CONCEPTUAL SCOPE OF MULTILAYER CUPRATE SUPERCONDUCTOR
~ IMPLEMENTATION OF MULTIPLE COMPONENTS ON A MACROSCOPIC QUANTUM STATE TOWARD A NEW QUANTUM PHASE ELECTRONICS ~

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Introduction

A conventional superconducting Josephson device is composed of two superconductors spatially separated and connected by Josephson junction. The phase difference between two superconductors is an element. When these two superconductors spatially overlap with each other, we can use the phase difference between these two without an artificial interface. It is a concept of multi-component superconductor and may be realized in the multi-band superconductors. One component resides in the first band and another resides in the second. These are coupled by an inter-band Josephson interaction. Conventionally this type of superconductor was designated as a multi-band superconductor [1]. If people specify its peculiarity based on relative dynamics of multiple components, we can call it a multi-component superconductor. In this talk, I will review a newly develop a multi-layer cuprate superconductor is a good candidate for the multi-component superconductor. We can open a new quantum phase electronics using this superconductor.

Before multi-layer cuprate

The physics on multi-band superconductors are studied in depth on Nb that is the typical multi-band superconductors. In the 1960's, numerous efforts are paid to understand typical features of mutlti-band superconductors [2,3]. A typical feature coming from two components was found in the specific heat study of Nb [4]. Theoretical study suggested a new phenomenon, which is the fluctuation of the relative phase between two components and that of BCS pairs' density. It was called as a number-phase fluctuation. But it is not still observed experimentally. The theorists suggest the minor modification of the science of a single band superconductor is enough to understand the physical properties coming from multi-component feature. The presence of the multi-band superconductor was gradually fading out and almost three decades are past.

Mutli-layer cuprate superconductor [5-7]

Since our group developed $TlBa_2Ca_3Cu_4O_y$ in 1987 [8], we have been paying special effort to find its identity. Through development of $CuBa_2Ca_3Cu_4O_y$ in 1993 [9], we are establishing the common feature that multi-layer cuprate superconductors have. Because there are nonequivalent CuO_2 planes, they has un-degenerated multiple bands [10,11]. We can tune band structure and magnitude of superconducting gap of the individual component by the selective doping [10-12]. Any conventional multi-band superconductor does not have this flexibility. Applying this tunableness, we are trying to implement multiple orders and components in one superconductor. One of the succeeded examples is coexistence of antiferromagnetic order and superconductivity in $HgBa_2Ca_4Cu_5O_y$ [13,14].

i-soliton

It was found the inter-component interaction is very weak, in the multi-components in the multi-layer cuprate superconductor [15]. The relative phase between two components can be vital parameter. The magnitude of the relative phase had been considered to be small and its fluctuation had been discussed before 2001 [3]. But theoretically it can grow up 2 π and makes a stable soliton solution. This is an inter-component phase difference soliton (*i*-soliton) [16]. This concept was confirmed by a scheme of the Universe theory just after our discovery [17].
It should be mentioned that the conventional multi-band theory, people considered a STRONG inter-band interaction is essential to elevate Tc [2, 18]. But the concept of a WEAK inter-component interaction was essential to discover *i*-soliton theory. In this mean, *i*-soliton is a child of the science of the multi-layer cuprate superconductor. The strength of the inter-band interaction will become a new key parameter for developing a new superconductor. Its importance might be comparable to that of Tc.
i-soliton twists a superconducting phase itself. There is no inter-component phase difference at its head and tail. But there is a phase slip between its head and tail. Gurevich and Vinokur considered that *i*-soliton is a phase dislocation in a macroscopic quantum condensate leading the quantum phase texture without any normal core like vortex in mixed state of type-II superconductor [19]. This phase texture is completely eliminated in the conventional single band superconductor. Several ways are proposed and under consideration to find *i*-soliton experimentally.

Film development of the multi-layer cuprate.

i-soliton have not been experimentally caught yet. To catch it, we need a film. We can realize one-dimensional configuration by patterning. It gives a hunting field. The layer-by-layer deposition technique is one way to make a multi-layer cuprate superconducting film. Balestrino group succeeded its development [20-22]. We are also trying to establish the film fabrication technology [23,24]. This film will be a final solution for a new quantum device.
To make the hunting possible, there are other criterions. Film would be easy to be treated and stable under atmosphere. If Tc_2, under which *i*-soliton becomes a stable, is higher than 77 K, the convenient hunting can be designed and enjoyed.
$TlBa_2Ca_3Cu_3O_y$ (Tl-1223) film may satisfy these demands. So we have been developing a special method for this film, which is called amorphous phase epitaxy (APE) method. We developed a film having high-Jc (>1 MA cm^{-2}) [25,26]. Now we are establishing the process making a circuit for hunting.

i-qubit

As one of the most feasible devices realized by the multi-component superconductors, a qubit using *i*-soliton (*i*-qubit) was proposed. Energy of *i*-soliton is proportional to the width of the superconducting line. If we make two narrow locations, it acts as two potential minimums for *i*-soliton. Putting one *i*-soliton into this line, we can make one qubit [26]. It is very simple and convenient. Moreover *i*-soliton is inactive against the electro-magnetic field unless putting it into ring. We can minimize decoherence due to unbidden electro-magnetic field. It is also shown fundamental gates can be designed. These studies are still in a infant stage, we have much room to do.

Concluding Remark

Multi-component superconductor realized by the multi-layer cuprate superconductor will open a new field of a macroscopic quantum dynamics. We now face un-explored macroscopic quantum condensate [28].

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