iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 **Issue:** XII **Month of publication:** December 2020

DOI: https://doi.org/10.22214/ijraset.2020.32663

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue XII Dec 2020- Available at www.ijraset.com

Review of the Lorentz Force and Superconductivity

Ram Swaroop Meghwal[1], DeepMala Meena[2]
[1, 2]*Department of Physics, Government College, Kota (Rajasthan), INDIA-324001.*

Abstract: In the classical realm to change the velocity of an electron, the presence of a Lorentz force is essential to act upon it. I argue that the classical picture is not adequate to understand such changes in the behaviour of microscopic particles. When I explain the response from quantum mechanical point of view, I find that there is no need to hypothesize the additional classical ideas. I propose to utilize the set of quantum theoretical principles to resolve the puzzles in the superconducting phase as pointed out by Hirsch [Phys. Lett. A 315(6)(2003) 474-479].
PACS: 74.10.+v,74.25.-q,74.90.+n,74.25.Qt

I. INTRODUCTION

To account for the behaviour of the physical object under the influence of a force field, we have to choose the classical or quantum points of view for the object and possibly as well as for the force field in accordance with the conditions of experimentation. In classical physics, the particle and the wave theories are related via the *Lorentz* law of force that an electromagnetic field (*wave nature*) exerts on an electron (*particle nature*). Classically, an electron does not change its state of motion in the absence of an electromagnetic force. That is, **E**=0 and **B**=0, make the *Lorentz force* [1]

$$\frac{d}{dt}\left[\vec{p}-e\frac{\vec{A}}{c}\right]=e\left[\vec{E}+\frac{\vec{v}}{c}\times\vec{B}\right] \qquad (1)$$

Thus the kinematical momentum must remain unaltered. But here we are considering the electron as a purely classical object and leaving no hole to enter the principle of uncertainty, which opens the possibilities to understand the peculiarities of a measurement. The central concept in any physical event is that of the measurement. By measurement, we mean the process of interaction between a quantum system and an apparatus which is generally a classical object. In the classical description of motion we always remain assured that we have measured the momentum and velocity with unlimited accuracy. But in quantum physics the two natures are not too distinct. The whole story cannot remain unchanged when we switch over to quantum theoretical version of the same problem as a momentum measurement of high accuracy made during a short time can occur only if there is a large change in the velocity as a result of the measurement process itself. So that the *uncertainty condition* [2]

$$\left|\left(v'-v\right)\Delta p\right|\Delta t \geq \frac{\hbar}{2} \qquad (2)$$

is fulfilled. This compels us to rethink about the Lorentz force description of behaviour of an electron; however, it is well described by the quantum mechanical state function. Rather we can think about the quantum mechanical version of the Lorentz force which is a manifestation of the Ehrenfest theorem [1]. The problem occurs when we try to find out instantaneous values rather than the average ones. Classically, a measurement must never change the physical state of system while, quantum mechanically, a measurement always causes the physical system to jump into an eigen state of the dynamical variable that is being measured [3]. Therefore, when describing the response of an electron in a measurement quantum mechanically, we allow the possibilities in behavioural response of the system and it becomes not strictly essential that electron would never change its state of motion in the absence of the Lorentz force. Thus there may be effect of magnetic field in the region where the field is identically zero at all. Such thing happens in *Aharonov- Bohm effect* in which the interference pattern depends upon the presence or absence of magnetic field inside the impenetrable region of state function [4]. Moreover, a quantum mechanical description of the motion claims the existence of a complex state function. It is well understood that the amplitude of state function plays an important role in such a description. In case of coherent state the phase of state function also becomes an entity of immense utility. The phase of state function depends upon the (magnetic) vector potential as well as upon the scalar (electric) potential. The change of phase with position may occur under the influence of such potentials. A change in phase can lead to dynamical response as observed in *Josephson Effect*. The superconductivity is a phase coherent quantum state and cannot be exactly understood on classical or semi-classical grounds.

II. THE MEISSNER –OCHSENFELD EFFECT

A superconductor is different from a perfect conductor in the context that within a perfect conductor, we observe the fields E=0 and B= *constant.* (*depending upon the previous history*), while well within the type I superconductor, we always have E=0 and B=0 (*independent of the previous history*). This is the well-known Meissner effect and it cannot be well understood in pure classical framework. It shows that a superconductor is a perfect diamagnet; magnetic flux is excluded from all but a thin penetration region near the surface. It is interesting to know that occurrence of the *Meissner effect* and presence of the *gap* are two correlated phenomena. In the normal state (*no gap*) we can expect the response of the matter to applied magnetic field in a very natural way. But in a superconducting phase (*with a significant gap*) the material must be idle to respond to external magnetic field as the carriers are not allowed to cross the gap to follow the external field and hence the interior region of the material must exhibit the independent magnetic property [5]. Since we hope that in the absence of any external field there must be no induction at all. We can very naturally set, B=H+4πM=0 i.e., χ =M/H=-1/4π. Thus we are in a position to explain if a perfect conductor were a superconductor B= *constant* = 0 (always!). Further, one can argue when no gap (normal phase) filaments are formed in the superconducting material, what we call type II superconductors; the response to field must be entirely amazing [6]. Of course we can accept Hirsch's idea [7]. Since the *vortices* are normal phase domains, the *flux quanta* not only penetrate the material, but they also move in response to the Lorentz force, F=J×B/c [8]. The only way for vortices to be formed and move around without global consequences is when each flux quantum contains a flux such that the path difference in Aharonov-Bohm effect is

$$\Delta\delta = \left(\frac{e}{\hbar c}\right)\Phi = n\left(2\pi\right) \qquad (3)$$

giving no observable phase [9]. In similar way we can expect that it is the gap which makes state function to be *rigid*. Now it is suitable time to propose safely that the concept of Lorentz force will work well to the electrons that have not participated in Cooper pair formation; but in my opinion the idea of the Lorentz force may not be so easily extended to explain the behaviour of the carriers in the entire superconducting regime. Moreover, the vortex motion can also be manipulated by thermal or Lorentz force in high temperature superconductors [10]. Kim et al. found that except the flux motion the broadened resistive transitions demonstrate the absence of the macroscopic Lorentz force [11].

III. THE EFFECT OF ROTATION ON SUPERCONDUCTIVITY

The semi-classical approach regarding the effect of rotation on superconductors is based on the London field [12]. However, to get more subtle understanding we have to reconsider the physics behind London's law. In presence of electromagnetic field the canonical momentum becomes the kinematical one and the ground state of superconductivity is one with zero momentum and zero spin. Hence we have, $mv_s = -\frac{eA}{c}$

and if the magnetic field is uniform, we can easily get, $\vec{A} = \frac{1}{2}\vec{B}\times\vec{r}$, if combined, these two expressions give, $mr\omega = -\frac{e}{c}\frac{1}{2}Br$.

Hence the desired expression for the London field comes out to be: $\vec{B} = -\frac{2mc}{e}\vec{\omega}$. Now the question arises in a very natural way; in case of superconductivity in no way there exists a uniform magnetic field. Rather we can accept, $B\left(x\right) = B\left(0\right)e^{-x/\lambda}$. Hence the London's law should no longer persist to be never violated. Of course, in multi-component superconductors it is really violated [13]. The above derivation of the London's law lies in pure classical framework. A quantum mechanical system can very easily give non-classical response. However, in response to exceeding a certain critical frequency of rotation, the single-component superfluid fraction comes into rotation by means of vortex formation. But in multi-component compounds vortices are not induced by rotation. Moreover, the *Onsager- Feynman* quantization rule is also violated [13]. Actually the violation of the semi- classical formulation of the laws may be inherent in their nature. The derivation includes the closed line integral alike in the case of *Bohr's Model*, while the probabilistic interpretation in three dimensions is more subtle to understand the behaviour of the microscopic particle being in motion. In fact, the semi-classical formalism is a special case of the quantum theoretical formalism. Hence we should not prefer to postulate new classical ideas to sustain the semi-classical formulation. The quasi-quantum mechanical analogue of London's law may be performed by noting that the superfluid velocity of electrons in a vortex at a large distance from the core is governed by $mv_s = \hbar\nabla\theta - \frac{2eA}{c}$, where θ is the phase of state function describing the condensate [14]. After such considerations the modified London's field comes out to be,

$$B = -\frac{mc}{e}\omega - \frac{\hbar c}{er}\nabla\theta \quad (4)$$

Neither the Lorentz law of force nor the London's law includes the super fluid velocity,

$$v_{s0} = -\frac{\hbar}{m}\nabla\theta$$

free from presence or absence of the electromagnetic fields. Since the presence of magnetic field in the thin surface layer is feasible, any changes in space-time domain will develop the consistent electric field. Hence we should expect correction to the electric field escaped in Hirsch's formulation. In classical theoretical framework, the quantum mechanical uncertainty relation, $\Delta N\Delta\theta \sim 1$, puts the limit to observe so rapidly changing phase if the number of particles is a constant [15].

IV. THE FLUX QUANTIZATION

The flux quantization and Aharonov- Bohm effect are two closely related phenomena, as the quantized flux gives no observable phase difference. The entire superconducting state is a phase-coherent one, so there must be no phase difference at all. However, I proclaim that if there is any violation of flux quantization, there would an observable Aharonov- Bohm effect! Recently, it has been found that the quantization of magnetic flux in LMH (*liquid metallic hydrogen*) is fractional [16]. In dual superconductors a vortex can possess arbitrary fraction of magnetic flux quantum

$$|\Phi| = \frac{\hbar c}{2e}\cos\theta \quad (5)$$

depending on parameter cosθ measuring relative densities of two condensates in superconductor. I suggest that there should be detectable Aharonov- Bohm effect. Such quantum –mechanical phenomena cannot be understood at all on the basis of new additional classical assumptions.

V. CONCLUSION

To sum up, I would like to suggest that the Lorentz force and the London's law are not enough powerful to explain the behaviour of an electron in superconducting phase. They help to understand the macroscopic properties of the superconductor and average motion of the vortices. But the full description is still not possible to be come out from these laws as there is no account of the phase of state function in such laws. Thus the phase related phenomena will not be explained in their framework. It is always fruitful to consider the superconducting phase with a well-defined complex state function with real amplitude and real phase. The fractional flux quantization will result in Aharonov-Bohm effect. Hence, in my opinion, there must be more emphasis on Aharonov-Bohm effect rather than on Lorentz force or London's field when discussing superconductivity. The breakdown of Meissner effect opened a new class of superconductors-Abrikosov superconductors with Schubnikov phase. The breakdown of flux quantization must open another class of superconductors- Aharonov-Bohm superconductors (say!), still not fully understood phase.

REFERENCES

[1] J.J. Sakurai, Modern quantum Mechanics, Addison Wesley, NY (1999).
[2] L. D. Landau and E. M. Lifshitz, Quantum Electrodynamics, Pergamon Press, NY (1982).
[3] P. W. Anderson, Measurement in Quantum Theory and Problems of Complex Systems in 'The Lesson of Quantum Theory', ed. J. De Boer et al., Elsevier Science Publisher B. V. (1986).
[4] Y. Aharonov and D. Bohm, Phys. Rev. 115, 485-491 (1959).
[5] R. S. Meghwal, Ph.D. Thesis, M.D.S. Univ. Ajmer (Raj.) India (2007).
[6] A. A. Abrikosov, Sov. Phys. JETP 5, 1174 (1957).
[7] J.E. Hirsch, Phys. Lett. A 315 (6), 474-479 (2005).
[8] P. W. Anderson and Y. B. Kim, Rev. Mod. Phys., 36(1), 39 (1964), pp.40.
[9] P. J. Mulders, Quantum Field Theory, vrije universiteit, Amsterdam (2008).
[10] Z. Wang et al., Phys. Rev. B 72, 054509 (2005).
[11] D. H. Kim et. al., Phys. Rev. B 41(16), 11642-11645 (1990).
[12] F. London, Superfluids, Wiley, NY (1950).
[13] E. Babaev and N. W. Ashcroft, Nature Physics 3, 530 (2007).
[14] P. W. Anderson, A Career in Theoretical Physics, World Scientific Singapore (1994), pp. 144.
[15] P. W. Anderson, Rev. Mod. Phys. 38(2), 298-310 (1966).
[16] E. Babaev, Phys. Rev. Lett. 89, 067001 (2002).