Superconductors in the high school classroom

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In this article, we discuss the behavior of high-temperature superconductors and how to demonstrate them safely and effectively in the high school or introductory physics classroom. Included here is a discussion of the most relevant physics topics that can be demonstrated, some safety tips, and a bit of the history of superconductors. In an effort to include first-year physics students in the world of modern physics, a topic as engaging as superconductivity should not be missed. It is an opportunity to inspire students to study physics through the myriad of possible applications that high temperature superconductors hold for the future.

Introduction

The phenomenon of low-temperature superconductivity in metals has been known for about 100 years,[1] but only in the past 30 years have materials scientists produced artificial superconductors that function at liquid nitrogen temperatures. These so-called "high-temperature superconductors" are not metals but ceramic oxides that—when cold enough—do not have any electrical resistance.

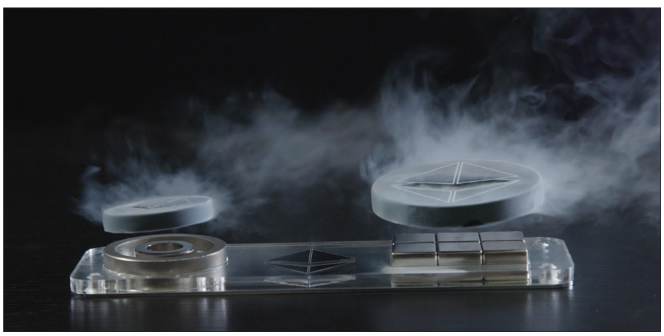

Fig. 1. Ceramic superconductors are contained in these levitating plastic disks. Below a critical temperature, they float in a stable configuration. The superconductor on the round magnet (left) will spin freely about its cylindrical axis.

As it is chilled with liquid nitrogen, the ceramic undergoes a phase transition from poor conductor to superconductor. It will now display the magnetic levitation (Fig. 1) that superconductors are known for. The expulsion of external magnetic field is called the Meissner effect; however, in this case the external field is strong enough to penetrate the superconductor so it is not a perfect example of it.[2]

The superconductor that we are using is known as YBCO ($YB_{a2}C_{u3}O_7$), which thinly coats a sapphire plate, enclosed by a layer of foam all within a plastic disk. The foam is important

Fig. 2. A solid silver coin does a lackluster imitation of a superconductor. This imitation improves as the coin is chilled with liquid nitrogen. With cold silver, the eddy currents are larger and effects can be seen easily. Since the resistance for metals drops with temperature, the coin is now a better conductor, and falls more slowly on the magnets, but it is still not a superconductor.

because it holds the liquid nitrogen in place, making the superconductor stay cold longer. This set is sold for classroom use by QuantumLevitation.com.[3]

Comparison with metal conductors

To explain how superconductors levitate, we must first discuss eddy currents. These can be demonstrated effectively with a good conductor, such as a solid silver coin (Fig. 2). When a magnet is moved relative to a conductor, current is generated and flows in loops or eddies, by Faraday's law of

Tips for working with liquid nitrogen

Teachers should practice alone before trying liquid nitrogen demos with students. If you are a beginner, you should ask a university physics demonstrator to help you practice. Initially, you will want to wear full leather gloves (not partially cloth, which is porous). Later, you will get comfortable working without gloves, which is better because the LN_2 can get stuck in the gloves. The Leidenfrost effect should keep your hands free from frostbite in most cases. Also wear closed-toed shoes. Beware of asphyxiation, keep the room ventilated, as nitrogen is an odorless gas that can displace oxygen and (unlike CO_2) it gives you no warning of how much of it is present.

Unless you can borrow one, you will want to buy a dewar. I recommend the 3-liter size, which will probably get you through the day. These containers are good because they have special lids that do not seal.

NEVER put LN_2 in a sealed container; it will become a bomb. Nitrogen can be acquired from your local AirGas store or university. If you are picking it up yourself, secure the dewar in a baby seat or otherwise squished between the front passenger seat and the rear passenger seat. Do not multitask the transporting of liquid nitrogen, for example, do not stop to buy groceries. Keep the car window down during transport.

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Fig. 3. The superconductors will not disturb the B-field of the magnet and two can be balanced by the same field.

Fig. 4. If the superconductor is inverted it will not fall out of place.

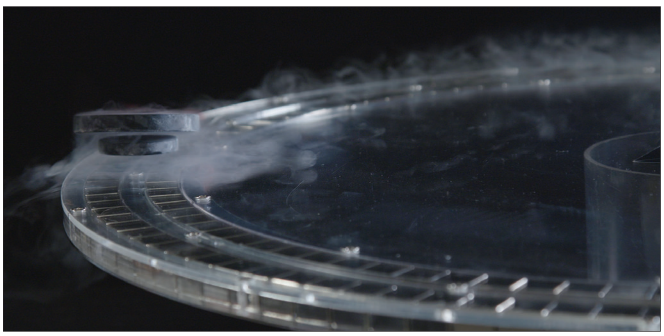

Fig. 5. The magnets along the track are all north up on the inner rim and south up on the outer rim. A chilled superconductor cruises easily a few centimeters above the surface. The larger superconductor passes over the small one, like two cars on the highway of the future. Because the magnetic field is the same anywhere on the track, the discs can move along the circumference but will not move radially due to flux pinning.

electromagnetic induction. These currents flow in such a way to oppose the change in magnetic flux. For example, if the coin is dropped, the eddy currents create a new magnetic field that opposes its fall (Lenz's law). The field does not last long because the eddy currents die out due to electrical resistance in the coin.

In the superconducting case, the disk will be completely stopped by its own eddy currents and held in place. This is because, in a superconductor, there is no electrical resistance and the eddy currents will continue once they are generated. They will even hold the superconductor in place when it is inverted (Fig. 3).

The idea of flux pinning helps to explain the striking stability of the magnetic levitation of the superconductor.[4] Although this is hard to demonstrate, the very thin superconductor does not contain a single large eddy current but rather has many thin filament vortices of current that allow for some penetration of the external magnetic field. Because these usually occur at specific locations (such as defects), the vortices tend to remain "pinned" in place. This prevents the superconductor's motion through the external magnetic field and accounts for its unusual stability (Figs. 3 and 4). This flux pinning can be taken advantage of in the construction of magnetic tracks, which allow movement along any line of constant flux (Fig. 5).

Measuring the critical temperature

To emphasize that the transition to superconductor is a phase change, it helps to demonstrate that this happens at a specific critical temperature. One of the superconductors in my set contains a temperature probe in contact with the YBCO disk.[5] If the superconductor is permitted to warm up slowly while in a hovering position, then at the moment it loses its ability to hover, we know that it is undergoing the phase change from superconductor to poor conductor. In my experience transition is always between 86 and 94 Kelvin, which is consistent with the expected value of about 90 K.

References

1. Dirk Van Delft and Peter Kess, "The discovery of superconductivity," *Phys. Today* **63** (9), 38 (2010).
2. YBCO superconductors have been discussed in this journal before [please see R. Brown, "Demonstrating the Meissner effect and persistent current," *Phys. Teach.* **38**, 168–169 (March 2000)]. I hope that my article can provide direction to those who would not know where to begin, and also helps justify their inclusion at the high school level. For a good explanation of theory that explains superconductivity as Cooper pairing, give Cooper's own article, Leon N. Cooper, "Theory of superconductivity," *Am. J. Phys.* **28**, 91–101 (March 1960).
3. TED Talk with Boaz Almog, the inventor of this device: https://www.ted.com/talks/boaz_almog_levitates_a_superconductor, in which he demonstrates an early version of it.
4. Even though it is out of date, I recommend Gavaler's article, J. R. Gavaler, "The search for better superconductors," *Phys. Teach.* **15**, 289–291 (May 1977) because of its excellent figures. Also, E. H. Brandt, "Rigid levitation and suspension of high-temperature superconductors by magnets," *Am. J. Phys.* **58**, 43–49 (Jan. 1990) discusses flux pinning and differentiates between Type I and Type II superconductors. YBCO is Type II.
5. The probe is a resistor and must be calibrated to serve as a thermometer. For example it has a resistance of 20 Ω at 77 K, which is the boiling temperature of liquid nitrogen.