So.......What *Would* Happen If a Magnet Were Dropped Down a Superconducting Tube? .....or....The Meissner Effect Revisited

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It is now more than a quarter century since this question was first posed to a small group of physicists and physics teachers - including Caltech's David Goodstein and Richard Feynman. The animated discussion of the many speculations that followed was sheer joy. Then a surprising answer was offered by Goodstein - which evoked an immediate and gleeful "Of course!" from Feynman (and I might add, from the rest of us as well!). The question is: What did Goodstein say that the rest of us agreed with so quickly? And why do we think his answer was right? This discussion will include how magnets and superconductors interact, Faraday's law, the Meissner effect and London's equation, magnetic forces, induced currents and persistent currents - and which of those principles and ideas are important to answering this question.

INTRODUCTION

It was in November 1987 - nearly an academic career ago, when the Southern California AAPT meeting at La Canada High School included a distinguished panel with then *AJP* editor John Rigden, Caltech's David Goodstein, and Richard Feynman, among others, discussing the question of what should be included in the high school physics curriculum. It was a great meeting. But it was what happened immediately following the meeting that any of us there will remember forever. The panel and a group of a dozen or so physicists and physics teachers were standing around reflecting on the day's meeting when the late Robert Wild (a celebrated physics teacher from UC Riverside, my freshman physics instructor) handed Feynman a thick-walled copper tube and a magnet - and dropped the magnet down the tube. Of course, it fell *s o s l o w l y*., a result of the induced currents which create a magnetic field inside the tube slowing the magnet's fall - a common demonstration that most of us know. Feynman played with this often used demo in his nearly childlike manner, repeatedly dropping the magnet down the tube - undoubtedly delighting in the interplay of the principles and ideas involved in this demonstration as well as the camaraderie of the physicists and teachers in the group. Then Wild asked *The Question*, "What would have happened had the tube been made of one of those new superconductors?" (This was the year of the high temperature superconductors - the discovery of the cuprates with T_C above liquid nitrogen temperature and of the “Woodstock of Physics”, the March APS meeting in Washington, D.C. dominated by this topic.) Feynman immediately responded, "I don't know anything about the *new* superconductors - so let's just think of it as an *ordinary* superconductor" (emphasis his, as if *any* superconductor is "ordinary"). And the mood of the group suddenly changed from light to serious - a new physics question had just been raised - one that had never been considered before. And there we were - all speculating on what would happen and in the presence of Richard Feynman!

"It would never make it into the tube," said one, "It would just levitate above the opening of the tube." "But it probably wouldn't be stable in that configuration", said another. "But even if it levitated, that is just due to a balance of forces. We could always force it into the tube", I injected. "But it would probably pop back out when released!", came a response. Someone thought it would just slowly work its way down the tube. Another said it might just come to a complete stop - or maybe oscillate in the tube. The speculations - with arguments and counter-arguments - in that animated discussion were such great fun! Would the magnet ever fall through the tube - or would it levitate? Would it come to a stop inside the tube or oscillate? If it didn't come to a stop, with what final speed would it leave the tube? Would persistent currents be induced in the tube? If so, what happens to those currents when the magnet finally *does* fall through - if it ever does? It is a problem worth thinking about - an interesting question of the type that drew us all into physics originally. How do the principles come together to allow us to explain what would happen?

Then David Goodstein made a pivotal observation. "If the magnet ever made it inside the tube," he said, "then it would ...." That is, in completing that sentence, he posed a solution to The Question. "Of course!", said Feynman in his grand exuberant style - with that great sense of excitement that comes with new insight into an interesting question. It was vintage Feynman. And nearly all the rest in the group either said or thought, "Of course", as well. We all left that meeting with lasting memories of that discussion - as if we had been "on holy ground", as John Rigden was to later write[1,2]. But what was Goodstein's observation? And why did Feynman so quickly agree? And why did the rest of us agree as well? (Well, I suspect I know why most of us agreed.) What do we have to know to be able to construct a careful answer to that question: "What *would* happen if a magnet were dropped down a superconducting tube?" And what did Feynman mean when he said we should just consider an *ordinary* superconductor - why is that restriction important?

The Magnet in a Normal Conducting Tube

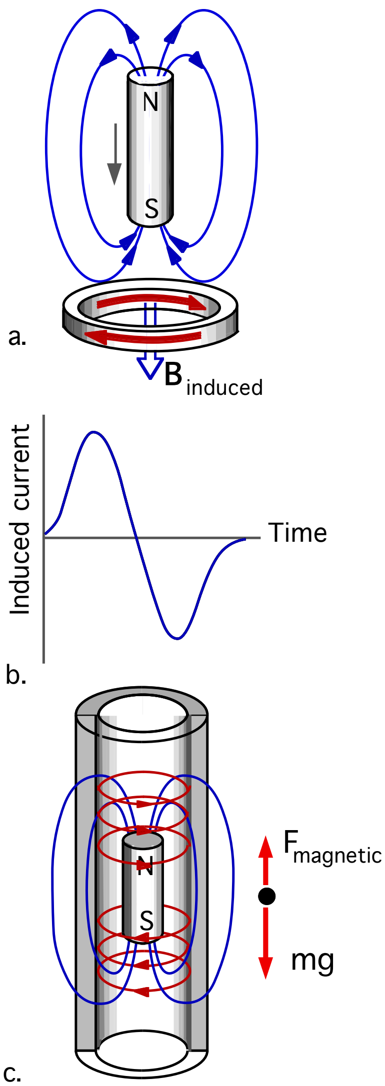

Figure 1

To address the question, we should first think about what happens in a normal conducting tube when a magnet is dropped through it. And even that is easier to think about by first just considering a conducting ring - in effect, a very short tube. As the magnet falls toward the ring as shown, the magnetic flux through the loop of the ring is increasing (vertically upward for the magnet polarity shown in Figure 1a). That changing magnetic flux induces an EMF in the ring (according to Faraday's law), which in turn drives a current in the ring creating a magnetic field which opposes the change in flux. The current is essentially proportional to the EMF, since the mean free time between electron collisions with the vibrating lattice is on the order of 10^{-14} seconds, hence the induced current nearly exactly follows the induced EMF.

As the magnet falls through the ring and is "centered", that is, as it crosses the plane of the ring, the magnetic flux through the ring is at a maximum - which means it is no longer changing. Consequently, the induced current goes to zero. The current then reverses direction as the magnet falls on through since the flux through the ring due to the magnet diminishes as the magnet falls away, and the induced current circulates in a direction to try to maintain the now diminishing magnetic flux.

The effect, of course, is that as the magnet falls toward the ring, the induced current creates a magnetic field pointed downward (for the magnet orientation shown) and that creates an upward force on the pole (S) of the magnet entering the ring. As the magnet falls through and then away, the current reverses and creates a field pointed upward - which also causes an upward force on the nearest pole (which is now N) of the magnet. That is, in both cases, the force on the falling magnet due to the field produced by the induced current in the ring is upward - hence opposing its fall. And the magnet falls more slowly through the ring than if it simply fell in the absence of a conducting ring.

When a magnet falls through a normal conducting tube, the result is essentially the same (Figure 1c). The induced current below the falling magnet has a direction such that the force on the magnetic pole on the lower end of the falling magnet is upward. The induced current above the falling magnet is opposite in direction, and exerts a force on the upper pole of the magnet which is again upward. So the magnetic force on the magnet due to the induced currents both above and below the falling magnet is upward - which opposes the effect of gravity. When the magnetic force equals the gravitational force, the falling magnet reaches a terminal speed and then falls through the tube without further acceleration. Of course, the loss of gravitational potential energy of the falling magnet is divided between kinetic energy and thermal energy due to i^2R heating in the tube – and becomes all thermal when the magnet reaches constant speed in its fall through the tube.

Although the copper tube is a very good conductor, it is not without resistance. But we *can* significantly reduce the resistance of the copper tube to see what effect that would have on how the magnet falls. Since the resistivity of a metal is approximately proportional to the absolute temperature, cooling the copper tube to liquid nitrogen temperature increases the mean free time between collisions by a factor of four - hence increases the conductivity by nearly the same factor. The result should be that the same falling magnet should induce larger currents in the tube - and in so doing create larger magnetic fields opposing the fall of the magnet, so it reaches its terminal velocity sooner. The magnet falls more slowly in the "even better conductor" - the copper tube cooled to 77 K. But the question then becomes, what would happen if the tube were a perfect conductor – that is, how would the magnet fall if the tube had *zero* resistance. And are *perfect* conductivity and *super*conductivity equivalent? And if not, how are they different and how does that affect this problem.

What is a Superconductor - How is it different than a *perfect* conductor?

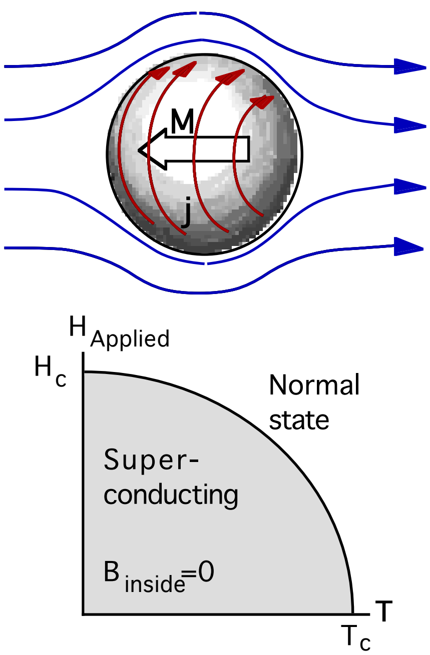

Figure 2

The superconducting state is characterized not only by zero resistance, but by the Meissner effect. Although a magnetic field is unaffected by the presence of normal non-magnetic solids, the magnetic field goes to zero in the interior of a superconductor. Magnetic flux is both excluded from penetrating a superconductor and will be expelled from a superconductor if already present and the temperature is lowered below the critical temperature T_c - as long as the field strength does not exceed a certain critical field strength. (The field actually does penetrate some right at the surface, diminishing exponentially to zero in a very small distance called the London penetration depth.) The effect was discovered by Meissner and Ochsenfeld[3] in 1933 and is called the Meissner effect. In this state, the superconductor is said to be a *perfect diamagnet* since the internal magnetization exactly opposes the applied field.

Although a magnetic field does not penetrate the interior of a superconductor, a sufficiently large magnetic field at the surface of a superconductor can quench the superconducting state and return the metal to its normal resistive state - even though its temperature is below T_c. The effect can be represented on a phase diagram - the H vs T curve showing the transition between the normal and superconducting state. At any temperature below the critical temperature, there is a critical value of the magnetic field at the surface which would quench the superconductive state and return the solid to its normal conductive state. This description is for a type I superconductor.

For a solid to be called a superconductor, it must exhibit both zero resistance and the Meissner effect below some critical temperature. It is the Meissner effect that distinguishes a superconductor from an idealized *perfect* conductor. That is, *just* the limiting case of zero resistance in a solid would not result in either the Meissner.

Type I and Type II Superconductors

The distinction between type I and type II superconductors resides in the Meissner effect. Type II superconductors behave in a more complex way than described above. Although the response to a low magnetic field is essentially the same, there is a critical field H_{c1} above which the superconducting state remains but for which the sample is not a perfect diamagnet. In this *intermediate state* or *mixed state*, as it is called, the sample resistance is still zero, but magnetic field lines can penetrate the bulk material (well beyond the London penetration depth) in thin filamentary regions called "flux tubes" which themselves have the properties of the normal metal. The bulk material between these filaments remains in the superconducting state. Only when the applied magnetic field exceeds a second, much higher, critical field H_{c2} is the superconductive state quenched and the solid "goes normal". Figure 3 depicts the phase diagram for a type

II superconductor and a superconducting disk in the intermediate state – showing some, but not all, field lines penetrating the superconductor.

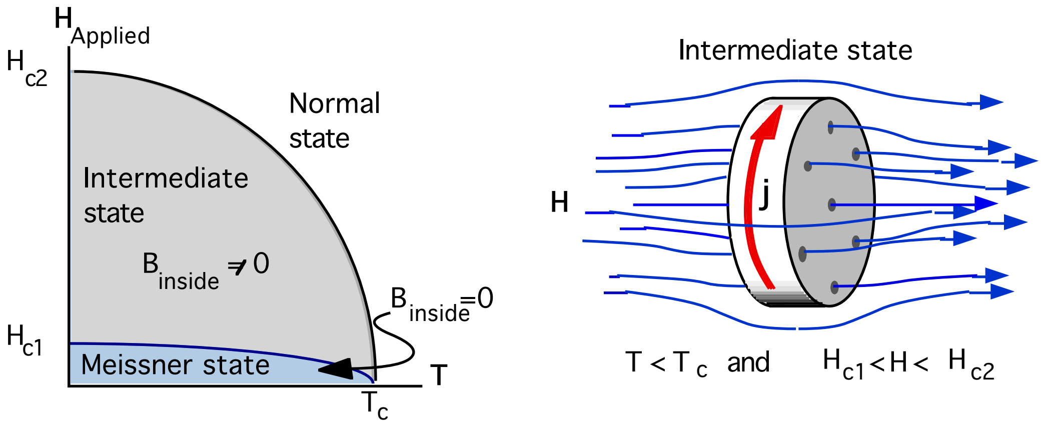

Figure 3

All of the alloy superconductors - and in particular, all of the high-temperature superconductors - are type II. What Richard Feynman meant when he said, "Let's consider only *ordinary* superconductors." was that we should only consider the magnet to be dropped down a *type I* superconducting tube (or, at least a tube that is in the Meissner state). That way we can assume that the magnetic flux is completely excluded from the interior of the material itself - and that would preclude any of the flux pinning effects that are so common in the high T_c superconductors (and results in the stability of levitating magnets in that common demonstration).

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LONDON EQUATION, MEISSNER EFFECT, AND SURFACE CURRENTS

In order to describe the Meissner effect mathematically, it is necessary to describe the relationships between the magnetic field at the surface of the superconductor and the induced surface currents. Combining Faraday's law

$$\frac{d\mathbf{B}}{dt} = \nabla \times \mathbf{E} \tag{1}$$

and that an electric field can exist in a superconductor only if the current is changing according to the equation (first stated by H. and F. London in1935 [4])

$$\mathbf{E} = -K\frac{d\,\mathbf{j}_s}{dt} \tag{2}$$

(where $\mathbf{j}_S$ is the current density due to superconducting electrons and K depends on the electron charge, mass, and the concentration of superconducting electrons) yields an equation of the form

$$\frac{d\mathbf{B}}{dt} = -\,K\,\nabla \times \frac{d\,\mathbf{j}_s}{dt} \tag{3}$$

This relationship between the time derivatives of the magnetic field and the current density predicts that induced surface currents in a perfect conductor would *prevent* any change in the magnetic field within the solid. This result *seems* to be consistent with the Meissner effect - that is, a superconductor would not allow a magnetic field to penetrate it since the changing magnetic field would produce a circulating current that exactly opposes the change. But it is not consistent with the more restrictive Meissner effect that a superconductor will even *expel* an existing magnetic field from its interior when it goes from the normal to superconducting state. That is, if a magnetic field were already present in a sample when it was in the normal state, then Equation (3) would suggest that it would be trapped in the superconductor when lowered to below the transition temperature, since a circulating current would be induced to prevent the field from changing. But that is not what was observed by Meissner and Ochsenfeld[2] when they showed that the superconducting state precluded a magnetic field from penetrating the superconductor regardless of the order in which the field was applied and the sample was cooled through the critical transition temperature. It was for that reason that H. and F. London postulated the phenomenological equation **j**=–*(some constant)***A** (where **A** is the vector potential such that $\mathbf{B} = \nabla \mathbf{x} \mathbf{A}$) or its equivalent in the form

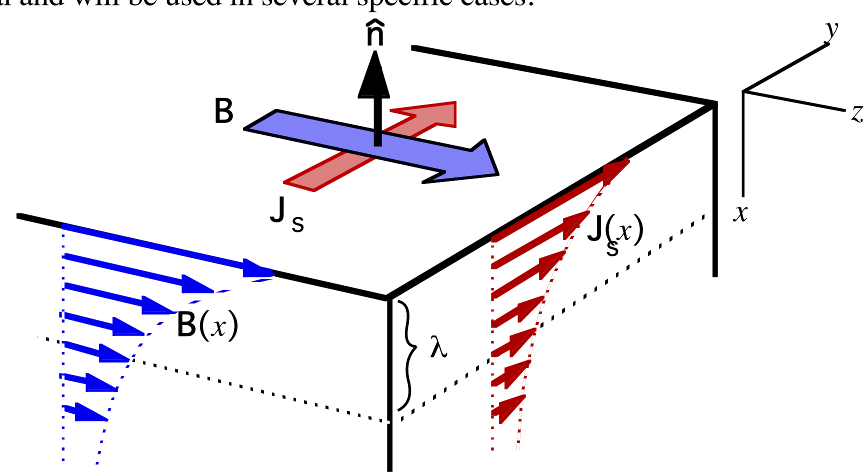
$$\mathbf{B} = -K \nabla \times \mathbf{j}_s \tag{4}$$

relating the magnetic field and the circulating current density at the surface of a superconductor. This relationship *is* consistent with both Meissner effects - that magnetic flux will not penetrate a superconductor and if a field were present when the material became superconducting, it would be expelled from the superconducting solid. That is, the London equation predicts that surface currents are induced by the *presence* of a magnetic field (and not just a changing field as predicted by Faraday's law) such that the interior of the superconductor is shielded from magnetic flux as long as the flux density is less than the critical field. Furthermore, combining London's equation and Ampere's law (in the form $\mathbf{j} = -\mu \nabla \mathbf{x} \mathbf{B}$), both the magnetic flux density **B** and the surface current density can be shown to decrease exponentially with distance from the superconductor's surface according to the relationships

$$\mathbf{B}(x) = \mathbf{B}_o e^{-\frac{z}{\lambda}} \quad \text{and} \quad \mathbf{j}(x) = \mathbf{j}_o e^{-\frac{z}{\lambda}}$$

where $\mathbf{B}_o$ and $\mathbf{j}_o$ are the values of the magnetic field and current density at the surface, z is the depth into the superconductor, and λ is the London penetration depth (which is typically of the order or a few microns in conventional superconductors).

The London equation also allows one to determine the direction of the induced surface current given the direction of a magnetic field at the surface of a superconductor. That is, if the surface current in a superconductor diminishes with depth into the sample, then the direction of **B** must be opposite the curl of that changing current density. And similarly, according to Ampere's law, the current density will be in the direction of the curl of the magnetic field. And that is just the direction for the induced current to properly shield the interior of the superconductor from the magnetic field. To be consistent with those two conditions, the induced current density **J** is in the direction of **nxB**, the cross product of the unit vector normal to the surface and the magnetic field at the surface and does not depend on whether the field is changing. This result is completely general and will be used in several specific cases.



1 Figure 4

Induced Currents in Superconducting Rings - Persistent Current

The effects of applying magnetic fields to superconducting cylinders and rings either before or after lowering the temperature below T_C have been described in various publications and textbooks[5,6] in the discussions of inducing persistent currents. The directions of the induced currents have not always been quoted correctly, however. Being consistent with the predictions of the BCS theory (and London's equation) yields some surprising results to some commonly described problems.

Consider the common description of the existence of a persistent current in a superconducting ring. The current is usually described as being initiated by inserting a magnet into the ring while it is in its normal state, cooling below T_c, and then pulling out the magnet. By Faraday's law, a superconducting current is induced which reproduces the magnetic flux through the ring - and the current persists indefinitely since there is no collision process for the superconducting electrons. But according to the London equations, current flows even prior to removing the magnet. Upon cooling the ring below T_c with the magnet in place, equal and opposite currents are induced on the inner and outer surfaces of the ring (Figure 3a). These currents are necessary to shield the interior of the superconducting ring from the magnetic field. The direction of the currents can be deduced from applying the London equation.

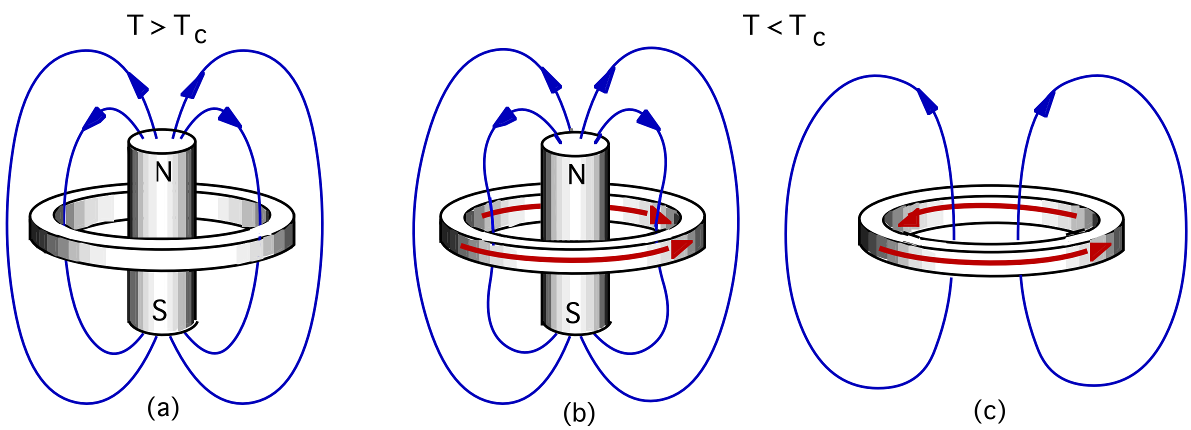


Figure 5

Removing the magnet indeed induces a net current in the ring in order to leave the net flux through the ring unchanged - a consequence of Faraday's law. But that changes the direction of the magnetic field at the inner surface of the ring, and consequently changes the direction of the surface current as shown in Figure 5c.

If the same ring is placed in a magnetic field and then cooled below T_c, as in Figure 6a, equal and opposite currents are again induced to shield the superconductor. But the currents are opposite in direction than in the previous case (Fig. 5b). Moreover, if the external field is now removed to induce a net persistent current according to Faraday s law, it is the current on the outer surface that changes direction (Figure 6b). This result is a consequence of the change in direction of the magnetic field at the outer surface due to the net current in the ring.

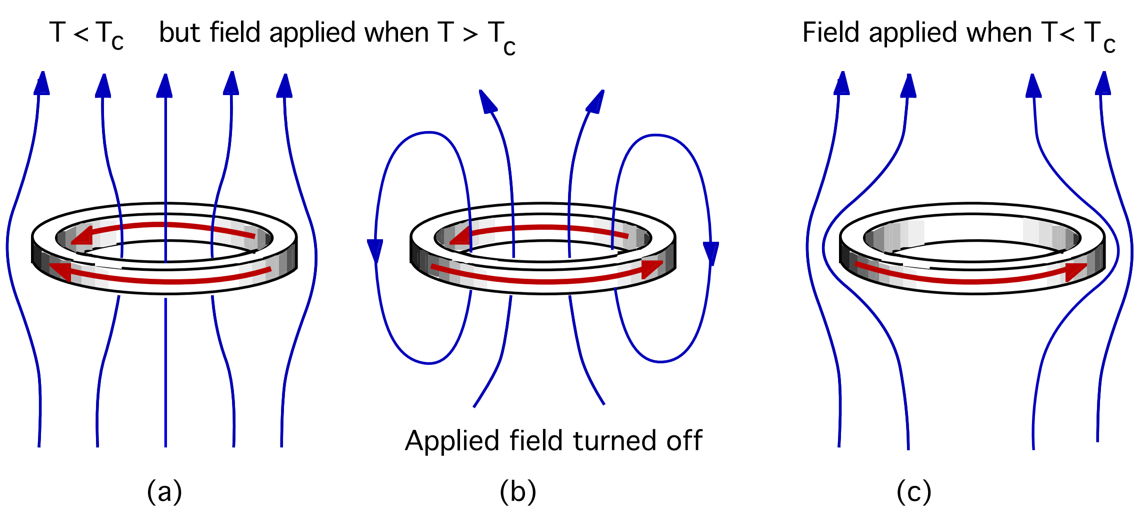


Figure 6

If the ring is cooled below T_c prior to applying the external field, the induced current in the ring prevents the flux from penetrating the ring itself. The magnetic field only contacts the outer surface of the ring, consequently only the outer surface carries the current which then shields both the superconducting ring and the interior of the ring from flux penetration (Figure 6c). This same result would occur if one used a disc instead of a ring. Current would be induced only on the outer surface shielding the entire disk from magnetic flux. Then removing the center of the disk to form a ring would result in no change in the magnetic field.

It is interesting to note that although the flux within the superconductor itself is zero whenever $T<T_c$, the flux through the ring depends on the order in which magnetic field is applied and the temperature is lowered.

Meissner Effect and Levitating Magnets

The existence of induced currents on the surface of a superconductor in the presence of a magnetic field not only shields the interior of the solid from magnetic flux, but the induced current also creates a magnetic force which repels the magnet which caused the field. Magnetic levitation is a result of this interaction and was first observed by P. L. Kapitza and reported by V. Arkadiev [7,8]. The effect has been used repeatedly to demonstrate the superconducting transition in tabletop demonstrations of the high T_c superconducting ceramics [9,10].

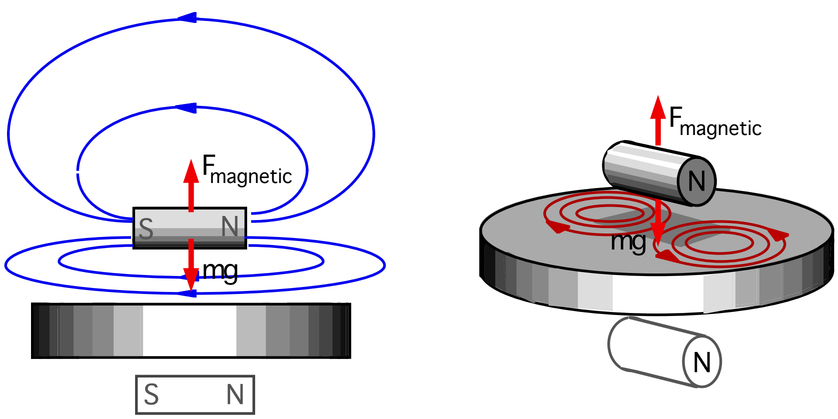


Figure 7

The effect of the surface currents is to create a magnetization within the superconductor which exactly cancels the "applied" field – *i.e.*, that due to the magnet. But for the surface current to cancel the field within the superconductor also means that it enhances the field outside the superconductor. In effect, the field lines are “compressed” near the superconducting surface creating a force which repels the magnet. The effect on the field lines above the surface (and hence on the magnet) is the same as if an identical image magnet were placed the same distance below the surface. Levitation occurs when the magnetic force equals the weight of the magnet. The demonstration showing the magnet rising from the superconducting disk as it cools below the critical temperature is actually a demonstration of the second Meissner effect - the expulsion of the magnetic field from the superconductor at the transition.

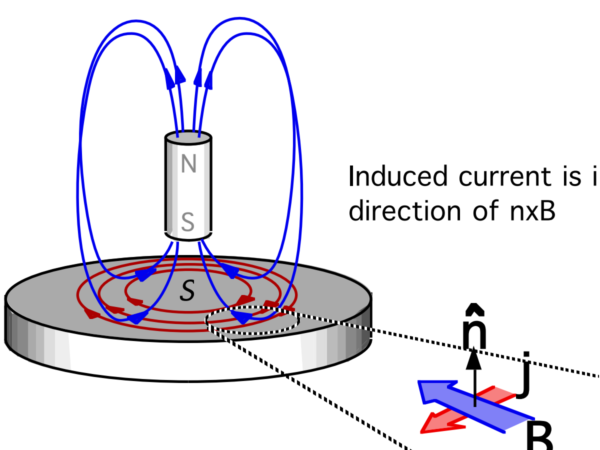


Figure 8

If a magnet is suspended vertically above the disk, even though that might not be a stable configuration, the currents circulate on the surface in such a way that the magnetic field again repels the magnet. That is, using **nxB** to determine the direction of the surface current results in the current circulation shown. But that current creates a magnetic field which points downward at the center of the superconducting disk - and hence a force is exerted upward on the magnet due to the field produced by the induced surface current.

If the disk had a hole in it so that the magnet could fall through, nothing would be significantly different about the field and currents until the magnet neared the disk. But since the Meissner effect (by virtue of the induced currents) precludes the field from penetrating the superconducing material, itself, the field lines would distort and begin to penetrate the hole.

The magnetic field would ultimately distort in such a way as to be squeezed inside the hole - and, by Meissner effect, would induce circulating currents on the inside surface of the hole to shield the material from the magnetic field. The field associated with the magnet would no longer approximate a dipole field, but rather would be squeezed inside the hole itself (contained by the induced currents on the two surfaces and on the inside of the hole). As the magnet falls through the hole, the magnetic field would as well.

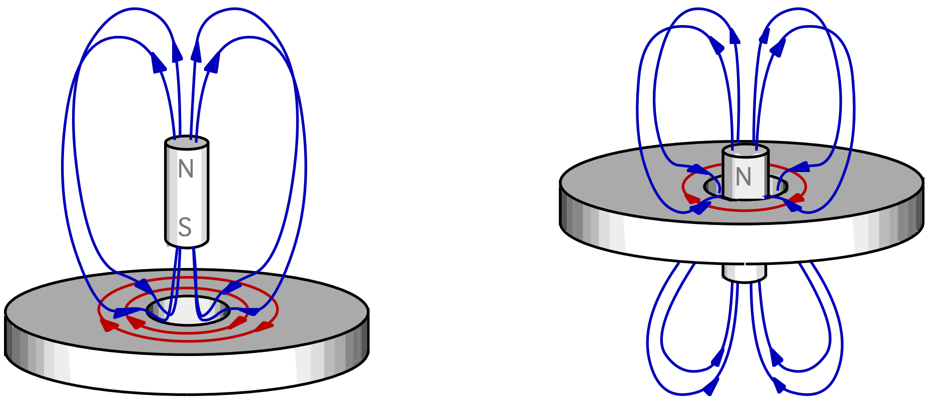


Figure 9

The direction of the current induced can be determined, of course, by applying the result from London's equation that the induced current is in the direction of **nxB**. That suggests that there is current wherever the magnetic field touches the superconducting surface. The currents diminish on the top surface as the magnet falls through the hole, is induced on the inside surface of the hole itself - in proportion to the field strength at the surface, then will circulate on the bottom surface as the magnet leaves the disk below (and would be circulating in the opposite direction from what it had on the top surface, although that is not important to our discussion).

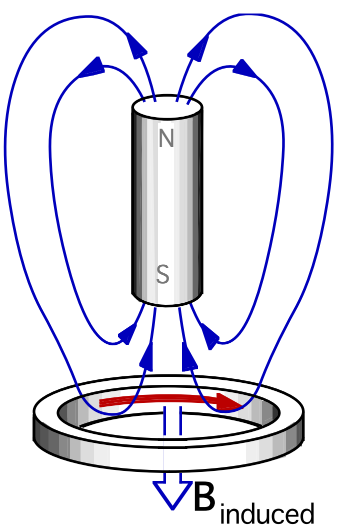


Figure 10

Of course, the exact same situation would occur for a magnet falling through a superconducting ring. That is, if the field squeezes through the hole in a plate, not being able to penetrate the superconducting material - the same must be true for a ring. So as the magnet approaches the ring from above, some surface current would be induced on the top surface and on the inner surface of the ring (to be consistent with the current having the direction **nxB**). When the magnet is centered in the ring, the field at the inner surface is a maximum - hence the current is as well. As the magnet falls past the ring, the field at the surface diminishes, and the current diminishes as well.

The Meissner effect requires an induced current in the ring such that the magnetic flux is excluded from the ring itself. Since the field cannot cut through the superconducting ring, it must feed itself through the ring. As a consequence, the field is contained within the ring and the induced current is only on the inside surface - since the field is only in contact with the ring on the inside surface while crossing the plane of the ring.

When the magnet is "centered" in the ring, that is, when it is crossing the plane of the ring, the field at the inner surface of the ring is a maximum - hence the induced current is also a maximum. That current is required to shield the superconductor from the magnetic field. Once the magnet has fallen past the ring, the field on the inside of the ring decreases - hence the induced current decreases since the induced current is proportional to the magnetic field at the surface.

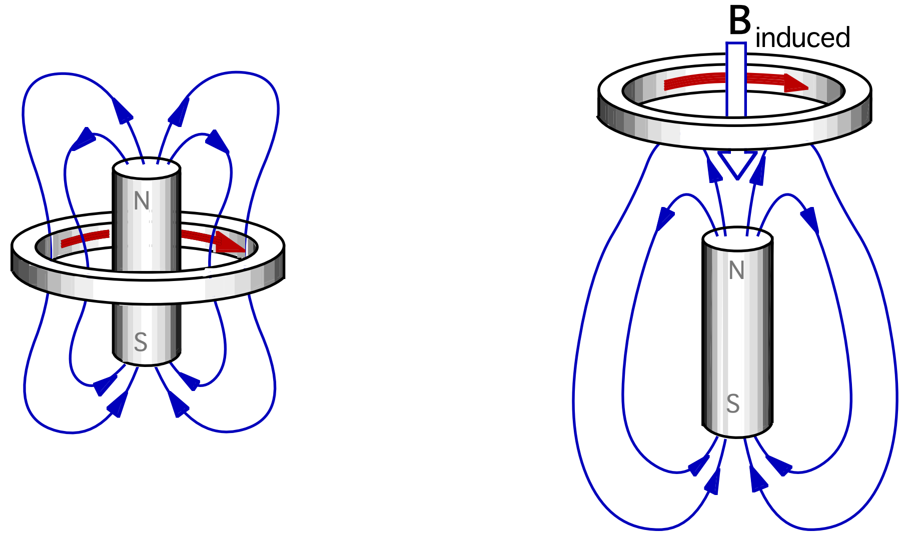


Figure 11

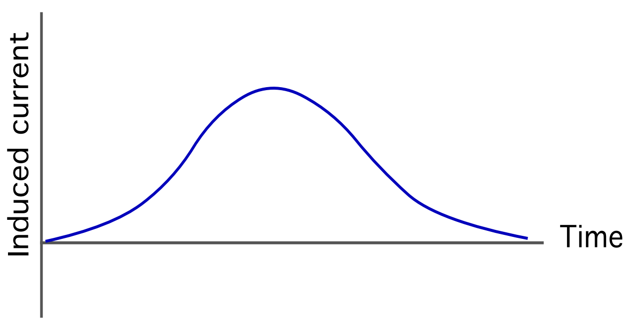


Figure 12

In contrast to the magnet falling through the copper ring (or any normal conducting ring) the current does not change directions as it falls through the ring. That is, the current exists because of the Meissner effect rather than the Faraday effect - which induces a current proportional to the changing flux through the ring. The current thus increases as the magnet approaches the ring from above, is a maximum when the magnet is centered, and then diminishes as the magnet falls away from the superconducting ring (and the current is independent of the speed of the magnet).

The effect is that the magnet *and* its magnetic field went through the ring with none of the magnetic field penetrating the superconducting ring. The current hence increases as the magnet approaches, is maximum when it is centered, and diminishes when the magnet falls away from the ring.

So.....What happens when you drop a magnet down a superconducting tube?

To understand the answer to this question, it is useful to compare the fields and currents for the two cases of the magnet in the normal conducting tube and the magnet in the superconducting tube. In the normal tube, the current induced by the falling magnet circulates in such a way as to oppose the changing magnetic flux both below and above the magnet. That is, the current reverses direction as the magnet falls through the tube, circulating one way "in front" of the magnet as it falls and the other way behind it. The field near the south pole of the magnet will be pointing downward - which implies the magnetic force is upward on that pole. The field near the north pole of the magnet will be pointing upward (the current having reversed directions) - and the magnetic force is thus upward on that pole as well. The net result is that the magnetic force is upward on the magnet which opposes the gravitational force and slows the magnet's fall. Of course, since the tube is a normal conductor, the currents diminish quickly due to the electrical resistance of the tube - in effect lasting only as long as the flux is changing due to Faraday's law. As a result, the potential energy that is "lost" as the magnet falls slowly goes into the i^2R heating of the tube.

For the superconducting tube, the current near the south end of the magnet is in that same direction - hence causes an upward force on the south end. But the current does not reverse direction since it is due to the Meissner effect and not Faraday's law - so the field and force on the north end are both pointing downward. Due to the symmetry of the problem (assuming a centered magnet – or infinitely long tube), those two magnetic forces are hence equal and opposite - so cancel. The only remaining force is gravitational.

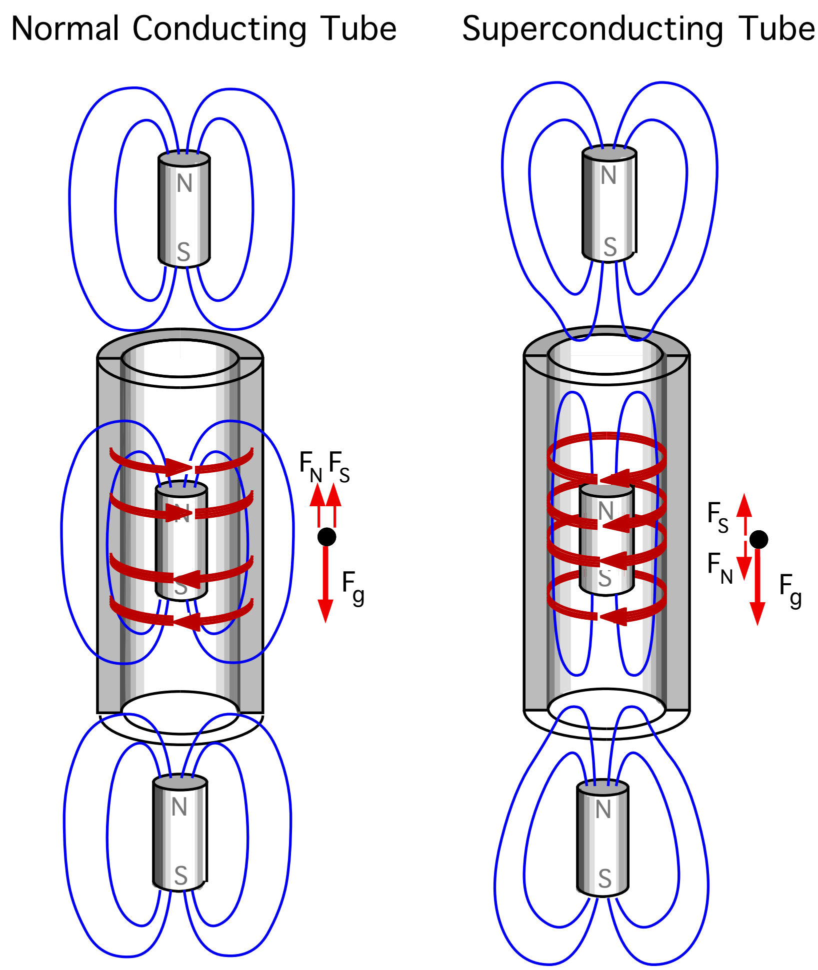


Figure 13

That is, once the magnet is inside the superconducting tube, it is in freefall. "Of course!"

As the magnet approaches the tube from above, of course, currents are induced near the top of the superconductor that would tend to oppose the fall. It would be possible to levitate the magnet (although the magnet might not be stable in the upright position). Currents would be induced which would produce a magnetic field which would tend to lift the magnet away from the superconductor. But the magnetic field would penetrate the hole whether or not the magnet itself did. That is, the field lines would be distorted or "squeezed" at the lower end to fit inside the hole. The magnetic force on the magnet due to the induced current in the superconductor would be upward - and the magnet would either levitate or not depending on the balance of forces. But it is important to recall that the Meissner effect prevents the field lines from penetrating the superconductor itself - other than in the small skin depth which also carries the induced surface currents. Since the field lines do not penetrate the bulk of the superconductor, there is zero net flux through any closed path within the superconducting tube - that is, there are the same number of flux lines up (internal to the magnet) as there are down external to it! Thus the magnetic flux inside the tube is zero and does not change. So movement of the magnet within the hole in the superconductor does not cause current flow in the tube due to Faraday's law. The induced currents only exist as needed to shield the bulk of the superconductor from magnetic field - according to the London equation ($\mathbf{B} = -K\, \nabla \times \mathbf{j}_s$) which leads to the Meissner effect (and is supported by BCS theory[10]). Since superconducting current flows without resistance, there is no energy dissipated. Consequently' once the magnet is completely inside the tube, there are no vertical forces on it due to induced magnetic fields and no mechanism for energy dissipation within the superconducting tube - so the magnet is in freefall due to gravity.

Of course, just as there would be a magnetic force upward on the magnet due to the induced currents as it is approaching the tube - and entering it, there would be a downward magnetic force on the magnet as it leaves the tube - in addition to the gravitational force - hence accelerating it. That is, the magnet would be *ejected* upon leaving the tube, thus compensating for the slowing that occurred upon entering. Since the induced currents only exist to preclude magnetic field from penetrating the superconductor, the current disappears as the magnet falls away from the superconductor. That is, even though the resistance is zero, the current does not persist since there was no current prior to introducing the magnet into the tube. The net effect would be that the final speed of the magnet would be the same as if dropped from the same height in the absence of the superconducting tube - that is, there would be no loss of energy of the system since the superconducting currents induced flow without resistance - hence dissipate no energy.

CONCLUSION

So what would happen in this hypothetical experiment is fundamentally controlled by the Meissner effect - and not Faraday's law. That is, the currents induced on the inner surface of the superconducting tube are a consequence of the magnetic field at the surface, and not the changing magnetic flux through a singly connected current path. The induced current shields the interior of the superconducting material of the tube from the magnetic field of the falling magnet. The effect of the field produced by those induced currents on the magnet itself is zero - that is, there is no net magnetic force on the falling magnet once it is inside the tube. As a result, it is subject only to the gravitational force. Since there is no resistance in the superconducting tube, energy is conserved.

What was it that David Goodstein said? "Once the magnet is inside the tube, it would be in *freefall*."

"Of course!", said Feynman, "It slows down going in, gets an extra kick going out and winds up just where it would have been."

POSTSCRIPT and QUESTIONS

1. *Could this all be tested experimentally?*

   That's a good question, actually. In principle, of course. But the problem is setting the conditions. First, the above description depends on complete exclusion of magnetic field from the superconductor - the tube should be an *ordinary* superconductor in Feynman's words. That is, it should either be a Type I superconductor and the magnet be sufficiently low field that the critical field not be exceeded - or it should be a Type II in the Meissner state (with the field of the magnet being less than the lower critical field so that flux not penetrate the superconductor).

   If, for example, a *lead* pipe were used - the experiment would have to be done at liquid helium temperatures, since lead has a critical temperature of about 7 K. But the critical field for that Type I material is about 800 gauss - or 0.08 Tesla. Care would have to be taken so that the magnetic field at the inside surface of the tube did not exceed that value as the magnet fell. If the superconducting tube were of one of the high T_c materials, the magnet would also need to be very weak since the lower critical field is typically a rather low value for these materials. And in both cases, of course, since the magnet would only be in freefall when it is completely contained at the center of the tube, it's motion within the tube would require remote sensing and very careful timing to determine whether it is in freefall at that point.

2. *Would the magnet still be ejected upon leaving the superconducting tube had it been inside the tube prior to cooling the superconductor below its critical temperature. That is, would the magnet still fall in a state of freefall and then be ejected upon leaving the tube (for the same reasons stated above) -*

which would then result in the falling magnet having a higher exit speed than if it had just fallen the same distance without the tube? And if so, what is the source of energy that would require?

To understand the problem requires thinking about the similar situation with the magnet in a superconducting ring prior to its being cooled, then being removed after the temperature is lowered below the critical temperature hence inducing a persistent current. The same would happen in the tube. That is, when the tube is in the normal state, the magnet's field would penetrate the tube and extend outside it - it would just be the normal dipole field of a magnet. When the tube then goes superconducting upon cooling, the magnetic field would collapse to within the tube, since it could not penetrate the superconductor (given all the conditions of field strength not exceeding the critical field, etc.). But that implies a change in magnetic flux within the tube - from whatever it was prior to cooling to *zero* when the magnetic field is completely contained within the tube. And, by Faraday's law, that changing flux would induce a current on the outside surface of the superconductor in addition to the (opposite direction) current on the inside surface to prevent magnetic field from penetrating the superconductor.

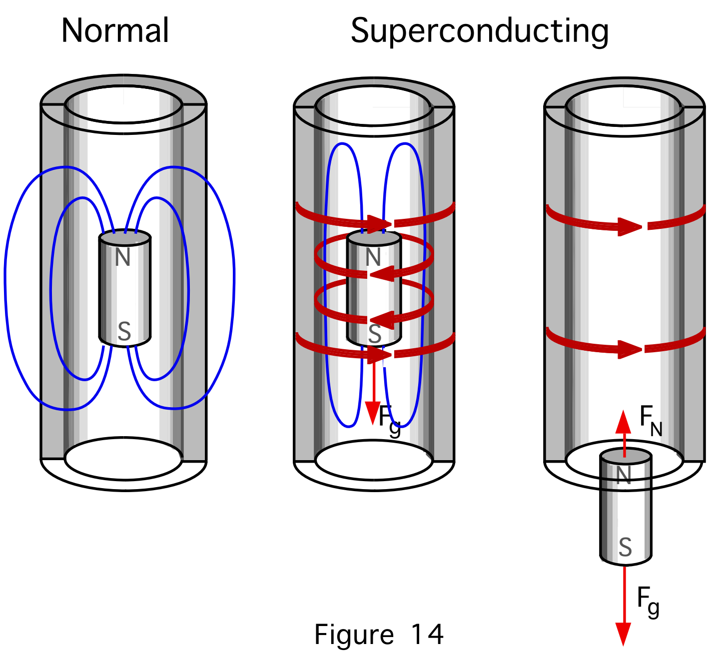


Figure 14

When released, the magnet would still fall subject to the gravitational field only, since its own magnetic field is contained within the tube *ala* Meissner effect. But the surface current induced on the outside of the tube also produces a magnetic field - and that is a persistent current (just as is the induced current when you remove a magnet from a superconducting ring). Upon leaving the tube, the magnet will be influenced by the magnetic field due to the persistent current on the outside surface. The field due to that current is upward (ie, it was created to oppose the change in flux within the tube when the tube went superconducting - and that flux was upward if the north pole of the magnet was pointing upward initially). That field's influence on the magnet as it falls away from the tube is an upward force that opposes the fall. That is, the magnet *slows* as it leaves the tube. The energy *lost* - that is, the difference between the change in potential energy of the magnet and its change in kinetic energy is just the energy stored in the magnetic field produced by the persistent current.

3. *Would the magnet be in freefall <u>anytime</u> it is inside the tube? Isn't the argument for freefall dependent on the symmetry of the fields and currents above and below the falling magnet? That is, when the magnet is dropped through a superconducting ring, the induced current is a maximum when the magnet is centered in the ring – and at that point only the net magnetic force on the magnet is zero since the induced field due to the current exerts equal and opposite forces on the two magnetic poles of the magnet. Shouldn't the magnet in the tube be similar?*

Indeed, the argument for zero magnetic force depends on the symmetry of the problem. That would mean that as the magnet approaches the tube from above, it would be slowed – since the upward force on the lower pole of the magnet would exceed the downward force on the upper pole. Then it would accelerate at an increasing rate as it falls through the tube since those two forces would approach equal values. The net magnetic force should be zero when it is centered in the tube – the magnet reaching freefall at that point. The acceleration must decrease as it is falling through the lower part of the tube, since the reverse of that situation would occur. The arguments given in this paper assume an infinitely long tube to maintain the symmetry of the currents and fields. Then, alas, the magnet is ejected from the tube as it leaves since the only current in the tube is above the magnet creating a downward force! In all, there can be no loss of energy as the superconducting currents diminish to zero as the magnet falls away from the tube – and no heating of the tube occurred since the superconductor is resistanceless.

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