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Levitation? Yes, it is possible!

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During July 2018, a group of top high school Spanish students attended a summer scientific camp at the University of Seville. The topic of the project was magnetic levitation. During the one-week-long stay, the students investigated several possible ways of achieving stable levitation. These included diamagnetic levitation, use of superconductors, induced current levitation, and the toy Levitron®. The experiments were accompanied by their corresponding conceptual and theoretical explanations.
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I. INTRODUCTION

The promotion of scientific and technical studies among teenagers is becoming a common activity in academic institutions. Many universities worldwide offer scientific summer camps for high school or college students. The aim of these camps is to stimulate among the young people the interest for science and its applications, and to allow them to have a first encounter with the academic world.[1,2]

The Spanish agency for science and technology, FECYT, organizes scientific camps around the country during the summer holidays. This program is almost a decade old and top Spanish universities participate in it. Each participating university offers four different projects, each of which are about one scientific or technical topic. Very talented students from all over the country apply for these projects. Many motivated students are selected according to their performance during the last academic year. During one week in July, they participate in one of the projects at the selected university.

During July 2018, our team of the Department of Electronics and Electromagnetism of the University of Seville participated with a project entitled “Levitation? Yes, it is possible.” The main objective of the project was to introduce the students to the world of magnetism and its laws and we did this by proposing a clear and surprising goal: to obtain stable magnetic levitation.

Levitation, understood as the power of overcoming gravitational force, is an ancient dream. Gods and saints of almost all civilizations are said to have had the power of levitation. Christ appears in the gospel walking on water. Tibetan masters are said to be able to levitate during meditation, something that Buddha himself is said to have done on several occasions. Levitation is also found in some classics of literature.[3] For instance, in one of his famous travels, Gulliver visited the kingdom of Laputa, an island that levitated over an extended region thanks to giant magnets that were controlled by the inhabitants.

The English priest, Samuel Earnshaw, proved in 1842 a theorem that, applied to magnetic forces, states the impossibility of stable levitation using permanent magnets in a static configuration. Earnshaw’s theorem forbids the kind of levitation appearing in Gulliver’s Travels, but we cannot blame Jonathan Swift for ignoring Earnshaw’s result, since Gulliver’s Travels were written by Swift a century before Earnshaw. Earnshaw’s theorem plays a central role in our project. The different techniques we propose for levitation are different ways to circumvent Earnshaw’s premises.

The project is structured in eight sessions, scheduled during the week (see Table I). In Sec. II, we sum up the content of every session.

II. PROJECT SESSIONS

The students participate in eight sessions. The first two sessions are a quick theoretical review, the five following sessions are devoted to experimental work at the laboratory. Finally, the students must prepare a presentation of the results obtained during the week. The camp finishes with a general session where the participants in the four projects hosted by our university present their conclusions.

A. Theoretical sessions

Magnetism is almost absent in the Spanish curriculum at the high school level. Besides a certain familiarity with the fact that like poles repel and unlike poles attract, at the beginning of the week the participants were ignorant of several important facts. For example, most of them did not know that an electric current produces a magnetic field. Therefore, the first theoretical session starts explaining some basic phenomena related to magnetism. Following Livingston,[3] we concentrated on ten facts, including: that an electric current produces a magnetic field; Faraday’s electromagnetic induction; magnetic fields produce a force on moving electric charges; and that a wire carrying an electric current experiences a force when subject to a magnetic field. All of these facts and laws are presented with the help of demonstrations and without complex mathematical formulation.

The second theoretical session is devoted to levitation itself and to the several ways we can achieve it. First of all, we presented Earnshaw’s theorem and let the students play with a set of magnets to convince themselves of the impossibility of a stable levitation with them. Having two permanent magnets at hand, we have two possibilities: levitation by attraction or levitation by repulsion. In the first case, the fixed magnet is above the one that we intend to levitate and unlike poles are facing. Although there is an equilibrium point, it is unstable to vertical displacements. In levitation by repulsion, the fixed magnet is below and like poles are facing. There exists an equilibrium point, but now it is stable with respect to vertical displacements. However, the situation is unstable with respect to horizontal displacements and, more importantly, the levitating magnet tends to flip. From

Table I. Week schedule.

	9.30-11.30 h	12.00-14.00 h	15.30-17.30 h
Monday	Welcome	Theory and demonstrations	
Tuesday	Force between magnets	Diamagnetic levitation	
Wednesday	Jumping ring and Alcon levitator	Superconductors	Levitron®
Thursday		Presentation elaboration	
Friday	Rehearsal	Presentation	…

these observations, we concluded that levitation by repulsion may be possible if one restricts the degrees of freedom of the floating magnet, avoiding lateral displacements and/or flipping. Both strategies are explored during the experimental sessions.

Once the limitations of permanent magnets are revealed, we turn to non-permanent magnets. At this point, we introduce the students to the different types of materials that exist from the point of view of their magnetic behavior: diamagnetic, paramagnetic, and ferromagnetic. Since the concepts involved in the theory of magnetic properties of materials are rather advanced, we introduce this topic in a very empirical way. We have a demonstration set, supplied by the company Phywe®, with three small bars of bismuth, tungsten, and nickel hung from a thread between the poles of a strong magnet. Avoiding to enter into the details of a microscopic interpretation of these behaviors, we let the students know that a diamagnetic material (like bismuth) behaves, in the presence of a magnetic field, as a magnet with poles opposing the external magnetic field. Ferromagnetic materials (like nickel) and paramagnetic materials (like tungsten) behave as magnets with the same orientation as the external field. The effect is strong for ferromagnetic materials but very, very weak for paramagnetic and diamagnetic ones.

Diamagnetism opens the possibility to obtain stable levitation. If we approach a permanent magnet to a diamagnetic sample, the magnetism induced in the material always opposes the permanent magnet. The only problem is that the effect is so weak that very strong fields are needed. Diamagnetic levitation was demonstrated by Geim and coworkers in a spectacular series of experiments, including levitating a frog, using a 16 T electromagnet in Nijmegen (The Netherlands).[4,5] Our proposal to the students of the camp was more modest, but relied on the same theoretical principles. They are asked to find a configuration to levitate a thin graphite pencil mine.

The next topic in our theoretical dissertation is superconductivity and the Meissner effect. Again, we do not enter into many theoretical details. The topic is addressed considering two aspects. First, we present a historical account of superconductivity, from Kamerlingh-Onnes discovery to high-temperature superconductors. Second, we describe the Meissner effect from a purely empirical point of view. What interests us is to show that superconductors can be seen as superdiamagnetic materials. At this respect, they behave as magnetic mirrors, which explains their use in levitation.

The last topic of this theoretical session is induced current. We present some demonstrations that show the principles of magnetic braking and how a magnet falls slowly through a hollow copper cylinder. From this, we can conjecture that an upward moving cylinder will be able to levitate the magnet if moving fast enough. This is the principle of the Alcon levitator: since moving a straight cylinder continuously upward is impossible, the Alcon levitator makes use of the lifting force produced by the currents a stationary magnet induces on two counter-rotating metallic cylinders.

We are aware of the difficulties of some of the concepts introduced during the theoretical sessions. Topics like the Meissner effect or induced currents are difficult to master even for university undergraduate students. This is why we introduced them on an empirical basis, always illustrating the concepts with demonstrations. In any case, the same ideas are recalled over and over again during the week.

B. Experimental sessions

In the following paragraphs, we give a brief description of the experimental sessions. A more detailed discussion can be found in the additional material.[6]

The first levitating technique we proposed was to restrict the degrees of freedom of the magnets. In the first experimental session, we asked the students to measure the variation of the repulsive magnetic force between two hollow disk magnets inserted along a plastic rod with like poles facing. The magnets come with a demonstration set (from "Antigravity magnetic levitation," a toy by Kidzlabs®). In order to measure the force, a plate is placed over the top magnet and the plate is loaded with glass beads until the distance between the magnets attains a desired value. The beads are weighed with the help of a digital balance. Figure 1 shows the experimental setup. The results serve to illustrate the concept of stable equilibrium. The magnetic force decreases as the distance increases. The equilibrium is achieved when the weight of the floating magnet equals the magnetic force. If the floating magnet is displaced towards the bottom magnet, the magnetic force becomes greater than the weight and the total force tends to push the magnet upward. On the contrary, if the floating magnet is displaced away from the other magnet, the weight is greater than the magnetic force and the magnet tends to fall. Actually, if we

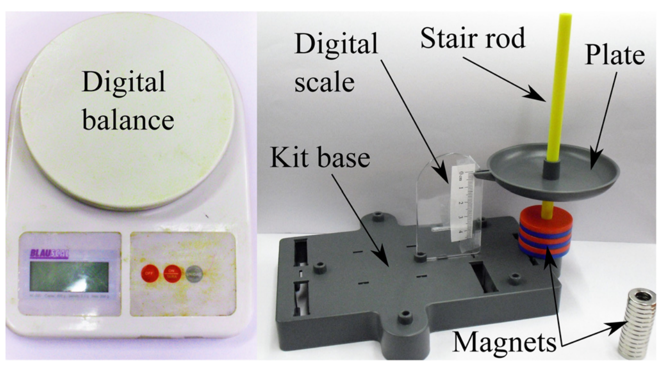

Fig. 1. Experimental set up for measuring the force between magnets.

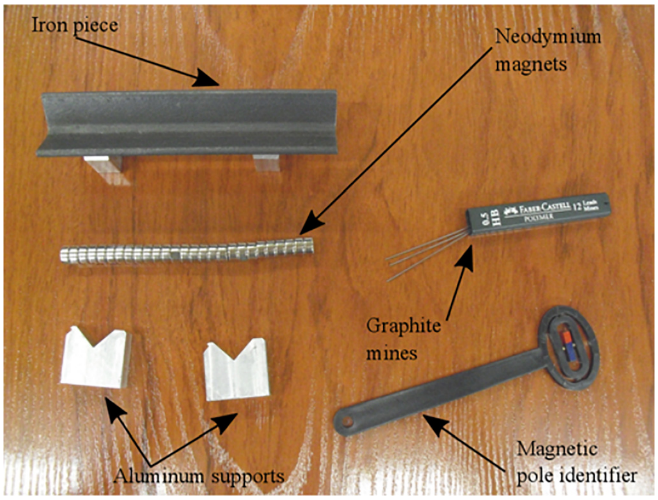

Fig. 2. Material needed for the diamagnetic levitation experiment.

displace the magnet from the equilibrium point it undergoes oscillations around the equilibrium. These oscillations are damped by friction.

During the second experimental session, we provided the students with the following material: a set of many disk-shaped neodymium magnets, a metallic (iron) piece with an angular shape making a 90 degree angle and 120 mm in length, two aluminum supports, a small compass-like device that helps to determine magnetic poles, and a graphite pencil mine 60 mm long (see Fig. 2). The iron piece is intended to aid the students to position the magnets. With all of these elements, the students are asked to find a configuration in which the graphite mine levitates freely.[7] All of the groups of students have been able to achieve levitation and they found several combinations in which a stable levitation is possible. Figure 3 shows a typical result.

Superconductors behave as superdiamagnetic materials and can be seen as magnetic mirrors: the magnetic field generated by the currents in the superconductor can be described as having been originated by a magnet equal in magnitude to the external magnet, and with like poles opposing. They can be used to levitate magnets because the "image" magnet continuously follows the external magnet.[3,8] In this experimental session, we use a disk shaped piece of type II superconductor (YBaCuO). The critical temperature of YBaCuo is 95 K, above the temperature of liquification of nitrogen (77 K). This makes possible the use of liquid nitrogen to cool the superconductor below its critical temperature. Due to safety restrictions, the students are not allowed to handle liquid nitrogen. For this reason, the experiment is done by one of us.

We proposed to our students two experiments with induced currents. The first one is the well-known jumping ring, also referred to as Thomson's ring.[9–11] The experimental setup consists of a 1200-turn solenoid, a ferromagnetic core (we used three pieces, each 10 cm long, stacked), a multimeter in the ammeter function, a switch, a set of cables, a ruler placed vertically, and a set of aluminum rings cut from the same tube at different heights. The solenoid is connected to the A.C. mains through the ammeter and the switch. Placing a ring on the solenoid, concentric with the iron core and closing the circuit, produces a sudden current pulse on the ring, hence a force that throws the ring a certain distance up. Another possibility is to switch the current on and then place the ring on the solenoid. In this case, the ring levitates continuously, the iron core preventing it from lateral displacements.

Alcon's levitator[3,12] makes use of the induced current on a moving conductor.[13] A schematic representation of the geometric configuration is shown in Fig. 4: two cylindrical metallic pieces rotate at the same angular velocity and a magnet is placed above the cylinders in the middle plane. The net force that the induced currents exert on the magnet is upward. If the rotation of the cylinders is fast enough, the magnet can be levitated. Since levitation requires rather high velocities, we decided, for safety reasons, not to propose that our students attempt a levitation experiment. Instead, we assembled a setup to quantify the effect and, eventually, calculate the angular speed required for levitation. An extrapolation of the measurements at low angular speed allows one to infer that at an angular speed of about 4300 rpm, the apparent weight would be zero, and the magnet could levitate. After the students have finished the measurements and analyzed the results, we made a complete levitating experiment with more powerful motors, taking appropriate safety precautions.

The last experimental session is devoted to Levitron®. Levitron® is a toy invented by Roy Harrigan and commercialized by Fascinations. It consists of a magnetic base and a magnetic top that hovers freely above it. The top levitates due to the strong magnetic repulsion between it and the base. The gyroscopic effect prevents the top from flipping. Stable levitation is achieved only in a certain range of angular velocities. Also the weight of the top must be carefully adjusted. If the top is too light, it will fly away; if it is too heavy, it will fall down. Levitron® comes with a set of washers of different weights to help adjust the weight of the top. The stability of Levitron® is a rather complex mathematical

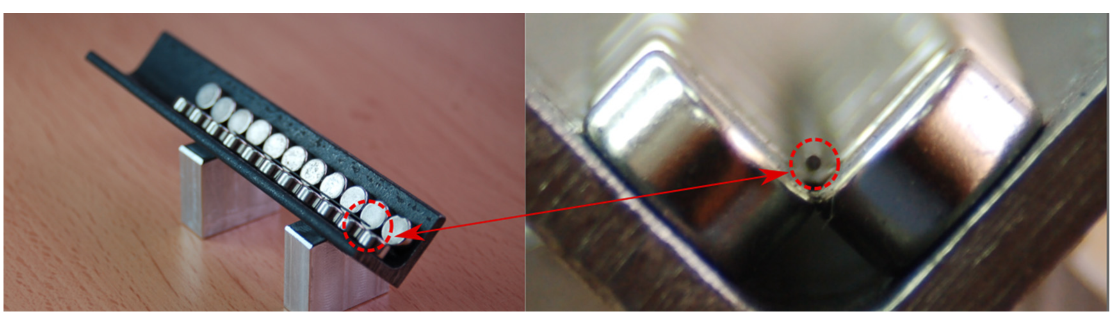

Fig. 3. Diamagnetic levitation of a pencil mine.

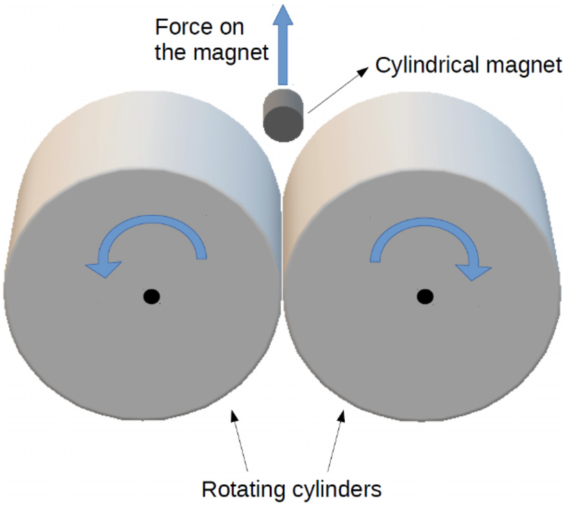

Fig. 4. Schematic representation of the Alcon levitator.

problem and has been addressed by several authors.[14–17] In this experimental session, our goal is that the students understand the relevance of the gyroscopic effect, and the stability in the vertical direction. After a short theoretical explanation, the students are asked to levitate the top. This is more challenging than it may appear with only three of the 31 students who attended the camp succeeding to levitate the top longer than 15 s in the two hour session allocated.

III. PREPARING THE PRESENTATION

For scientists, reporting the results of their research is a key step. We, as scientists, should be able to communicate science in a clear, honest, and inspiring way. Since our summer camp is intended to attract young people into scientific disciplines, this important aspect of scientific work could not be absent. On the other hand, the process of assembling the information, thinking how to present it, selecting the important data, etc., is, in itself, very formative. For all these reasons, the week finishes with a session common to the four projects hosted by our university. Every group has 20 min for the exposition.

We reserve the whole morning of the fourth day to prepare the final project exposition. This time is necessary because the students need to review the most important concepts, clarify their own doubts about some of the experiments performed, organize the presentation, and perform some rehearsals. This preparative session also serves to give us a feedback on the students' understanding of their experimental work.

IV. DISCUSSION

Taking into account the students' opinion at the end of the week, we cannot but say that the camp was a success. Almost unanimously, they expressed that they enjoyed a very good week, both interesting and funny. Some criticized that there were too many new concepts involved in the project. But most understood the necessity of introducing, at least superficially, these concepts.

The final presentation serves us as a probe of the students' progress during the week. It is the moment of explaining an experiment when one demonstrates that he or she has understood what has been done. Having in mind that they are top students in their schools, there is certain variability in their achievements. In any case, the general impression we received the day of the presentation was very positive. Even students who had been doubtful or unclear during the rehearsals did well in the end. In any case, one should remember that magnetism is not an easy topic and that our students had little contact with it previously; therefore, a full understanding of all the experiments and activities that were carried out is out of the question.

This summer camp highlights the advantages of a project-focused teaching approach.[18] From the beginning, the students are motivated for a defined final goal, which helps to structure the different proposed activities. This scheme is very adequate for a summer camp or similar occasions.

Magnetism seldom appears in the curriculum of high school. However, it has many applications in today's industry and its laws are a part of the core of our scientific understanding of nature. Our project demonstrates that it is possible to give high school students some basic understanding of the most important magnetism concepts.

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Demonstration Eye

The human eye is an organ that can be easily demonstrated in the lecture hall using this apparatus. At the rear of the brass "egg" is a brass tube (on the right-hand side of the model) that can be slid in (to demonstrate hypermetropia, or youthful far-sightedness) or out (to demonstrate the far more common near-sightedness.) To ameliorate the former, the positive lens at the left can be swung up to add to the power of the eye's lens. Swinging up the negative lens solves the problem of near-sightedness by decreasing the overall power of the eye lens. This apparatus is at the collection at Transylvania University in Lexington, Kentucky. A number of years ago I made my own version of this 19th century apparatus by using a *L'eggs* pantyhose container; see Thomas B. Greenslade, Jr., "The Demonstration Eye", *Phys. Teach.*, 21, 39 (1983). (Picture and Text by Thomas B. Greenslade, Jr., Kenyon College.)