# Mysterious relationship between magnetic impurities and superconductivity

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Everything in the world is made of atoms. Especially, the properties of matter are determined mainly by the electrons that make up the atoms. For example, one of the most important properties of matter is electrical resistance or conductance, which characterizes the ability to resist or to conduct an electric current. If electrons can move freely in a matter, the matter shows high conductivity, and it known as a metal.

Resistance basically reflects the effects of impurities, defects, or vibrations in matters. While the resistance caused by impurity or defect is generally independent of temperature, resistance due to vibration is remarkably suppressed at low temperature as vibration is a result from heat fluctuation. Some of the metals have exactly zero electrical resistance at low temperatures, i.e., superconductors. Superconductivity, a state of metal, is one of the most important phenomena for physics and has been many applications such as MRI.

In terms of applications, to understand influence of impurities in normal metals and superconductors is important since impurities decreases efficiently of materials. One may think the problem of impurities is not so fascinating, however, when the impure atom is magnetic metal, impurities show unexpected phenomenon and this phenomenon also regards as one of the central problems in physics, namely the Kondo effect.

Besides, the coexistence of superconductivity and magnetic impurity leads to an intriguing state of matter. It also has the potential to provide the architecture for quantum computers. Therefore, I believe that the study of relationship between magnetic impurity and superconductivity is worthy of being called a “hidden gem” of science. This essay aims to describe superconductivity and the Kondo effect and to focus on recent research on the relationship between the two.

First, let me explain magnetism. While magnets are a very familiar phenomenon in our daily life, magnetism is the origin of magnets. It arises from a “spin” property, which is like the rotation of an electron. Electrons have a certain direction magnetic orientation; this is called the spin. Specific atoms, including iron, also have spin. When the direction of the spin of these atoms in a material, a magnet is created.

It is also necessary to introduce quantum statistics. There are two different types of particle statistics in quantum mechanics: fermions and bosons. For instance, an electron is fermion. Briefly, in a physical system, there the states are determined for each energy. Each particle must take on one of those states. Fermions cannot occupy the same state with two or more particles, an exclusion law. On the contrary, bosons can occupy a same state over any number of particles. The lowest energy state of fermions is that occupies particles in order from the bottom up due to the exclusion law. In contrast, the lowest energy of a boson is that all particles are in the lowest energy state.

In certain metals, there is an attractive force between electrons, and if so, electrons can make paring. Electrons are fermions, however, pairs of electrons are regarded as bosons. At low temperatures, particles generally tend to take on a lower energy state. Therefore, pairs of electrons occupy same state at low temperatures. In this state, pairs of electrons move freely. This is the origin of the superconductivity.

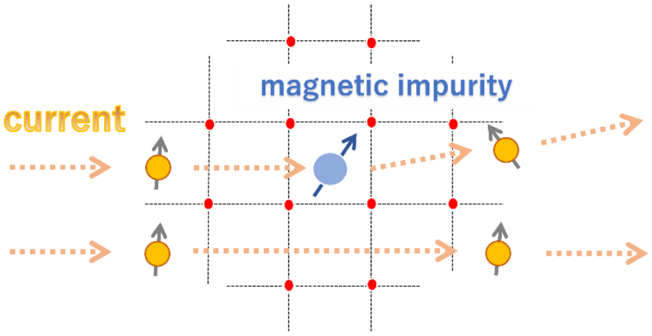

Fig. 1 Schematic diagram of the Kondo effect. Electrons as current flow from left to right (dashed arrows). Arrows in the particle represent each spin. The magnetic impurity located center of the crystal and an electron scatter, blocking the current.

Usually, the transition temperature of superconductivity $T_c$ is between a few Kelvin and several tens of Kelvin.

In contrast, the Kondo effect, in which the effect of fermions plays an important role. The Kondo effect was originally known as a phenomenon in which a noble metal such as platinum, containing a magnetic metal such as iron as an impurity, increases electrical resistance at low temperatures. This increase arising from around 10 Kelvin in typically.

The resistance enhancement by magnetic impurities, first revealed by J. Kondo, is caused by the scattering process with spin-flip between magnetic impurity spin and conduction electrons. Unlike the scattering process of ordinary non-magnetic impurities, the spin direction of magnetic impurities depends on temperature, which influences the scattering process. Kondo revealed that such dependence, in which the resistance increases with decreasing temperature, is due to the electron exclusion law. More curiously, the resistance enhancement will suppress in very low temperatures. This suppresses is caused by conduction electrons screening the impurity spins. The suppression begins at a certain low-temperature region (referred to as the Kondo temperature $T_k$). Finally, the magnetic impurity behaves as a non-magnetic impurity because of the screening. Such the screening effect, now known as the Kondo cloud, has been observed experimentally [2].

Next, what happens to magnetic impurities in superconductivity? In fact, magnetic impurities break pairs of electrons in superconductors and similarly, superconductivity interferes with the Kondo effect. In other words, the two are in competition. After all, the impurity spin is either rotating freely or screened like the Kondo effect. Which emerges depends on the competition with the temperature $T_K$ at which the Kondo cloud begins to create and the transition temperature $T_c$ of superconductivity. If $T_c$ is greater than

$T_K$, the spins spin freely in superconductivity, creating a new state called the Yu–Shiba–Rusinov (YSR) state. Conversely, if $T_c$ is smaller than $T_K$, the spins are screened in superconductivity, creating a state like the Kondo effect. In this essay, we call the former the unscreened phase and the latter the Kondo phase.

Recently, C. P. Moca and colleagues theoretically studied the Kondo cloud in these two phases [3]. In this paper, they analyze the size of the Kondo cloud in superconductivity analytically and numerically. According to their research, the Kondo cloud exists even in the unscreened phase where the spin screening is small. They also found that the nature of screening changes between two phases. The behavior of the Kondo cloud is a nontrivial prediction, especially in the unscreened phase since the Kondo cloud is expected to destroy by superconductivity.

In summary, there are two important points in this study worthy of being called a "hidden gem" of science. First, they focused on the Kondo cloud in a superconductor that has been overlooked in previous studies and pointed out the unexpected properties of the Kondo cloud. The fact that Kondo clouds remain in superconductivity is a very interesting phenomenon.

The second point is its application to quantum computers. Quantum computers are expected to outperform conventional computers. It has been pointed out that the YSR state, produced in the unscreened phase. creates a Majorana bound state under certain circumstances. This suggests that they can be applied to quantum computers. Therefore, making the YSR state, which is usually about 10 nanometers in size [2], more efficient control is important for applications. Their study has the potential to be the beginning of that development and now it seems to have received less attention than other methods for quantum computing. Thus, the problem of magnetic impurities in superconductivity offers more fascinating physics and has the potential to contribute to future technology.

## Reference

[1]
Z. Scherübl *et al.*, “Large spatial extension of the zero-energy Yu–Shiba–Rusinov state in a magnetic field,” *Nat Commun*, vol. 11, no. 1, p. 1834, Dec. 2020, doi: 10.1038/s41467-020-15322-9.

[2]
F. Pientka, L. I. Glazman, and F. von Oppen, “Topological superconducting phase in helical Shiba chains,” *Phys. Rev. B*, vol. 88, no. 15, p. 155420, Oct. 2013, doi: 10.1103/PhysRevB.88.155420.

[3]
C. P. Moca, I. Weymann, M. A. Werner, and G. Zaránd, “Kondo Cloud in a Superconductor,” *Phys. Rev. Lett.*, vol. 127, no. 18, p. 186804, Oct. 2021, doi: 10.1103/PhysRevLett.127.186804.