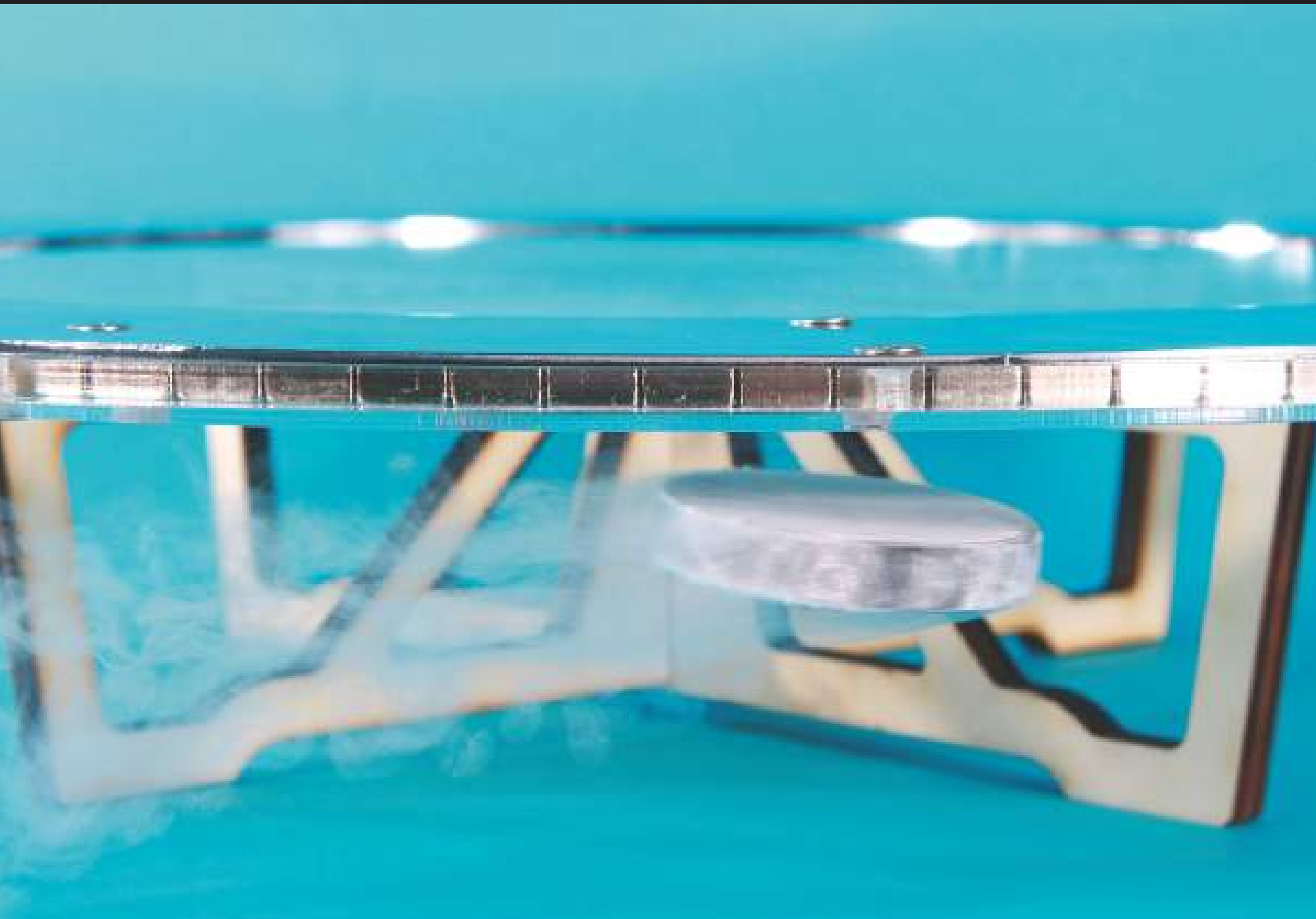
QUANTUM EXPERIENCE

Quantum Levitation

For Undergraduate and High School Teachers

Demonstrations, student activities and the physics behind them



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Superconductivity in high school?

Since its discovery in 1911, superconductivity was only discussed at the high school physics level as an interesting topic or an anecdote. The phenomenon couldn't be observed in class because it occurred only at extremely low temperatures – a few degrees above absolute zero (0 K).

During the late 1980s, the rapid succession of newly discovered high-temperature superconductors which can operate at liquid nitrogen temperatures (77 K) turned the tables. Superconductivity was now well within the reach of high school students. It was now possible to perform classroom demonstrations of magnetic levitation and to easily observe quantum phenomena using relatively cheap liquid nitrogen!

Quantum Levitation demonstrations always capture students' attention. They become entranced by an upside down levitated magnet, they wonder how it works and predict what it can be used for – scientific inquiry has begun! Students' curiosities will be limited only by their imagination.

Superconductivity is widely regarded as one of the great scientific discoveries of the 20th century and, in four occasions, the Nobel Prize in Physics was awarded for work on superconductivity. Nevertheless, the history of superconductors is only just now beginning. The possible discovery of room temperature superconductors has the potential to bring superconducting devices into our everyday lives. Superconductivity is already being applied to many diverse areas such as transportation, power production, medicine and more. At the dawn of the 21st century, superconductivity forms the basis for new horizons that are transforming our daily life as we speak.

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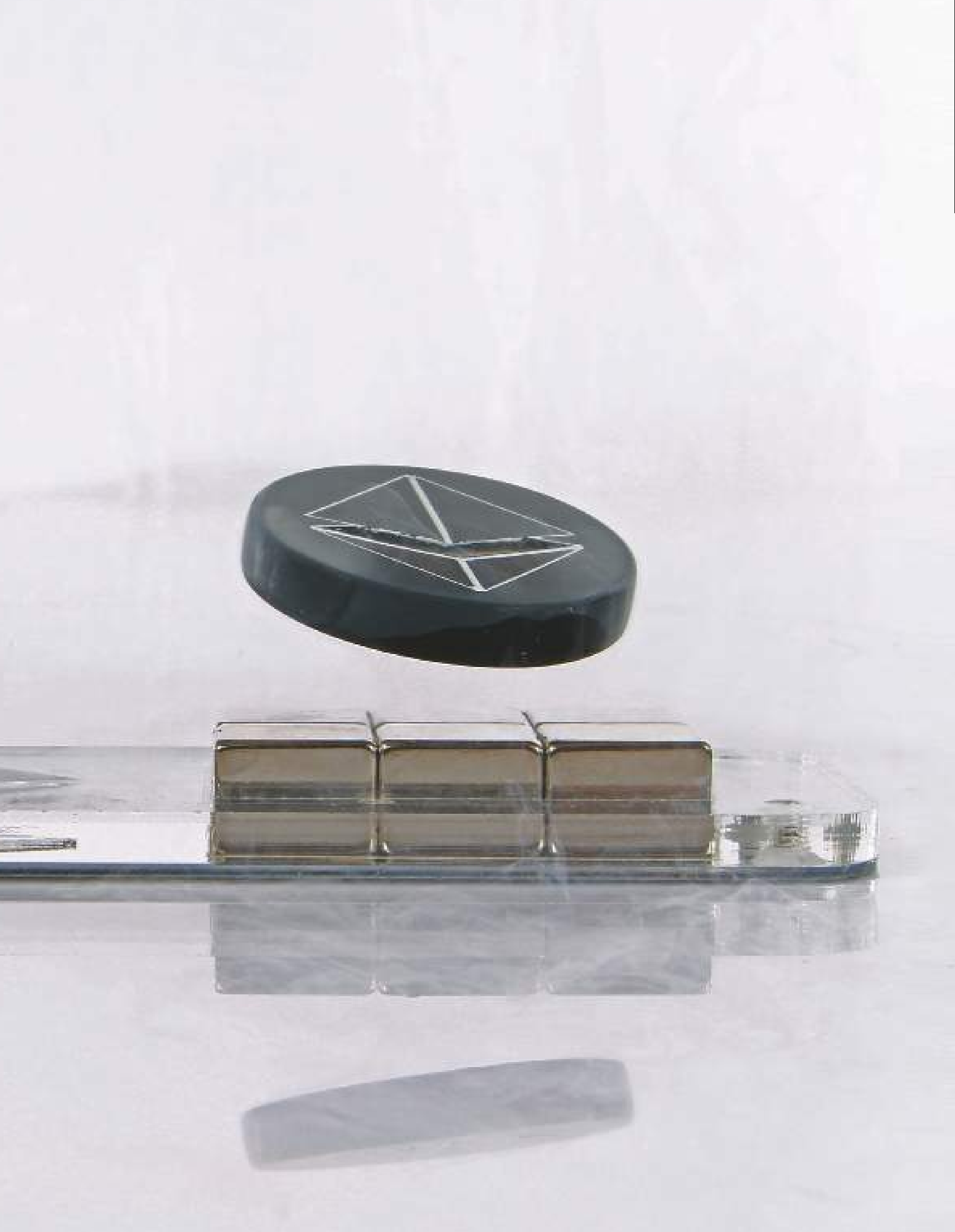


Chapter A

Fascinating properties of superconductors

1. Zero Resistance at low temperatures

It had been known for many years that the resistance of metals fell gradually when cooled below room temperature, but it was not known what limiting value the resistance would approach if the temperature were reduced to very close to absolute zero.

The era of low-temperature physics began in 1908 when Dutch physicist Heike Kamerlingh Onnes first liquefied helium, which boils at 4.2 K. Three years later, Onnes passed a current through a very pure mercury wire and measured its resistance as he steadily lowered the temperature. Much to his surprise, there was no leveling off of the resistance until the temperature reached 4.2 K, at which point the resistance suddenly vanished. Current was flowing through the mercury wire and nothing was stopping it; the resistance was **zero**. Onnes called this new state of zero resistance ‘**superconductivity**.’

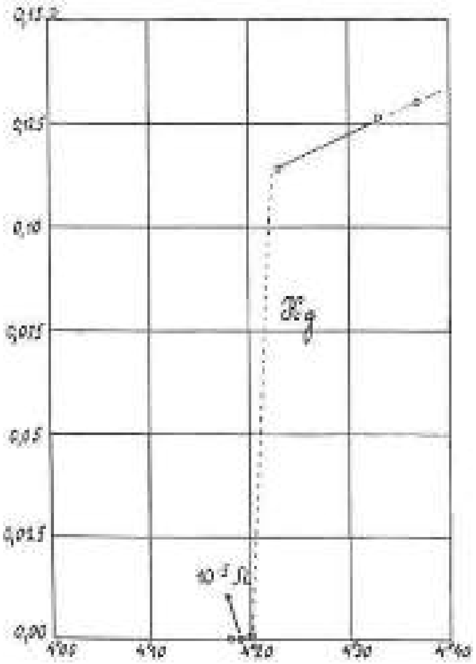


Figure 1: *The original graph from Onnes’s publication from 1911 showing the resistance of mercury as a function of its temperature. (H. K. Onnes, Comm. Leiden, 124c, 1911).*

In 1913, Onnes was awarded the Nobel Prize in physics for the study of matter at low temperatures and the liquefaction of helium. Soon afterwards, many other metals were found to exhibit zero resistance when their temperatures were lowered below a certain characteristic temperature, called the **critical temperature**, or T_c.

The importance of this discovery to the scientific community as well as its commercial potential was clear. An electrical conductor with no resistance could carry current to any distance with no losses.

Did you know?

In one experiment conducted by S. S. Collins in Great Britain, a current was maintained in a superconducting ring for 2.5 years, stopping only because a trucking strike delayed delivery of the liquid helium that was necessary to maintain the ring below its critical temperature.

2. Expulsion of magnetic fields – the Meissner effect

The magnetic properties of superconductors are as dramatic as their complete lack of resistance. In 1933, Hans Meissner and Robert Ochsenfeld studied the magnetic behavior of superconductors and found that when certain ones are cooled below their critical temperatures, they have an interesting property of expelling a magnetic field. They discovered that a superconductor will not allow a magnetic field to penetrate its interior. It achieves this by producing a "magnetic mirror," surface currents which produce a magnetic field that exactly counters the external field. The phenomenon of the expulsion of magnetic fields from the interior of a superconductor is known as the **Meissner effect**.

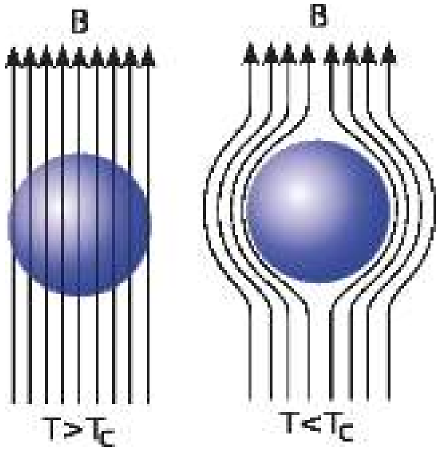


Figure 2: *superconductor in the presence of an external magnetic field. (a) At temperatures above T_c, the field lines penetrate the sample because it is in its normal state. (b) When the rod is cooled to $T<T_c$ and becomes superconducting, magnetic flux is excluded from its interior by the induction of surface currents.*

A good comparison to electricity is that a good conductor expels static electric fields by moving charges to its surface. In effect, the surface charges produce an electric field that exactly cancels the externally applied field inside the conductor. In a similar manner, a superconductor expels magnetic fields by forming surface currents. At ordinary temperatures, these currents decay almost instantaneously due to the finite resistivity of the conductor. However, when cooling the superconductors below T_c, persistent surface currents are induced and produce a magnetic field that exactly cancels the externally applied field inside the superconductor.

Levitation of a magnet above a cooled superconductor can been explained by the Meissner Effect. If a superconductor is cooled below its critical temperature while in a magnetic field, the magnetic field surrounds but does not penetrate the superconductor. The magnet induces currents in the superconductor which create a counter-magnetic force that causes the two materials to repel. The induced currents are due to the presence of the external field and not due to flux changes as frequently seen in metals (Faraday's and Lenz's laws).

Note that the Meissner effect will occur only if the external magnetic field is smaller than the superconductor's critical magnetic field, or B_c. If the magnetic field becomes too great, it penetrates the interior of the metal and the metal loses its superconductivity.

3. High temperature Superconductors

It has long been a dream of scientists working in the field of superconductivity to find a material that becomes a superconductor at room temperature. About half of the metallic elements and also a large number of alloys have been found to super-conduct at very low temperatures, which requires the handling of liquid helium, a complex and expensive task. Therefore, a great deal of effort has been directed towards finding new superconductors with higher critical temperatures.

Early in 1986, Georg Bednorz and Karl Alex Müller made a remarkable discovery that has revolutionized the field of superconductivity. They found that an oxide of lanthanum, barium, and copper became superconducting at about 30 K. Inspired by these developments, scientists worldwide worked intensively to discover materials with even higher Tc values. A year later, a ceramic material, $YBa_2Cu_3O_7$ (YBCO), was found to super-conduct at 92 K. This was an important milestone in high-temperature superconductivity because the transition temperature of this compound is above the boiling point of liquid nitrogen (77 K), a coolant that is readily available, far safer, inexpensive, and much easier to handle than liquid helium.

Did you know:

The mercury-based cuprate $HgBa_2Ca_2Cu_3O_{8+\delta}$ *exhibits the highest known critical temperature known to date: around 133 K at ambient pressure.*

In recognition of their important breakthrough in the discovery of ceramic superconductors, Bednorz and Müller were awarded the 1987 Nobel Prize in Physics.

The superconductor material encapsulated inside the levitator of Quantum Levitation is YBCO, a compound made from yttrium, barium, copper, and oxygen. Its atoms are arranged in an orthorhombic crystallographic structure (a cuboid shaped unit cell). The material is a bad electrical conductor at room temperature and becomes a superconductor below 92 K. The superconductor thickness inside the levitator is only 1-3 microns, crystal grown on top of a metallic substrate (hast alloy/stainless steel) and protected by a silver layer.

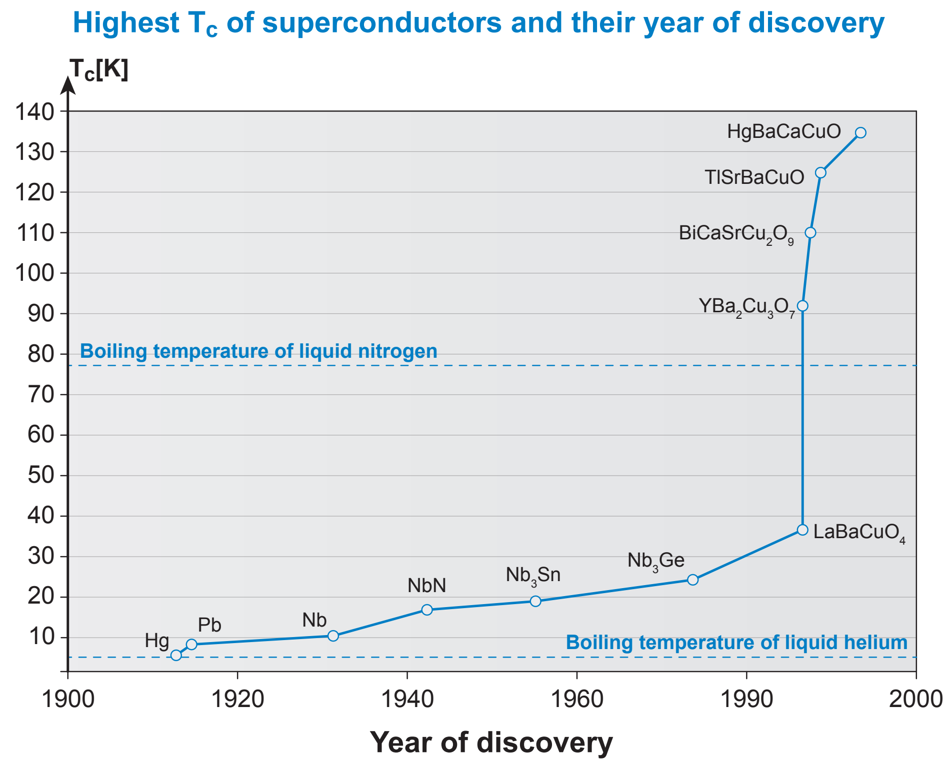


Figure 3: *Timeline of the highest* T_C *superconductors and their year of discovery.*

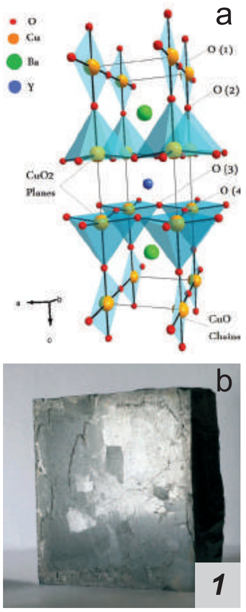


Figure 4: *(a) YBCO sample (the dimensions of the sample are 4x4x1 cm), and (b) a part of its lattice structure.*

4. Applications of superconductors

Electrical Power

The ability of superconductors to conduct electricity with zero resistance can be exploited in the use of electrical transmission lines. Currently, a substantial fraction of electricity is lost as heat through resistance associated with traditional conductors such as copper or aluminum. If power transmission lines could be made superconducting, these losses could be eliminated and substantial savings in energy costs would result.

New High Temperature Superconductors (HTS) technologies have undergone rapid development in the comparatively short time of three decades since 1987. Today, the HTS industry has advanced to full-scale power equipment prototypes and demonstration projects.

Figure 5: *Regular and high temperature superconducting cables for 12,500 amperes used at and Large Hadron in CERN (above and below respectively).*

The foundation of these applications is a new generation of wire, capable of carrying vastly (on the order of 100 times) higher currents than conventional copper wires of the same dimension, with zero or negligible resistive losses.

Today's prototype and demonstration technologies have made use of a proven, readily available and high-performance second generation HTS wire. These wires, in short, bring the promise of a revolution in the way electricity is generated, delivered and consumed – much as the introduction of optical fiber led to a technological leap forward in the telecommunications industry.

Transportation

Magnetically levitated trains, employing superconducting electromagnets on the train, offer a way to make trains literally "fly" to their destination by using powerful magnets which allow them to float above their railway or track. Superconductor electromagnets on the train induce currents in the railway beneath the train, which in turn create magnetic forces that repel the onboard electromagnets thereby levitating the train. In 2015, the SCMaglev, a superconducting magnetically levitated train in Japan, attained top speeds in excess of 600 km/h.

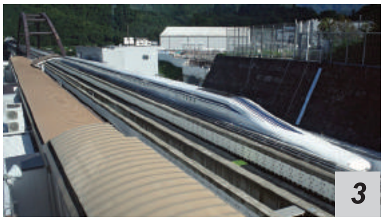
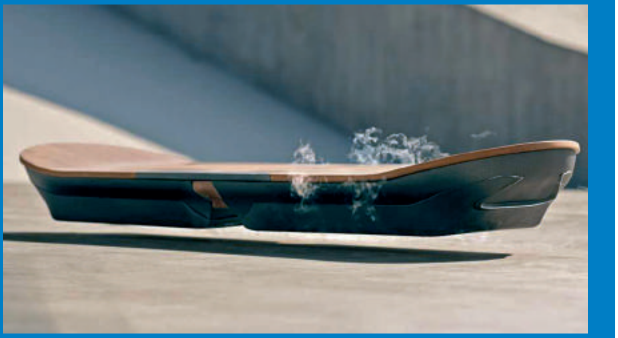


Figure 6: *Maglev train undergoing test-running on the Yamanashi Test Track, Japan.*

Superconductivity can leverage the advantages of electrified transportation of various types, ranging from high-speed trains to advanced ship propulsion systems. The incorporation of superconductor technology into transportation system design can improve the efficiency and performance, reduce weight and fuel consumption, and extend the range of transportation systems of all types. One can envision a future society of vehicles of all sorts gliding above a freeway, making use of superconducting magnets.

Did you know?

In 2015, Lexus revived Back to the Future's famous hover-board by constructing it from an isolated core containing high temperature superconducting blocks. These were housed in a reservoir of liquid nitrogen inside the board which was placed above a track containing permanent magnets.



MRI

The first large scale commercial application of superconductivity was in magnetic resonance imaging (MRI). The intense magnetic fields that are needed for these instruments are a perfect application for superconductors.

Although normal electromagnets can be used for electromagnets, because of resistance they would dissipate a great deal of heat and have huge power and heat dissipation requirements. Superconducting magnets on the other hand have almost no power requirements apart from cooling. Once electrical current flows in the superconducting wire, the power supply can be switched off and since the wires are formed into a loop the currents will persist indefinitely, as long as the temperature is kept below the transition temperature of the superconductor.

The heart of any MRI system is a superconducting magnet. The typical field values required for its operation cannot be achieved using conventional magnets. Just as importantly, high homogeneity and stability of the magnetic field are essential to achieve the resolution, precision and speed required for economical clinical imaging, and superconductors provide a unique solution to these requirements.

5. The physics behind superconductivity – a quantum phenomenon

Superconductivity is a pure quantum phenomenon. Not surprisingly, a successful theoretical explanation had to wait almost 50 years for the basis of quantum mechanics to be well consolidated, until the theory could be formulated.

> *The theoretical understanding of superconductivity requires knowledge of quantum mechanics which is beyond the scope of this booklet. In this section, fundamental terms and phenomena of superconductors will be discussed qualitatively.*

BCS and Cooper pairs

According to classical physics, part of the resistance of a metal is due to collisions between free electrons and the crystal lattice's vibrations (called phonons). In addition, part of the resistance is due to scattering of electrons from defects or impurities in the metal. Soon after the discovery of superconductivity, scientists recognized that this classical model could never explain the superconducting state because the electrons in a material always suffer some collisions, and therefore resistivity can never be zero.

In 1957, three American physicists at the University of Illinois, John Bardeen, Leon Cooper, and Robert Schrieffer, developed a model that has since stood as a good mental picture of why superconductors behave as they do.

The central feature of the theory is that two electrons in the superconductor are able to form a bound pair called a Cooper pair if they somehow experience an attractive interaction between them. This notion, at first sight, seems counterintuitive since electrons normally repel one another because of their similar charges. However, a net (or effective) attraction can be achieved if the electrons interact with each other via the motion of the crystal lattice as the lattice structure is momentarily deformed by a passing electron. The second electron (the Cooper pair partner) comes along and is attracted by the displaced ions.

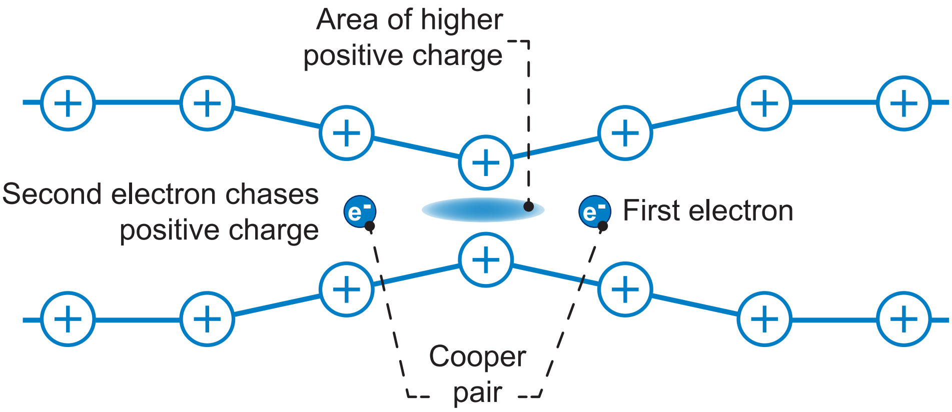


Figure 9 *shows two electrons inside the atom lattice. The existence of electron 1 causes nearby ions to move inward toward the electron, resulting in a slight increase in the concentration of positive charge in this region. Electron 2 (the second electron of the Cooper pair) is attracted to the distorted (positively charged) region. The net effect is a weak delayed attractive force between the two electrons, resulting from the motion of the positive ions.*

The interaction between a Cooper pair is transient. Each electron in the pair goes on to form a Cooper pair with other electrons, and this process continues with the newly formed Cooper pair so that each electron goes on to form a Cooper pair with other electrons. The end result is that each electron in the solid is attracted to every other electron forming a large network of interactions.

For the advanced reader: The new pair acts as a new effective particle that has completely different properties than the original electrons. Unlike their creators, the new particles are Bosons (named after the Indian physicist, Satyendra Nath Bose) which possess the ability to occupy the same energy state. The Pauli Exclusion Principle does not apply to Bosons and so all the Cooper pairs condensate to occupy the same lowest energy level available. This new state has substantially lower energy and hence highly stable. Cooper pairs passing current inside the Superconductor will not shift their energy upon collision and hence no energy dissipation will occur.

The model is expressed in terms of advanced ideas of the science of quantum mechanics, but the main idea of the model suggests that electrons in a superconductor condense into a quantum ground state and travel together collectively and coherently. In 1972, Bardeen, Cooper and Schrieffer received the Nobel Prize in Physics for their theory of superconductivity, which is now known as the **BCS theory**, after the initials of their last names.

Flux pinning

High-temperature superconductors are characterized by a partial penetration of the magnetic field under a high enough external magnetic field. The penetration is in the form of thin filaments, called flux lines or vortices. These magnetic vortices, which create a cylindrical swirl of current surrounding it, repel each other and move to arrange themselves in an orderly array known as a fluxon lattice.

Depending on the quality of the superconductor, the vortices may either be free to move (clean samples) or may be strongly pinned to defects (dirty samples). In practice, high temperature superconductors have defects (missing or misplaced atoms, impurity atoms) in their crystal lattices. The crystal defects and boundaries stop the motion of the vortices, known as flux pinning. Pinning the motion of the magnetic field lines also means stopping the motion relative to the magnet. Pinning sites can be intentionally introduced into superconducting material by the addition of impurities or through radiation damage.

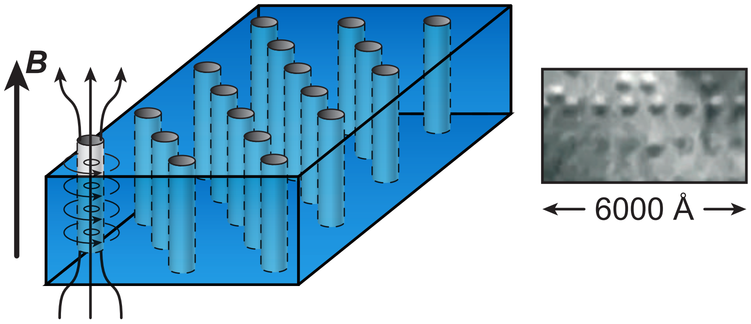


Figure 10: *The partial penetration of a magnetic field is in the form of a regular array of normal conducting regions (shown as the dark regions in Figure 10). These normal regions allow the penetration of the magnetic field in the form of thin filaments. The vortices are so named because each is a "vortex" or swirl of electrical current (shown on the left in Figure). One can view a vortex as a cylindrical swirl of current surrounding a core that allows some flux to penetrate the interior of the superconductors.*

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Chapter B

Problem Solving

Questions:

1) Discuss the problems that scientists must overcome before superconductors can be effectively used in our daily lives.

2) In your own words, explain the Meissner Effect.

3) Why was the discovery of YBCO so important? What made it different from the other superconductors that were known at that time?

4) List the four occasions the Nobel Prize was awarded to advancements in the field of superconductivity and mention the prize motivation in each case.

5) List two applications of superconductors that are currently in use today and describe the role of the superconductors in their application.

Problems:

6) What is the resistance of a superconductor at room temperature if 500 milliamps of current are passing through the sample and 3.5 millivolts are measured across the voltage probes?

Answer: $R = 0.007\ \Omega$

7) What is the resistivity of the superconductor in problem #6 at room temperature assuming the sample is rectangular? The sample is 2.5 mm wide, 3.4 mm high, and the distance between the probes is 2.5 cm?

Answer: use $R = \rho\frac{l}{A}, \rho = 238 \times 10^{-6} [\Omega cm]$

8) What is the temperature in Kelvin and what state of matter will nitrogen be in at $T = -319\ ^{\circ}\mathrm{F}$. [assume atmospheric pressure]. The conversion formula from Fahrenheit to Kelvin is $T_K = (T_{^{\circ}\mathrm{F}} + 459.6) \times \frac{5}{9}$.

Answer: The nitrogen temperature is 78 K, which is above its boiling temperature. The nitrogen is in gas state.

Graph analysis:

9) A student ran an experiment to collect data on a YBCO sample. During the experiment, a 100mA current was flowing through the sample and the student measured the voltage on the superconductor. The voltage measured and temperature are in the following table.

R (Ohm)	Temp (K)	Voltage (V)	R (Ohm)	Temp (K)	Voltage (V)
	93.8	0.000844		118.2	0.001037
	93.5	0.000783		116.1	0.001027
	93.2	0.000639		114.8	0.00106
	93	0.000505		112.9	0.001049
	92.6	0.000379		110.9	0.001035
	92.1	0.000243		109.1	0.001022
	91.7	0.000093		106.9	0.001009
	91.4	0.00001		105	0.000989
	91	0.000003		103.5	0.000975
	90.8	0.000002		102.2	0.000967
	89.9	0.000002		100	0.000951
	89.5	0.000001		97.9	0.000944
	88.8	0.000001		95.8	0.000918
	85.5	0.000001		95	0.000911
	85.1	0.000001		94.3	0.000892

a) Complete the table above using Ohm's law.

b) Using the data, make a graph plotting resistance as a function of the temperature.

c) Calculate the slope of the graph where the temperature is above $T = -173\,℃$. The conversion formula from Celsius to Kelvin is $T_{(K)} = T_{(C)} + 273$.

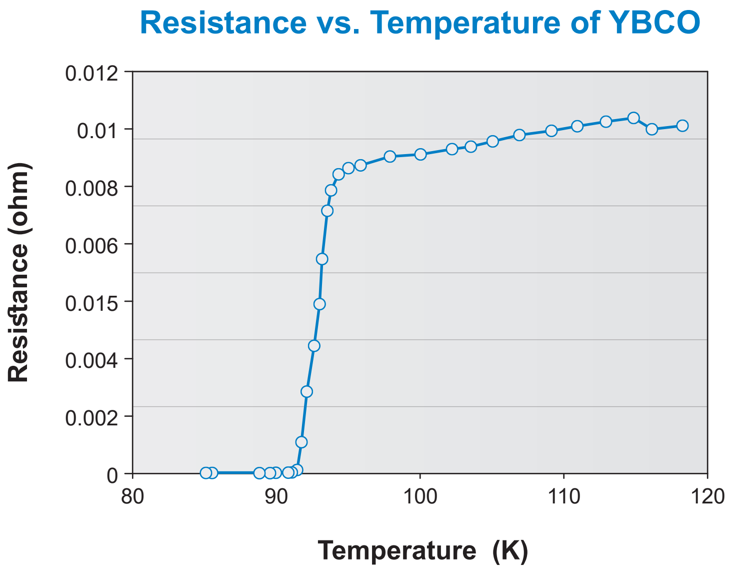
d) Estimate the critical temperature from the slope of the graph and the data in the table. Explain how you determined it.

Answer:

1) The completed table:

R (ohm)	Temp (K)	Voltage (V)	R (ohm)	Temp (K)	Voltage (V)
0.0084	93.8	0.000844	0.0104	118.2	0.001037
0.0078	93.5	0.000783	0.0103	116.1	0.001027
0.0064	93.2	0.000639	0.0106	114.8	0.00106
0.0051	93	0.000505	0.0105	112.9	0.001049
0.0038	92.6	0.000379	0.0104	110.9	0.001035
0.0024	92.1	0.000243	0.0102	109.1	0.001022
0.0009	91.7	0.000093	0.0101	106.9	0.001009
0.0001	91.4	0.00001	0.0099	105	0.000989
0.0000	91	0.000003	0.0098	103.5	0.000975
0.0000	90.8	0.000002	0.0097	102.2	0.000967
0.0000	89.9	0.000002	0.0095	100	0.000951
0.0000	89.5	0.000001	0.0094	97.9	0.000944
0.0000	88.8	0.000001	0.0092	95.8	0.000918
0.0000	85.5	0.000001	0.0091	95	0.000911
0.0000	85.1	0.000001	0.0089	94.3	0.000892

2)The graph:



3) Slope: $a = 7 \cdot 10^{-5} \frac{ohm}{K}$

4) $T_c = 91.5\,K = -181℃$

10) A critical magnetic field (B_c) is the external magnetic field that will cancel the superconductivity of a superconductor.

The formula for B_c as a function of temperature (T) is an empirical formula based on experimental evidence rather than on a solid theoretical foundation: $B_c = B_0\left(1 - \frac{T^2}{T_c^{\,2}}\right)$.

Here T_c is the critical temperature in the absence of an external magnetic field. B_0 is B_c at 0 Kelvin.

In the table below, you can see four different metals, their critical temperature, and their critical magnetic field (at 0K).

B_c (T)	T_c (K)	Element
0.01	1.20	Al
0.0058	1.08	Ga
0.041	4.15	Hg
0.1991	9.26	Nb

1) Use the formula above and plot curves for the following elements of B_c (y-axis) against T (x-axis). The temperature scale should be from 0K to T_c (T_c is the max value on the x-axis).

2) Is mercury (Hg) a superconductor when an external magnetic field of 0.03 [Tesla] in applied and it is cooled to a temperature of 3 K? Explain.

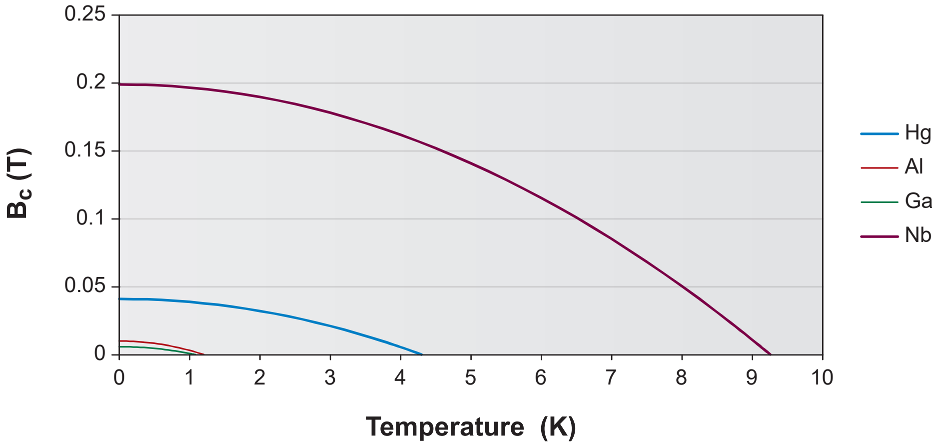
3) Is aluminum (Al) a superconductor when an external magnetic field of 0.002 [Tesla] is applied and it is cooled to a temperature of 1 K? Explain.

4) From the four elements in the table, which one is the least sensitive to an external magnetic field? Explain.

Answer:

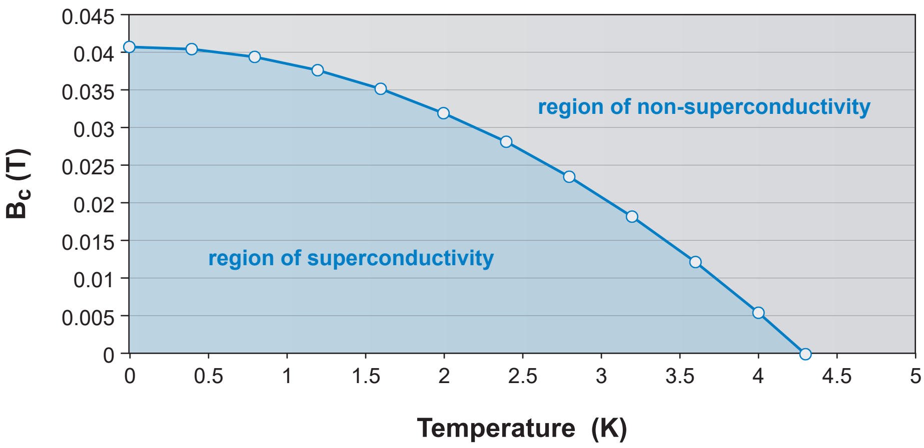
a. The graphs of all four 4 elements:

Critical Magnetic Field vs. Temperature of various elements



b. No, mercury is not a superconductor when an external field of 0.03 [Tesla] is exerted on the element at a temperature of 3 K. The superconductor is above its critical magnetic field as can be observed by its coordinates in the plot.

Critical Magnetic Field vs. Temperature of Mercury



c. Yes, aluminum is a superconductor when an external field of 0.002 [Tesla] is exerted on the element at a temperature of ~1 K. The superconductor is below its critical magnetic field as can be observed by its coordinates in the plot.

(iv). Niobium (Nb) is the least sensitive to an external magnetic field. The area under the curve of Niobium is the largest of all the elements in the table.

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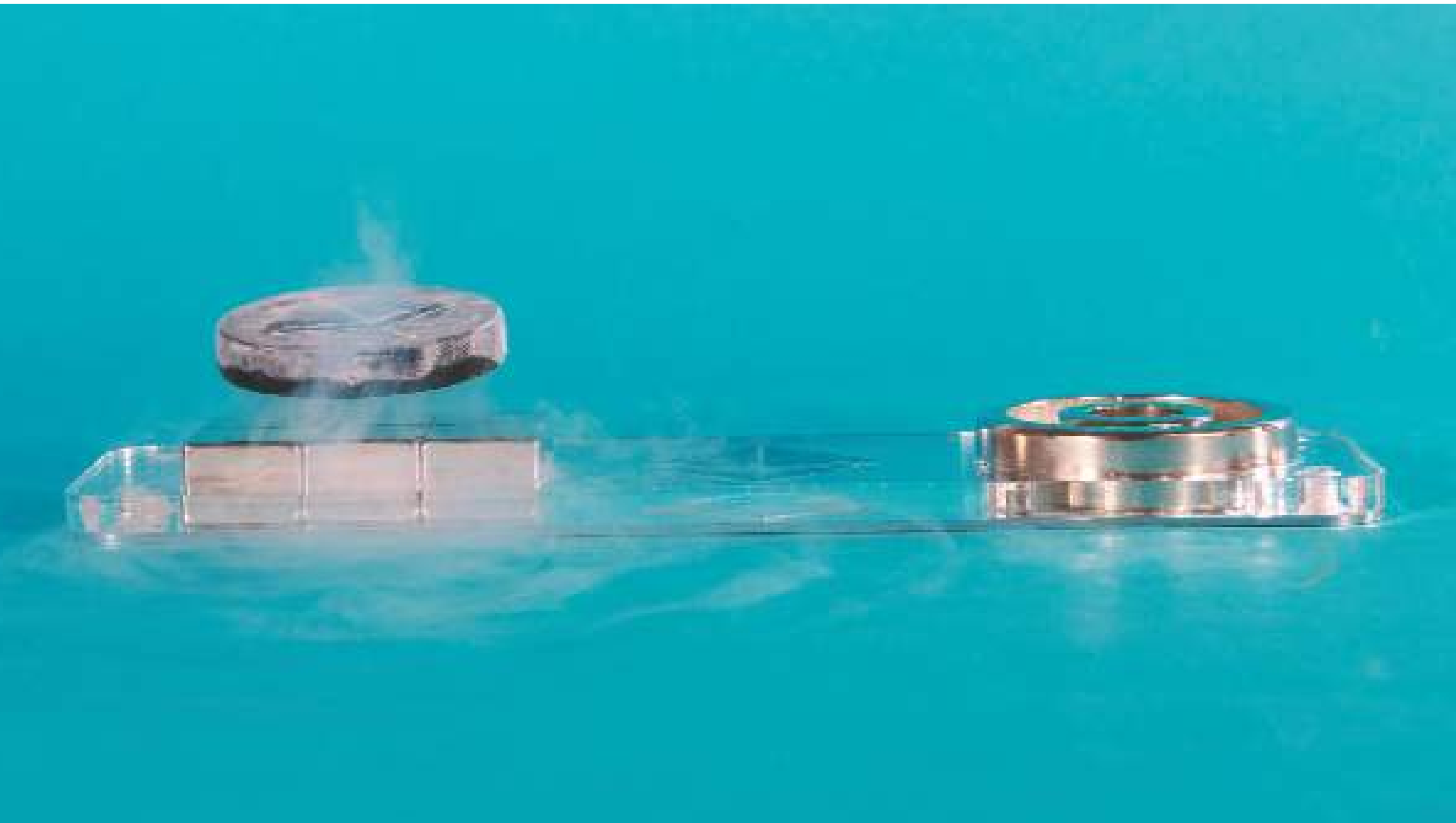


Chapter C

Demonstrations and Student Activities

This part of the booklet contains the demonstrations and the student activities that can be performed with the Classroom Quantum Levitation kit.

The activities in this booklet are written as student activities that can be executed individually or in small groups. They can also easily become teacher demonstrations and be accompanied by a discussion in the classroom.

Each activity is accompanied with the necessary equipment, a description of the demonstration, and a physical explanation using the theoretical knowledge students have acquired beforehand. The demonstrations and activities in this booklet will increase the student's theoretical knowledge and allow them to experience the practical side of superconductors.

Warning – Neodymium Magnets:

The "Quantum Levitation" experiments uses extremely strong neodymium magnets. If not handled carefully, these magnets can cause serious injury! These magnets need to be kept away from magnetic materials and sensitive electronics.

Warning – Liquid Nitrogen:

Liquid Nitrogen is extremely cold: -320 ºF. It can cause severe frostbite or eye damage upon contact. Substances may become brittle upon contact with liquid nitrogen and shatter sending pieces flying. Proper personal protective equipment should be worn at all times. This includes gloves, goggles or other eye protection, and lab coats.

Quantum Levitation

The phenomenon of quantum levitation is composed of two different effects that occur simultaneously:

1. The Meissner Effect.
2. Quantum locking.

The rationale behind this teaching sequence is to separate these two effects. Therefore, students will be able to understand the role each effect plays in the levitation. After demonstrating the levitating effect to the students, POE (Predict, Observe and explain) student activities are listed. These activities start by focusing on the Meissner Effect, continue by showing the special quantum properties of quantum locking, and are finalized by creating frictionless motion through symmetry in the magnetic fields.

Teacher demonstration -Quantum levitation

Equipment:

Quantum Levitator, plastic tweezers and a strong magnet.

Method:

1) Cool the levitator in liquid nitrogen and place it on the table - logo face down.
2) Take the small magnet and gently lower it towards the levitator.
3) When the magnet is about 2cm above the levitator, let go of the magnet. The magnet will levitate and wobble above the levitator.

Teacher's Explanation:

This simple yet amazing demonstration can be explained by two effects which were explained in the theoretical background: (1) the Meissner Effect and (2) quantum locking.

The Meissner Effect causes the magnet to levitate due to a repulsion force between the magnet and the superconductor. The magnet induces this effect in the superconductor, by creating a magnetic field that repels the magnet.

The quantum locking causes the magnet to stay in place and rotate only on its own axis. This locking force is created on the superconductor and is resistant to any change, due to Newton's third law the same locking force is exerted on the magnet, but in an opposite direction. Therefore, the magnet is locked in position and is only able to rotate around its symmetrical axis. This does not harm the magnetic flux inside the superconductor. The purpose of this separation is to address the two phenomena that occur in quantum levitation.

The purpose of this separation is to address the two phenomena that occur in quantum levitation.

POE student activity – Predict, Observe, Explain

POE is a teaching strategy that allows immediate observations that can be used for finding out students' initial ideas and can generate discussions through confronting the students' predictions and observations.

There are three steps for the POE activities:

Step 1: Predict - Ask the students to write their prediction of what will happen and explain it based on their previous knowledge.

Step 2: Observe - Carry out the demonstration allowing time to focus on observation and ask students to write down what they observe.

Step 3: Explain - Ask students to amend or add to their explanation. This is to take in to account their observations. After students have committed their explanations to paper, bring the class together to discuss their ideas.

The Meissner Effect

Student activity #1

Equipment: Quantum Levitator, plastic tweezers and a strong magnet.

Instruct the students to cool the levitator in liquid nitrogen. Remove the levitator from the liquid nitrogen and gently bring the levitator closer to a small magnet that sits on a table.

Predict:

What will happen to the small magnet as it gets closer to the cooled levitator? What will happen if we repeat the experiment with the magnet flipped upside down? Use the Meissner Effect to explain your prediction.

Observe:

The small magnet will always be repelled from the levitator even when we flip its polarity!

Teacher's explanation:

This is a beautiful demonstration of the Meissner Effect. The superconductor repels the magnet regardless of its polarity (unlike the forces between regular magnets). When a magnet is placed near a superconductor, currents are formed in the superconductor and create a magnetic field similar in size, but opposite in direction to the original magnetic field that formed it. This magnetic behavior is called "Diamgnetism". A superconductor is a perfect diamagnet.

When the magnetic field near the superconductor changes, due to the flipping of the magnet for instance, the magnetic field inside the superconductor immediately changes to create a mirror field.

This effect causes the superconductor to produce a magnetic field that repels every magnet close by, no matter the polarity of the magnet.

Student activity #2

In this activity, the students observe trapped magnetic forces and currents inside the superconductor.

Equipment: Quantum Levitator, plastic tweezers, Handheld magnetic device and a compass.

Demonstrate the magnetic force the magnet in the Handheld magnetic device exerts on the compass needle by slowly brining the compass towards the magnets.

Predict:

What will happen if a cooled superconductor is first locked in a magnetic field and then, when the surrounding magnet is removed, placed next to a compass? Consider the Meissner effect.

Observe:

The compass needle moves due to magnetic fields created by the superconductor which is acting as a magnet.

Teacher explanation:

When the superconductor is placed in an external field currents begin to circulate inside, creating an opposite internal magnetic moment in an effort to expel the external field (Meissner effect). Since there is no electrical resistance, the currents do not dissipate even when the superconductor is pulled away from the magnet thus turning the superconductor into a magnet.

Quantum Locking

In this activity, the students are faced with a phenomenon that cannot be explained by the Meissner Effect. It can only be explained by the quantum locking effect.

Student activity #1

Equipment: Quantum Levitator, plastic tweezers and the handheld magnetic device.

Instruct the students to soak the levitator in liquid nitrogen and then place it above the magnetic matrix. The levitator will levitate.

Predict:

What would happen if we try to gently move the levitator while it is levitating above the magnet (using the tweezers)?

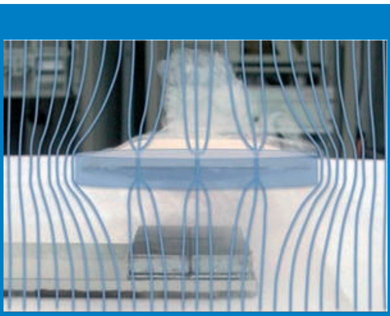


Illustration: Some of the external magnetic field lines penetrating the superconductor

Observe:

The levitator will resist any change to its position.

Teacher's explanation:

In type II superconductors, like the YBCO in our levitator, when the external magnetic field is strong enough it will penetrate the superconductor in discrete quantities, called fluxons or magnetic vortices. Since, inside any vortex superconductivity is locally destroyed, the superconductor will prefer to have these at spots where superconductivity is the weakest. The fluxons will be locked in these pinning centers thereby locking the entire superconductor in space.

This phenomenon is called quantum locking and is a key component to understanding Quantum Levitation. If the levitator moves from its position, the vortices' positions will shift from their original location and the energy will increase. This energy change is translated to a drag force that resists any movements.

Student activity #2

Equipment: Quantum Levitator, plastic tweezers, and the Handheld magnetic device.

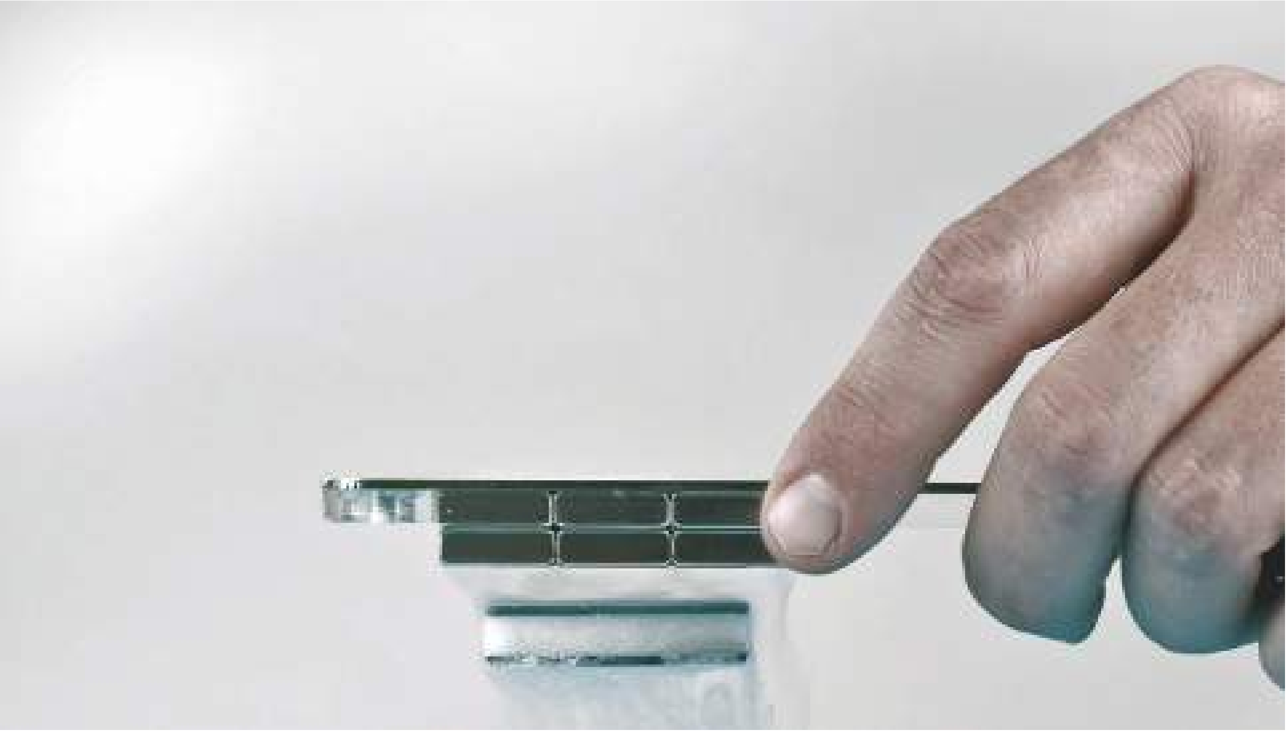
As in the previous activity, instruct the students to cool the levitator and place it above the magnetic matrix.

Predict:

What would happen if the magnets are turned over upside down? Will the levitator fall? Try to predict what will happen by using the quantum locking phenomenon.

Observe:

The levitator will hover underneath the Handheld device, and will not fall to the ground!



Levitator hovers under the magnets

Teacher's explanation:

The quantum locking forces can either be attractive or repulsive. The locking force acts to keep the superconductor in the same place, thanks to the magnetic vortices that are pinned to defects in the superconductor.

The levitation in this case cannot be explained by the Meissner Effect which is strictly repulsive. Therefore, a quantum locking phenomenon is observed!

POE – Quantum locking and Frictionless Bearing

Equipment: Quantum Levitator, plastic tweezers and the Handheld magnetic device.

The small magnetic rings in the Handheld device are made of two circular magnets.

Predict:

What would happen if a cooled levitator is placed on the circular magnet? Consider the magnet's radial symmetry.

Observe:

The levitator will rotate freely around the symmetry axis of the rings (not around the center of the levitator! Try to lock it sideways and see).

Teacher explanation:

In this setting there is a radial symmetry around the center of the circular magnet rings. This symmetry also exists in the magnetic field lines which enables the superconductor to freely move perpendicular to the radial axis (or rotate around the center of the rings). The superconductor will not be able to move parallel to the radial axis because it will result in changes to the magnetic flux inside it (the field changes along the radius).

Final demonstration – The Maglev Track

This is the most impressive demonstration of quantum levitation.

Equipment: Quantum Levitator, plastic tweezers and the Maglev track.

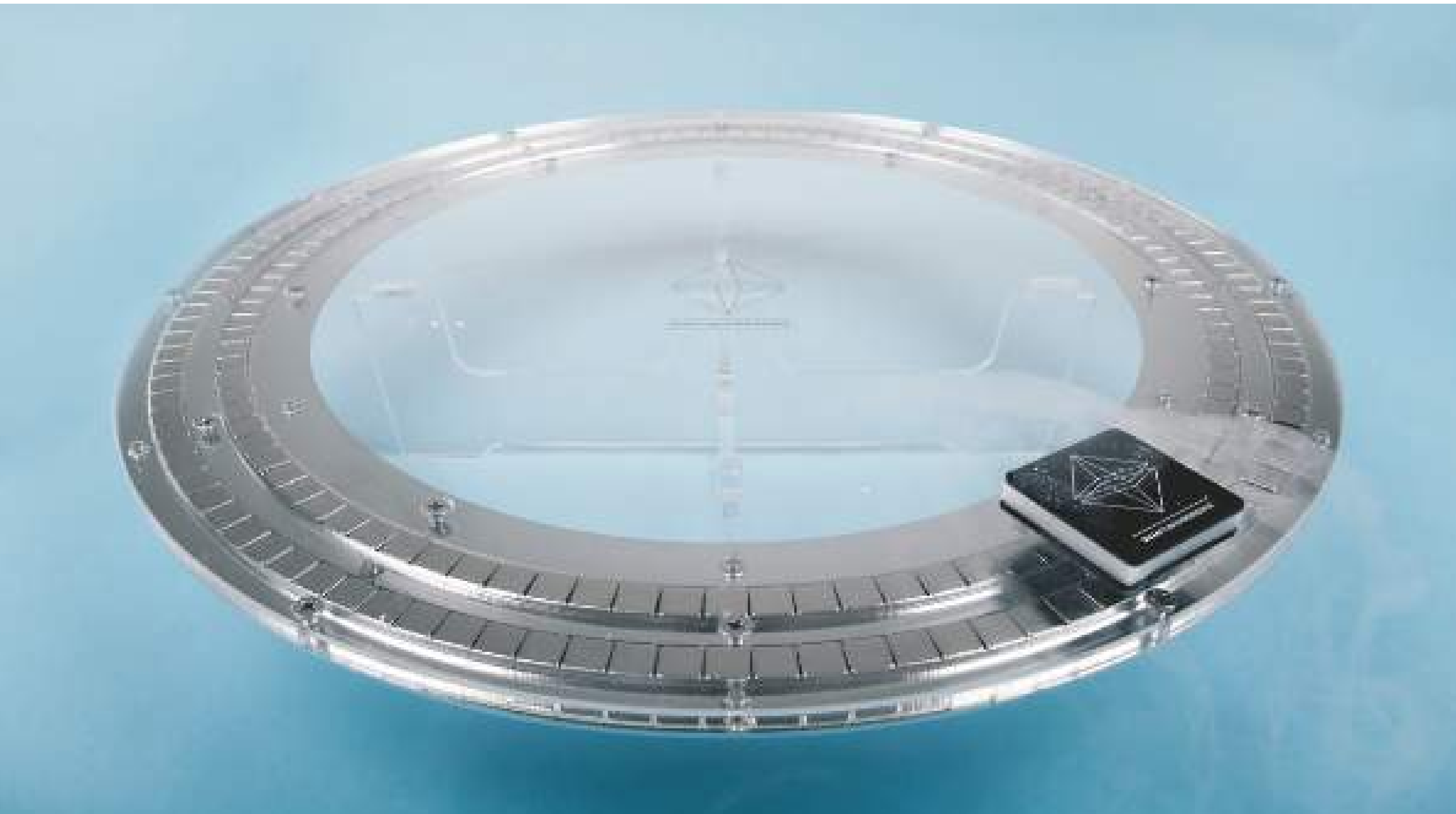
Method:

Have the students cool the levitator in liquid nitrogen and then place the cooled levitator on the circular magnetic rail. Push the levitator slightly towards the magnets until it is locked. Allow the levitator to move freely along the track with a slight push.

Teacher explanation:

The magnetic track is assembled of magnets with their North/South polarity pointing perpendicular to the plane. All of the magnets in the inner ring point north and all the outer magnets point south.

This configuration forms a symmetry axis similar to the rings in the Handheld device. The magnetic field is identical along the track which allows the superconductor to move freely in that direction, but to be locked in all other directions.



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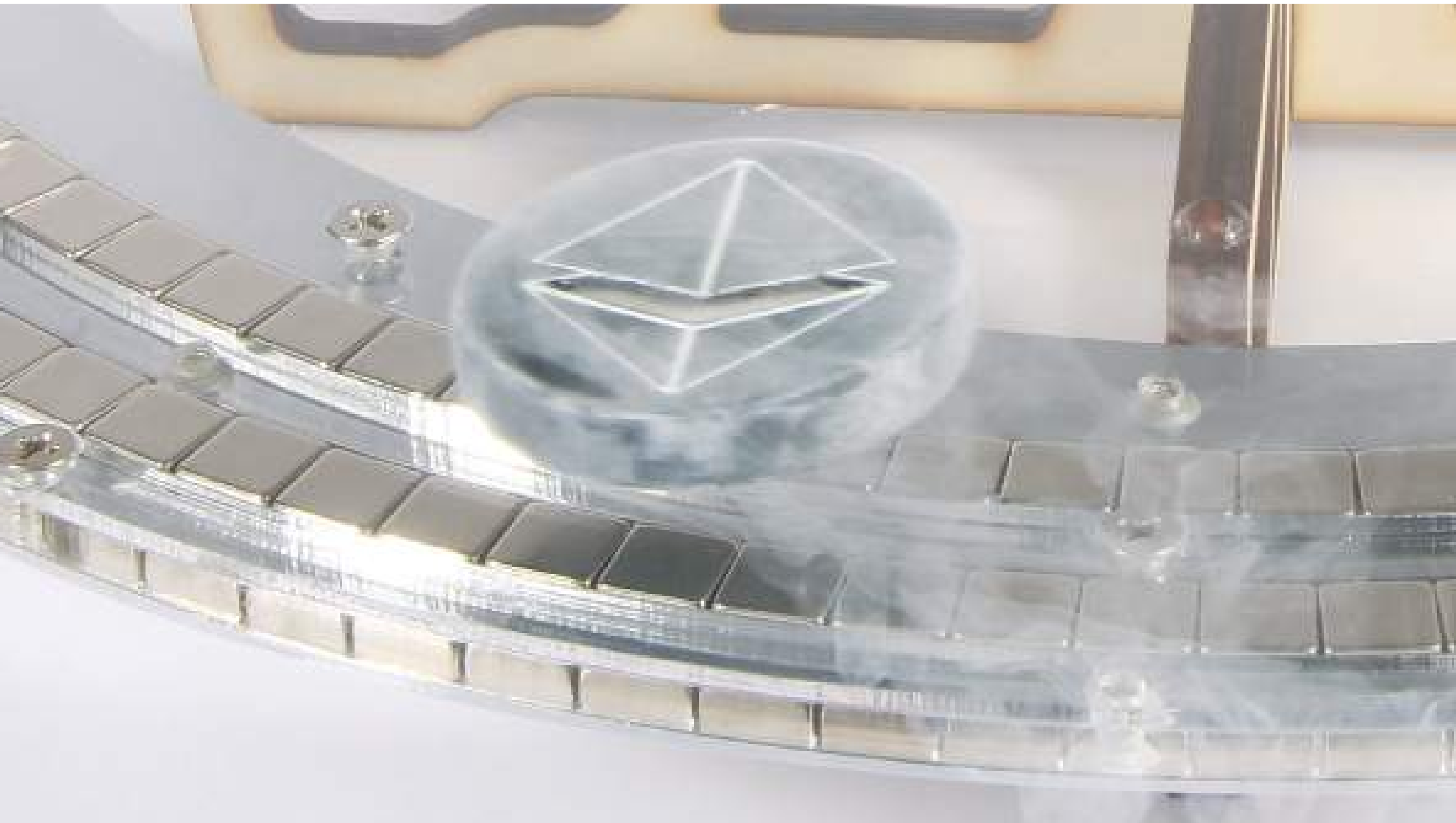


Chapter D

Quantitative Experiments and Science Fair Projects

Quantum levitation allows students not only to observe the quantum phenomena in a qualitative manner but also to perform quantitative measurements of the phenomena. This section provides ideas for easy to conduct student experiments that can be measured using simple and common sensors. These experiments will enrich your student's understanding and enable them to measure real quantum phenomena with their own hands!

Experiment 1: Measuring the Levitation Force

Objective: Measure the levitation and locking forces of the Meissner effect and quantum locking.

Equipment: Handheld magnetic device, quantum levitator, plastic tweezers, liquid nitrogen and a Force Sensor Balance Stand.

Methods:

1) Place the Handheld magnetic device on the force sensor and tare the scale of the sensor to 0.
2) Cool the levitator using liquid nitrogen and hold it with the tweezers while you start the recording of the force sensor.
3) Bring the levitator closer to the magnets until reaching a distance of a few millimeters and then continuously pull it back up and increase the distance from the magnet in a continuous manner.
4) Repeat the measurement until a clean and continuous graph is achieved.

Data analysis:

If the experiment was performed correctly, the resulting graph should look similar to the graph in Fig. D1.

As the levitator gets closer to the magnet (Region 1), the repulsion force between the levitator and the magnet increases and the net force that the magnet applies on the force sensor increases. Both the Meissner effect (always repulsive) and the locking force (resists the increase in the field) are repulsive in this region and contribute to the force. This makes a net force that sums up to ~1 Newton.

According to Newton's third law, the levitator experiences the same force but in an opposite direction (in our case upwards against gravity). We can conclude that the repulsion force between the magnet and the levitator can carry a weight as high as 100 grams. This fact is amazing especially since the levitator itself weights only ~3 grams, but even more strikingly, the mass of the superconductor inside is less than 0.025 grams. The superconductor levitates a weight that is a couple of thousand times its own weight!

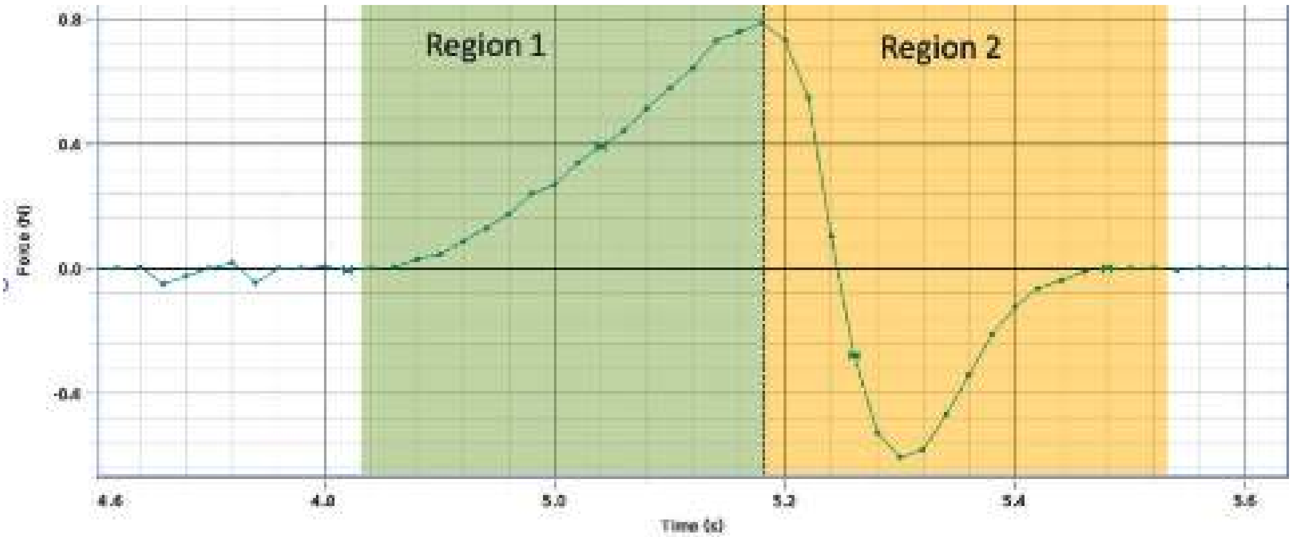


Figure D1: *The change in force acting on the force sensor is due to the interaction between the magnetic matrix in the handheld device and the superconductor in the levitator. Region 1 represents the movement of the levitator towards the magnet and Region 2 represents the movement of the levitator away from the magnet. The force sensor is tared to 0 when the Handheld device is placed upon it.*

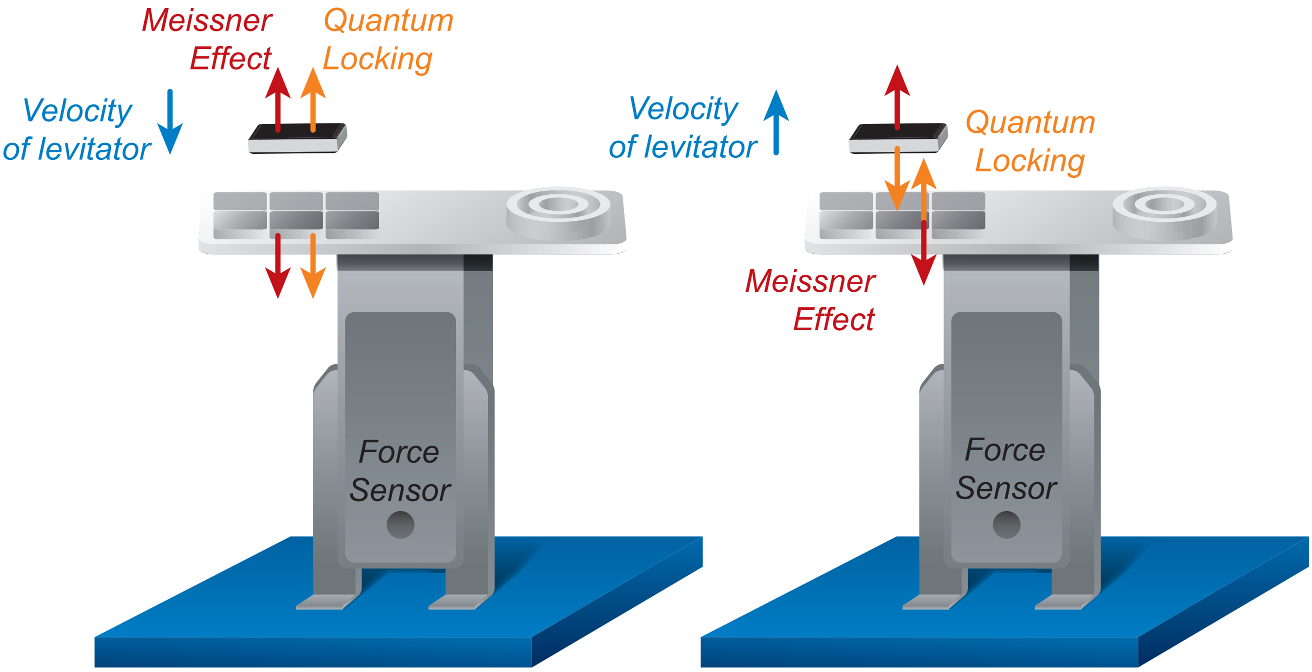


Figure D2: *The magnetic forces acting on the levitator and Handheld device throughout the motion of the levitator towards (left) and away (right) of the magnet. Only the magnetic forces that are acting on the levitator and magnets are shown in this figure.*

Did you know?

The superconductive layer inside the levitator is only a few microns (10^{-6}m) thick, but can carry up to 50,000 times its own weight. If we could synthesize a superconductor a few centimeters thick with the same quantum properties as our levitator, it would be able to levitate a small car!

One of the most interesting parts of the experiment occurs when the levitator moves away from the magnet (Region 2). As expected, the force gradually decreases with distance, but instead of gradually decreasing to 0 the net force on the magnets becomes negative - a force is **pulling the magnets upwards**. This attraction cannot be explained by the Meissner Effect which can only create a repulsion force between the levitator and the magnet. This leaves the quantum locking force which resists changes to the magnetic flux inside the superconductor and hence acts as a friction force – always opposite to the direction of motion. In region 2 the motion is upwards and the locking force is pointed downwards on the levitator and upwards on the magnets (Newton's third law). If the locking is strong enough to negate the Meissner repulsion, the total force will be negative (attractive) and the magnets will be pulled upwards.

You just observed a quantum phenomenon that can be measured by both macroscopic and quantitative tools!

Experiment 2:
Measuring the Critical Temperature Using Magnetic Levitation

Objective: Measure the critical temperature of the superconductor using a resistance thermometer.

Equipment: Levitator with a resistance thermometer attached, multimeter, Handheld magnetic device, tweezers, and liquid nitrogen.

Methods:

Phase A: Calibrating the resistance thermometer

A platinum resistance thermometer is thermally coupled to the superconductor in the levitator. Resistance thermometers are used as sensors to measure temperature. This is done by correlating their resistance with temperature. Platinum resistance thermometers offer excellent accuracy over a wide temperature range (from –200°C to +850°C) because the relationship between temperature and their resistance is, within good approximation, linear in the above temperature range.

There are several ways to calibrate the resistance thermometer. A simple way is to use a home thermometer or a thermocouple and measure the temperature of an object as it is cooled with both the reference thermometer (home thermometer or thermocouple) and the resistance thermometer. The object can be cooled using ice or any another method. During cool down we can record the resistance values at each temperature, plot a graph of the values, and calculate a trend line to find the formula of the temperature as a function of resistance of the thermometer.

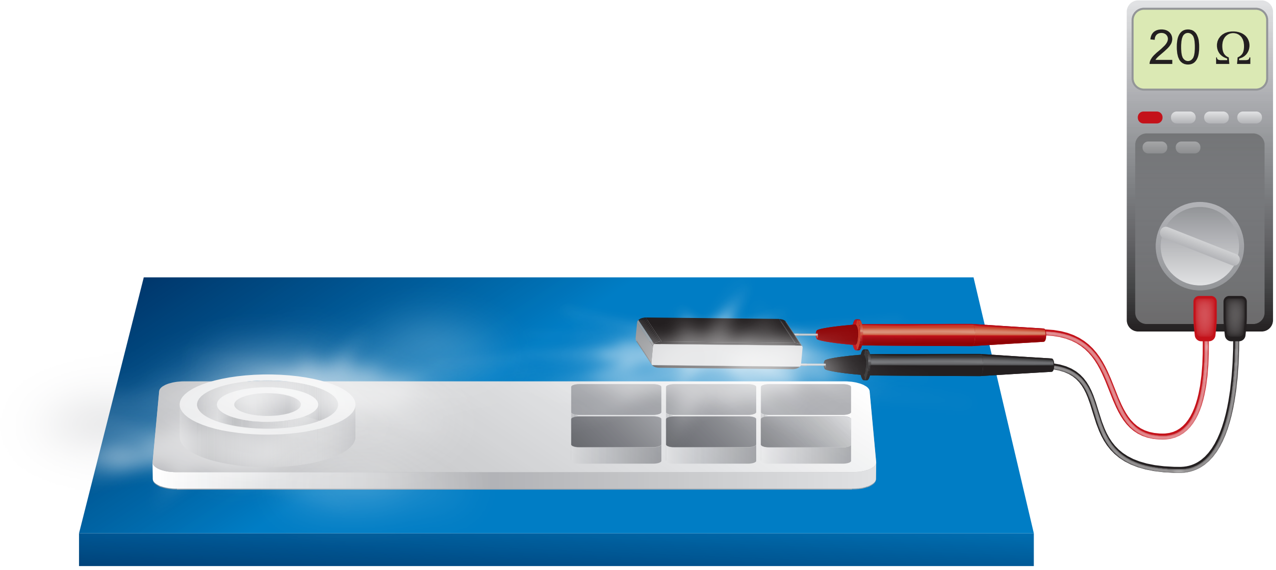
Phase B: Measuring the critical temperature using magnetic levitation

1) Connect the resistance thermometer to the multimeter and cool the levitator using liquid nitrogen.

2) Place the levitator horizontally above the magnetic matrix of the Handheld magnetic device and record the temperature when the levitator stops levitating and completely lands on the magnet. The lack of any levitation is an excellent indicator for the state of the superconductor and the transition temperature: above the critical temperature the material is in the normal state and does not possess any magnetic properties (the magnetic field penetrates the material and the Meissner and locking effects are completely eliminated).

Data Analysis:

Compare the experimental results with the theoretical value of the critical temperature of YBCO. What may be the reasons for a difference between the two?



Experiment 3:
Superconductivity as a Mean to Investigate Classical Mechanics

Quantum Levitation and frictionless motion provide an excellent accessible and easy to use tool to investigate classical phenomena that involve motion. We can use the lack of friction to get better measurements of classical quantities such as energy, speed, etc.

Harmonic motion

Objective:

Investigate the harmonic motion of the levitator at different values of the restoring force.
In this experiment, students measure the frequency of the motion as a function of the slope angle of the Maglev Track.

Equipment:

The Maglev Track, a stand to change the slope angle of the track, a stopwatch, liquid nitrogen and a levitator.

Methods:

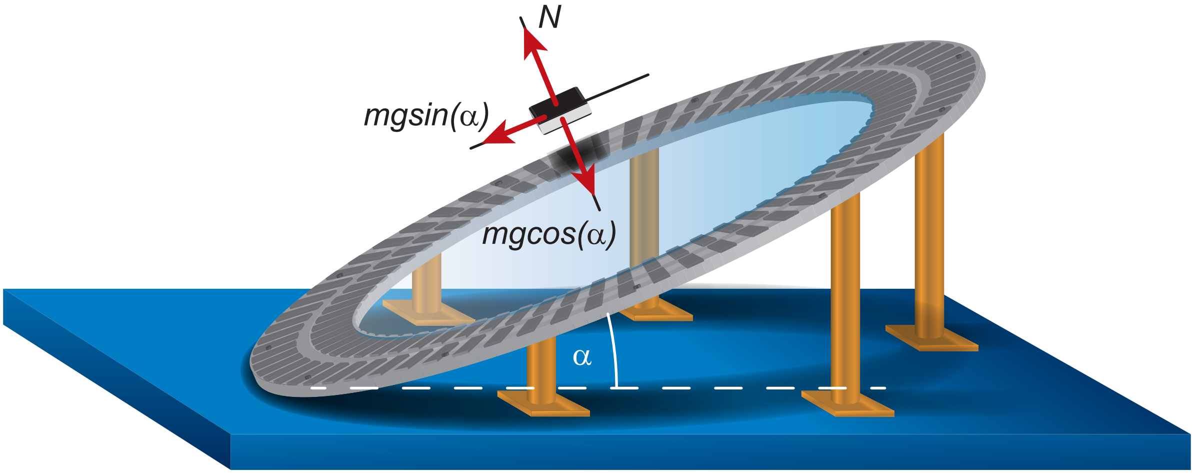
1) Cool the levitator in liquid nitrogen.
2) Place the cooled levitator on the tilted Maglev Track at a low point and release.
3) The levitator should move in a simple harmonic motion along the circular magnetic track. The gravity force has two components -
   I. perpendicular to the surface (Normal) which is canceled by the levitation force
   II. Parallel to the surface and along the track.
   The latter acts as the restoring force in the harmonic motion.
4) Change the angle of the track by adjusting the height of the stand.
5) Using the stopwatch, measure the time it takes the levitator to complete its harmonic motion.
6) Take several measurements at the same height to reduce the measurement error.

Data analysis:

The motion of the levitator can be simulated by the motion of a mathematical pendulum that is tied by a rope of length L (in our experiment the radius of the track). Using small angle approximation, the time period of a simple gravity pendulum is $T = 2\pi\sqrt{\frac{L}{g}}$.

In our case the effective gravity is only the component which is parallel to the surface. We can now formulate a relation between the time period T, and the slope angle α: $T = 2\pi\sqrt{\frac{L}{g\sin(\alpha)}}$

The results of the experiment can be shown using a linear graph of the square of the period time as a function of $\frac{1}{\sin(\alpha)}$.



Conservation of mechanical energy

Objective:

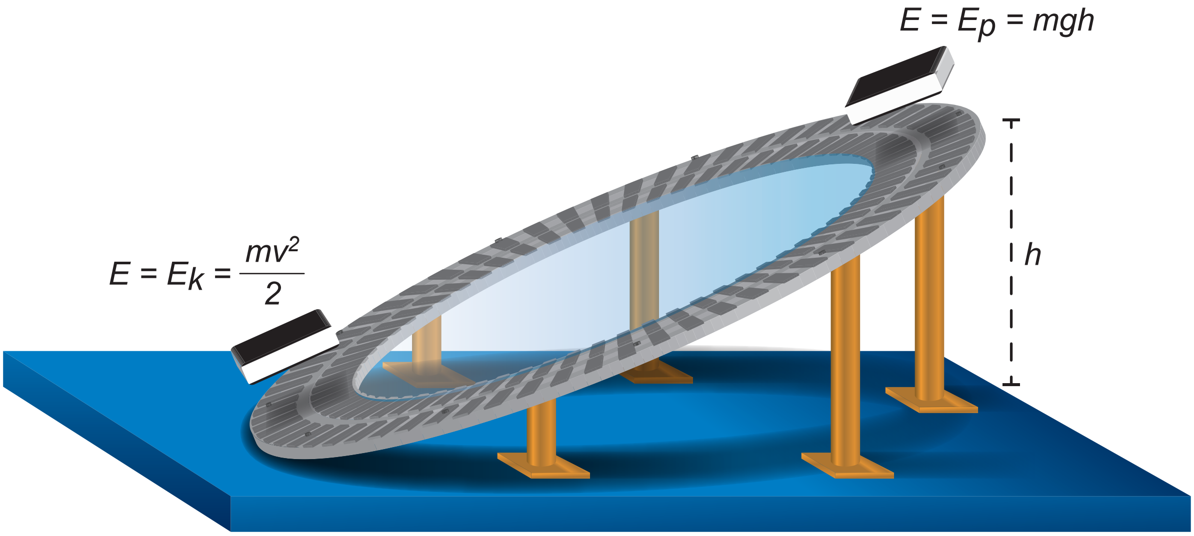
Investigate the law of conservation of mechanical energy in a frictionless system. In this experiment, students find the relationship between the velocity of the levitator as a function of the height it was released from on the Maglev track.

Equipment:

The Maglev track, a stand to change the slope angle of the track, levitator, liquid nitrogen, long ruler, a photogate or high speed camera, and a Tracker software.

Methods:

1. Cool the levitator in liquid nitrogen.
2. Measure the initial height from which the levitator will be released from relative to the lowest point on the track using the long ruler.
3. Set up the instrument to measure the velocity of the levitator either using the photogate or high speed camera with tracker software.
4. Place the photogate at the bottom of the track and ensure the levitator passes entirely through the photogate horizontally with its sides parallel to the track.
5. Film the levitator with the high speed camera at the bottom of the track and analyze the video using Tracker software to obtain the velocity.
6. Repeat the experiment at different heights and take multiple velocity measurements at each height to increase the accuracy of your measurements. Remember to measure the height every time it is changed.



Data analysis:

Conservation of mechanical energy occurs when the work of all non-conservative forces is equal to 0. In our case friction is negligible and the magnetic force is in a radial direction that is perpendicular to the motion of the levitator; therefore, it is not exerting work. The initial potential energy of the levitator is transformed to the kinetic energy at the bottom of the track:

$$K_E = P_E$$

$$\frac{mv^2}{2} = mgh$$

Solving the equation yields the relationship between the final velocity v and the initial height h:

$$v = \sqrt{2gh}$$

The students can plot the relationship between and in order to receive a linear graph.

Credits

Picture 1

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Picture 2

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Picture 4

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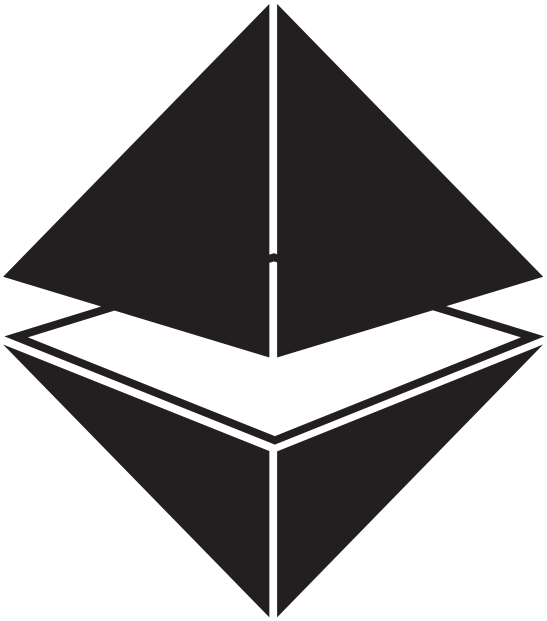

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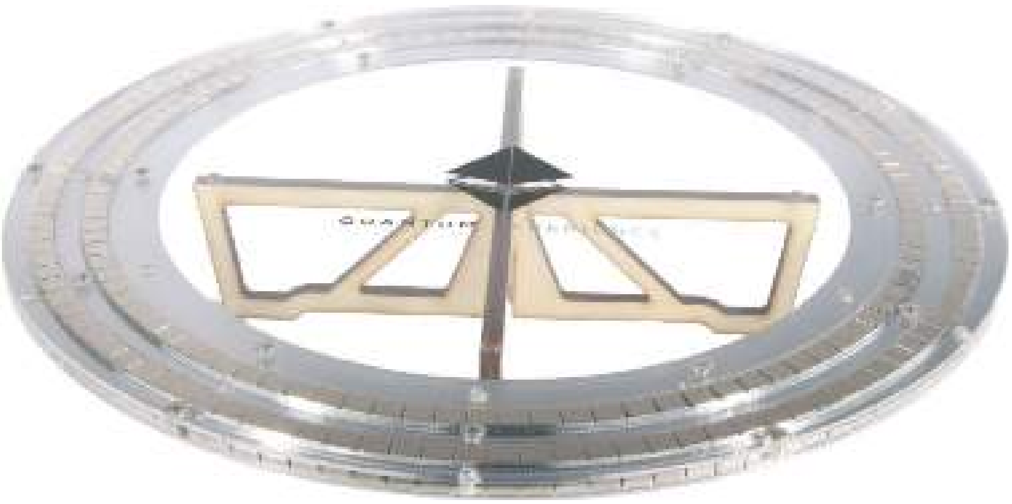

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