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On the reversibility of the Meissner effect and the angular momentum puzzle

J.E. Hirsch

Department of Physics, University of California, San Diego, La Jolla, CA 92093-0319, United States

HIGHLIGHTS

- The normal-superconductor phase transition is reversible.
- Within the conventional theory, Foucault currents give rise to irreversibility.
- To suppress Foucault currents, charge has to flow in direction perpendicular to the phase boundary.
- The charge carriers have to be holes.
- This solves also the angular momentum puzzle associated with the Meissner effect.

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ABSTRACT

It is generally believed that the laws of thermodynamics govern superconductivity as an equilibrium state of matter, and hence that the normal-superconductor transition in a magnetic field is reversible under ideal conditions. Because eddy currents are generated during the transition as the magnetic flux changes, the transition has to proceed infinitely slowly to generate no entropy. Experiments showed that to a high degree of accuracy no entropy was generated in these transitions. However, in this paper we point out that for the length of times over which these experiments extended, a much higher degree of irreversibility due to decay of eddy currents should have been detected than was actually observed. We also point out that within the conventional theory of superconductivity no explanation exists for why no Joule heat is generated in the superconductor to normal transition when the supercurrent stops. In addition we point out that within the conventional theory of superconductivity no mechanism exists for the transfer of momentum between the supercurrent and the body as a whole, which is necessary to ensure that the transition in the presence of a magnetic field respects momentum conservation. We

E-mail address: jhirsch@ucsd.edu.

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propose a solution to all these questions based on the alternative theory of hole superconductivity. The theory proposes that in the normal-superconductor transition there is a flow and backflow of charge in direction perpendicular to the phase boundary when the phase boundary moves. We show that this flow and backflow explains the absence of Joule heat generated by Faraday eddy currents, the absence of Joule heat generated in the process of the supercurrent stopping, and the reversible transfer of momentum between the supercurrent and the body, *provided the current carriers in the normal state are holes*.

1. Introduction

The experimental discovery of the Meissner effect in 1933 [1] suggested that the transition between normal and superconducting states in the presence of a magnetic field is a reversible phase transformation between well-defined equilibrium states of matter to which the ordinary laws of equilibrium thermodynamics apply [2]. For example, the Rutgers relation [3] relating the specific heat jump between normal and superconducting phases at the critical temperature to the temperature derivative of the thermodynamic critical field follows from this description. In fact, the Rutgers relation had been found experimentally and interpreted theoretically using thermodynamics [4] before the discovery of the Meissner effect, in a sense anticipating it. Subsequent extensive experimental tests [5,6] confirmed that in the ideal situation the normal-superconductor transition occurs without entropy production within experimental accuracy, i.e. is reversible, and this has been generally believed ever since.

In this paper we point out that within the conventional London-BCS theory of superconductivity [7] the experiments testing reversibility [5,6,8] should have detected irreversibility because they did not proceed slowly enough to prevent significant generation of Joule heat due to eddy current generation as the magnetic flux changed. However, we point out that the absence of Joule heat generated by eddy currents could be explained if there is charge flow in direction perpendicular to the normal-superconductor phase boundary when the phase boundary moves, which is not predicted by the conventional theory.

In recent work we have proposed that charge transfer in direction perpendicular to the normal-superconductor phase boundary is necessary to explain the dynamics of the Meissner effect [9,10]. In this paper we show that this charge transfer explains why the transition between normal and superconducting states is found to be reversible to the degree that has been observed in the experiments [5,6]. In addition, we point out that this physics also explains how the supercurrent stops in the superconductor to normal transition without generation of Joule heat, as required by reversibility. Furthermore, we show that this charge transfer resolves the angular momentum puzzle associated with the Meissner effect that we pointed out in previous work [11,12]. We show all of this is true *if and only if the normal state charge carriers are holes*.

2. Phase equilibrium

In a seminal paper [13], H. London analyzed the phase equilibrium between normal and superconducting states in the presence of a magnetic field. The situation is shown schematically in Fig. 1. Following the treatment and notation of Ref. [9], in the superconducting phase ($x < x_0$) a current flows along the y direction parallel to the phase boundary located at $x = x_0$, given by

$$J_y(x) = -\frac{c}{4\pi\lambda_L} H_c e^{(x-x_0)/\lambda_L} \tag{1}$$