A classroom demonstration of levitation and suspension of a superconductor over a magnetic track

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The suspension and levitation of superconductors by permanent magnets is a fascinating consequence of superconductivity, and a wonderful way to generate interest in low-temperature physics and electrodynamics. We present a classroom demonstration of the levitation/suspension of a superconductor over a magnetic track that maximizes the levitation/suspension time and the separation distance between the magnetic track and superconductor. The demonstration, as described, is both inexpensive and easy to construct. © 2009 American Association of Physics Teachers.

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I. INTRODUCTION

Observing first hand the phenomenon of stable suspension and levitation of type II superconductors over permanent magnets is an inspiring and thought-provoking experience of great general interest.1 In the 1930s, Meissner first observed the expulsion of magnetic field from the bulk of Type I superconductors.2 The resulting nearly perfect diamagnetism produces unstable levitations of magnets over flat superconductors. To produce stable levitations, Arkadiev cooled a concave lead slab with liquid helium and placed a small permanent magnet over it.3 The concave shape of the lead slab allowed stable levitations of the magnet within the potential well.

Stable levitation is also possible with type II superconductors. Type II superconductors allow magnetic flux line penetration through their bulk when the applied field \( H \) is between \( H_{c1} < H < H_{c2} \), where \( H_{c1} \) and \( H_{c2} \) are called the superconducting critical fields. The penetration of magnetic flux lines produces circulating supercurrents with normal-conducting cores inside. As the flux lines move, the motion of the normal cores causes dissipation. This dissipative force acts like a frictional force and leads to stability. Until the discovery of high-temperature superconductors by Bednorz and Müller in 1986, the phenomenon of stable levitation in type I or type II superconductors was reserved only for those working with liquid helium. Today, with superconductor critical temperatures above 77 K, it has become possible to bring this experience into the classroom using liquid nitrogen.4–6

High temperature superconductors can be used to demonstrate many different levitation phenomena. When superconductors with high flux-pinning capabilities are used, both levitation above and vertical suspension below permanent magnets are possible. Reference 7 provides a description of the pinning forces that create levitation and suspension, and Refs. 8 and 9 provide detailed explanations of levitation and suspension within the context of intermediate electrodynamics. Much of the stability of our demonstration comes from placing the superconductor in a magnetic field gradient. If there is a strong magnetic field gradient in one direction and no gradient in the other direction perpendicular to gravity, you can create a magnetic track that both levitates and suspends—the principle behind a superconductively levitated “MagLev” train.10

We present modifications to a magnetic track classroom...
Table I. Table of insulation materials, time below the superconducting transition temperature, and height above the track. This list represents only a subset of the insulation materials and methods we tested. The final design, three layers of tissues, mylar, and teflon tape, did not have the longest time below the critical temperature, but had the highest levitation height of the one-minute-plus levitation time designs.

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Levitation time (s)</th>
<th>Levitation height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al foil and floral foam</td>
<td>249</td>
<td>0.762</td>
</tr>
<tr>
<td>Al foil and styrofoam</td>
<td>203</td>
<td>0.63</td>
</tr>
<tr>
<td>Layered tissues, mylar, and teflon tape (three layers)</td>
<td>118</td>
<td>1.8</td>
</tr>
<tr>
<td>Layered tissues, mylar, and teflon tape (two layers)</td>
<td>85</td>
<td>1.9</td>
</tr>
<tr>
<td>Packaging foam, mylar, tissues, and teflon tape</td>
<td>45</td>
<td>0.89</td>
</tr>
<tr>
<td>Uninsulated</td>
<td>13</td>
<td>2.0</td>
</tr>
</tbody>
</table>

demonstration first presented to us by Gregory S. Boebinger of Florida State University with design suggestions from Martin Simon of UCLA. Our rendition of the demonstration utilizes lightweight and sleek insulation materials to maximize the superconductor’s levitation height and time while maintaining an aesthetically pleasing appearance. This demonstration is inexpensive and easy to build.

Our demonstration begins with a superconductor levitating above a track, free to move back and forth along the track. Then, the track is lifted and turned upside down. Now the superconductor is suspended below the track and is still free to move back and forth along the track.11

II. DEMONSTRATION APPARATUS

The demonstration apparatus is a simple combination of a type II bulk superconductor, neodymium-iron-boron magnets (Nd-Fe-B), and sheet steel. The superconductor used is a hexagonal YBa2Cu3O7 (YBCO) bulk superconductor, wrapped in insulation to prolong the time its temperature remains below the superconducting phase transition temperature. Sheet steel forms the base of the track. Thinner sheets are used as flux trapping shims and are mounted underneath the track. The neodymium magnets are magnetized perpendicular to the track and arranged on the base to maximize the cross-sectional gradient of the track’s magnetic field.

The superconductor is designed to enhance flux pinning. We bought our superconductor for $125 from SCI Engineered Materials Inc. It is roughly 3 cm in diameter and weighs 19 g. We have measured a maximum trapped field of roughly 250 mT and a transition temperature of about 92 K. Tests conducted with the uninsulated superconductor above our magnets produced levitations of 2.5 cm and levitation times between 7 and 15 s.

In order to increase time before the superconductor reaches the transition temperature, a multitude of insulation materials and combinations were investigated, a subset of which is listed in Table I. We decided to use a combination of 0.051 mm thick aluminized mylar, teflon tape, and tissues (Kimwipes). We cut three geometrically similar patterns out of mylar, each successive pattern slightly larger than the previous to compensate for the inner layers. We wrapped the superconductor in a tissue followed by the smallest mylar pattern, and sealed it using teflon tape. This procedure was repeated twice, with the final layer leaving mylar exposed to the viewer on the hexagonal faces (in Fig. 1, only the sides of the superconductor and the yellow teflon tape used to seal the insulation are visible). A long strand of fishing line was tied around the superconductor to provide a leash to lift the superconductor from the nitrogen bath to the track. Although our final design did not produce the longest levitation/suspension time, this insulation model is compact and lightweight, provides a levitation height close to that of the uninsulated superconductor, and increases the levitation time by a factor of 9. The largest downfall of this design is the 20 to 25 min required to cool the superconductor from room temperature to liquid nitrogen temperatures. Figure 1 shows the insulated superconductor both levitating above and suspended below the magnetic track.

The base of the track is a $305 \times 610 \times 7.6$ mm³ sheet of 410 grade stainless steel ($50$). Type 410 stainless steel has a
high magnetic susceptibility, is easy to work, and is relatively inexpensive. We bent the sheet into a U-shape to serve as a stand, though this is not necessary for the track to function properly. The finished track is shown in Fig. 2(a). We also purchased 0.31 mm thick stainless steel shim stock of grades 410 and 430. The shims are attached to the bottom of the base, directly under the magnets, and should be wide and long enough to cover the entire area of the track. The shims capture and direct the magnetic field underneath the track. The shims also help to bind the track together and overcome the repulsion between track sections due to fringe fields.

To build the track, we used Nd-Fe-B ceramic permanent magnets, grade N42 ($4 each). The dimensions of the magnets are $76 \times 13 \times 6.4$ mm$^3$. The magnets are aligned along the track in a three by seven configuration, as shown schematically in Fig. 3. The arrangement of field orientations produces a magnetic field gradient in the $x$-direction above the track which acts to confine the superconductor in the $x$-direction while allowing motion in the $y$-direction. At each end of the track, a magnet is placed perpendicular to the others. The field of these two magnets is parallel to the field of the magnets at the center of the track. These magnets act as brakes for the track and reflect the superconductor with minimal loss of energy.

Fig. 2. (Color online) (a) Our straight magnetic track. The magnets are aligned in a S-N-S configuration. The brakes at the end of the track are aligned with N up. The track is made of 410 grade steel with thinner shims underneath the track. (b) A roller-coaster track that can demonstrate levitation and suspension simultaneously as the superconductor travels around the loop. The superconductor is in motion at the bottom of the loop.

III. OPERATIONAL NOTES

The functionality of this demonstration depends not only on the amount of flux pinning in the superconductor, but also on the way in which the demonstration is prepared. The superconductor behaves markedly different depending on whether it is cooled in a zero or in a nonzero magnetic field.

For zero field cooling, the puck is cooled in a styrofoam cup more than 20 cm away from the track. Once cold, the superconductor is lifted by its string and placed on the track. Zero field cooling will create the maximum levitation heights, and the superconductor will stay on the track and reflect off the brakes. However, it will not suspend upon inversion of the track.

In order to get good adherence of the puck to the track and allow both levitation and suspension, the magnetic flux lines produced by the track’s magnets must be pinned by the superconductor. This can be achieved either by forcing the flux lines through the bulk of the superconductor or by cooling it in a nonzero magnetic field. In the first method, we cool the superconductor in zero field, place it on the track, and then firmly press it onto the surface of the track. The superconductor will rebound slightly and then exhibit both levitation and suspension. By forcing the superconductor onto the track, we force the magnetic flux lines to penetrate the bulk and be pinned. In the second method, we cool the superconductor in an external field. When we cool the superconductor in liquid nitrogen directly over the middle of the track, the sample will go through the phase transition while already immersed in the track’s magnetic field. This pins the track’s field into the superconductor and provides ample adhesion for track inversion and suspension. Field cooling may also be conducted over a magnet which is not part of the track. For best results, we suggest field cooling in a nonmagnetic container, directly above the middle of the track, and minimizing the time and displacement from the track when removing the sample from the nitrogen bath.

As with any classroom demonstration, there are procedures for safety associated with this apparatus. Liquid nitro-
gen is necessary to cool the superconductor below its transition temperature. Because liquid nitrogen is extremely cold (77 K), contact with the liquid or with an object cooled in the liquid can cause severe frostbite. Whenever dealing with any cryogen, insulated gloves, protective eyewear, and a laboratory coat or smock should be used. For more information on proper cryogenic procedures in a pedagogical setting, please see Ref. 6.

The Nd-Fe-B magnets used in the track are very strong and should not be handled without protective gloves; we suggest tough work gloves. The magnets are brittle and have been observed to break upon collision, resulting in jagged edges and small sharp fragments. Finally, the YBCO superconductor is made from heavy metals and should not be handled using bare hands, and care should be taken to ensure that any dust particles are not inhaled.5

IV. THEORY

The levitation in this demonstration occurs due to the Meissner effect—the expulsion of magnetic flux by superconductors.9 A superconductor expels magnetic flux by creating a magnetic field in the direction opposite to that of the external field, becoming a perfect diamagnet. This diamagnetism provides a force of repulsion, and the superconductor levitates above the source of the external field. Most diamagnetic or ferromagnetic materials can levitate in an external magnetic field, although the levitation is an unstable equilibrium except in certain special cases, such as the lead bowl discussed in the Introduction1 or other, more complicated, arrangements of magnets.12 Type I superconductors, such as lead, tin, and mercury, act as diamagnets, expel all magnetic flux from their bulk up to the critical field $H_{c1}$, and create maximum repulsion. The superconductor used in this demonstration, though not type I, will also expel magnetic flux, similar to the Meissner effect, when zero field cooled. This creates the high levitation heights discussed in the previous section.

Type II superconductors, such as Nb$_3$Sn or the more recently discovered high-temperature superconductors, such as YBCO, allow certain amounts of flux to penetrate through their bulk. These flux lines penetrate the superconductor and create a circulating supercurrent around a normal core: this entire collection is called a vortex. The size and distance between vortices is roughly the same as the superconducting coherence length $\xi$ and varies strongly with temperature ($\xi \sim (T-T_c)[1/2]$). The normal core of a vortex has a diameter on the order of hundreds of micrometers,2,13 and the minimum spacing between the vortices is of the same order.

In general, the vortices are free to move in the superconductor. Moving the normal cores creates dissipation in these materials. In practice, grain boundaries or impurities often trap the vortices in one place, “pinning” them to one spot in the superconductor. This keeps them from moving and allows dissipation-free current flow in type II superconductors—often increasing by several orders of magnitude both the critical current $I_c$ that can flow in the superconductor and the critical field $H_{c2}$ that the superconductor can endure without reverting to the normal state.13 The flux pinning can be enhanced by growing the superconductor with additional impurities. Regular type II flux line pinning produces a frictional force that provides drag as vortices move from one pinning site to another, and creates stable levitations. Enhanced flux line pinning is so strong that both levitation and inverted suspension are possible.14

In practice, a field cooled type II superconductor, especially one with enhanced flux pinning, acts very much like a perfect conductor rather than a superconductor. When a type II superconductor is cooled directly above a magnet, it will levitate to a small height due to the Meissner effect. If it is cooled slightly above the magnet, e.g., by using shims, it will stay stationary in the field. In both cases, no further motion will occur until you attempt to displace the superconductor, and then a repulsive or attractive force appears related to the induced flux change. This occurs because moving vortices from one pinning site to another requires a large amount of energy, and so the superconductor reacts to minimize flux changes, much as a perfect conductor would.

The crucial aspect of this demonstration is the design of the track. Along the length of the track, in the $y$-direction, there is no variance in the field, which allows the superconductor to move back and forth with no loss of energy. Perpendicular to the length of the track, the bar magnet’s poles are aligned anti-parallel to each other (S-N-S). This alignment produces a considerably strong gradient in the $x$-direction. This strong gradient can be seen in the measured magnetic field strength at various heights above our track, as shown in Fig. 4. The variance of magnetic field strength from one side of the track to the other is large, and the pinning in this superconductor is strong, creating a large restoring force. If the superconductor is given a small push in an attempt to force it from the track, it will oscillate slightly and quickly return to its original position.

V. CONCLUSIONS AND FUTURE WORK

We have constructed a demonstration that simultaneously illustrates levitation and suspension of superconductors above and below a magnet. The simplicity of this demonstration provides the researcher with a wealth of possible project refinements and opportunities.

The gaps between the magnets along the length of the track create small magnetic gradients which create drag and
reduce the speed of the superconductor as it moves along the track. By measuring the energy loss, a quantitative value for that magnetic drag can be obtained. When combined with measurements of the trapped field, students can determine the pinning force in the superconductor, which can be compared to other measurements of the pinning strength of superconductors in the literature. Another possible area of interest is to measure the magnetic force between the superconductor and the track.\textsuperscript{15}

The insulation for the superconductor is the most flexible aspect of the demonstration. The extent of the insulation studies done for our project was limited by our budget and the arts and crafts stores in our town. Students may expand their search and find other insulation methods that work better than our final design, though some suggested insulation materials, such as aerogels, may remain outside of most budgets. Another option is to use a container that has a liquid nitrogen reservoir that can keep the superconductor cold for much longer times. The drawback of such system is that it is heavy and difficult to invert.

A final area of exploration is in the track design. Although a straight track is by far the easiest track to build, you can build circular tracks\textsuperscript{10} or other more exotic designs. Based on student suggestions, we have built a superconducting roller-coaster: an inclined plane leading into a vertical loop, as shown in Fig. 2(b). This track can be used to simultaneously demonstrate levitation and suspension as well as energy conservation. Other possibilities include a hanging roller-coaster or a helical track.

**ACKNOWLEDGMENTS**

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\textsuperscript{1}Electronic mail: mcsullivan@ithaca.edu
\textsuperscript{2}As an example, the popular website “wikipedia.org” contains a listing for “physics.” As of this writing, the picture posted on that site for “physics” is a magnet levitating above a superconductor.
\textsuperscript{3}M. Tinkham, *Introduction to Superconductivity*, 2nd ed. (Dover, Mineola, NY, 1996), Chapter 1.
\textsuperscript{12}Videos of the demonstration can be seen at (http://www.ithaca.edu/hs/depts/physics/facstaff/mcsullivan) and (http://youtube.com/watch?v =1zwBoBbHR4I).
\textsuperscript{15}For a more complete discussion of this phenomenon, see Ref. 2, 4, 7, or 8.

**Demonstrations of analog-to-digital conversion techniques**

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Two analog-to-digital conversion techniques are demonstrated using the *ScienceWorkshop* data-acquisition system and the *DataStudio* software from PASCO scientific. © 2009 American Association of Physics Teachers.

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Most of our students do not know how a digital multimeter (DMM) measures a dc voltage and displays it in digital form. This is surprising because DMMs are extensively used in student laboratories, and descriptions of the analog-to-digital conversion techniques can be found in many textbooks.\textsuperscript{1–4} Some of these techniques are very simple and can be explained in minutes. Two such methods, both based on voltage-to-time conversion, can be demonstrated quantitatively with the *ScienceWorkshop* data-acquisition system and the *DataStudio* software from PASCO scientific.\textsuperscript{5}

The first method uses the single-slope integration technique. With this technique, a ramp-up wave generator, such