How does the orientation of several consecutive polarizers affect the intensity of the light passing through them?

1 Introduction

I have always been really interested in quantum physics, as it has represented, from a general point of view, the scientific revolution of my time. I see quantum physics as the frontier between the conventional, classical reasoning of the universe, and a deeper theory, further from human logic than we can ever imagine, that is yet to come. For the first time in the History of physics, we posses an entire field of physics solely centred around a topic that can only makes sense to us through math, and not real experiences. The more we discover, the more we strive further from our human, simplistic perspective of the cosmos, approaching a more complete, irrational to us, but perfectly rational on a whole, understanding of the universe.

I always associated quantum physics with the microscopic world, as I am not used to seeing basket balls passing through walls because of quantum tunneling, and my cat always seems pretty alive to me. However, I recently came across two videos[1][2] which tried to demonstrate the quantum nature of light using only polarizers, meaning it has macroscopic effects. The videos claimed that by arranging said polarizers in a given angle, the intensity of the light passing through them is affected in such a way that quantum phenomena start affecting the macroscopic results we observe. That means that my goal is to explain the following question:

How does the orientation of several consecutive polarizers affect the intensity of the light passing through them?

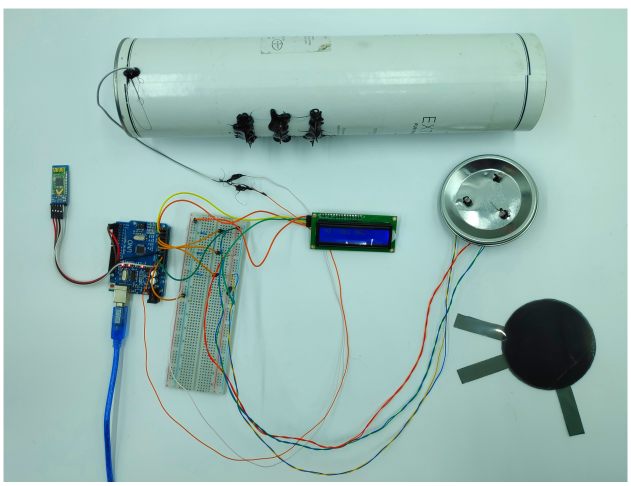
Being the main reason for why am I doing my research on this specific topic, the videos previously mentioned are a big bias for my current hypothesis on what is going to happen. Assuming there has to be a difference by the results predicted by the classical and quantum definitions of light, in order to somehow observe a quantum phenomenon, I expect there to be a quantum equivalent for Malus's Law, which somehow produce slightly different results than the conventional Malus's Law.

[1]https://www.youtube.com/watch?v=MzRCDLre1b4

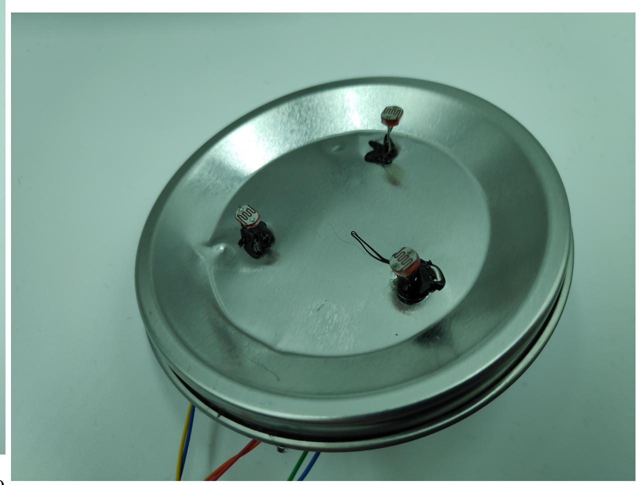
[2]https://www.youtube.com/watch?v=zcqZHYo7ONs

2 Methodology

In order to be able to measure the intensity of the light passing through a two-polarizer and a three-polarizer system in the most accurate way possible, I developed a measuring instrument of my own. I started by taking a 35cm cardboard cylinder with a 8.5cm radio with metallic lids on both sides. On one of the lids I glued some LEDs (the source of light for the experiment), and on the other I drilled 3 pairs of holes, through which I then introduced, facing inside the cylinder, 3 photoresistors (the measuring devices). I connected both the LEDs and the photoresistors, either with jumper cables or by soldering, to an Arduino Uno board, to which I later added a LCD display, to show me the photoresistors' reading in real time; and a Bluetooth module, in order to send the readings wirelessly to my computer. I then hot-glued all exposed wires, and sealed all holes in the cylinder so exterior light would not affect the measurements. Finally, after cutting out three circles from a DIN-A4 sheet of linear polarizer, I made three cuts in the cylinder, and sealed them with hot glue as tight as possible while allowing the cut-out polarizers to slide right in. Once inside, the polarizers had enough room to rotate up to 180º degrees, although in most of the experiments conducted only a range of 90º degrees would be used.

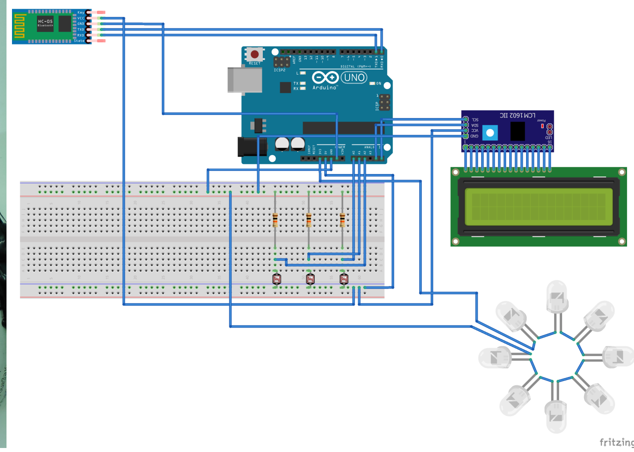


(a) Cardboard cylinder (top), Bluetooth module, Arduino Uno and resistors (left), LCD screen (middle), photoresistors and polarizers (right).



(b) Closeup of photoresistors.

(a) Closeup of polarizers inside the cardboard cylinder.



(b) Electronic schematics.

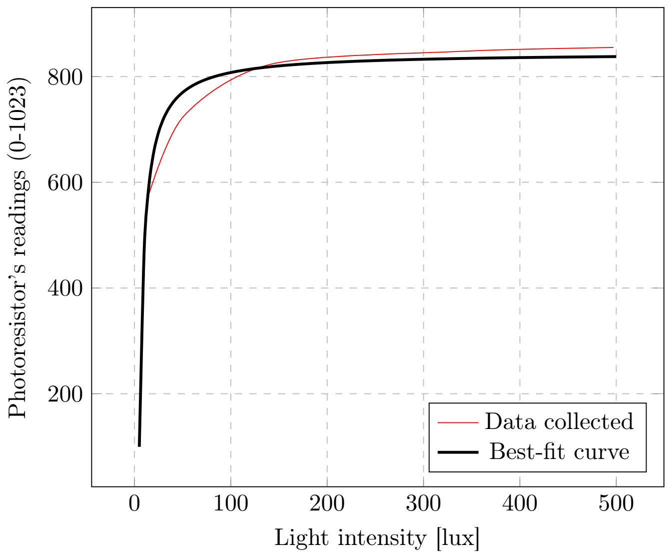
Figure 2: Measuring device built for this project.

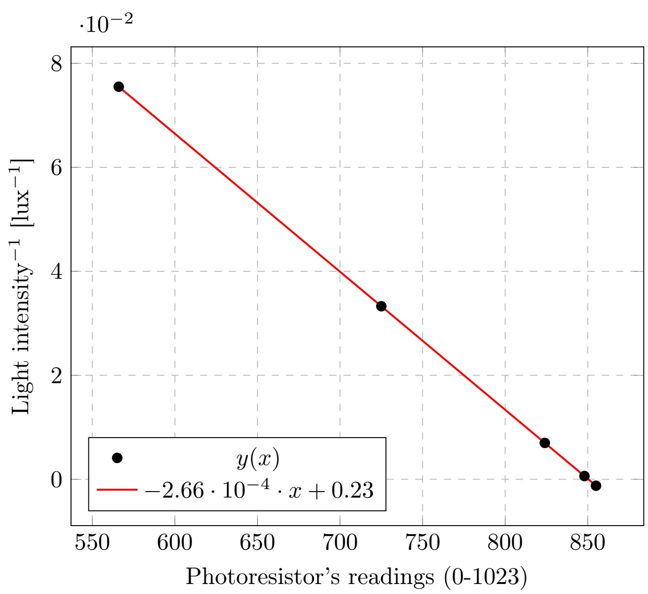
I then programmed the code needed for the photoresistors' reading to be processed by the Arduino board, and later transmitted via Bluetooth to the nearest computer, while displaying it on the LCD screen at the same time. The data was then processed again by a script running on the receiving computer, which converted it into a graph, and compiled all the information into .txt files.

The photoresistors' readings go from 0 to 1023, and represent the voltage drop caused by its varying resistance, which depends on the light intensity. In order to calculate the intensity of the light using the voltage drops, it is necessary to establish the relationship between the two, and find the best-fit curve, which can later be used to transform the incoming volts into luxes, or in other words, calibrate the measuring device. To do that, data was collected using a light meter. The best-fit curve was the calculated using an online tool[3], and has the following formula: $I = \frac{a}{R+b}$. Where I is the intensity of the light, R the sensors' readings, and a and b are constants unique to each photoresistor (due to minor manufacturing deviations). This relationship demonstrated a hyperbolic nature, and, if linearized, it is possible to conclude that the inverse of the intensity decreases at a rate of $2.66 * 10^{-4}$ with respect to the sensors' readings, and a systematic error of 0.23^{-1} luxes, or 4.35 luxes. With this in mind, it is now possible to transform the photoresistors' readings into the light's intensity.

[3]https://planetcalc.com/5992/

Intensity meausred	**Photoresistor's readings**
497	855
342	848
143	824
51	725
13	566





The experiments will consist in swooping left and right some of the polarizers, while leaving the others at rest, and studying how it affects the intensity of light passing through. In these experiments, the angle of the turning polarizer is the independent variable, and will be controlled manually, with a range from 0 to 180 degrees. Its random error is equal to $\pm 2\, degrees$. On the other hand, the intensity of the light passing through is the dependent variable, and will be measured with three photoresistors at the end of the measuring device, which have a range varying from 50 to 500 luxes, and a random error equal to 10%. The controlled variables in these experiments are the distance between the polarizers and the photoresistors, the voltage across the photoresistors (always stable at 5V by the Arduino board), the ambient light (nearly 0, as all light were turned off), and the angles of all the polarizers not being turned in each specific experiment.

2.1 Materials

1 - 35cm by 8.5cm cardboard cylinder
1 - DIN-A4 sheet of light polarizer
3 - Photoresistors
1 - Arduino Uno
1 - Bluetooth module
1 - Small LCD screen
Wire and jumper cables
1 - Hot glue gun
2 - Opaque black silicone sticks
1 - Soldering iron
Tin solder
1 - Cutter
1 - Ruler

2.2 Safety Considerations

During this project. some amount of soldering and gluing was needed. I had to carry out both these tasks at home. so I was forced to take some extra safety considerations. Due to the bad ventilation present in my bedroom. I carried out any activity which produced considerable amounts of toxic fumes. such as soldering with tin or the use of a hot glue gun. was performed outside. In order to enhance safety a bit more. I protected my working bench with parchment paper (which does not stick to hot glue. thus preventing it from solidifying in undesirable places). apart from a thick layer of hard non-flammable plastic. In addition to all that. all said activities were carried out while using a mask and protective glasses. All electric currents handled during the experiments had lower than 5V tensions.

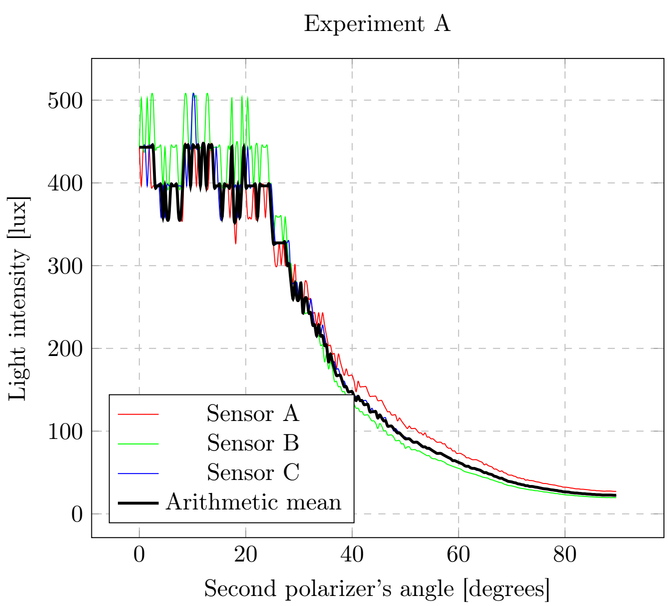
2.3 Error-preventing measures

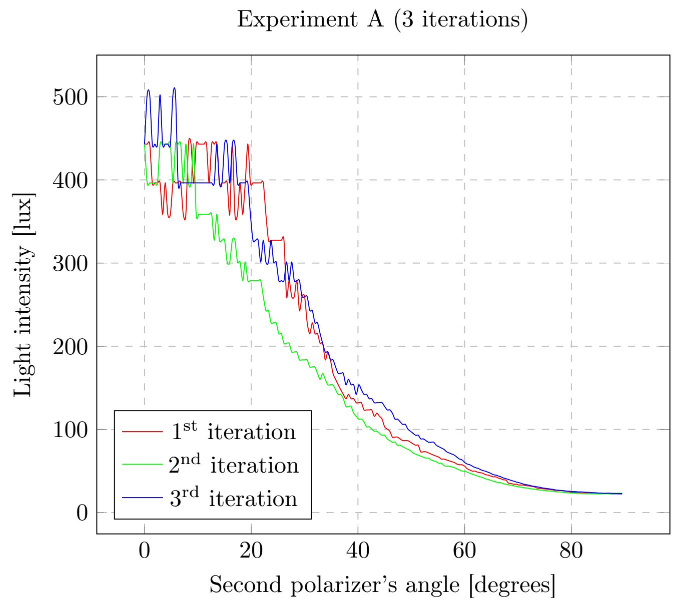
In order to prevent the magnification of the errors present in this kind of experiments, I designed the measuring device with this in mind. Instead of using a cellphone's light meter, I decided to install three photoresistors, which would make it much easier for me to transmit up to 400 measures per experiment, and would be transmitted automatically to my computer, hindering the possibility of some "human error" while passing the data from one point to another. I also decided to seal the cuts in the cardboard cylinder with silicon, which was deliberately much more protective from outside light than a simple cut. Using electronics developed by my own gave much more control, allowing me to tune them in the best possible way for the experiments, as is the case for the speed of transmission between the Bluetooth module and my computer. In addition to all these, I conducted the experiments with the least amount of ambient light possible.

3 Results and Analysis

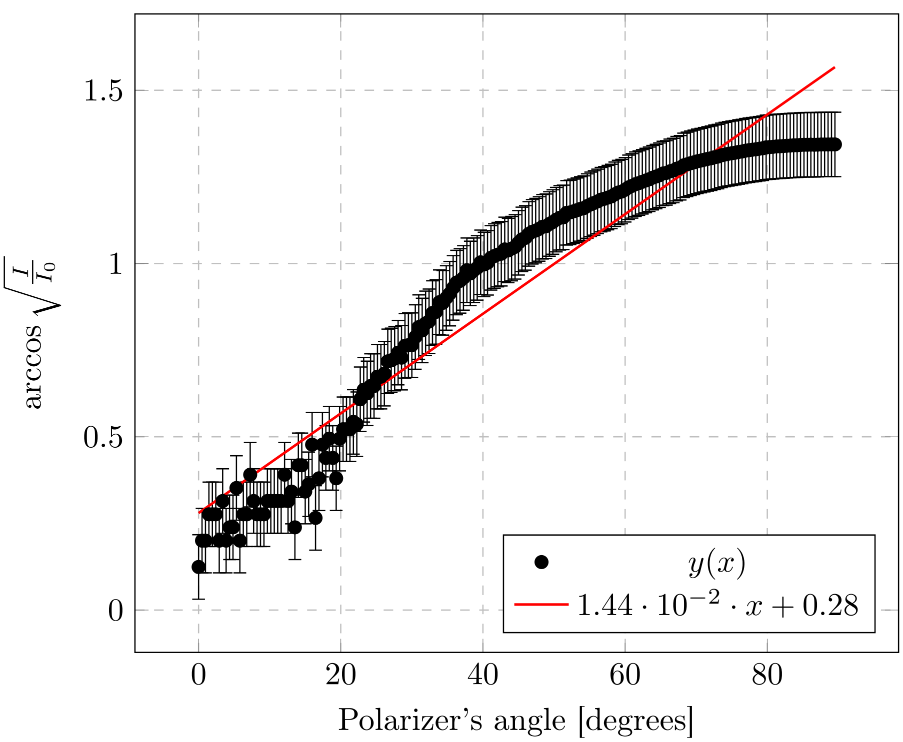
3.1 Experiment A

In Experiment A, a constant flow of light coming from the LEDs at the top of the measuring device will stream through a first polarizer with an angle of 0º, and then through a second polarizer whose angle will gradually change from 0º to 90º. It will then arrive to the photoresistors, which will measure I_{12}.



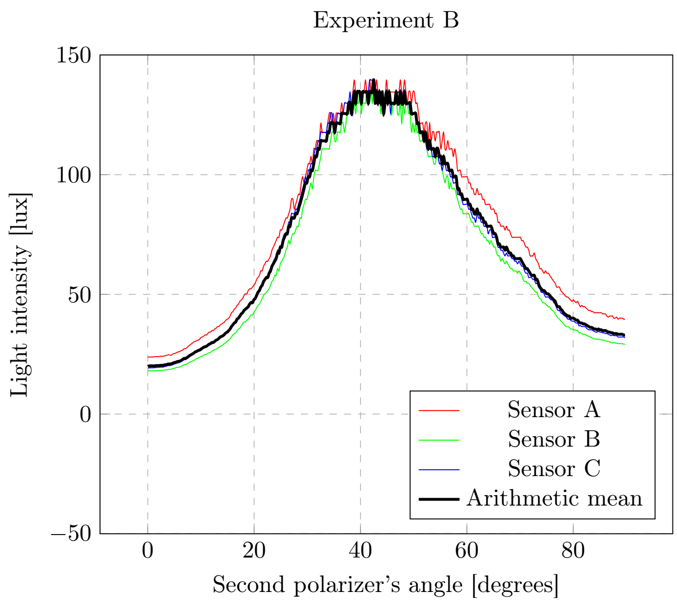


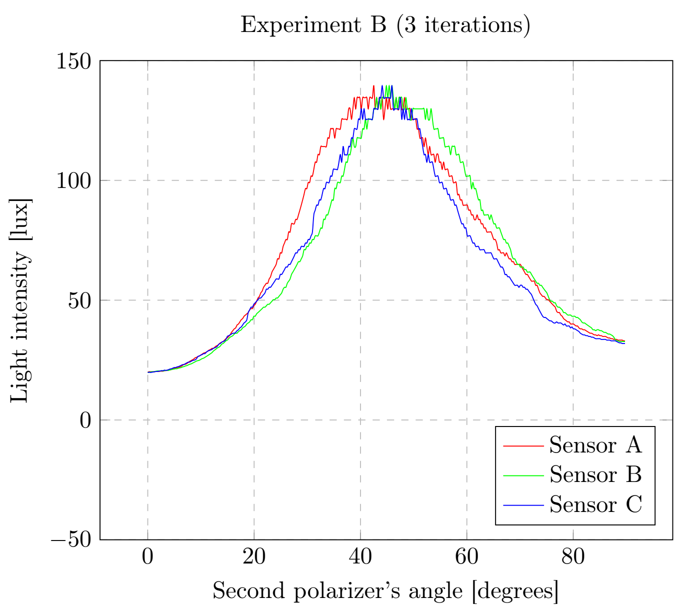
The photoresistors' random error cannot be shown explicitly in the figures due to the large amount of measurements represented (more than 300 per experiment). In order to calculate the systematic error, the data collected will be linearized, so a trendline can be calculated. It is known that $I = I_0 \cos^2(\theta_i)$, meaning that the equation $\arccos\sqrt{\frac{I}{I_0}} = \theta_i$ would succesfully represent a direct relationship between the polarizer's angle and the other term.



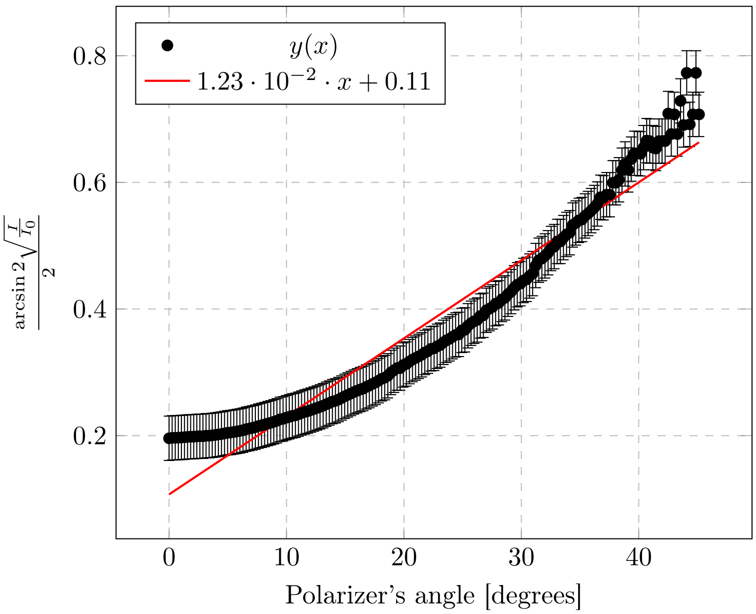
3.2 Experiment B

Very similar to experiment A, in Experiment B a constant flow of light coming from the LEDs at the top of the measuring device will stream through a first polarizer with an angle of 0º, then through a second polarizer whose angle will gradually change from 0º to 90º, and finally through a polarizer with an angle of 90º. It will then arrive to the photoresistors, which will measure I_{23}.





Once again, in order to calculate the systematic error, the data collected will be linearized, so a trendline can be calculated. It is known that $I = I_0 * (cos(\theta)^2 * cos(90 - \theta)^2)$, meaning that the equation $\frac{\arcsin 2\sqrt{\frac{I}{I_0}}}{2} = \theta_i$ would succesfully represent a direct relationship between the polarizer's angle and the other term.



Regarding systematic errors, all photoresistors have maximum and minimum values, meaning that at some point, a systematic error will not allow them to work correctly. Because of this, photoresistors need to be purchased having in mind their future purpose. In my case, I was forced to acquire medium-low quality photoresistors because of my limited budget. That means that they have a limited range of action, and if exposed to too high or too low intensities, a systematic error will most certainly show up, as is the case. Although not as important, external noise and interference may be another cause for the random and systematic errors present, aside from the measuring device's quality.

In addition to that, one of the polarizers suffered some minor imperfections during the process, and may by accountable for some reduced amount of the systematic error in the measures, although it is mostly unnoticeable. Last but not least, there exists a slight difference between the lowest values at both sides of the curve (around 0º and 90º) in Experiment B. Theoretically they should be the same. The most likely cause for this is a loss of energy between polarizers 2 and 3 (due to the cardboard's energy absorption and small light leaks). The loss of light throughout the cardboard is also noticeable when experiments A and B are compared, as the first has a maximum intensity of 450 luxes, and the latter a maximum of 150.

Although random errors are considerably high (most possibly caused by the fact that the polarizers's were rotated manually, opening the door to human errors), the functions deduced from the data collected demonstrate a similar nature to that of an squared cosine function, mainly because of its periodic behaviour, and the overall shape. In other words, the errors present in both experiments are bearable, and further conclusions may be made.

4 Conclusion

Clear relations have been established between both variables, polarization angle and intensity of light, and reasonable conclusions can be reached from them. In Experiment A, the systematic error can be pinpointed to be $\arccos\sqrt{0.28} = 58$ luxes. The random error can also be found by subtracting both the obtained and expected values for each angle, which returns an average equal to $\arccos\sqrt{0.093} = \pm 72$ in the linearized equation, or in other words, 15%. In Experiment B the systematic is equal to $\frac{\arcsin 2\sqrt{0.11}}{2} = 20.8$ luxes. The random error is $\frac{\arcsin 2\sqrt{0.035}}{2} = \pm 11$ in the linearized equation, or, again, in other words, 10%. The gradients of the linearized equations deduced from both experiments are not of much use, given the difficulty of the relations between these and the original curve ($\arccos\sqrt{\frac{I}{I_0}} = \theta_i$ and $\frac{\arcsin 2\sqrt{\frac{I}{I_0}}}{2} = \theta_i$ respectively). Regarding these relations, it is reasonable, taking the errors present into account, to conclude that for a two-polarizer system, the formula which relates the orientation of the last polarizer to the intensity of the light passing is $I = I_0 \cos^2(\theta_i)$; and for a three-polarizer system, with the first and last polarizers perpendicular to each other, the formula which relates the orientation of the second polarizer to the intensity of the light passing is $I = I_0 * (cos(\theta)^2 * cos(90 - \theta)^2)$.

5 Evaluation

A strong point of this research is the vast amount of data collected. The ability to record several measurements per second, thanks to the utilization of electronics, helps eliminate the need for more experimental data, as the entire graph can be drafted from the information obtained, and there is no reason to guess any point in the curve.

The method used in this research proved to be over-complicated. A Bluetooth module and a LCD display were implemented in order to make the measuring device more portable, so moving it to the High School I am being evaluated in would be more versatile. However, I ended up carrying out the experiments at home, so that part of the project proved useless. In addition to that, sealing the polarizers with silicone was rather tedious, and at the end, made the polarizers themselves hard to move and turn. I would recommend the use of a 3D-printed piece for the turning mechanism of the polarizers, an idea I had at the beginning of the project, that later got discarded because of budget and time issues. Last but not least, the loss of energy throughout the cardboard could have been prevented by covering the inside layer of the measuring device with a reflective coating, such as aluminium foil.

However, it was mentioned in the introduction that the main reason as to why I decided to do research on this topic was the fact that I was interested in macroscopic quantum phenomena showing up using three polarizers, and, for now, no conclusion has been reached on that topic. Theoretically, both classical and quantum predictions for the intensity of light passing through a three-polarizer system are the same. Quantum mechanics can divide waves into two components, just as in classical mechanics. However, notations are a bit different, apart from their overall interpretation. A photon can be described as the superposition of the quantum states $|{\rightarrow}\rangle$ and $|{\rightarrow}\rangle$ ($|{\rightarrow}\rangle$ representing a unitary vector on the X axis, and $|{\uparrow}\rangle$ on the Y axis), and can be formulated as:

$$|{\nearrow}\rangle = \alpha\,|{\rightarrow}\rangle + \beta\,|{\uparrow}\rangle \tag{1}$$

Where α and β are constants.

These means that that given photon can be in either of the two states. As soon as the photon passes through the first polarizer, its wave function collapses, and it chooses in which of the two states it is. In order to calculate the probability of it choosing either state, we need to square their value, which results in an exact replica of the Malus's Law.

Both, the results from using Malus's Law and from using quantum mechanics, are exactly the same. Still, Malus's Law tells us the amount of energy of the photon that passes through, while quantum mechanics tells you the probability of the photon choosing either quantum state. That means that in classical mechanics, the amplitude can be changed, while in quantum mechanics it remains constant. But even if we take into account that last bit of information, both methods have demonstrated to be capable of accurately predicting the results to the experiment. That means that the experiments conducted in this research are not sufficient to prove the quantum nature of electromagnetic waves, as classical mechanics is able to predict the results just as well. Although a clear relationship has been established between intensity and the polarizers' angles, there is no reason to believe the phenomena observed during this study is, in fact, a macroscopic quantum manifestation. Coming back to the videos which served as stimuli for this project after finishing my research, I can now comprehend better the ideas they explained. I understand now that they never intended to prove quantum dynamics with the three-polarizer experiments, but just demonstrate Bell's inequality. They explicitly said that to accurately prove it you would need entangled particles, apart from working spaces very far from each other (in order to discard the possibility of photons interacting with one another), among other requirements.

In conclusion, even if the experiments conducted successfully established a direct relation between the polarizing angle and the intensity of light passing through (the question of this research), the deeper goal of attempting to observe macroscopic quantum phenomena was not reached. My initial hypothesis, explained in the introduction, proposed the existence of a quantum Malus's Law, an equivalent of the original law which takes into account quantum dynamics. As we can now see, that hypothesis proved to be false, and instead of a new law, what we discovered was a mere difference in the understanding of what light is.

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