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Malus' Law Derived from Deterministic Particle Behavior

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Abstract

A polarized beam of energy is usually interpreted as a set of particles, all having the same polarization state. Difference in behavior between the one and the other particle is then explained by a number of counter-intuitive quantum mechanical concepts like probability distribution, superposition, entanglement and quantized spin. Alternatively, I propose that a polarized beam is composed of a set of particles with a cosine distribution of polarization angles within a polarization area. I show that Malus' law for the intensity of a beam of polarized light can be derived in a straightforward manner from this distribution. I then show that none of the above-mentioned counter-intuitive concepts are necessary to explain particle behavior and that the ontology of particles, passing through a polarizer, can be easily and intuitively understood. I conclude by formulating some questions for follow-up research.

Keywords

Quantum Mechanics, Bell, Malus Law, Superposition, Entanglement, Quantum Fields, Spin, Hidden Variables, Locality, Non-Locality

1. Introduction

In contemporary physics, light is seen as either a wave or a set of particles. If seen as a wave, it is normally depicted in a somewhat abstracted form as an alternating electromagnetic field like in **Figure 1**.

This type of wave is known as a transversal wave since the amplitude variation is orthogonal to the axis of motion of the wave. So the light wave is modeled as an analogy to the travel of a wave through a wire. Notice that the electric field in **Figure 1** is in a vertical position. The direction of the electric field vector is normally called the "polarization state" of this light beam. If the surface, in which the electric field is depicted, shows another angle with the y-axis, we say that we have another polarization state. One polarization state is thus identical to a specific direction of the electric field vectors. Using this nomenclature, the difference between polarized light and unpolarized light can be defined as follows:

> *definition A*: unpolarized light has the orientation of the electric field vectors in all possible directions, whereas polarized light has the electric field oriented in a single direction.[1]

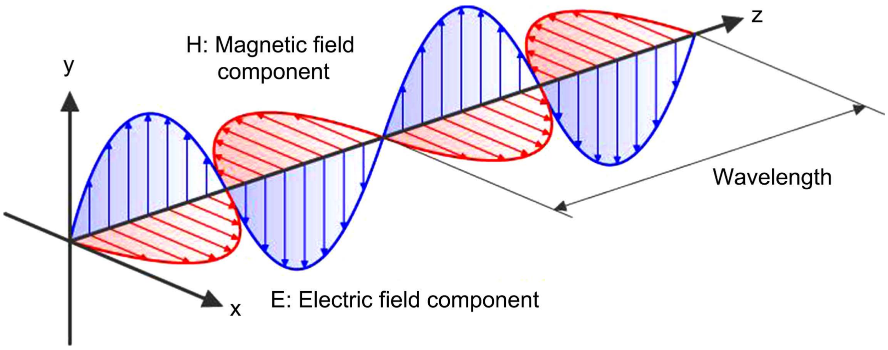

Figure 1. An electromagnetic wave.

This definition is used almost universally and seems not to be contested. Notice that this definition contains an ontological assumption, namely that particles in a polarized beam all share the same polarization state. Otherwise stated, the electric field of all particles is in the same direction. This enables the particles' polarization state to be interpreted as quantized, namely either pointing the one way or the opposite way. I assert that if this assumption proves to be incorrect, some of the more exotic concepts in quantum mechanics like quantum spin, probability distribution, quantum entanglement and the exclusion of hidden variables, lose their most important empirical pillar. Also, many questions arise from this assumption. If, for example, particles are in the same state of polarization, is it not "weird" that the one moves through a polarizer while the other is blocked? Historically, this "weirdness" was not seen as a reason for re-investigating this interpretation, but rather as a confirmation that a historic discovery was made, namely of the huge difference between our macroscopic (classical) world and a subatomic (quantum) world. I will show that re-investigating definition A is not only possible but also very worthwhile. It turns out that there is no need to assume that particles in a polarized beam share a common polarization state.

2. A New Definition for Polarization

If we divide a circle on the x-y plane into eight equal sections as in **Figure 2**, and call the two sections adjacent to the direction of polarization the *polarization area* (pa), we can formulate a new definition as follows.

[1]Source: https://protonstalk.com/light/malus-law/, last consulted on 30 Jan. 2022.

Definition B: unpolarized light has the orientation of the electric field vectors in all possible directions, whereas polarized light has the electric field directions distributed over its polarization area.

I will now show in a number of logical steps how this seemingly small difference has huge consequences.

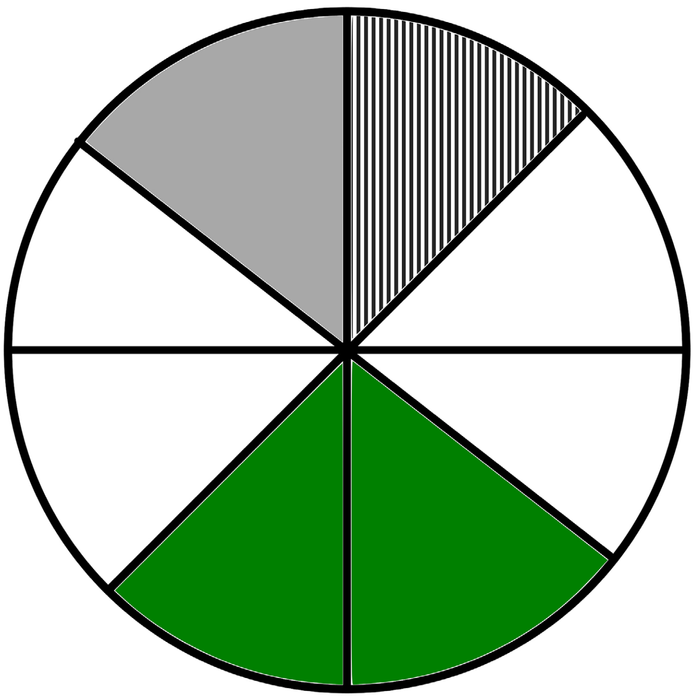

Figure 2. Polarization angles in eight sections.

Let us take as a convention that a vertical upward direction of the electric field vector has a 0-degree polarization. We can now divide the x-y plane of **Figure 1** into the sections 1 until 8 like in **Figure 2**. Let us number the hatched section as 1 and increment clockwise. Let us now place a polarizer in the x-y plane in a vertical position. Such a polarizer would have sections 1 and 8 as its polarization area (the two marked top sections). Of course, the polarization area should not be seen as fixed. If the polarization is in an angle of for example 20 degrees, its whole polarization area shifts 20 degrees along with it. To be complete in my description, I have to add that the two marked sections at the bottom also belong to the polarization area, because the polarization process can be mirrored. If we turn the polarizer upside down, nothing will change in its operation. We may thus assume that a polarization of for example 10 degrees is identical to a polarization of 190 degrees. Having completed the introductory remarks, let me now add another important detail to the polarization process:

Input rule: an incident photon can move through the filter only (and only then) if its electric field vector has a polarization state that is within the polarization area of the filter.

Let us now consider a polarizer and two extra polarizing filters, called analyzer 1 and analyzer 2 lined up in the trajectory of a beam of light, like in **Figure 3**.

Figure 3. A typical polarization setup.

An incident beam on the polarizer is polarized into a vertically polarized beam according to our new definition B. If we place analyzer 1 in a 90 degrees angle to the polarizer, we can easily see that the polarization areas of the polarizer and the analyzer do not overlap. And so, no light will come out of analyzer 1. But if we place analyzer 1 in a 45 degrees angle to the polarizer, then we can see that the polarization areas of polarizer and analyzer overlap at section 1. Thus, all photons in this section will pass. At the output of analyzer 1, we would then have, through the polarization process, an equal distribution of photons over the sections 1 and 2. So, although none of the photons enter the analyzer in section 2, half of them come out at that section. If we now would place analyzer 2 in a 90 degrees angle to the polarizer, this analyzer would let all the photons in section 2 pass and would distribute them over slices 2 and 3 at its output. Thus, the initial intensity of the incident light is cut in half by the polarizer and then further in half by each analyzer, yielding an intensity at the output of analyzer 2 of precisely $\frac{1}{8}$th of the initial intensity. Theoretically, this process could be repeated indefinitely with extra analyzers, further decreasing the intensity of the output.

3. Mathematical Formalization

There is more subtlety to the process though. The distribution of photon polarity states at the output of a polarizer is a bit more complex than previously described. Photons are indeed distributed evenly over the two adjacent sections, but in order to conform to empirical facts, we must assume that they are not distributed evenly over the area of a section. To start a formalization of this distribution, let θ be the angle between the polarization direction of an incident light beam and the polarization direction of a first analyzer. Then if we would count the number of photons at the output of the analyzer and measure their polarization and plot these in a graph, we would see a maximum photon count around 0 degrees and a zero count where θ is $-\frac{1}{4}\pi$ or $+\frac{1}{4}\pi$. We could now define an intensity I as the total intensity of the beam, measured in the amount of passing photons per second. Let then the flux P be the count of photons per second with a specific polarization angle, plus and minus $\frac{1}{2}\Delta\theta$. I assert that for very small values of $\Delta\theta$, this flux would have a distribution, presented by the following formula:

$$P = P_{\max}\cos(2\theta) \tag{1}$$

A negative value of P is interpreted as a zero flux. This means that there are no photons coming out of the polarizer that have a polarization angle above $\frac{1}{4}\pi$ rad or below $-\frac{1}{4}\pi$. In infinitesimals, a small change in the intensity of the beam in relation with a small increase in the angle of theta can be formalized as:

$$\delta I = k\cos(2\delta\theta) \tag{2}$$

Here, k is an arbitrary proportionality constant. If we now perform an integration, we would find:

$$I = \frac{1}{2}k\left(1+\sin(2\theta)\right) = \frac{1}{2}k + \frac{1}{2}k\sin(2\theta) \tag{3}$$

If we now take a vertically polarized beam, incident upon a vertical polarizer, the polarization area of the polarizer starts at $-\frac{1}{4}\pi$ (at the left side of section 8). In this position, there is total overlap between the polarization areas of beam and polarizer. Therefore all photons will pass. Then, if we start to turn the polarizer clockwise or counterclockwise, the photons in the area without overlap will not pass anymore. Thus, if we want to find the intensity of the beam by integration, we should use a value of $-\frac{1}{4}\pi$ for θ to start our integration. This means that 2θ becomes $2\theta - \frac{1}{2}\pi$ Now we can reformulate to:

$$I = \frac{1}{2}k + \frac{1}{2}k\sin\left(2\theta - \frac{1}{2}\pi\right) = k\cos^2\theta \tag{4}$$

It is easy to recognize the constant k as the maximum intensity. And so we get:

$$I = I_{\max}\cos^2\theta \tag{5}$$

Which is the famous Malus law. So as we shift the polarizer to the right or the left, the intensity of the beam decreases according to the Malus law.

Notice that we could also look upon one single photon and define the chance that this photon would exit the polarizer with a specific polarization angle. This would be the same as assigning a probability amplitude to a photon according to Equation 1. This would lead us to the same Malus law. The probability is then however not in the behavior of a single photon at the polarizer input, as is propagated by QM, but resulting from the interaction of polarizer and photon at the polarizer output, as proposed in this article.

Notice also that the above alinea answered the question asked by Einstein, Podolsky and Rosen [1], whether the quantum-mechanical description of physical reality (the wave function) can be considered complete. I answer "no" in favor of Einstein, since I assert that the alternative interpretation of polarization as given by definition B provides a more complete description of reality than definition A does (the latter being a quantum mechanical description of physical reality).

We can conclude from this that if we interpret polarization according to definition B and assume that the polarization angle of photons is distributed as a cosine, we obtain the Malus law by integrating the polarization-intensity over the polarization overlap area. This means that definition B, by leading us to the Malus law, conforms just as well to empirical evidence as definition A. And thus we can take on any challenge to its validity.

4. On Bell's Inequality and Entanglement

Let us take as an example, the Bell type experiment, named after the inventor J.S. Bell [2]. For this, we place the first analyzer at an angle θ to the polarizer and the second analyzer at the same angle θ to the first analyzer. It is now logical to assume that the first and second analyzer both block a certain amount of photons. But if we would remove the first analyzer, then what happens? Will more or less photons be blocked? This is the central question in a Bell type experiment.

We know the answers to this question, by experiment, but I fear many misconceptions exist in the explanation of these answers. I will therefore try and boil it down to its simple essence with the help of a metaphor, namely a fishing expedition. We have two identical small nets and one big net. The opening area of a small net is exactly half the opening area of the big net. Now let us compare a fishing expedition using one big net (fe-1) with one using two small nets (fe-2). The two nets in fe-2 go through the same sea as fe-1 does and this sea contains—on average—always the same amount of fish. So we may safely assume that both expeditions catch—on average—the same amount of fish. But now it turns out that scientists have discovered that fish are better at spotting big nets and thus have a better chance to evade the big net. And so the two small nets should—on average—catch more fish than the big one, because they are less evaded. This is an example of Bell's inequality. But in reality, fe-1 often catches more fish than fe-2. So in reality, Bell's inequality is often violated. We could explain this by supposing that if the two small nets in fe-2 are aligned in a specific manner, the fish see them as one big net, even bigger than the one in fe-1.

This same logic can be applied to a Bell type experiment. Let us call the situation where we have 2 analyzers "Bell experiment two" (be-2) and the one with only the second analyzer in place "Bell experiment one" (be-1). Here, the angle between two polarizers is θ in be-2 and two times θ in be-1. So in be-2, we should catch more photons in smaller nets, since the fish are less capable of escaping them. The Bell inequality now says that the amount of photons that are blocked in be-2 should on average be greater than in be-1. But experiments show that this is not the case for angles of θ between 0 and 45 degrees. So we have a violation of Bell's inequality here. It is precisely this oddity, that gave rise to concepts like probability distribution, superposition and entanglement. But I derived Malus Law mathematically, using definition B, the input rule and an assumed distribution according to equation 1, without the need of any other speculative physical process. And by this achievement, my explanation for the violation of Bell's inequality is simpler and more consistent than quantum mechanical explanations.

To recapitulate my explanation, I assert that photons are not distributed evenly over the area of a section. If this would be the case then, at values of θ in between 0 and 45 degrees, be-1 and be-2 would show the same amount of blocked photons. But now that we do not have an equal distribution, but a cosine distribution, we will see that with θ angles in between zero and 45 degrees, be-1 shows more blocked photons than be-2. We can do an example to prove this. Let θ be 15 degrees. Then we can calculate the intensity in be-1 as

$$I = D_{\max} \cos^2 30^\circ = 0.75 D_{\max} \tag{6}$$

And in be-2 we would have:

$$I = D_{\max} \cos^2 15^\circ \cos^2 15^\circ = 0.87 D_{\max} \tag{7}$$

If we translate these intensities to the blocked percentage of photons, we can see that in be-1 25 percent of the photons is blocked, whereas in be-2 only about 13 percent of photons is blocked[2]. So the big net catches more fish than the two smaller ones. This means that Bell's inequality is violated without having to invoke quantum mechanical concepts for explaining the violation.

This same logic can be applied to another Bell type experiment, called the CHSH inequality. Recently, Hensen [3] conducted such an experiment and claimed to have proven entanglement of particles over distances of more than a kilometer. The reasoning goes as follows. If I have two analyzers as in be-2, Bell's inequality might be violated because there is some hidden interaction between photon and analyzer that we are not aware of. We could exclude that such is happening by sending two *entangled* particles with opposite polarization in opposite directions through a set of analyzers. So each particle of the entangled pair moves through a separate, but identical be-2 setup. If there would be some sort of weird interaction going on between a specific photon[3] and an analyzer, the entanglement with the paired photon would be broken. In this type of experiment, if both sides of the experiment violate Bell's inequality in the same way, this is taken to mean the following:

- Entanglement is validated. If the particle pair was not entangled, they would not be able to share their choices (for either passing through a polarizer or

[2]The percentage difference between be-2 and be-1 can actually very simply be formalized in general terms as $100\left(\cos^2(2x) - \cos^4(x)\right)$.

[3]I am aware that nowadays, many experiments are conducted with electron-positron pairs or even other particles, instead of photons. For the arguments as presented in this article, the actual type of particle is not relevant, as long as it can be regarded to have polarization states. The detectors in such an experiment act just as polarizers do, only letting particles pass that have a polarization state that is within its polarization area, with the only difference that the particle is "detected" when it does not pass. I will not go in to the details of this assertion here. I fear that will distract from the main message of this article. Therefore, I only use the photon as an example of a specific particle.

not).

- Hidden variables are excluded. This means that any sort of unknown mechanism in the behavior of an individual photon is invalidated, apart from its probabilistic behavior. Such unknown mechanism is often called a "hidden variable". The reasoning goes that if it were present, it would break the entanglement (and this would contradict the first item in this list).
- The existence of a local theory, explaining a subluminal interaction between the entangled particles is invalidated. If there would be some local interaction between the entangled particles going on, there would be a delay between action and reaction, since the velocity of such "messaging" between particles is limited to the speed of light. Such a delay can be excluded by experimental setup. Since no such delays are identified, proof of entanglement can also be taken as a invalidation of local interaction between entangled pairs.

The reasoning in the above items may not be shining with simplicity and clarity, it is not illogical as long as definition A for polarization is upheld. According to this definition, all photons in a polarized beam have the same polarization. The only reason why they would then choose to not go through an analyzer is in their probabilistic nature. And so every single photon throws a dice and acts according to the probabilistic numbers thrown, either through the polarizer or not. Consequently, if the behavior of photon pairs can be shown to be correlated, entanglement becomes a logical option, because then both photons must somehow throw the same dice. But if we adopt definition B, suddenly none of this makes sense anymore. The photons all have their own polarization angle and act accordingly. If a photon's polarization angle lies outside of the polarization area of the polarizer, it will certainly not pass the polarizer. If it lies within, it will certainly do. No probability is in their behavior and the correlation between an "entangled" pair is just normal (statistical) correlation between two photons, behaving similarly and going through a similar process.

5. Conclusion

By showing that polarization can be interpreted as a distribution of polarization angles over a polarization area, I have proven that the passing of the particles through a polarizer can be interpreted as entirely deterministic.

6. Further Research

The interpretation of the polarization process as described in this article generates open invitations to further research. At least there are two physical events to be explained:

- Particles with a polarization angle outside of the polarization area of the polarizer do not pass. Why is that?
- As the particle exits the polarizer, its polarization is randomly fixed in a specific angle. How does this work? And how can it be that a $\cos(2\theta)$ distribution of these angles emerges?

Apart from these two priorities, it would also be worthwhile to investigate if the distribution of particles on a screen after a slit or a double slit could be explained by polarization distribution, according to definition B.

I am convinced that the answers to these questions will reveal some details of the rich and surprising ontology of the subatomic world, now hidden behind an incomplete mathematical description of the polarization process.

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Author Contributions Statement

Peter Schuttevaar created/discovered the new definition for polarization (definition B) and derived the Malus law from it.

Conflicts of Interest

The corresponding author confirms that there have been no involvements that might raise the question of bias in the work reported or in the conclusions, implications, or opinions stated.

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