temperature.

In a heavy fermion system we encounter a considerably more complex situation because here mobile electrons interact with localized magnetic degrees of freedom. These systems described by the so-called Kondo lattice model have so far been explored mainly for their magnetic and metallic properties [18]. On the microscopic level superconductivity still remains an unsolved problem and poses a major challenge for theoretical physics.

In conclusion, unconventional superconductivity in strongly correlated electron systems is one of the most fascinating fields of solid state physics. The very complex properties of such materials include a large potential for many new and unexplored phenomena. It is really exciting to work in this field which is the likely basis for future technologies that could change our life as profoundly as semiconductors did.

In my research I benefited much from the collaboration with many

colleagues in this field. In particular, I am very grateful to Prof. Maurice Rice who encouraged and guided me with his experience and enthusiasm during many years. I would like to thank also my colleagues at the ETH in Zurich and in many other places in the world. Last but not least, I am very grateful to my parents who supported me in many ways during all the years of my education and studies.

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