

Meissner Effect in Classical Physics

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Abstract—The Meissner effect is explored based on the acceleration-dependent component of the Weber force. According to the Maxwell theory, a steady circulating current does not produce any dynamics on external resting charges; however, according to the Weber theory, the charges of the circulating current exhibit a centripetal acceleration, which affects the external charges at rest. It is demonstrated that the current generated in this manner can explain the Meissner effect in classical physics.

1. INTRODUCTION

There seems to be a widespread opinion that the Meissner effect, i.e., the expulsion of the magnetic field from a superconductor, is a macroscopic phenomenon for which there is no explanation within classical physics. It is usually believed that its cause is hidden in quantum mechanical dynamics, and this fact is generally found in student textbooks. Although there have been some proposals for its explanation, both within classical physics [1–3] and quantum mechanics [4], so far, no one has been able to find its true dynamics without introducing some assumptions or new phenomena, making it difficult to obtain a conceptual understanding.

2. WEBER FORCE

In this paper, we will show that there are some forgotten dynamics within classical physics, which may be able to account for the Meissner effect. This is described by the Weber force, which forms the theory of field-free electrodynamics [5–8]. This force is formulated as a mutual pairwise interaction between elementary charges, and it has been proven that it contains all Maxwell's equations, together with the Lorentz force, which is the conventional base for describing electrodynamics [9–13].

The Weber force was historically formulated based on an incorrect assumption of the elementary charges constituting the current in a conductor. Weber assumed that the current consisted of both positive and negative charge carriers and, in addition, his force formula considered the speeds of the charges to be relative to each other. Possibly for this reason, his electrodynamic theory was suppressed. However, this approach was later corrected and Weber's force formula was reformulated by Moon and Spencer during the 1950s [9–12].

In electrodynamics, we deal with electrostatics, magnetism, and induction. From the perspective of the forces between elementary charges, this corresponds to charges at rest, charges in uniform motion, and charges under acceleration. The acceleration-dependent part of the Weber force adds a feature to electrodynamics, which tends to be neglected in Maxwell's field theory; however, it may be able to explain the Meissner effect. This interaction reads

$$\bar{F}_1 = -\frac{q_1 q_2}{4\pi\epsilon_0 c^2 R} \frac{d\bar{v}_2}{dt} \quad (1)$$

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as the force on charge 1. R is the distance between the two charges. The acceleration of charge 2 will set charge 1 in motion even if it is initially at rest. This force is the electromagnetic inductive force. It plays the role of motional resistance (electromagnetic inertia) when electrons are accelerated in a conductor. It is, therefore, the source of magnetic energy, and is equivalent to the Faraday–Henry induction law. The minus sign in the formula reflects Lenz’s law in the sense that it ensures motional resistance between accelerating same-sign charges.

3. MEISSNER EFFECT

Consider a conducting material at rest on a table. A coil carrying a constant current, equivalent to a permanent magnet, is placed on the material [†]. The Meissner effect tells us two things. First, a magnetic field is expelled from the superconductor [15], and second, there is a repulsive force between the coil and the conducting material, which sometimes causes levitation [16, 17]. The coil may be oriented in two ways. In Fig. 1(a), the coil dipole moment is oriented parallel, and in Fig. 1(b), it is oriented perpendicular to the surface normal. The circular lines on the conductor surface illustrate the currents generated to achieve both the repulsive force and the expulsion of the field.

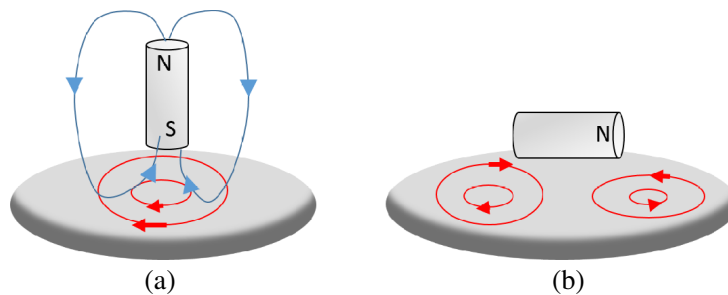


Figure 1.

The Meissner effect appears in the case where the coil is initially resting upon the material. Therefore, the Faraday–Henry effect cannot explain the current induced during the transition to the superconductive state. However, a possible dynamic is provided by the Weber force in the following way.

Figure 2(a) is a representation of Fig. 1(a), viewed from above. According to Maxwell’s theory, the coil current is associated with a uniform motion, which is associated with a static magnetic field that cannot generate any current in the material. According to Weber’s theory, however, the charges do not exhibit uniform motion since they are moving in circles, and therefore, experience centripetal acceleration. The acceleration-dependent force of Weber’s theory then causes a force in the opposite direction on the charge carriers of the material, Fig. 2(b). This means that they start moving towards the coil windings, i.e., radially outward. This motion is, in turn, influenced by the Lorentz force for a charge in motion in a magnetic field, i.e., a magnetic force, which is also included in Weber’s theory, Fig. 2(c). In this way, a current is formed in the direction opposite to that of the coil current, which opposes the magnetic field generated by the coil. A repulsive force appears since opposite currents repel.

There are dynamics outside the coil radius as well. Here, charges will move away from the coil center, but the Lorentz force will be reversed because of the reversed magnetic field. The circulating current will also be reversed, resulting in cancellation of this field.

An equivalent argument is applicable to the case in Fig. 1(b). The centripetal force puts the charges in motion radially outward (radial with respect to the coil axis), causing both horizontal and vertical motion. This motion takes place through the magnetic field of the coil, and therefore, is influenced by the Lorentz force. Currents as those in Fig. 1(b) are then set up. These cause both cancellation of the magnetic field inside the material and a repulsive force.

[†] The case for which the current in the coil is alternating and thereby expells the magnetic field inside the superconductor is treated in Ref. [14] based on the Weber force.

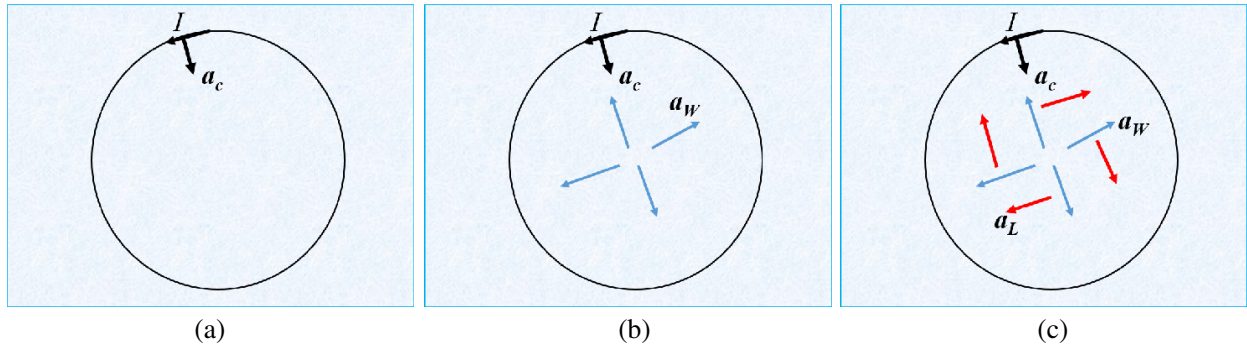


Figure 2. (a) Coil carrying current I is placed on a conducting material. Charge carriers of the coil are accelerated centripetally. (b) Charge carriers of the material respond with a force opposite to the centripetal force. (c) Since the material is influenced by a magnetic field, the Lorentz force generates a circulating current in the opposite direction.

In both cases, we note that the Lorentz force always acts so that the influenced charge sets up a motion associated with a field counteracting the influencing field. This is Lenz’s law, and a crucial condition for the Meissner effect.

For a normal material, the current generated in this manner is minute as the Weber centripetal force is small, see next section. However, in a superconductor, there is no resistance; therefore, a significant amount of current will be generated rapidly, independent of the magnitude of the influencing force. For the case illustrated in Fig. 2, the magnitude of this current will, in the final state, be equal to that of the coil. In general, from the field perspective, the current in the material will increase until the magnetic field is cancelled. This is due to Lenz’s law, which will prevent the current from increasing above this limit.

In addition, Weber’s force explains the London penetration depth conceptually, stating that the currents generated will appear in a tiny region close to the surface [18]. Consider the case in Fig. 1(a), but now with a coil so large that the entire material is influenced by a homogenous field. The charges will then move, because of the radial Weber force, without limit, towards the periphery of the material.

The arguments presented are deliberately put forward without using mathematics. Because of the special characteristics of superconductors, numbers are not essential here. The superconductor will generate the current required to expel the magnetic field, irrespective of how small the Weber force is, by counteracting the coil field. As soon as the radial motion is initiated, the currents will automatically be adjusted until the Meissner effect appears. The basic dynamics are therefore described by classical physics. However, the detailed descriptions of the resistance-less dynamics are based on quantum mechanics [19].

4. QUANTITATIVE CONSIDERATIONS

The Weber force on a conduction electron in the material due to the current-carrying interacting coil may now be calculated. It is then assumed that the coil has a circular cross section and is thin.

Denote an element of charge of the coil as $dq' = \lambda dL'$ where λ is charge per length and dL' is a length element. Let it interact with a charge q of the material, placed on the z axis, Fig. 3.

The Weber force between the charges becomes

$$d\bar{F}_q = -\frac{\mu_0}{4\pi} \frac{q dq'}{R} \frac{d\bar{v}}{dt} = -\frac{\mu_0}{4\pi} \frac{q \lambda dL'}{R} \frac{v^2}{a} (-\hat{\rho}) \tag{2}$$

where the centripetal acceleration has been introduced and $\hat{\rho}$ is the radial vector pointing outwards. In order to get the total force on charge q , an integration around the coil is needed. To this end, the

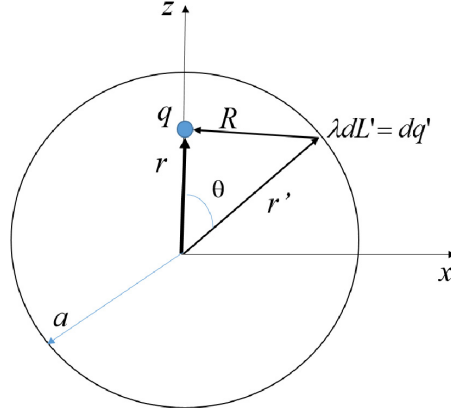


Figure 3. The circular solid line represents the current-carrying coil. Inside there is the superconducting material containing the charge q , placed on the z axis without loss of generality.

following replacements are done:

$$\begin{aligned} dL' &= a d\theta' \\ \hat{\rho} &= \hat{x} \sin \theta' + \hat{z} \cos \theta' \\ R &= (r'^2 + z^2 - 2r'z \cos \theta')^{1/2} \end{aligned}$$

so the force on charge q may be written

$$\bar{F}_q = \frac{\mu_0}{4\pi} q \lambda v^2 \int_0^{2\pi} \frac{d\theta'}{(a^2 + z^2 - 2az \cos \theta')^{1/2}} (\hat{x} \sin \theta' + \hat{z} \cos \theta') \quad (3)$$

The first term vanishes since the integrand is an odd function multiplied by an even proving the correct direction of the Weber force in order to account for the Meissner effect.

Next, we calculate the magnitude of the force to verify that it is significant. Number of electrons per cubic meter copper is $8.5 \cdot 10^{28} \text{ m}^{-3}$. The charge density becomes $1.4 \cdot 10^{10} \text{ C/m}^3$. Assuming a coil of 10000 turns and a total cross section $100 \cdot 10^{-4} \text{ m}^2$ the amount of charge per meter become $\lambda = 1.4 \cdot 10^8 \text{ C/m}$. The drift speed is of the order $v = 1 \text{ mm/s}$. The force on a conduction electron of the material then becomes

$$\bar{F}_q = 2 \cdot 10^{-24} \int_0^{2\pi} \frac{\cos \theta' d\theta'}{(a^2 + z^2 - 2az \cos \theta')^{1/2}} \hat{z} \quad (4)$$

The integral may be calculated for different radii z of charge q . The table shows the result:

Compare this force with a typical force on an electron due to a battery in a basic circuit. For a battery voltage of 1 mV acting over a distance, say 0.5 m, the electric field is of the order of 2 mV/m giving a force of $3 \cdot 10^{-22} \text{ N}$, i.e., of the same order of magnitude as the Weber force in the above example.

5. EXPERIMENTAL VERIFICATION OF WEBER FORCE

Moon and Spencer, as well as Assis [9–13], have shown the equivalence between the Weber acceleration-dependent force formula and the Faraday–Henry induction formula. In this derivation, one also obtains the important Neumann formula for inductance [20]. It is quite feasible, for example, to apply the Weber force in antenna theory. This was done by Moon and Spencer [13] to obtain all features of antenna theory as obtained from Maxwell's equations with respect to loop and dipole antennas. This forms a solid proof of the equivalence between the theories. For a summary and additional applications, see Ref. [21].

However, as shown above, Weber's dynamics emphasizes an extra dynamic, which is more or less hidden in Maxwell's theory. Recently, this extra feature was demonstrated experimentally by exploring

Table 1.

z/a	$a = 0.01 \text{ m}$ $F_q (\cdot 10^{22} \text{ N})$
1/10	0.62
2/10	1.3
3/10	1.9
4/10	2.7
5/10	3.5
6/10	4.4
7/10	5.6
8/10	7.1
9/10	9.8

exactly the same dynamic used above, i.e., the centripetal acceleration of the electrons in a loop [22]. Smith et al. studied the interaction between a steady current-carrying coil and a free electron beam. It was found that the effects from the centripetal acceleration in the coil could contribute significantly to the interaction, which was also confirmed experimentally. This experiment, together with the Meissner effect, forms a solid evidence for the correctness, uniqueness, and indispensability of the Weber force formula.

However, the Weber acceleration-dependent formula (1) is actually contained in the Maxwell's theory; although it is somewhat obscure. This is presented in the next section.

6. WEBER FORCE IN MAXWELL THEORY

When dealing with the Faraday-Henry induction law, one usually thinks of closed conductors associated with a magnetic field. From these phenomena, however, Weber inferred the basic and fundamental interactions between the constituents and formulated formula (1). To obtain this formula from Maxwell's theory, one needs to introduce the electric and magnetic potentials. As is well known, the electric field may be written as

$$\bar{E} = -\nabla\phi - \frac{d\bar{A}}{dt} \quad (5)$$

where ϕ is the electric potential, and the magnetic vector potential is given by

$$\bar{A} = \frac{\mu_0}{4\pi} \oint \frac{Id\bar{L}}{R} \quad (6)$$

R is the distance between the current element and the field point, and μ_0 is magnetic permeability. Utilizing the fact that the current element

$$Id\bar{L} = dq\bar{v} \quad (7)$$

i.e., the infinitesimal charge dq (electron charge) times its velocity v , the Weber formula assumes that the contribution to the vector potential from a single charge q is given by

$$\bar{A}_q = \frac{\mu_0 q\bar{v}}{4\pi R} \quad (8)$$

The possible terms that vanish when integrating over the closed path in formula (3) are neglected. Therefore, the Weber force (1) should be considered as a hypothesis. Note that the Weber acceleration-dependent force is associated with an electric field in field theory.

7. CONCLUSIONS

We have shown that the Weber force may account for the Meissner effect within classical physics. We explained this first conceptually making clear the basic dynamics behind the effect. The Weber force was then calculated showing the necessary direction and a significant magnitude. The Liverpool experiment [22] has earlier verified the validity and indispensibility of the Weber force within a basic phenomenon. From the consideration of this paper there is further evidence in this direction.

Finally, it is interesting to note that an equivalent formula to Weber's force appears in general relativity. This was derived by Einstein in his book "The Meaning of Relativity", formula (118) [23], in the linear approximation of general relativity. As the Weber force (1) accounts for electromagnetic inertia, a term coined by Maxwell [24], the corresponding GR force may account for mechanical inertia, which has been applied many times [25–28].

This connection between electrodynamics and GR is due to the fact that the velocity and acceleration-dependent dynamics are motional corrections to the static formulas, and are, as such, derivable from the Lorentz transformations [29].

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