Demonstrating Magnetic Levitation *AND* Persistent Current

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ABSTRACT

As has been so well documented, levitating a magnet above a superconducting disk is a good simple demonstration of the exclusion of magnetic fields from the interior of a superconductor - the manifestation of the Meissner effect. The interplay of ideas included in this demonstration fascinate even those who have seen the demonstration many times (a reminder to me that what has captured us all in this discipline is the richness of it - and our need to observe and then explain nature's subtleties). And although we speak of superconductivity in terms of the disappearance of electrical resistance, we usually demonstrate the magnetic effects associated with the Meissner effect rather than the absence of resistance. But there is a simple extension of the standard demonstration that also shows the superconductor to be a perfect conductor.

The Standard Demonstration

Lower a small magnet near the surface of a superconducting disk and it will reach a point where the magnetic force on the magnet equals the gravitational force causing the magnet to levitate - a demonstration of the Meissner effect, the exclusion of the magnetic field from the interior of the superconductor. But often the magnet is quite unstable if the magnet is lowered in such a way that the magnetic field at the disk's surface is never allowed to exceed the lower critical field of the Type II cuprate superconductor used in these demonstrations. That is, if the magnetic field is excluded by the superconductor so that the flux density is zero in the interior - a condition called the Meissner state, the levitating magnet appears to ride on an imaginary "bubble" and any small displacement will result in the magnet quickly falling to the side.

However, if the magnet is forced close to the superconducting surface, the lower critical field can be exceeded resulting in the superconductor being in the intermediate or vortex state - with some magnet flux penetrating the sample through normal filaments or flux tubes (in single flux quanta according to the theory of superconductivity). These flux lines become pinned on impurities in the sample resulting in much enhanced stability. When released, the magnet then rises from the superconducting surface - but not to as great a height as when lowered slowly and it is "on the bubble". Furthermore, the magnet will actually resist being displaced and even oscillate about an equilibrium position because of the flux pinning.

If the magnet is placed on the surface of the superconducting disk prior to its being cooled below the transition temperature, magnetic field penetrates the disk as it will any non-magnetic material. When cooled below the transition temperature, the strong Meissner effect expels the magnetic field (as opposed to simply excluding it as when the magnet is lowered toward the disk) and the magnet levitates. But since the field inside the superconductor exceeded the lower critical field prior to cooling, the expulsion of magnetic flux is not complete and the superconductor is in the intermediate state with field lines from the magnet being pinned on impurities giving the magnet great stability (and, again, a lower ride height than when the field is completely excluded).

Persistent Current - Zero Resistance

Extending this demonstration to also show the persistent currents associated with zero resistance in a superconductor simply requires lifting the magnet from the surface of the superconducting disk. The magnetic field that had penetrated the superconductor and become pinned to impurities will remain after the magnet is removed. That is, according to Faraday's law the changing magnetic flux as the magnet is lifted induces surface currents in order to oppose the change within the superconductor. These induced surface currents thus maintain the magnetic field lines that had penetrated the disk. But since the superconductor has zero resistance, these currents do not diminish with time - hence persistent current and the field lines remain.

The effect can be observed by placing a small compass above the superconducting disk and noticing that the compass needle will align in the direction of the polarity of the magnet which had been used to imbed the pinned field lines. Rotating the superconducting disk results in the compass needle rotating with it.

To demonstrate the persistence of the surface currents, the demonstration can be done at the beginning of a lecture - and then submerging the disk in liquid nitrogen without letting it return to the normal state. If the superconductor is kept below its transition temperature, the currents will flow forever. Although that might be difficult to demonstrate, the disk can be removed from the liquid nitrogen at the end of the lecture and the "compass effect" is undiminished. This shows that the currents remained for at least a micro-century - ie, a standard 50 minute lecture period - rather than the fraction of a picosecond relaxation time typical of the normal state. Watching the compass realign with earth's magnetic field as the sample warms above its transition temperature is then a compelling demonstration that the currents had persisted.

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