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Observation of magnetic field lines in the vicinity of a superconductor with the naked eye

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Abstract. This paper describes a new method of demonstration about superconductivity. A GdBaCuO high temperature superconductor of 60 mm in diameter and 10 mm in height, a sintered NdFeB cubic magnet with the edge length of 100 mm, and iron wires coated by colored vinyl are used to visualise the magnetic field lines in the vicinity of the superconductor, when it is placed in a magnetic field. The spatial distributions of iron wires make it understandable how the magnetism of superconductivity causes the levitation and suspension of conventional demonstrations. This paper is intended to be read especially by teachers of undergraduate courses and educators of science museums or science centers.

1. Introduction

Superconductivity is a phenomenon occurring in certain materials generally at low temperatures, characterized by the two distinct properties of (1) exactly zero electrical resistance and (2) the expulsion of the interior magnetic field. The latter property is called Meissner effect [1], and makes the superconductor exhibit perfect diamagnetism. The former property, combined with the discovery of high-temperature superconductors (HTSs) in and after 1986 [2], aroused the expectations of applying the superconductivity technology in industry.

As soon as the discovery of HTS took place, the method to demonstrate the Miessner effect was presented [3] and apparatus were developed [4, 5]. Discussion of rigid levitation and suspension of an HTS by a magnet also followed soon, by taking account of the pinning effect [6] (this effect is explained in Appendix). These demonstrations have allowed the general audience to observe the effects of superconductivity in larger scale and to come to a better understanding of the related physics than before. (Note that the practical HTSs used in the recent large scale demonstration show the diamagnetism caused by the pinning effect much stronger than that caused by the Meissner effect [7]; see Appendix for details.)

Examples of such conventional demonstrations, which the author has prepared in an especially large scale, are given in figures 1 and 2. Figure 1 shows a demonstration of repulsion, in which a sintered NdFeB ring magnet (hereafter called ring magnet) is repelled by a GdBaCuO HTS. The magnetic flux density of the ring magnet is about 0.4 T at the surface. A pair of chopsticks restricts horizontal movements of the ring magnet to make it float just above the HTS. Without this restriction, the magnet cannot levitate but goes away from above the HTS and falls down onto the table. Figure 2 shows a demonstration of the stable holding of an HTS at approximately constant distances from the ring magnet. Namely, in the continuous shots, an HTS is seen held (a) under, (b) on a side of, and (c) over a ring magnet, at almost the same relative positions with respect to the magnet. Note that any restriction of horizontal movements as shown in figure 1 is not necessary for this levitation. The physical explanations of these phenomena are given in section 2. These demonstrations can be presented successively to show the difference between the two phenomena of repulsion and stable holding. From these procedures, however, it is hard to understand the physics in the vicinity of the HTS and magnet.

Figure 1. Conventional demonstration of repulsion in a large scale. A ring magnet is repelled by an HTS, which is immersed in liquid nitrogen for cooling. A pair of chopsticks restricts horizontal movements of the magnet.

(a) (b) (c)

Figure 2. Conventional demonstration, in a large scale, of holding an HTS. An HTS (the white object) can be kept (a) below, (b) on a side of, and (c) above a ring magnet (the black object held by a hand) at approximately constant distances from the magnet.

For educational purposes, it is desirable that the magnetic field lines be visible for such superconductors to make the underlying physics understandable. Quantitative analysis has been done extensively [6, 8-9], and visualisation of real superconducting phenomena has been discussed. Tonomura et al., for example, demonstrated visualisation of magnetic field lines in superconductor at the vortex level by using electron holography and digital phase analysis [10]. While being useful for basic research and industrial applications, these methods cannot easily be used for demonstration to general audience and students because of high technicality.

The present author has studied new methods of demonstration, which requires no specialized device or skills and therefore are easily prepared and conducted by non-experts for educational use, and has discussed a simple method to visualise external magnetic field lines repelled by the HTS in the previous papers [11], showing that the phenomena of the effect are easily observed without a supplementary device. The present paper describes the results of the exploration of demonstrating magnetic field lines connected to the pinned flux in the HTS as well as the repelled field lines. The latter and the former field lines related to repulsion and stable holding shown in figures 1 and 2, respectively. The new demonstrations are considered useful for giving qualitative understanding of these phenomena to the observers.

It is often explained that the repulsion of the magnet as shown in figure 1 and the holding of the HTS as shown in figure 2 are caused by the Meissner effect. However, the latter phenomenon is caused obviously by the pinning effect (see subsection 2.2), and the former phenomenon is also considered possibly by the pinning effect [7] (see Appendix).

2. Visualisation of magnetism in superconductivity

In this section, the author discusses visualisation of magnetic field lines in the vicinity of the HTS in two scenarios shown in figures 1 and 2. The HTS used was fabricated by Nippon Steel Corporation [12], and is 60 mm in diameter and 10 mm in height. The HTS is immersed in an external magnetic field, which is produced by a sintered NdFeB cubic magnet with the edge length of 100 mm (hereafter called cube magnet). This cube magnet is of the type used in nuclear magnetic resonance imaging, and the magnetic flux density is about 0.5 T at the surface (figure 3). The magnetic field lines are observed through iron wires of 0.3-mm diameter coated by colored vinyl, so-called twist tie.

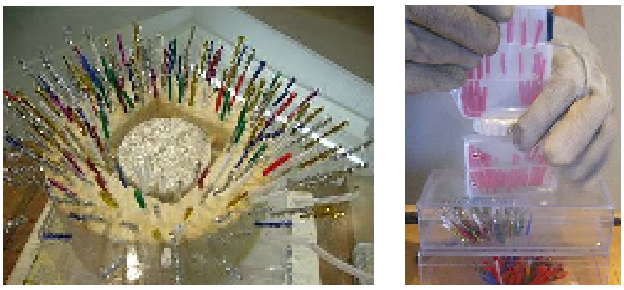
Figure 3 shows that the pieces of wire in acrylic cases stand against the gravity under the influence of the magnetic field. Light fragments of wire are easily aligned to magnetic field lines with minor friction against the acrylic case, and point in the direction tangent to magnetic field lines. Thus the distribution of the wires reflects the magnetic field strengths at different places. Simple tapping of the acrylic case is enough to reduce the friction momentarily to the negligible level and to get an arrangement of wires close to the real density distribution. The underlying principle of this method is identical to that of the well-known iron filings, and the effect of the gravitational force is negligible compared with that of the magnetic force in the vicinity of the magnet.

Visualisation of magnetic field lines in the vicinity of the HTS causing repulsion and pinning are described in the following subsections.

Figure 3. Demonstration of magnetic field lines. Iron wires in transparent acrylic cases show magnetic field lines coming out of a cubic magnet with the edge length of 100 mm. The magnetic flux density of the magnet is about 0.5 T at the surface.

2.1. Repulsion of external field

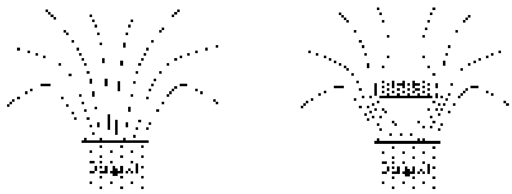
Two pictures of figure 4 show demonstrations of the magnetic field near an HTS placed above the cube magnet, similarly to the scenario shown in figure 1. The HTS is immersed in liquid nitrogen, which in turn is in a Styrofoam container. In figure 4 (a), the wires initially placed directly above the HTS are pushed out by the magnetic field to their present positions; namely, the distributions of wires shows that there is no magnetic field line just above the HTS. In figure 4 (b), the distribution of wires shows the magnetic field lines in the spaces surrounding the HTS; namely, how magnetic field is repelled by the presence of the HTS. These distributions of wires correspond to two views of figure 5 (b), which is the schematic diagram of the repulsion by an HTS placed in the magnetic field shown by figure 5 (a). Thus, figures 4(a) and (b) are effective demonstrations of the diamagnetism by the use of magnetic field lines.



(a) (b)

Figure 4. Repulsion of magnetic field lines. (a) An HTS is immersed in liquid nitrogen in a Styrofoam container. A cube magnet is located under the container. Wires to show the magnetic field lines are put on a transparent plastic plate, which in turn is placed on the container. Those wires that were initially put above the HTS are pushed out by the magnetic field to the positions

now seen in the picture. (b) Small plastic cases containing wires are placed above and below the HTS. Large plastic cases with wires are placed below the lowest small plastic case. The cube magnet is placed below the lower large plastic case. The distributions of wires again show that there is no magnetic field line passing through the HTS.



(a) (b)

Figure 5. Schematic diagrams of the repulsion of magnetic field lines. The external magnetic field lines coming out of a magnet, as shown in (a), are repelled by the presence of an HTS, as in (b). These diagrams have been drawn on the basis of a theoretical consideration.

From the demonstrations of figure 4, the explanation of the phenomenon shown in figure 1 can be derived as follows: The magnetic field lines emanating from the ring magnet in figure 1 are repelled by the HTS. If the magnet gets closer to the HTS, the distortion of the magnetic field grows, and the distortion energy becomes higher, causing the repulsion of the magnet, and accordingly levitation under the restriction of horizontal movement. Note that the HTS in figure 5 (b) seems to levitate without the restriction. If the horizontal component of the repulsive force is directed to the center of the magnet, levitation will occur without the restriction. The early demonstrations of levitation were of such kind. In fact, a small HTS can levitate without the restriction above the ring magnet. Such levitation and the stable holding as shown in figure 2 are different phenomena. The latter is explained in the next subsection.

It might be supposed that figure 5 shows the Meissner effect. In the case of the practical HTS used here, however, the pinning effect is considered to be responsible for the observed repulsion of the external field [7] (see Appendix for details).

2.2. Pinning of external field

To obtain the HTS in the scenario shown in figure 2, an HTS is cooled in the presence of a magnetic field, which is produced by the ring magnet placed above the HTS as shown in figure 6. The magnetic field in the HTS does not change by cooling. After cooling and taking away of the magnet, the magnetic flux in the HTS stays there because of pinning (see Appendix for details).

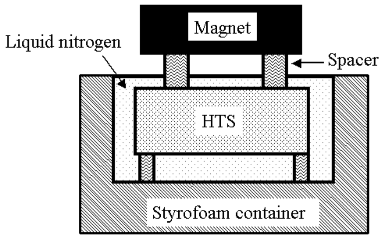


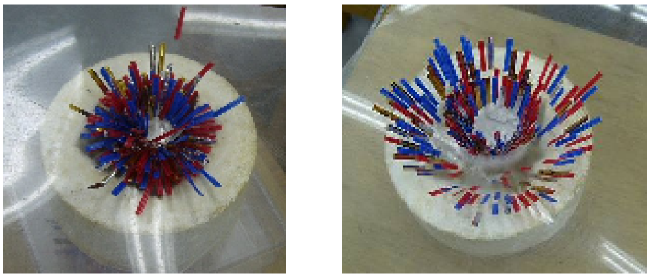
Figure 6. Schematic diagram of arrangement to produce the pinning of magnetic flux. After cooling, the magnetic field lines before cooling are pinned in the HTS.

Figures 7 and 8 show demonstrations of the magnetic field lines around the HTS with pinned magnetic flux when the HTS is placed at different positions with respect to the cube magnet. Schematic diagrams to explain these demonstrations are given in figures 9 and 10. Details of these figures are explained below.

In figure 7, wires show magnetic field lines when the HTS is moved horizontally above the cube magnet. The magnetic field due to the HTS itself reflects the flux distribution of the ring magnet when the HTS was cooled in the arrangement of figure 6. Figures 7 (a) and (c) demonstrate respectively that when the HTS is brought to the left and right, the magnetic field lines are distorted so as to be connected tangentially with the internal magnetic field lines of the HTS as shown in figures 9 (a) and (c). Inside the HTS, however, the magnetic flux is pinned, so that the field lines stay as they are.

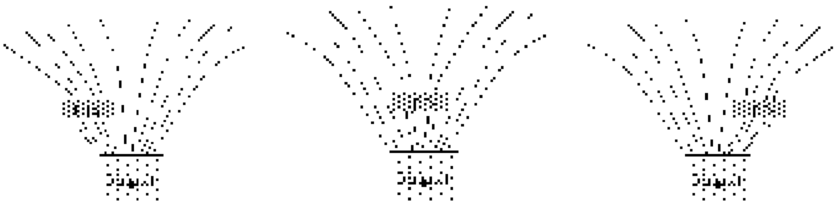
(a) (b) (c)

Figure 7. Change in magnetic field lines above the HTS in which magnetic flux is pinned, as observed when the HTS is put (a) above left, (b) just above and (c) above right with respect to the cube magnet. The HTS is put in the Styrofoam container of figure 6. It can be understood from this demonstration that the magnetic field trapped in the HTS is held fixed regardless of change in external field.



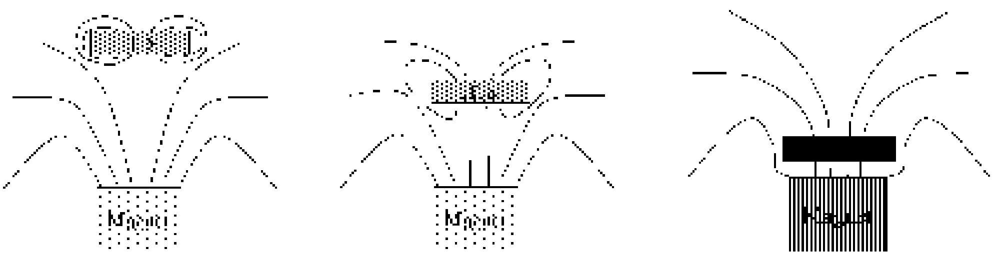
(a) (b)

Figure 8. Magnetic field lines above HTS with pinned magnetic flux, in a varying external magnetic field strength. The HTS, put in the Styrofoam container of figure 6, is placed above a cube magnet. The distance between the HTS and the magnet is 190 mm in (a), and 60 mm in (b). Flux pinning in the HTS was caused in advance by a ring magnet in the arrangement of figure 6. It can be understood from this demonstration that the trapped magnetic field is held fixed in position regardless of change in external field.



(a) (b) (c)

Figure 9. Schematic diagrams of the pinning effect resisting the horizontal movement in an external magnetic field. The external magnetic field lines are deformed for tangential connection with the field lines in the HTS. The HTS is shifted horizontally (a) to the left and (c) to the right, but the internal magnetic field is not altered because of the pinning effect. These diagrams have been drawn on the basis of a theoretical consideration.



(a) (b) (c)

Figure 10. Schematic diagrams of magnetic field lines around an HTS with flux pinning, placed at different distances from a magnet. The bound magnetic field lines are connected with the external magnetic field lines, but the internal magnetic field is not altered because of the pinning

effect. These diagrams have been drawn on the basis of a theoretical consideration.

In figure 8 (a), the HTS is placed at a distance of 190 mm above the cube magnet. The corresponding magnetic field lines around the HTS are schematically drawn in figure 10 (a). Because the magnetic field due to the HTS is stronger than that caused by the cube magnet at the position of the HTS, the field lines near the HTS make closed loops. When the HTS is lowered to a distance of 60 mm as shown in figure 8 (b), the magnetic field lines from the part of the cube magnet just below the HTS become connected to the internal field lines of the HTS, as shown in figure 10 (c), and those outside that part are expelled by the diamagnetism. In either condition, the trapped magnetic field lines are unaltered.

By the demonstration of figures 7 and 8, it can be understood that the magnetic field lines are fixed inside the HTS, showing the macroscopic pinning (see Appendix in detail). From these demonstrations, the phenomena in figure 2, i.e., the holding of an HTS at approximately constant distances, can also be understood as follows: Before cooling by the arrangement shown in figure 6, the magnetic field lines emanating from the north pole of the ring magnet penetrate the HTS, and stream into the south pole. In this situation, the magnetic field is in the ground state. After cooling, any change in the relative position between the HTS and the ring magnet distorts the ground state magnetic field and increases the energy of the field, because the magnetic field lines are pinned inside the HTS. In other words, a restoring force acts the HTS for any change in the relative position between the HTS and the ring magnet. Because of the tight pinning effect of the practical HTS and the large magnetic flux density of the ring magnet (0.1 T at the HTS), the restoring force is so strong that the effect of the gravitational force is negligible. Therefore, the relative position before cooling is stable, and thus the stable holding of the HTS at approximately constant distances is made possible.

So far the author has described methods to visualise the magnetic field in the vicinity of an HTS in an applied external magnetic field by means of fragments of wires. Although it is not possible directly to observe the microscopic picture of vortex lattices of the pinning effect (see Appendix), macroscopic results of the pinning effect can easily be demonstrated by the use of accessible materials.

3. Concluding remarks

The author has developed a simple and easily accessible method to visualise the repulsion and pinning of the magnetic field lines by an HTS. By the use of this method, the breakdown of superconductivity can also be demonstrated when the HTS above the cube magnet in figure 7 is warmed in the room temperature environment. Several movies have been prepared and posted at a Web site [13] to help readers obtain a better picture of the demonstration described in this paper. The movies are made to supply much information on superconductivity to non-experts, and the effectiveness has been demonstrated at Osaka Science Museum, Osaka, Japan, where visitors not only enjoy the less intuitive physics phenomena, but also deepen their understandings by picturing the magnetic field lines surrounding the HTS and the magnets in their minds. This demonstration should also be useful in introductory courses on superconductivity, because the method presented is simple, easy to set up and use, and the device is large enough to be observed by relatively large audience at once. The HTS and the cube magnet as used here are presently available only in Japan, namely, from Technology Research Laboratories, Nippon Steel Corporation [14], and Jishakukobo [15], respectively. Even if the equivalents of these were not found, the demonstration would be possible with scaled-down equipment.

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Appendix. Basics of superconductivity

In this appendix, we give a brief description of the basics of superconductivity and introduce the pinning effect at microscopic level [16].

Two types of superconductors, i.e., Types I and II, are known. A Type I superconductor, when it is placed in an external magnetic field weaker than a critical value H_c, is in the superconducting state (called Meissner state) and shows the Meissner effect, i.e., the expulsion of the interior magnetic field. In a magnetic field stronger than H_c, it is in the normal state, at which superconductivity is destroyed. A Type II superconductor is in the Meissner state for a magnetic field weaker than a critical value H_{c1}; in the vortex lattice state for a magnetic field between H_{c1} and a second critical value H_{c2} ($H_{c1} < H_{c2}$); and in the normal state for a field stronger than H_{c2}. In the vortex lattice state, the magnetic flux from the external field is not completely expelled but the superconductor is still superconducting. At the microscopic level, quantized flux lines penetrate into the superconductor through the normal state core of vortex. The interactions of such vortices form a vortex lattice [10, 17]. Thus the Type II superconductor in the vortex lattice state allows the field to penetrate, while the penetration is completely forbidden in the Meissner state. The values of H_{c1} and H_{c2} depend on temperature; namely, these values increase when temperature is decreased. All known HTSs are of Type II. A Type II superconductor shows the phenomenon where magnetic flux becomes trapped or “pinned” inside the material. This is called pinning effect, and is possible when there are defects that act to resist the movement of the vortex to some extent just like the static friction force and to trap the vortex lattice in the crystalline structure of the superconductor.

The practical HTS used in this work includes finely dispersed non-superconductor crystal in the matrix of the pure GdBaCuO crystal HTS [12]. The non-superconductor crystals make the pinning effect very tight. In other words, non-superconductor crystals cause the strong static friction for the magnetic field lines. This tight pinning effect exhibits the holding of the HTS as shown in figure 2 as well as the powerful repulsion of the eternal magnetic field, which could be a few T from experience [18]. It cannot be claimed that the repulsion of the magnet shown in figure 2 and that of the wires in figure 4 are caused by the Meissner effect [7]. The reason is as follows: Though the value of H_{c1} of the GdBaCuO HTS is not in the review work of the author, in the case of YBaCuO HTS, H_{c1} at liquid nitrogen temperature is 10–20 mT [19]. Therefore, the repulsion of the external magnetic field by the Meissner effect can be seen up to about 10–20 mT. However, the magnetic flux densities at the surface of the HTS in figures 2 and 4 are about 50 mT and 30 mT, respectively. These values are higher than H_{c1} of YBaCuO. In any case, the practical GdBaCuO HTS exhibits the repulsion of the magnetic field lines caused by the tight pinning effect much stronger than the one caused by the Meissner effect.

If the HTS is cooled in the presence of a magnetic field, the magnetic field in the HTS does not change at the naked-eye level by cooling because of the pinning effect. Physically speaking, a continuous magnetic field in the HTS changes to discrete ones, i.e., bundles of the quantized magnetic flux lines penetrating vortices. The HTS in the scenario shown in figure 2 was obtained by this method, i.e., by cooling under the ring magnet as shown in Figure. 6. The details of the scenario are as follows. When any region in the HTS is cooled to such a temperature that H_{c2} is above the applied magnetic field strength (note that H_{c2} increases as the temperature is decreased), the vortex lattice state is achieved in that region, and the magnetic field lines that pass through normal state cores inside the HTS are fixed by the pinning effect. Thus, the HTS becomes the vortex lattice state with non-uniform vortex density. This state does not change even if the HTS is cooled further or if the ring magnet is taken away, because the magnetic field lines are pinned.

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