

Teaching Discussion on Microscopic Mechanism of Diamagnetic Substance and Diamagnetism

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Abstract—Firstly, the different microscopic interpretations of the magnetic field affected by diamagnetic substance appearing in the textbook are introduced, and the doubts that are easy to arise are pointed out. Finally, a simple and lucid explanation is proposed.

Keywords—Diamagnetic substance, induced magnetic moment, Faraday's law of electromagnetic induction, Lorentz force

I. INTRODUCTION

In the electromagnetic teaching materials, according to the characteristics of magnetic field, magnetic media can be roughly divided into three categories: paramagnetic, antimagnetic substance, and ferromagnetics. The microscopic interpretation of the magnetic field affected by paramagnetic and ferromagnetics is almost identical in various textbooks. For diamagnetic materials, the internal magnetic field is slightly smaller than the applied magnetic field. Most of the textbooks use electronic orbital motion as an example to explain. The conclusion is that when the diamagnetic substance with zero molecular natural magnetic moment is under the action of an external magnetic field, an induced magnetic moment opposite to the direction of the applied magnetic field shows magnetic property on the macroscopic scale and slightly weakens the magnetic field. However, different electromagnetic teaching materials have different interpretations on the production mechanism of the induced magnetic moment. There are roughly three explanations. Here, the author briefly introduces these three explanations, and then proposes the students' doubts and even misunderstandings about the three explanations. Finally, a simple and easy-to-understand interpretation method is proposed.

II. THE MICROSCOPIC INTERPRETATION OF THE MAGNETIC FIELD AFFECTED BY DIAMAGNETIC SUBSTANCE

A. The First Explanation (the Electrons that Make Orbital Motion in the Molecule are Subjected to Lorentz Force when they are Added to the External Magnetic Field^[123])

Taking the orbital motion of electrons around the nucleus under the action of Coulomb force FC as an example, when adding an external magnetic field, the case that the angular momentum direction ω of circular motion of the electron is the same as the direction B of the external magnetic field ($\omega // B$). As shown in Figure 1(a), the direction of the Lorentz force received by the moving electrons points to the center of the circle, and the centripetal force increases to

$$(F = F_C + F_L)$$

$$\left(F = \frac{mv^2}{r} \right)$$

Assume that the orbital radius r does not change, according to the centripetal force formula, the speed of electron movement d must be accelerated, and the current increases, which is equivalent to increasing an additional current in the direction of the original current. The direction of original current is counterclockwise, and the direction of the additional current is also counterclockwise, so the direction of the additional magnetic moment generated by the additional current is downward, opposite to the direction of the original magnetic field.

Consider the case where the angular momentum direction ω is opposite to the direction of the external magnetic field B ($\omega // B$). As shown in Figure 1(b), the direction of the Lorentz force received by the moving electrons is back to the circle center, and the centripetal force is reduced. If the orbital radius r is constant, the speed of electron movement must be slowed down, and the current is reduced, which is equivalent to adding an additional current in the opposite direction of the original current. The direction of the original current is clockwise, and the direction of the additional current should be counterclockwise, so the

direction of the additional magnetic moment generated by the additional current is still downward, opposite to the direction of the original magnetic field.

See the reference [23] for specific proof.

In short, when the orbiting electrons are added to the external magnetic field, according to the two cases above, the direction of additional magnetic moment is always opposite to the direction of the external magnetic field, and extending to the electron spin and the nuclear spin, they also generate the additional magnetic moment in the opposite direction of the magnetic field under the action of external magnetic field. So, the sum of all the additional magnetic moments in the molecule is the induced magnetic moment of the molecule, which is opposite to the direction of the external magnetic field.

Taking the orbital motion of electrons around the nucleus under the action of Coulomb force as an example, the process of adding an external magnetic field is a process in which the magnetic induction intensity is increased from 0 to B , considering the case where the angular momentum ω direction of the circular motion of electron is the same as the direction of the external magnetic field B ($\omega // B$). As shown in Figure 2(a), the change of magnetic field will induce the induced electric field $E_{\text{感}}$, and the direction of induced electric field has a left helix relationship with B . The induced electric field force $F_{\text{感}}$ of the electron is opposite to the direction of induced electric field, and has the right helix relationship with B , so the induced electric field force direction is tangential and has the same direction with the electron velocity, increasing the speed. If the centripetal force of the electron is constant, the increased velocity dv will cause the electron to deviate from the circular orbit, but if an appropriate centripetal force is added at the same time, it meets the centripetal force formula.

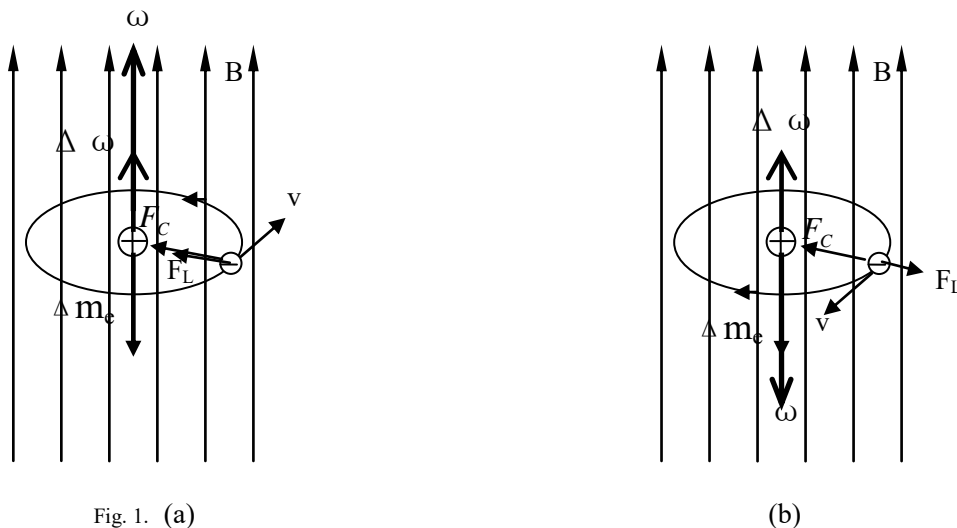


Fig. 1. (a)

(b)

B. The second explanation (electrons that have orbital movements in the molecule, adding an external magnetic field, are affected by the induced electric field force and the Lorentz force [4])

$$F_C + F' = m \frac{(v_0 + dv)^2}{r} \quad (1)$$

Then, the electrons can maintain the original circular orbit (r does not change), but the line speed increases.

In the process of adding an external magnetic field, the electron is not only affected by the induced electric field force at the tangential direction, but also by the normal Lorentz force, and the Lorentz force direction just points to the center of the circle, which can be proved^[45]

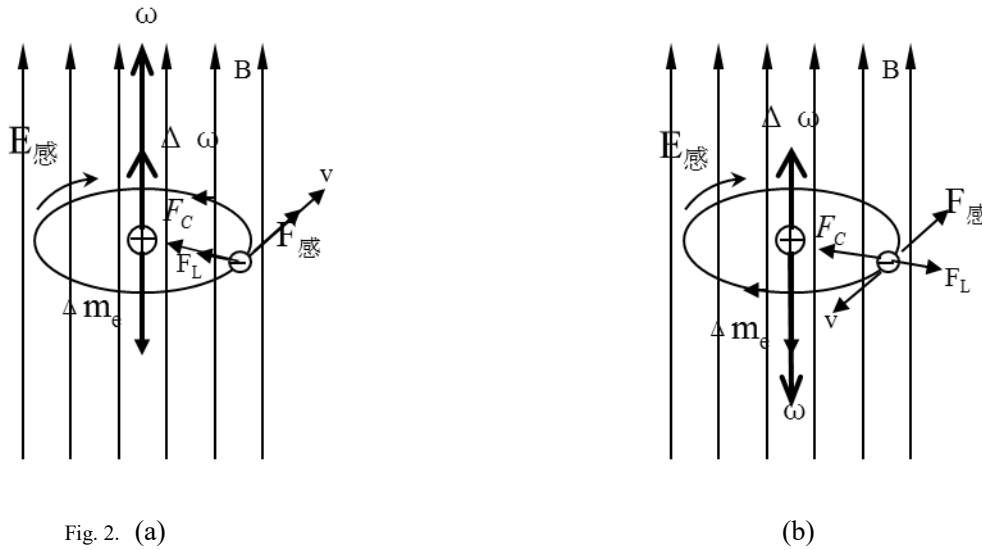
$$F' = F_L \quad (2)$$

Under the joint action of the two forces of the moving electrons, the radius does not change and the rate increases. As the rate of electrons increases, the current of electrons increases, which is equivalent to the addition of an additional current in the

direction of the original current. The direction of the additional magnetic moment Δm_e generated by the additional current is opposite to B .

Similarly, when $\omega // -B$, as shown in Figure 2(b), the induced electric field force is opposite to its speed, the direction of Lorentz force is back to the center of the circle. The radius is constant, the rate is reduced, and the electron current is reduced,

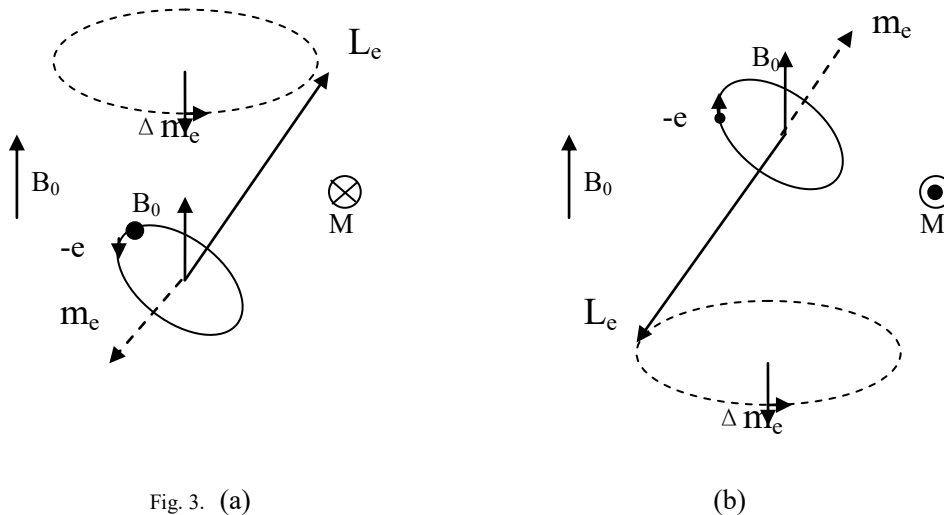
which is equivalent to adding an additional current in the opposite direction of the original current, and the direction of the additional magnetic moment Δm_e generated by the additional current is also opposite to B.



C. *The Third Explanation (the Electrons with Orbital Motion in the Molecule, Adding an External Magnetic Field, are Subject to the Action of Magnetic Moment, Generating the Precession, which Generates the Induced Magnetic Moment*^[6])

As shown in Figure 3, the electrons that make orbital motion have magnetic moments. In either case, the torque is generated under the action of the external magnetic field. From the torque moment formula $\vec{M} = \vec{m}_e \times \vec{B}_0$, the direction of the moment of force is perpendicular to the direction of the external magnetic field. According to the knowledge of mechanics, the rotating object generates precession under the action of a moment that is perpendicular to its angular momentum. Whether the included angle is less than 90 or greater than 90, the angular velocity of the precession is the same as the direction of the external magnetic field, so the additional magnetic moment generated by the precession is opposite with the external magnetic field.

See the reference [7] for specific proof.



III. DOUBTS IN THESE THREE EXPLANATIONS

For the first explanation, since only Lorentz force is mentioned, the biggest question for students is: 1. the direction of Lorentz force is in the normal direction, and it changes the direction of velocity, so the orbit should be changed, and the orbit is unchanged, why? 2. the direction of Lorentz force is not in the tangential direction, and Lorentz force should not change the electron velocity, why does the Lorentz force change rate? 3. If the Lorentz force changes the rate, it means that Lorentz has

done the work. This is contradictory with that Lorentz force do not work, but can only change the direction of charge speed and cannot change the speed.

The third explanation has the following problems: 1. It is necessary to understand the part of the fixed-point rotation to understand this interpretation; the general mechanics textbook introduces this part less, and it is difficult for students to understand; 2. According to this explanation, When the direction of the magnetic field is parallel or anti-parallel to the angular momentum, the magnetic moment is zero, there is no precession, and there is no additional magnetic moment, which seems to be unreasonable.

In contrast, the second explanation is more reasonable, but there are also problems: 1. To understand that the two forces work together to make the electron radius constant and the rate change. There must be quantitative theoretical derivation, and the derivation process is more complicated; 2. A special case where the direction of magnetic field is parallel or anti-parallel to the angular momentum is only explained.

IV. PROPOSE A PLAIN INTERPRETATION METHOD (FARADAY'S LAW OF ELECTROMAGNETIC INDUCTION)

The path of the electrons orbiting under the action of Coulomb force can be equivalent to the current loop with zero resistance due to their non-stop motion^[8]. During the process of adding the magnetic field, the magnetic field increases from 0 to B , and the magnetic flux on the current loop area increases, and the induced electromotive force is induced on the loop according to Faraday's law of electromagnetic induction, whether the angle between ω and \mathbf{B} is greater than or equal to zero or less than or equal to zero. According to Lenz's law, the direction of induced electromotive force and the external magnetic field follow the left helix (when the magnetic flux increases), the corresponding induced current direction also follows the left helix with the external magnetic field. And the induced magnetic moment direction generated by the induced current and itself also follows the right helix, so the direction of the induced magnetic moment is opposite to the direction of the external magnetic field.

When the magnetic field is stabilized, since the circular current has no resistance, the induced current remains unchanged, and the induced magnetic moment still exists. When the external magnetic field is removed, the magnetic flux is reduced, and the newly generated induced current direction is opposite to the original induced current direction (when the external magnetic field is applied), and the two cancel each other, making the induced magnetic moment disappears.

This explanation is simple and clear, and is suitable for any angle. It is easy to accept according to the students' existing knowledge and is not easy to produce ambiguity. Inadequacies can only be explained qualitatively.

V. CONCLUSION

To sum up the above four explanations, the starting point is to generate the induced magnetic moment, but the methods of interpretation are different, and each has its own advantages and disadvantages. Teachers can choose one or several to introduce according to the students' situation. Maybe there will be more explanations in the future, or eventually find a relatively uniform and complete explanation.

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