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On the direction of the magnetic line and the circulating supercurrent of a vortex in type-II superconductors

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ABSTRACT

The relationship between the direction of the magnetic line and the circulating supercurrent of a vortex in type-II superconductors is discussed. Contrary to the views presented in some articles, we will make it clear that the magnetic line and the circulating supercurrent of a vortex have a "right hand" relationship by considering basic electrodynamics and the lowest energy principle.

1. Introduction

It is well-known that in type-II superconductors, for applied fields H_a such that $H_{c1} < H_a < H_{c2}$, the magnetic field can penetrate into the superconductor in the form of quantized vortices [1–7], each carrying a single flux quantum $\phi_0 = h/2e$. In the absence of disorder, the vortices form a regular lattice of parallel defect lines. Fig. 1 shows the microscopic structure of an isolated vortex [3,8,9]. At the very center it is a short-range (of order of coherence length ξ) normal core accommodating the penetrated field $\vec{H}_v$. Around the normal core it is a long-range (of order of penetration depth λ) circulating supercurrent $\vec{J}_s$. However, a number of figures in the literatures published recently show that the understanding of the direction of $\vec{H}_v$ and $\vec{J}_s$ is quite confused. Some authors [10–12] have concluded that $\vec{H}_v$ and $\vec{J}_s$ form a "right hand" relationship as shown in Fig. 2a, while other authors [13–17] believe that $\vec{H}_v$ and $\vec{J}_s$ form a "left hand" relationship as shown in Fig. 2b. The purpose of this paper is to clarify the actual relationship between the direction of $\vec{H}_v$ and $\vec{J}_s$.

2. Methods description

The confusion stated above is generally caused by the misunderstanding of the Meissner effect, in which a screening supercurrent will be generated on the surface to maintain the superconductor as a diamagnetic body at a temperature below its T_c. The field generated by the screening supercurrent must be in opposite direction to the applied magnetic field so that it can expel the applied magnetic field out of the superconductor. This can also be shown by referring to London's second equation. The authors who applied this idea to a vortex will get a "left-hand" relationship as shown in Refs. [13–17]. However, it is questionable whether or not the ideas used in explaining the Meissner effect can also be applied to a vortex. In order to clarify the relationship between the direction of $\vec{H}_v$ and $\vec{J}_s$, we need to answer the following question first: does $\vec{J}_s$ screen the applied magnetic field $\vec{H}_a$ out of the superconductor, or help $\vec{H}_a$ to penetrate into the superconductor? Since any current generates magnetic fields, $\vec{J}_s$ also generates a magnetic field. If $\vec{J}_s$ helps $\vec{H}_a$ to penetrate into the superconductor, $\vec{J}_s$ should generate a magnetic field in the same direction as that of $\vec{H}_v$, so $\vec{H}_v$ and $\vec{J}_s$ should have a "right hand" relationship. But if $\vec{J}_s$ helps to screen $\vec{H}_a$ out of the superconductor, $\vec{J}_s$ should generate a magnetic field in the direction opposite to that of $\vec{H}_v$, so $\vec{H}_v$ and $\vec{J}_s$ should have a "left hand" relationship. To answer the above question, let us consider the following three aspects:

2.1. Vortex entry at $H_a \approx H_{c1}$

The reason that an applied magnetic field H_a can penetrate into a type-II superconductor is that the type-II superconductor has a

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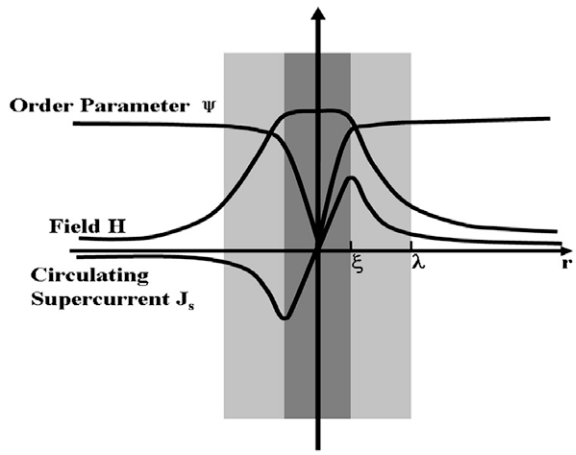

Fig. 1. Sketch of the microstructure of a vortex, which consists of a short-range (of order of coherence length ξ) normal core surrounded by a long-range (of the order of penetration depth λ) circulating supercurrent.

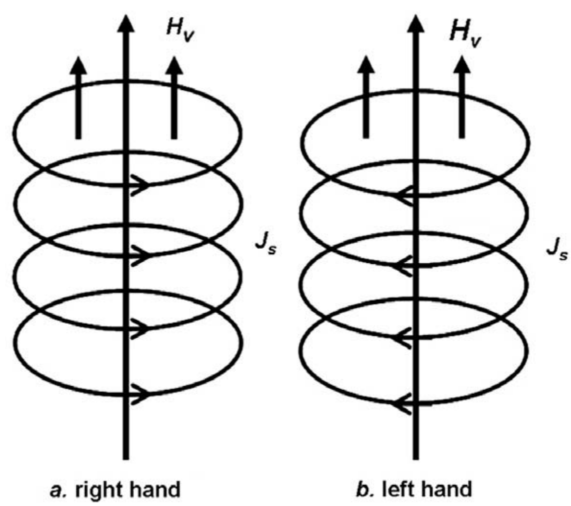

Fig. 2. Schematic diagram of the possible relationship between the direction of the magnetic line and that of the circulating current of a vortex.

negative surface energy at the applied magnetic field $H_{c1} < H_a < H_{c2}$, which means that the coexistence of the superconducting phase with a magnetic field has a lower energy. Such coexistence turns out to be favorable in energy for preserving the superconducting state. In this case, the superconductor prefers to let part of the applied magnetic field penetrate into its body (in the form of quantized vortices) to reduce the energy. Consider a superconductor which is subjected to an applied magnetic field $H_a < H_{c1}$. Now increase the applied magnetic field to a higher value which is slightly larger than H_{c1}, that is, $H_a - H_{c1} \ll H_{c1}$. In the first instance, the superconductor will stay in a "metastable" Meissner state, let us denote the total energy as E_i. The superconducting state is unstable because the applied field is above H_{c1}, eventually the applied magnetic field will start to penetrate into the body of the superconductor. Suppose now the superconductor allows the entry of one vortex into its body see Fig. 3, and the energy of the superconductor is then reduced to a lower value E_e. Since the field of the vortex is in the direction of the applied magnetic field, the screening effect on the applied magnetic field (or the energy of the superconductor) should be reduced after the entry of the vortex into the superconductor. So the circulating supercurrent of the vortex must generate a magnetic field in the direction opposite to the screening magnetic field to cancel out part of the screening effect, thus, we have $E_i > E_e$. In this way, $\vec{H}_v$ and $\vec{J}_s$ should have a "right-hand" relationship as shown in Fig. 2a. On the contrary, if $\vec{H}_v$ and $\vec{J}_s$ have a "left hand" relationship, $\vec{J}_s$ would increase the screening effect, and the energy of the superconductor would be increased, and then we have $E_i < E_e$. If this is true, vortex entry will not occur.

2.2. Trapped vortices in a superconductor

Suppose a magnetic field $H_a > H_{c1}$ is applied to a superconductor and the vortices penetrate into the superconductor. Now, turn off the applied field $\vec{H}_a$ slowly, some of the vortices are trapped on the pinning centers and remain in the superconductor as shown in Fig. 4. Since the vortex magnetic field $\vec{H}_v$ is static, it must have a source. $\vec{H}_v$ is in the direction of the applied magnetic field $\vec{H}_a$, but as $\vec{H}_a$ is turned off, the screening surface current also disappears. Thus, if we can further manage to stop the persistent current induced when turning off the $\vec{H}_a$ (which is theoretically reasonable), then the only possible source for $\vec{H}_v$ is the circulating supercurrent $\vec{J}_s$. This means that $\vec{J}_s$ generates $\vec{H}_v$, and their direction can be determined by the "right hand" rules as widely used in solenoids.

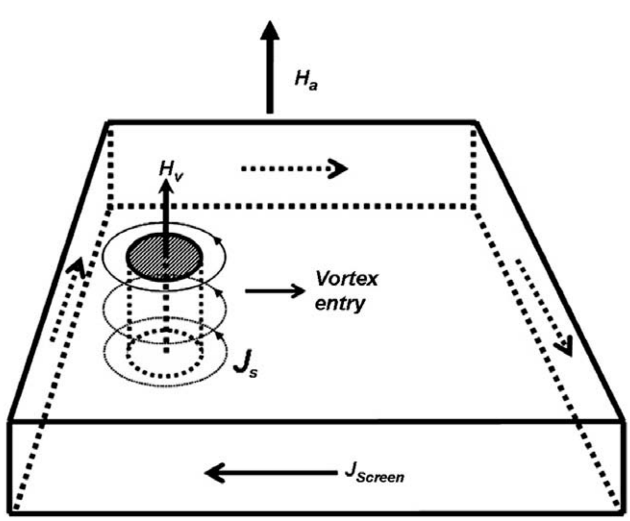

Fig. 3. Schematic diagram of the entry of a single vortex into a type-II superconductor for the applied fields H_a such that $H_{c1} < H_a < H_{c2}$.

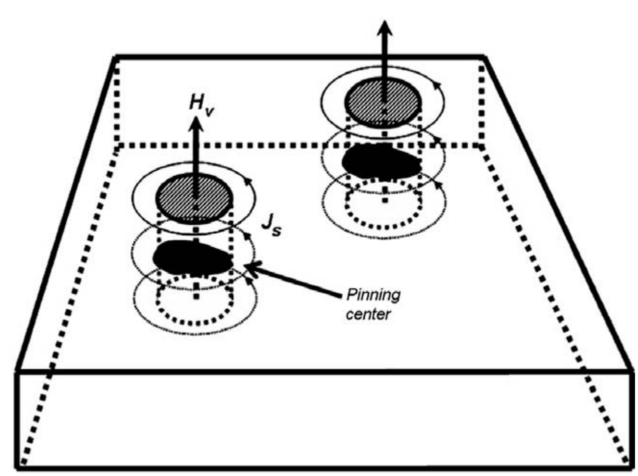

Fig. 4. Isolated vortices were trapped on the pinning centers in a type-II superconductor after the applied magnetic was turned off. The circulating supercurrents generate the magnetic fields of the vortices. The direction of the magnetic field and that of the circulating supercurrent of a vortex have a "right hand" relationship.