Investigating the force on an electric charge moving through a magnetic field

Abstract

The purpose of this physics investigation is to prove the equation $F = qvB\sin\theta$, an equation found in the IB's *Physics Data Booklet* (first examination 2016). This investigation was impossible to prove by the hands-on method so I decided to us a computer simulation. My results prove the equation.

Personal Engagement

During physics in grade 11, we learned about fields and forces, one type of which was magnetic. Within the topic of magnetic fields, we looked at how charged particles (or currents in wires) interacted with magnetic fields. We learned the formula $F = qvB$, that states that the force experienced by a particle in a magnetic field depends on three factors: the particle's charge, the particle's velocity, and the strength of the magnetic field. However, I had some trouble with this topic, and didn't really understand it, so I decided to use this investigation as an opportunity to get more involved with the topic and better my understanding of it.

Therefore, the purpose of this investigation is to confirm the equation experimentally. Originally, I planned to conduct a hands-on investigation, but I quickly realised that this would not work. To set up this lab, I would first need to generate a magnetic field strong enough to actually have an effect on the "particle," which was not feasible with the lab equipment that was available to me. Next, I would need to find a way to make a plane on which my "particle" could roll, and since I was not investigating the angle between the field and the particle, I would need to find a way to make the surface of the plane on which the "particle" rolls perpendicular to the field. I would also need to find a set of charged metal balls of various charges with a small enough mass to be affected by the field and demonstrate motion; however, this relatively low mass would mean that friction would be a lot more significant that it would otherwise be and therefore the force would change too greatly. Finally, I would need a way to measure the force on the ball, which is not that easy to do. Since all these issues would accumulate in the uncertainties and errors in my investigation, I figured it would be better to use a simulation.

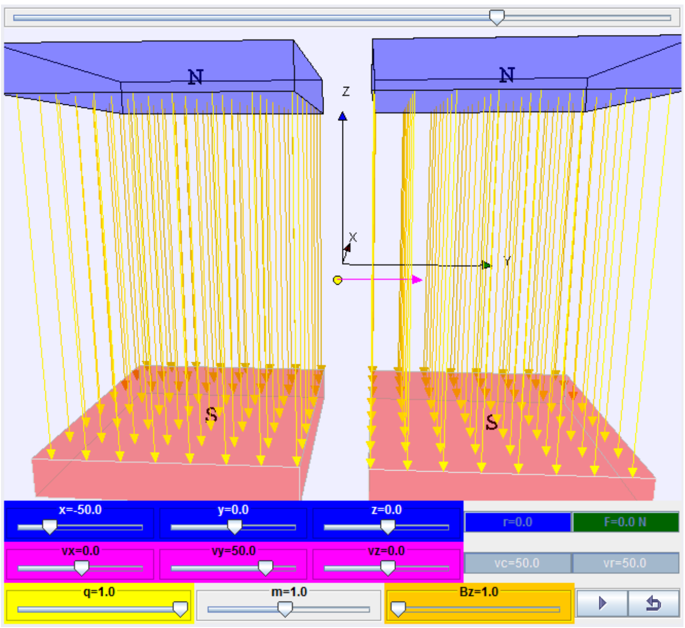
Evaluation of Possible Simulations

Before selecting my simulation, I found a selection of three different ones. All were Java-based simulations that I found on a forum dedicated to physics Java-based simulations. The first one that I came across was called "Charged Particle Motion in E/B Field." This simulation was quickly discarded. It contained not only a magnetic field, but also an electric field. The focus of this simulation was the electric field more than the magnetic, which would not be good for my investigation. There was no option to input an initial velocity or to change the charge (only the charge/mass ratio, which does not give definitive results on the cause of the change). Possibly the largest factor in not choosing this investigation was that there was no quantitative measure of force on the particle or the radius; it was only qualitative (by looking at the path traced out by the particle). Since this simulation does not allow me to change all the independent variables that I decided on for my investigation, this simulation was not the one for me.

The next simulation that I found was better than the first, although it still was not the correct simulation for me. The second simulation was called "Charged Particle Motion in Static Electric/Magnetic Field." This one had more changeable parameters than what I needed, so it was still not right. Unlike the previous one, this one allowed me to input an initial velocity, and in any direction. Like the other one, it allowed me to change the strength of the magnetic field and the magnitude and direction of the electric field. However, this simulation had no option to change charge, and again, like the previous, had no quantitative results about the force experienced by the particle. This simulation was not chosen.

<u>The Correct Simulation</u>

The third simulation that I came across was the one that I chose because it had everything that I needed to for my investigation without being too complicated. The simulation was called "Charge Particle in Magnetic Field B Java Applet in 3D." Here is an image of the screen.



(http://www.phy.ntnu.edu.tw/ntnujava/index.php?topic=1972.0)

This is the simulation that I ultimately chose to use for my investigation. Unlike the previous two, this one focuses on the magnetic field aspect rather than the electric field. Looking at the changeable parameters I could, among other things, change the initial velocity (in all directions), the charge of the particle, and the strength of the field. Also, it had measures of the force on the particle and radius of the particle's motion at any time displayed. Since these are all the things that I wanted to change/measure in my investigation, it was obvious that I should choose this simulation over the other two.

Data Collection

1. The effect of changing magnetic field strength on the force experienced by the particle.

Field Strength (T ± 0.1T)	Force (N ± 0.1N)
1.0	50.0
2.0	98.1
3.0	149.0
4.0	199.9
5.0	248.0
6.0	299.0
7.0	349.9
8.0	398.0
9.0	448.9
10.0	499.8

The control variables were as follows:

- Particle Mass: 1.0g ± 0.1g
- Particle Charge: 1.0C ± 0.1C
- Initial Particle Velocity: 50.0m/s ± 0.1m/s

2. The effect of changing the particle's initial velocity on the force experienced by the particle.

Velocity (m/s ± 0.1m/s)	Force (N ± 0.1N)
0.0	0.0
10.6	52.5
20.0	102.0
30.1	149.6
40.0	205.8
51.2	261.1
60.0	306.0
70.7	353.2
80.0	408.5
90.2	468.9
100.0	501.9

The control variables were as follows:

- Particle Mass: 1.0g ± 0.1g
- Particle Charge: 1.0C ± 0.1C
- Magnetic Field Strength: 5.0T ± 0.1T

3. The effect of changing particle's charge on the force experienced by the particle.

Charge (C ± 0.1C)	**Force (N ± 0.1N)**
-1.0	250.9
-0.8	194.1
-0.6	153.1
-0.4	90.0
-0.2	60.9
0.0	0.0
0.2	60.9
0.4	90.0
0.6	153.1
0.8	194.1
1.0	250.9

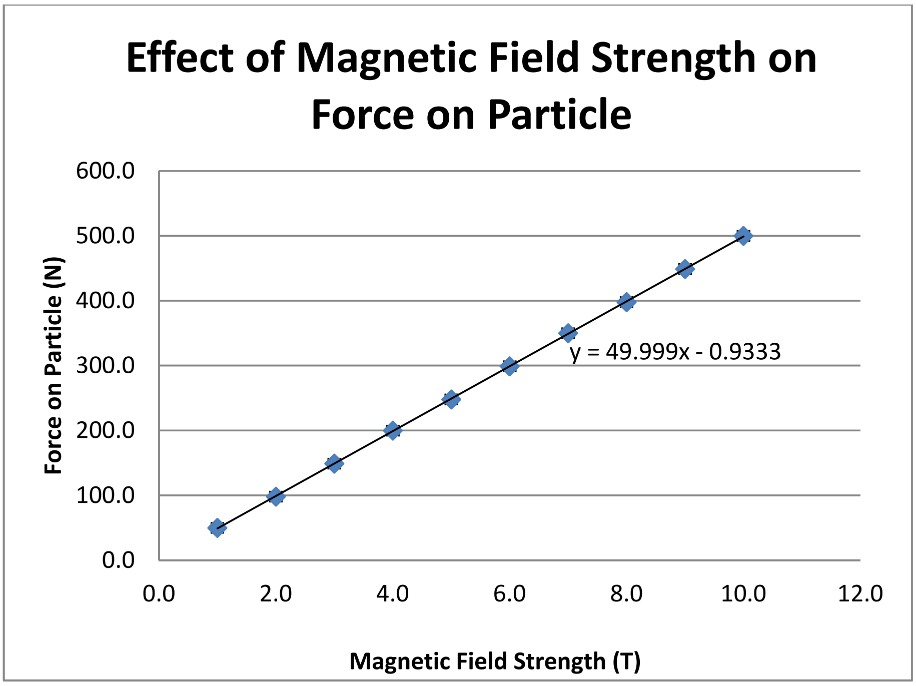
The control variables were as follows:

- Particle Mass: 1.0g ± 0.1g
- Initial Particle Velocity: 50.0m/s ± 0.1m/s
- Magnetic Field Strength: 5.0T ± 0.1T

<u>Graphs</u>

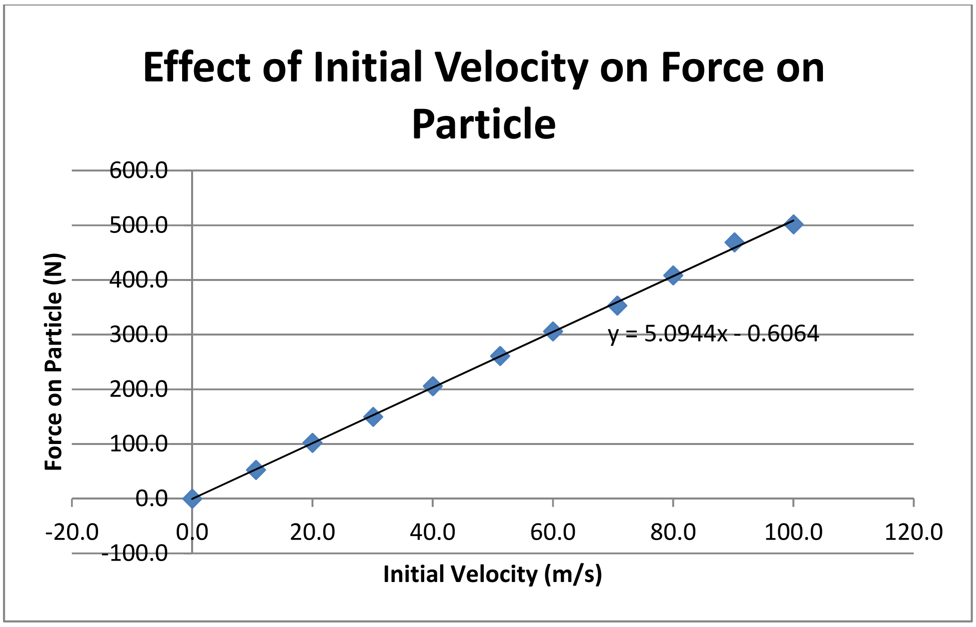
To prove the formula $F = qvB$, I graphed the data I collected using Microsoft Excel to see if there was a relationship between the variables, and what type of relationship there was if one was present.

<u>Graph One (data 1)</u>: The relationship between magnetic field strength and force on particle.



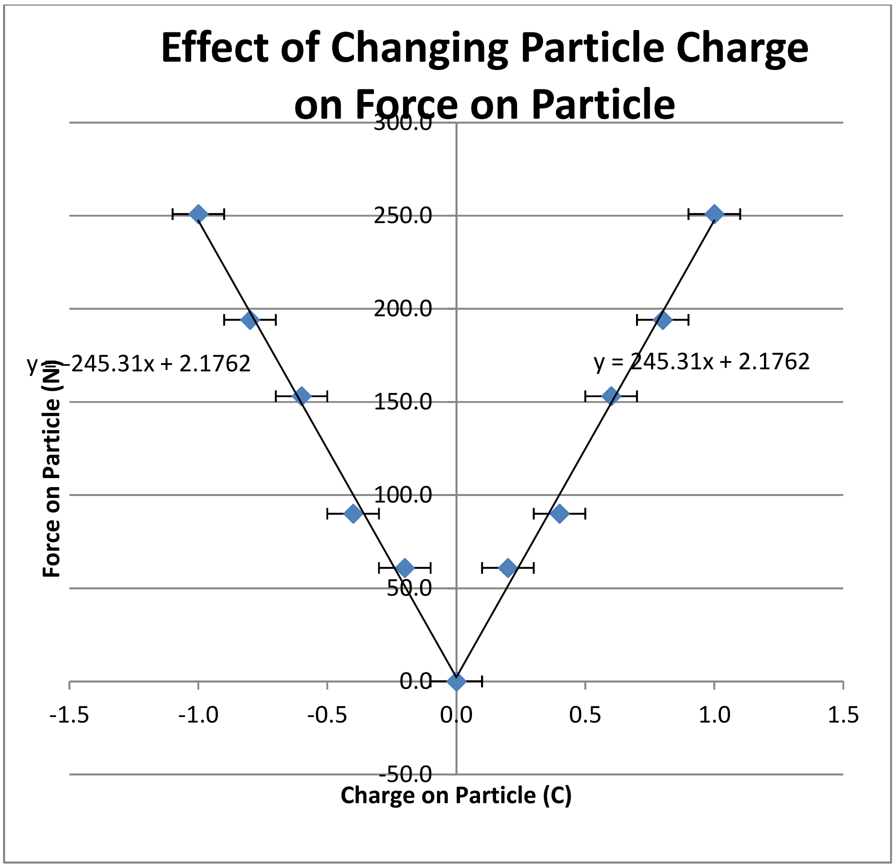
As you can see, the data has a linear relationship, so we can say that $F \propto B$, or $F = kB$. If the formula is true, then $k = qv$. On the graph, the value of k would be the slope of the trend line; we know this by comparing $F = kB$ to $y = mx + b$. To see if this is the case, I multiplied the values of the control variables together (and propagated the associated uncertainties) to get the result k = 50.0C•m/s ± 5.1C•m/s. The percentage difference between the obtained value for the slope and the calculated value is 0.0002%, which is almost entirely negligible. Since the value of the trend line's slope is equal to the product of the control variables (within the associated uncertainty), the aforementioned proportionality is proven true.

<u>Graph Two (data 2)</u>: The relationship between the particle's initial velocity and the force which it experiences.



This data also has a linear relationship, so $F \propto v$ or $F = kv$. Using the same technique as above, we can prove the proportionality true by comparing the product of the control variables (in this case, charge and magnetic field strength) to the slope of the trend line on the graph. k = 5.0C•T ± 0.6C•T. The percentage difference between the slope value of the trend line and the calculated value is 1.89%, which is again almost negligible. Since the slope of the trend line is within this range, this proportionality is also proven true.

Graph Three (data 3): The relationship between particle charge and force on the particle.



This last graph appears a little bit different than the other two. This data can be represented by an absolute value function, which can be written in the form $y = m|x| + b$. What this means is that the sign of the x-value is irrelevant to the y-value. This makes sense when we consider the independent variable: charge. Charge on a particle can be either negative or positive, but this will not affect the force on the particle. The only thing that matters is that there *is* a charge on the particle. As an example, whether the charge on the particle is 0.4C or -0.4C, the force it experiences is still 90.0N. We can say that $F \propto |q|$, or $F = kq$. This time, however, the value of k is a little bit different; since the slope is negative when charge is negative and positive when charge is positive, we can use the signum function (which takes the sign of the argument) to make sure the value of k is accurate. Therefore, we have $k = \text{sgn}(q)$vB. Calculating this, we have k = ±(250.0T•m/s ± 5.5T•m/s). The percentage difference between the obtained slope value of the trend line and the calculated value is 1.88%, which is almost negligible. Since the value of the trend line is within the range, the proportionality is proven true.

Conclusion

Now that we have proved the proportionalities $F \propto B$ ($F = (qv)B$), $F \propto v$ ($F = (qB)v$), and $F \propto q$ ($F = (vB)q$), we can put them all together to obtain $F \propto qvB$. Since each of the previous obtained formulas are just rearrangements of this proportionality, we know that the proportionality constant is 1 and $F = qvB$. However, I would like to re-write the formula as $F = |q|vB$ since, without the absolute value, Force would have to negative when charge is negative, but we know this to be false from the investigation, as force is always positive.

The problem with using a computer simulation is that it is programmed to work based on the rule, so they aren't a very good substitute for actually conducting the lab. By using a simulation, the only way to show that the simulation helps you to arrive at a conclusion is if you first assume that the laws upon which the simulation is based are true. In this case, since I am trying to prove the law upon which the simulation was created, I cannot say that the law holds true in the real world, because I didn't test it in the real world. As well, simulations are often programmed to not have uncertainty, so this is another aspect of the real world which (most simulations) do not represent. If this lab was to be repeated, and there was access to better and more accurate materials, it would definitely be a large improvement to physically carry it out rather than using a simulation.

Also, in doing this investigation another time, a few extensions could be made. For example, the simulation that I chose allows the user to modify the particle's mass as well as the other independent variables that I changed. Another interesting factor to investigate is how the radius of the particle's motion is affected by changes in the independent variables used here, or even how the angle at which the particle travels relative to the field could be measured. Possibly, using one of the other simulations, one could also see how electric fields combine with magnetic fields to affect the particle's motion.

Bibliography

"Physics: Principle with Applications" (Prentice Hall, 5th edition) by Douglas Giancoli

"Physics Data Booklet" (International Baccalaureate, first examination 2016).

http://www.phy.ntnu.edu.tw/ntnujava/index.php?topic=1972.0