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Lorentz' force as a tool for physics inquiry: studying particle tracks in cloud and streamer chambers

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Abstract

A sequence of experiments aimed at exploring magnetic force on moving charged particles is presented. At first students work with equipment that reproduces Thomson's experiment of 1932. Afterwards they analyze images of sub-nuclear particle tracks in cloud and streamer chambers in historical experiments. The sequence has been tested with high school students. Our results compared with the ones reported in the literature indicate that students' understanding of the direction and magnitude of the magnetic force markedly improved and some typical difficulties were overcome.

1. Introduction

Many researches have investigated students' difficulties in understanding main features of magnetic force on moving charged particles (Galili 1995, Guisasola 2004, Sağlam 2006, Scaife 2010). Results show how students easily confuse electric and magnetic fields and how they are inclined to think that the force experienced by a moving charged particle is directed toward a magnetic pole or has the same direction as the magnetic field lines independently of the velocity of the charged particle (Scaife 2007). To help students overcome these difficulties our idea is to stress the peculiarity and uniqueness of this force as it appears in real experiments involving elementary particles. In this way Lorentz force and its characteristics are introduced as tools of physics inquiry rather than a formula to be memorized.

In this paper we present three of such experiments which are included in a wider sequence of activities on electromagnetic interaction. They have been designed in cooperation with a group of high school teachers involved in a program funded by the Ministry of Education and aimed at preparing students for science studies at university. Two main choices were shared by the group:

- ✓ emphasizing the experimental approach;
- ✓ making students carry out quantitative measurements by themselves while working in groups.

In order to keep to these choices we resorted to an extensive use of digital camera and image processing software that made it possible for the students work directly not only on tracks obtained by the experimental apparatus available in the laboratory, but also on images acquired in historical experiments. The experiments included in the activity sequence are:

- o The study of the magnetic force on electrons, emitted by a cathode, moving through a homogeneous magnetic field.
- o The experiment made in 1932 by C. Anderson, while studying cloud chamber tracks left by cosmic rays, that allowed the "discovery" of the positron.
- o The pion-muon-electron (pi-mu-e) decay chain resulting from antiproton annihilation $\pi \to \mu \to e$, observed at Experiment PS 179 at CERN, Geneva in 1983.

The activity sequence has been planned for students in high school or in introductory physics courses and tested with about 100 high school students. The students worked in groups of four and completed the sequence in two sessions of three hours. They used tutorials and worksheets designed to guide their work and to collect data on their ideas, predictions, experimental results, and interpretations. In the following the activities are briefly described and examples of results obtained by the students are reported.

2. The Thomson experiment and the Lorentz force on electrons

The first experiment refers to the study of the magnetic force on electrons moving through a homogeneous magnetic field. At this purpose an apparatus designed to reproduce Thomson's experiment for measuring the electron charge-to-mass ratio is used[1].

Actually with this kind of equipment the magnetic force

$$\vec{F} = \frac{q}{m}\vec{p}\times\vec{B} \quad , \qquad (1)$$

was first measured by J.J. Thompson in 1897.

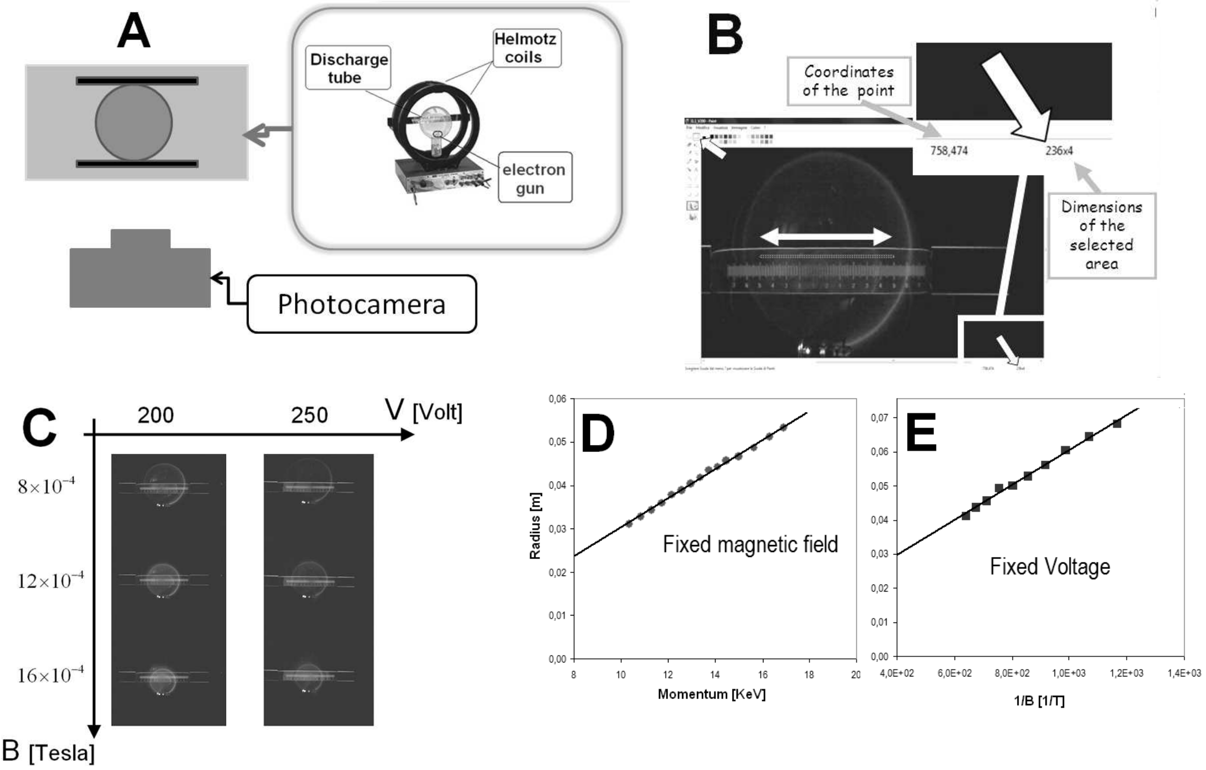

Figure1: (A)The Experimental apparatus for measuring the Lorentz force. A discharge tube is placed within the uniform magnetic field produced by two Helmholtz coils. Photos are acquired by the Web Cam. (B) Students can find the coordinates of any point of the electron track by moving the cursor in the picture. They can measure straightforwardly the diameter of the circular electron track, or use a formula to compute the radius of a circle going through three points. (C) Photos acquired at different values of the accelerating voltages (200 and 250 V) and of the magnetic field (8 to 16 Gauss). (D and E) Experimental results show a linear relation between the momentum of the particle charge and the radius of the trajectory and an inverse relationship of proportionality between the magnetic field and the radius.

In order to do a quantitative analysis students acquire, by means of a digital CCD camera (see Figure1), the images of the circular electron orbits and then use the photos to find the quantitative relationship between force, cyclotron radius and electron momentum. A sequence obtained by varying the magnetic field and the accelerating voltage is reported in Figure 1-C. The momentum, p, of the electrons can be obtained from the electric potential V applied between anode and cathode and expressed in keV/c (c is the velocity of light in a vacuum) by using the formula $cp = \sqrt{m_e c^2}\sqrt{2eV}$. The photo analysis develops in the following steps:

- From measurements of the radius R at fixed magnetic field, and with increasing accelerating voltage students obtain that the radius of the cyclotron orbit depends on the

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[1] In particular, we used the PASCO e/m apparatus available in the students' laboratory of our Physics Department.

momentum of the electron according to a direct proportionality (Fig.1-D) $r \propto p \Leftrightarrow r = \eta(B) \cdot p$

- From the measurements of R at fixed accelerating voltage and with increasing magnetic field students find that the radius of the circular trajectory and the magnetic field are inversely proportional (Fig.1-E),. $r \propto 1B \Leftrightarrow r = \frac{\beta(p)}{B}$. Then $r = \lambda \frac{p}{B}$, where λ does not depend on p, nor on B. Since $\eta(B) \cdot p = \beta(p) / B = \lambda \frac{p}{B}$ we can write $\lambda = \eta(B)B$. The value of λ can be determined by finding η for a given value of B.
- From data in Figure 3 we can find, for $B = 1{,}01 \cdot 10^{-3} T$, $\eta \approx 0.337c\left[\frac{m \cdot T}{KeV}\right]$. By converting in SI units we obtain $\eta \approx 0.337 \cdot 3 \cdot 10^{8}\left[\frac{10^{-2} \cdot T}{10^{3} e}\right] = \frac{0.11}{e} 10^{3}\left[\frac{T}{C}\right]$, then: $\lambda = \eta(B)B = \frac{1.02}{e} \approx \frac{1}{e}$, and $r = \frac{p}{eB}$. The value of r is connected to the centripetal force needed to produce the observed circular motion: $|\vec{F}_c| = p^2 / m_e r$, then $|\vec{F}_c| = \frac{e}{m_e} pB$.
- Finally, the direction of the magnetic force is considered. Students are guided to recognize that the force on the moving charges results always perpendicular both to the field and to the velocity (momentum). Data collected in testing this activity with high school students show that most of the student groups obtained graphs as the ones reported in Fig. 1.D and E and were motivated to find the relation among $|\vec{F}_L|$, $|\vec{B}|$, and $|\vec{v}|$, following the suggestions included in the worksheets.

The experience acquired by the students in working on digital photos, taken while observing directly a phenomenon, was helpful to prepare them to the following activities, based on the analysis of sub-nuclear particle tracks in cloud and streamer chambers as they appear in images taken by researchers in their original experiments. In these experiments the momentum is generally expressed in MeV/c, then it is useful to transform previous results in a compact formula with conventional units. We obtain: $r[cm] \approx 0.33 \frac{p[MeV/c]}{B[T]Z}$, then $p[MeV/c] \approx 300 r[m] B[T] Z$, where r is the radius of the orbits measured in cm, p is the momentum in MeV/c, B is the magnetic field given in Tesla and Z is the charge in electron units. This formula, which holds also in relativistic mechanics, allows students evaluate the momentum of a particle from the measurement of the radius of the particle track.

3. Particle Tracks in Wilson chamber: the Anderson experiment

Students analyze particle tracks in cloud chambers by using images of real historical experiments and retrace Anderson's experiment of 1932 that led to the observation of the "positron", the first evidence of antimatter (Anderson 1933). At first they observe the tracks of different known particles in a cloud chamber (Fig. 2-A) and answer to some questions about the masses and the charges of the particles "photographed" in the figure. Then they analyze Anderson's photo (Fig. 2-B) and are guided by worksheets to follow the procedure devised by Anderson to discover the charge of the unknown particle. Students measure the radii of the particle tracks in pixels and transform it in centimeters once known the width of the lead plate. Typically students measured a larger radius of 13.7 cm and a shorter of 5.5 cm in an external field of 15000 Gauss, corresponding to an electron momentum of 62 and 25 MeV/c respectively. They calculated that the particle loses about 37 MeV/c of its momentum when it passes through the lead plate (the fitting circumferences are plotted in Fig. 4-C). So they argued that the charged particle is coming from the bottom of the picture, where the curvature radius is larger, thus the velocity higher. Once known the direction of the magnetic field they were able to conclude that the tracks were left by a positive charged particle, the *positron*.

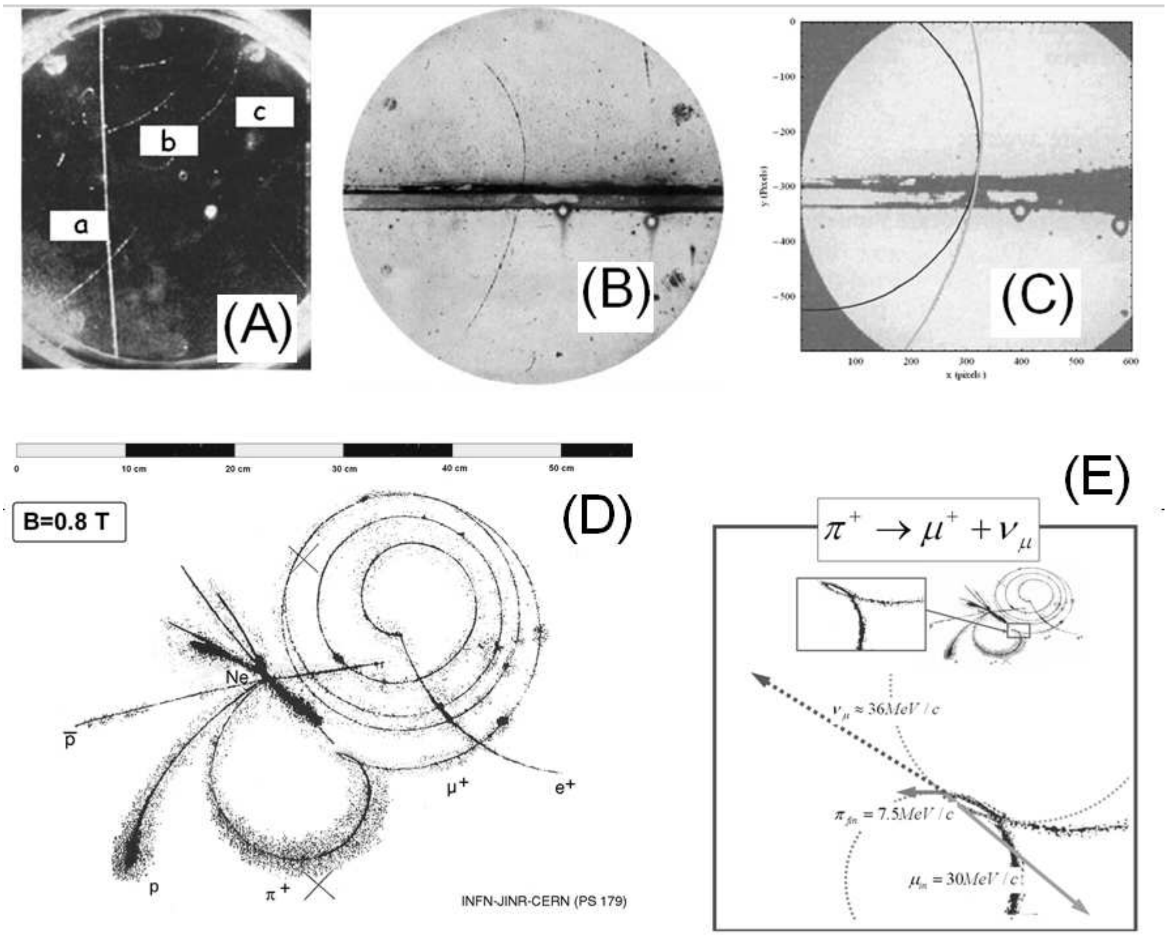


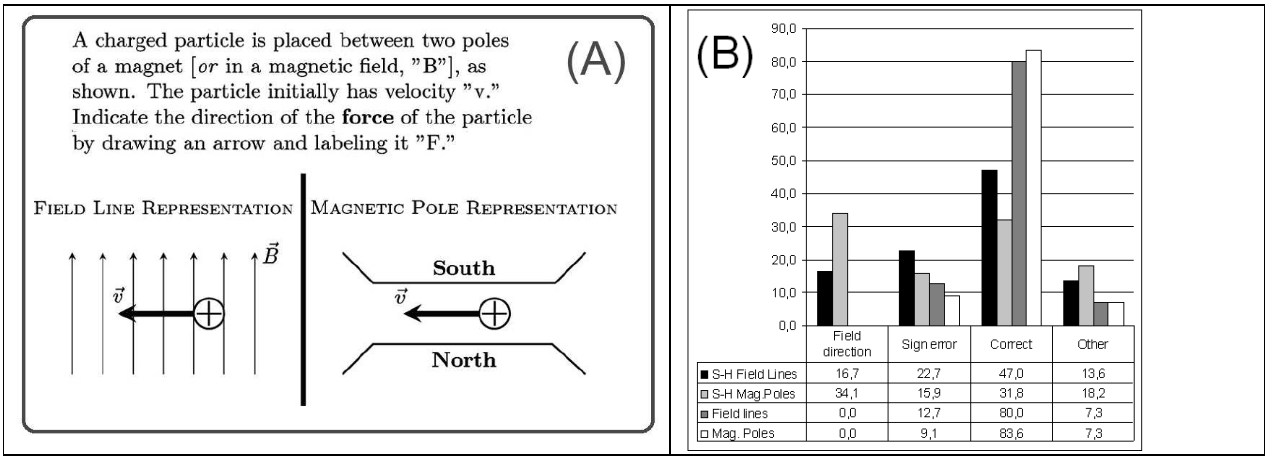
Figure 2: (A) The density of ionization is consistent with the assumption that the track (a) corresponds to a proton (Anderson 1936). (B) Cloud chamber photograph by Anderson of the first positron ever identified. A lead plate, 6 mm thick, separates the upper half of the chamber from the lower half. A positron passes through the lead plate and emerges as a electron. (C) Circumferences drawn by students to fit the particle tracks. (D)The streamer chamber photo of a $\pi \rightarrow \mu \rightarrow e$ decay chain resulting from an antiproton annihilation. At each decay the tracks change direction sharply, indicating simultaneous emission of an unseen neutrino. (E) Analysis carried out by a group of students, who measured the linear momentum of each particle. They added the momenta (dashed arrows) of unseen neutral particles.

4. The pion-muon-electron decay and the invisible neutrinos

In the last experiment students examine a streamer chamber photo of a pion-muon-electron (pi-mu-e) decay chain resulting from antiproton annihilation (Piragino 1989). The image (Fig. 2-D), recorded in 1983, shows the annihilation of antimatter: an antiproton ($\overline{p}$) produced in the accelerator at CERN, annihilates in the collision with a nucleus of neon (Ne). This produces a pion (π^+) slow moving along a spiral before decaying into a muon (μ^+), and a neutrino(ν_μ) which cannot be observed as a track as it has no electric charge. The students are guided to measure the linear momentum of each particle focusing on the decay events where the tracks change direction sharply. They measure the radius of curvature of the last part of the pion track and obtain the value of the momentum of this particle. In the same way they obtain the initial muon momentum. Using these results students can plot the vectors corresponding to the pion and muon momenta respectively and verify that the total momenta after the pi-mu decay and before the reaction are quite different both in the magnitude and in the direction (Fig. 2-D). They are guided to interpret this result as the production of new neutral particles.

5. **Results and final remarks**

At the end of the work we asked the students answer some questions on the direction of the force experienced by a charged particle moving through a magnetic field, drawn from the literature[1].Two different representations of the field are used: by magnetic poles and by magnetic field lines (Fig. 3-A). Results reported in Figure 3 refer to one of the questions used. They show that the work on the pictures improved high school students' understanding about the direction of the magnetic force and the experience acquired step by step in doing the activities also reduced the frequency of sign errors. We think that image analysis of particle tracks carried out by the students in small groups helped them in focusing on main characteristics of magnetic force (direction and dependence both on the particle momentum and on the magnetic field). Students experimented how the knowledge acquired allowed them to make the same type of analysis and predictions made by scientists in the original experiments and this awareness seemed not only to enhance their interest in the topic, but also to favor their understanding.



A charged particle is placed between two poles of a magnet [*or* in a magnetic field, "B"], as shown. The particle initially has velocity "v." Indicate the direction of the **force** of the particle by drawing an arrow and labeling it "F."

	Field direction	Sign error	Correct	Other
■ S-H Field Lines	16,7	22,7	47,0	13,6
▨ S-H Mag.Poles	34,1	15,9	31,8	18,2
▩ Field lines	0,0	12,7	80,0	7,3
□ Mag. Poles	0,0	9,1	83,6	7,3

Figure 3: Text and illustrations for the pole and field representations questions used in the study described in ref. 1 and answered by our students. (B) Proportions of correct, sign error, and field direction answers in the study described by Scaife and Heckler's for the pole and field representations after instruction on magnetic force (S-H) compared with the answers given by our students after the activity sequence.

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