Classical linear wave superposition produces the appearance of interference. This observation can be interpreted in two equivalent ways: one can assume that interference is an illusion because input components remain unperturbed, or that interference is real and input components undergo energy redistribution. Both interpretations entail the same observable consequences at the macroscopic level, but the first approach is considerably more popular. This preference was established before the emergence of quantum mechanics. Unfortunately, it requires a non-classical underlying mechanism and fails to explain well-known microscopic observations. Classical physics appears to collapse at the quantum level. On the other hand, quantum superposition can be described as a classical process if the second alternative is adopted. The gap between classical mechanics and quantum mechanics is an interpretive problem.

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I. INTRODUCTION

When two waves overlap, they merge into a single formation and the principle of superposition applies: at every point, the net amplitude is equal to the vector sum of the input components. In contrast, the energy of a wave is proportional to the square of its net amplitude. This means that the net state acquires a surplus of energy at every point of constructive interference. It also loses a complementary amount at every point of destructive interference. The total amount of energy remains constant, but the problem is to explain the underlying physical mechanism. Does energy flow locally from the areas with destructive interference to the areas with constructive interference, or does it simply vanish and appear independently at each point? The observation of redistribution cannot be dismissed as an illusion, because useful work can be extracted from net states, according to their content. In particular, it is impossible to extract energy from a null region, but the extra energy is readily available in the areas with constructive interference.

This problem is aptly captured by the question: do waves go through each other unperturbed? The typical response is to adopt a positive answer. If one takes a moment to observe the propagation of water waves in a ripple tank, it is very hard to deny the appearance that waves are transparent to each other. Similarly, human ears have no trouble distinguishing simultaneous sounds from different sources, just like the multimedia devices that isolate electromagnetic signals with high fidelity from complex input mixtures. If that is not enough, rational arguments can be used to support this position as well. For example, the principle of superposition applies to any point in the interference volume of two light beams. Yet, a ray from the first source must collide with billions of rays from the second source before it reaches a region of interest (Fig. 1). As it is known, the net state at any point is calculated with utmost accuracy just by taking into account the distances between the target and each source. The slightest perturbation would have been amplified at the numerous intermediate points, falsifying the underlying principle. In short, it seems necessary to assume that waves go through each other unperturbed, without really interacting with each other.

The principle of non-interaction of waves is widely taken for granted as the correct interpretation of linear classical superposition. It is omnipresent in the literature at any level, from introductory textbooks to high profile research reports. Unfortunately, it has a major interpretive shortcoming. If interference is assumed to be an illusion, then energy redistribution (which is not an illusion) has to be described as a non-local process. According to this approach, it seems unavoidable to conclude that classical interference is fundamentally non-classical. Yet, this is not the only valid interpretation at our disposal. The same predictions would be obtained if we assumed that energy redistribution was a local process. For example, Richard Feynman dedicated a whole chapter to this problem in his Lectures on Physics [1]. He admitted that local energy conservation sounded strange in some contexts, but he also emphasized its necessity. The theory of relativity and the principle of momentum conservation would be in trouble as ontological models, if energy redistribution was non-local in the physical world.

To some readers, Feynman’s conclusions might sound counter-intuitive. Perhaps, when two identical waves overlap, it might be hard to tell if they go through each other or bounce back. We get identical outputs in either scenario. Yet, more often than not, overlapping waves are not perfectly identical. When a tall wave intersects with a short wave, the two of them keep on going in the
original directions, as if they never met each other. Thus, it seems inappropriate to suggest that the waves do not go through each other unperturbed. Nevertheless, rigorous quantitative analysis suggests that the two models are indeed equivalent. For example, Dowling and Gea-Banacloche analyzed the behavior of intersecting light beams under the assumption that they bounce off, instead of going through each other at the microscopic level. They found that the macroscopic predictions are identical in both cases, even if the input beams are distinguishable by amplitude, frequency, or polarization. Output beams are quantitatively similar to the input components, but cannot be assumed to be qualitatively identical because of the possibility of symmetric energy exchanges during interference.

As it turns out, there are three major interpretations of wave interference that are experimentally indistinguishable. One can assume that waves go through each other unperturbed, or that they undergo specular reflection, or finally that input waves merge into a single net state. The latter seems particularly vulnerable to objections. If two unequal waves are truly able to merge into a single net state, then why don’t we get two outputs with equal amplitudes? Why does it seem that the taller wave maintains its original shape and direction after overlap? The answer is that this objection and the ones invoked earlier in this text are based on superficial observations. Wave behavior is not predicted by macroscopic qualities, such as “shape”, but rather by the analysis of microscopic processes in accordance with Huygens’ Principle. The net state at every new frontline is calculated by adding up the effect of wavelets from every point of a previous frontline. Whether we apply this method at the level of net states or independent components, the final predictions are exactly the same in all three models. Indeed, we would have to deal with a mathematical contradiction if this was not the case. The relevant distinction between the three scenarios is only found in the domain of qualitative considerations. The ideas that waves can “go through” or “bounce off” each other are based on particle models of propagation. Yet, mechanical waves do not transport particulate matter. They only carry momentum from one region to the next in elastic media. Thus, only the third approach is compatible with the classical notion of a mechanical wave, and it is also the one that does not entail any complication with regard to energy redistribution.

Modern physics has two incompatible branches: classical mechanics and quantum mechanics. The usual assumption is that classical mechanics is easy to interpret, while quantum mechanics is not. We wish to suggest that the interpretive problems of classical mechanics have been underestimated, and that wave interference in particular has been predominantly tackled with a model that is qualitatively non-classical. This is especially relevant for the debate about the boundary between classical phenomena and quantum phenomena. A growing number of scientific conferences have been recently devoted to this issue. After attending some of them, we were surprised by the sheer number of arguments in favor of the formal compatibility between the two branches. This inspired us to inquire if the gap between classical mechanics and quantum mechanics is truly ontological. Would we get identical conclusions, if classical phenomena were subjected to the same level of scrutiny as quantum phenomena with regard to their qualitative implications? This essay has three goals: 1) to explain the non-classical essence of current approaches to wave interference; 2) to share our findings regarding the quantitative and the experimental equivalence of alternative approaches to this phenomenon; and 3) to outline the relevance of these conclusions for the understanding of quantum phenomena.

II. THE HIDDEN DIMENSIONS OF LINEAR SUPERPOSITION

Non-linear wave superposition is a process with clear physical consequences: input components are transformed and become unrecognizable at the output. In contrast, linear wave superposition is very ambiguous. On the one hand, output states are similar to input states, as if no interaction ever takes place. On the other hand, interference is observable in the area of overlap (Fig. 2). Is the similarity between inputs and outputs illusory, or is interference just a misleading appearance? The main
challenge is to explain what happens in the coincidence volume. Why do we see energy redistribution? Is it because detectors sum up the effect of independent components, as they pass through each other unperturbed, or is it because the two components really interact and change their physical properties at the microscopic level? From a quantitative point of view, it is far more convenient to assume that waves do not really interfere. The outcome is the same in both scenarios, but the calculations are much simpler in this case. Though, Brownian motion can also be ignored at some levels of analysis where it is inconsequential. That does not change anything about its status as a real phenomenon. Why should interference be different? A possible answer is that Brownian motion has independent effects that cannot be explained otherwise. The same cannot be said about interference: every known effect of this phenomenon can be reproduced by assuming that superposed components never interact. What is there to be lost, if the reality of interference is denied? Our reply, as explained below, can be summarized in two words: classical mechanics.

A. Classical waves cannot propagate through each other

A classical mechanical wave is a pattern of oscillation that is produced by the relative displacement of small regions in an elastic medium. The cause of this phenomenon is the tendency of excited volumes to return to their state of equilibrium, rather than to run away. In other words, mechanical waves do not transport matter. When they run, it is because the state of motion of one region is transferred to the next. For example, consider the effect of a membrane on a gaseous medium (e.g., air). In a toy model for this process (Fig. 3), atmospheric particles can be replaced by solid balls, interconnected by elastic springs that can transfer momentum from one region to the next without losses. Whenever one molecule is pushed by the action of the membrane, it gets closer than normal to its adjacent particles. As a result, the balance between the forces of these entities is disrupted. The action of the displaced molecule on its neighbors is temporally stronger than the action of the rest of the medium. These adjacent particles end up being displaced as well. The outcome is a close analogue to a half-spherical wavelet, as captured by the Huygens principle. Applying this description to each molecule that is displaced by the first one, we can follow the same principle in order to arrive at the description of a macroscopic half-spherical wave-front. If the active size of the membrane is increased, many molecules are displaced simultaneously in the same plane. The macroscopic effect of their wavelets is to produce an interference front that is closer to the plane wave approximation. As explained by Huygens [11], the final shape and direction of a macroscopic front is determined by the amplitudes and the relative phases of microscopic wavelets. The latter may overlap in many directions, but the wave-front develops in the direction where they add up constructively. A particle will only produce wavelets if it moves, and it can only move if it receives a net momentum in a given direction. Hence, a “wave front” is really a “constructive interference front”.

When two different wavelets overlap on a single point, it means that one particle is the recipient of action from
FIG. 3. (Color online) A toy model for Huygens' Principle. Classical molecular media can be mimicked with a macroscopic construct, in which identical solid balls are interconnected in a symmetric mesh with elastic springs. The whole structure is under tension, due to the compressive effect of gravity. At rest, there is a state of equilibrium in which the balls are assumed to be equidistant from each other. (A) If a single ball is suddenly displaced from its point of equilibrium, it will intrude on the adjacent space in the direction of action. All of the immediate neighbors from the point of maximal intrusion will experience a net radial outward force. As they move away from this source of compression, they must produce a pattern of motion that can be described as a spherical wavelet (at least at the early stage of the process). These displaced balls are going to have a similar effect on their own neighbors. Yet, given that a larger number of balls act at the same time, their impact will add up constructively or destructively at different points. The net effect will be a macroscopic spherical front of constructive interference. (B) If a large number of balls from the same plane are displaced simultaneously in the same direction, they will produce wavelets like in the previous example. Yet, this time their effect will add up to a front of constructive interference that resembles a plane wave, rather than a spherical wave. Thus, Huygens' Principle captures very closely the dynamics of perturbation of molecular media. At the macroscopic level, the distance between any two molecules is negligible. Accordingly, every point on a wave-front can be treated as a source of secondary wavelets. Note that only the points on the front of constructive interference are relevant. The regions with destructive interference contain entities with zero net displacement. If the latter do not move, then they cannot produce compression. Therefore, they cannot act as sources of wavelets.

different directions. For simplicity, this process can be illustrated in terms of elastic collisions between macroscopic balls (Fig. 4A-B). If a ball is hit horizontally from the left, it must be displaced to the right. If it is hit from below, it should end up moving upwards. The only way to claim that input momentum can “go through” is to show that the receiving particle is able to transfer it by moving accordingly. However, classical mechanical entities cannot move in two directions at the same time! When several sources exercise their action simultaneously, the target can only move in the net direction, in this case diagonally. (Hence, the corresponding particle in the medium will only be able to initiate a wavelet in the net direction). If two identical balls are placed in the appropriate configuration after the impact, they may end up moving in the original direction of the inputs (Fig. 4C). Yet, the role of the intervening carrier, which merges all the input units of action into a single physical motion, is to replace the input states, effectively destroying them. The latter can be recreated afterwards, but they cannot be preserved. Similarly, when two balls with equal momentum arrive simultaneously from opposite directions (Fig. 4D-E), the central ball cannot be displaced at all. If it does not move, then it cannot carry momentum of any sort in any direction. Its physical function is to work as a “wave breaker”, like a rigid wall. From a quantitative point of view, it makes no difference whether we assume that two identical balls recoil from each other or pass through - the outcome is the same. From a qualitative point of view, things are very different. As long as the principles of classical mechanics are assumed to be at work, only the first alternative is plausible. For this reason, the action of air molecules cannot be assumed to propagate “through” the areas of destructive interference. Their momentum has to be redirected into the areas with constructive interference. As a result, the molecules from the regions with constructive interference must oscillate with higher amplitudes. They carry the summed momentum of particles that happen to push directly through, and of the particles that recoiled
FIG. 4. (Color online) **Momentum transfer during linear wave superposition.** Macroscopic waves are reducible to microscopic instances of momentum transfer in classical media. In the same vein, superposition can be analyzed in terms of simultaneous elastic collisions. (A) Two blue balls exercise pressure on the same red ball from orthogonal directions. If the upward ball acted alone, the red ball would be displaced vertically. Similarly, the red ball would move to the right, if the other blue ball acted alone. Yet, the red ball cannot move in two directions at the same time. (B) The only possible way for it to move is in the direction of the net force vector. Moreover, the input components cannot be physically preserved in the net state of motion. The ball is simply moving. The same motion could be produced by two balls acting from other angles, or by any other number of balls. (C) Two green balls appear to carry forward the exact momentum of corresponding blue balls. Their motion is quantitatively identical whether blue balls act one by one or at the same time. Is it also qualitatively identical? The red ball can only move diagonally in the case of simultaneous action. Ergo, the direction of the green balls is determined by their position relative to the moving red ball. If the starting arrangement was not symmetric, the green balls would carry the same total momentum in different directions. (D-E) This is a different context, in which two blue balls act simultaneously from opposite sides. The net force acting on the red ball is equal to zero, so that it does not move. Instead, it acts as a rigid wave-breaker. The blue balls appear to transfer their momentum to each other, but this is physically impossible if the red ball cannot move. It is at least equally plausible that they bounce back with their own momentum, or that the two inputs merge into a single state and become indistinguishable. Ergo, it is no longer possible to determine unique origins for the output momentum states. These two examples suggest that input components must be reflected from the areas with destructive interference and become indistinguishable in the areas with constructive interference, as these types of interactions are repeated numerous times during linear wave superposition. In order to avoid this conclusion, one might have to assume that real classical entities move in several directions at the same time, and also transfer real momentum without moving.

from adjacent regions. In contrast, the molecules from the areas with destructive interference cannot move at all and their amplitude of motion is null. This is an intuitive explanation of the known properties of macroscopic wavefronts, as produced by microscopic wavelets.

Huygens’ model implies that a wave is nothing but a state of constructive interference on a medium. To describe the energy of a macroscopic wave is to describe the area of constructive addition of microscopic wavelets. For example, the diffraction angle of a wave can be changed by inducing phase delays between wavelets [12]. When a wave is focused, all the billions of wavelets can be assumed to have real amplitudes in the original (unfocused) direction. It is only the front of constructive interference that converges on a point. Nevertheless, the common sense description is that the wave converges and that the energy in the focal point is really all the energy available. The wave happens where the medium oscillates. To speak of energy outside the detectable wave is both counterintuitive and impractical. If the wave is not assumed to correspond to the observable oscillations, energy must be described as if it was spread over the entire medium.
and then it becomes impossible to describe what propagates, where, and how. Indeed, there are no debates in the scientific community (to the best of our knowledge) about this aspect of the nature of single waves. The problems only emerge when several coherent waves overlap. In this case, typical patterns emerge in the form of interference fringes, but the waves appear to return to their original shapes after overlap, at least in some cases. For reasons that do not concern us here, interference is suddenly interpreted as a process with unperturbed input energy, even in the destructive null zones where no oscillations are detectable. This is a major inconsistency. A single wave is a process of superposition between numerous microscopic wavelets. Two-wave superposition is the same process, multiplied by two. Yet, single-wave energy is presumed to be localized exclusively in the observable oscillations, while double-wave energy is not. Moreover, non-interference implies that elementary particles in the medium can move in several directions at the same time, and even transfer momentum without moving at all! That is a clear departure from the principles that define Newtonian physics.

The motion of any physical entity may be represented by a vector during formal analysis. Any “real” vector, in turn, is equivalent to the sum of two or more “virtual” vectors that add up to the same net state. Sometimes, these components are physically significant, but their virtual nature is self-evident. For example, if two football players kick the same ball at the same time, the action of each of them can be represented by a dedicated vector, but the ball can only move in the net direction. Its displacement is captured by a “real” vector, while its hypothetical components (had it been struck by either player alone) must be represented by “virtual” vectors. The same relationships are found in the behavior of a medium when two waves become superposed. The net state is detectable, but the components are not. Yet, here we get the unique standard operating procedure, passed down from one generation of scientists to the next, to assume that unobservable input components are “real”, while the observable net states are “virtual”. Regardless of the practical advantages of this preference, it comes with the heavy interpretive toll that was described in the previous paragraph. The ontology of this approach is non-classical and the analysis of wave behavior is conceptually inconsistent.

A possible objection to this argument concerns the relevance of real elastic media for a general approach to classical waves, given that light waves appear to propagate without a medium. Indeed, some textbooks maintain that electromagnetic waves are not compatible – in any physical sense – with the Huygens postulate, even though it works with unrivalled accuracy. In particular, they question the idea that light can be treated as a source of light at every point of its wave-front. The relevant concern here is that electromagnetic radiation can only be produced by accelerated charges. If light is made of photons without charge that move at a constant speed, it should be impossible to generate new forms of radiation. On closer inspection, this problem appears to be based on a misunderstanding. Huygens’ postulate does not entail that waves produce wavelets. Instead, it redefines the waves, by describing them as the net state of a totality of wavelets. A wave can be described either as a running perturbation with a specific shape, or as a process of sequential generation of secondary wavelets that add up to the same shape. Hence, only wavelets produce wavelets and the starting conditions (be they mechanical oscillators or accelerated charges) only serve to explain the origins of this process. According to the most common interpretation, electromagnetic waves propagate by generating component fields. Changing electric fields induce changing magnetic fields that induce changing electric fields and so on. At least formally, these fields can operate like the wavelets of other types of classical waves, because they are assumed to be constantly created locally at every new wave-front. More importantly, the same considerations about the net state versus component states apply to this case. For example, when two electric fields act on the same point, the resulting magnetic field will have detectable effects only in the net state. This aspect will be described in greater detail in the following sections. In short, light waves are both quantitatively and qualitatively compatible with the properties of other types of classical waves.

B. Superposition entails energy redistribution

Let us now consider the quantitative aspects of linear superposition. When two laser projections overlap, the net distribution of energy in the cross-section may be determined by one of two rules. If the beams are mutually coherent, irradiance is proportional to the square of the vector sum of their electric field amplitudes at any point:

\[ I = k(A_1 + A_2)^2 \]  

(1)

where \( k = \epsilon_0 c \). If the beams are incoherent, it is the sum of the squared amplitudes that gives correct predictions:

\[ I = k(A_1^2 + A_2^2) \]  

(2)

Given that

\[ (A_1 + A_2)^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos \theta \]  

(3)

for any two vectors, the difference between equation (1) and equation (2) reduces to

\[ 2kA_1A_2 \cos \theta \]  

(4)

where \( \theta \), in this case, corresponds to the phase delay between the two coherent wave patterns. Expression (1) is generally known as the “interference term”. In practice, the rules (1) and (2) account for the observed presence or absence of interference fringes when multiple beams overlap, and their application is straightforward. The difficulty is to explain the meaning of the difference between
them. Is there something physical behind the interference term $I_1$, or is it just a product of mathematical manipulation?

According to the left side of the equation (2), we must assume that the local state of two component fields is sufficient to explain the observed amount of irradiance. The two fields do not interact and their individual amplitudes remain constant over time. Yet, their joint action can generate the appearances of fringes, because of the varying phase angle between their amplitude vectors at different points in the cross-plane. When the amplitudes point in the same direction, we could assume that they add up. When they point in opposite directions, they should similarly cancel each other out. This relationship can only be stable over time for mutually coherent beams. Hence, there is a plausible explanation for the difference between the cases that require equation (1) and the ones that require equation (2). In contrast, the right side of equation (4) suggests a radically different scenario. Instead of vector addition, we have the sum of two scalar values. These individual components add up to a common state at every stage of the process, just like in the case of incoherent superposition. For this reason, the local properties of undisturbed beams cannot explain the emergence of fringes. The latter must be described by assuming the existence of a process of energy exchange between adjacent regions, as captured by the interference term $I_1$. As a corollary, we have two incompatible stories that happen to be mathematically equivalent.

The standard interpretation of interference does not involve redistribution. When crests overlap with troughs, they are presumed to cancel out each other’s effect. When crests overlap with crests, the amplitudes are expected to resonate. This effect is somewhat similar to that of two horses pulling a cart. If they pull in opposite directions, there is no net displacement. If they pull in the same direction, their force adds up. Unfortunately, this analogy does not work if energy is taken into account. When horses pull in opposite directions, a lot of energy is dissipated in the form of heat. When waves are out of phase, no heat is released. Instead, the waves are supposed to keep on propagating through each other. Furthermore, when two horses pull in the same direction, it is impossible to get more than two horse power. Yet, energy is supposed to multiply when two wave crests overlap, because the linear summation rule applies to amplitudes. For example, constructive interference between two beams with equal amplitudes ($A_1 = A_2$) produces an irradiance that is:

$$I = k(2A_1)^2 = 4A_1^2 k .$$

This is twice as much as the irradiance of two incoherent beams in superposition:

$$I = k(A_1^2 + A_2^2) = 2A_1^2 k .$$

It makes sense to assume that incoherent beams cannot resonate. Perhaps, their joint energy is lower because their oscillations “average out” somehow? The answer has to be negative because the irradiance of incoherent beams in superposition is equal to the sum of their individual irradiance, measured separately. If the interaction of incoherent beams were to “average” something out, the net state should be less than the sum of input components. Since this is not the case, there is no local “reserve” for the extra energy in a bright fringe, and an external source must be identified. Amplitude vectors may cancel out and add up in various ways, but energy is supposed to be a conserved scalar quantity. Either it becomes observable in one spot when it is unobservable in another, due to some sort of non-local transaction, or it has to be physically redistributed by local means. Yet, the whole point of amplitude summation was to avoid the conclusion of energy redistribution. Therefore, energy modulation has to be treated as an illusory but natural consequence of amplitude summation, according to this approach, such that the appearance of overall energy conservation during interference is merely a coincidence.

If this conclusion is accepted as an ontological element, how can it be justified? One possible strategy would be to assume that wave crests always obey the rule of linear addition. In other words, coherence might bring out an essential property of waves, which could simply be hidden in the case of incoherent wave overlap. Indeed, wave crests always add up during superposition, but is it a fact of Nature that this addition is always linear with respect to amplitudes? Consider the case of a collimated laser beam. If it crosses a 50-50 beam-splitter (Fig. 3A), we should assume that the amplitude is split in half, as the beam is divided in two output projections. Yet, the proportionality of irradiance to the square of the amplitude implies that the power of each output beam should drop to 25% of the input beam. This corresponds to an expected net energy loss of 50%, compared to the input amount. Of course, the actual observation is that irradiance is split 50-50 by the beam-splitter, without unusual losses. This means that the actual amplitude of each output must be about equal to 71% of the input value, when a beam is split in half. Conversely, when the beam-splitter is removed from the path of the laser beam, the amplitude returns to its original value. The energy of the input beam is not amplified. Yet, this case is physically similar to the one in which two coherent components overlap. If the amplitudes were added before squaring, as suggested by rule $I_1$, quoted above, the total energy should double. Again, there is a conflict between interpretive expectations and reality. To be sure, this is not an attack on the quantitative parameters of superposition. If the amplitude of a beam is doubled, of course it must have a quadruple amount of energy. The difficulty is to account for the reverse relationship: a beam must quadruple its energy before its amplitude can double. This holds for single beams, whose power can be modulated, and it must also hold for superposed beams.

The implications of this problem can be illustrated with the following example. At the first beam-splitter...
FIG. 5. (Color online) The amplitude paradox. When a laser beam interacts with a beam-splitter (A), it is observable that the power of the beam is split 50-50. Similarly, if the transmitted beam (B) or the reflected beam (C) of the first beam-splitter is allowed to pass through the second beam-splitter of a Mach-Zehnder Interferometer, the power readings in each channel drop in half again. Yet, when two beams are superposed in phase in the same output channel (D), their total energy doubles, as if the bright channel absorbed all the radiation from the dark channel. If energy redistribution is denied, then interference must be due to linear amplitude effects. This means that amplitudes must be split 50-50 at each beam-splitter, dropping by a factor of 2, rather than $\sqrt{2}$. Unfortunately, this assumption entails predictions that contradict the observed energy levels for individual as well as superposed beams. The only way to derive the correct amplitude values that work for linear amplitude addition is by assuming that the reverse version of the same physical process is paradoxically non-linear.

In a Mach-Zehnder Interferometer (MZI) the input beam is split 50-50. Yet, at the second beam-splitter the two halves become superposed and co-propagate. If only one path is open alone, it can be seen that each beam is split 50-50 again (Fig. 5B-C). If both paths are open at the same time, we see the appearance of interference (Fig. 5D). The net irradiance in each output path is determined by the measurable irradiance of individual components, in accordance with the interference equation:

$$I_t = I_1 + I_2 + 2\sqrt{I_1I_2}\cos\theta.$$  \hspace{4cm} (7)

In one output, the two components are in phase. They display constructive interference, and their total energy doubles ($1+1=4$, not 2). In the other one, they are out of phase and no radiation is detectable ($1+1=0$, not 2). The bright channel contains all the energy that enters the interferometer, as if it absorbed the radiation from the dark channel. Yet, the principle of non-interaction of waves forces us to assume that only the detectable energy is canceled in one output, because the amplitudes of the two components point in opposite directions. Similarly, the detectable amount of radiation seems to have doubled in the bright channel, because the amplitudes point in the same direction and they must be added before squaring in this case. This means that superposition is not physically effective at the level of irradiance, as suggested by equation (7), but rather at the level of the amplitudes themselves, as suggested by the equivalent equation (1). Yet, when we define the amplitudes as the physical agent of linear superposition, the whole beam...
dynamics has to be interpreted in the same terms. For example, if the starting amplitude is equal to 4 conventional units, then each component should emerge with 2 units after NPBS1. This implies that the detectable energy after NPBS1 should drop to 25%, contrary to the actual observation of 50%. Furthermore, the amplitude should be split again in half after NPBS2, falling to a value of 1 unit, in which case the observed irradiance should become equal to about 6% of the input beam if every path is open alone (by blocking the other path), contrary to the observed value of 25%. Yet, when we calculate the total output energy of superposed components, even by adding the amplitudes before squaring, we get only half of the actually observed energy. With or without superposition, it is impossible to get correct predictions about observable beam properties, if we assume that amplitudes can really add up and subtract like vectors. Thus, we get the paradoxical situation in which we have to assume that amplitudes do not undergo vector addition, in order to derive correct values that can be used for vector addition.

This example brings out the crucial ontological difference between the two main approaches to wave interference. The principle of interference treats energy as indestructible, with the necessary implication that it is always redistributed, one way or another. In the case of incoherent overlap, redistribution is assumed to be so fast and random that only average effects are detectable in normal conditions. In the case of coherent overlap, redistribution is stable over time and follows a strict rule. As a result, we get the macroscopic appearance that amplitudes add up like vectors. In contrast, the principle of non-interference denies the reality of energy redistribution. Amplitude addition is assumed to be the primary physical process, even at the microscopic level. The special symmetry of this process results in equal amounts of energy creation and destruction. Therefore, we get the appearance of energy conservation, when total amounts are taken into account. In the first case, it is energy that propagates, and the net impact of this process at every point is manifest in the form of amplitudes. In the second case, it is the amplitudes that propagate as independent physical entities, and their local net effects are imperfectly measured in the form of energy. A neutral way to sum this up is that both phenomena – amplitude summation and energy redistribution – are “appearances”. We have to treat both interpretations as “stories”. Though, one of these stories is compatible with the principles of classical mechanics while the other is not. The principle of non-interference also entails conceptual inconsistencies, as shown above, because amplitudes “refuse” to display linear manifestations, except in the cases where avenues for energy redistribution happen to be present. More importantly, the appearance of energy redistribution cannot be avoided. It can only be dismissed as unphysical, without the ability to substantiate this claim. As it is known, the output beams of the MZI remain dark or bright indefinitely.

C. Energy redistribution is permanent

A possible objection to the preceding conclusion might be that beam-splitter interferometers are not appropriate for this discussion. For all we know, reflecting surfaces or other components of these devices might really induce energy redistribution. If so, the non-interaction principle should not be employed for their analysis. Instead, free-space interference alone should be interpreted as an example of overlap without interference. The implied expectation is that energy redistribution can be ruled out with certainty in this context.

In many discussions, free-space interference is invoked in reference to beams that cross each other and then separate completely. Yet, the interference volume is not always longitudinally finite. The natural diffraction of radiation and the small angle between the beams (required for visible fringes) often result in light-cones that are perpetually superposed (Fig. 6). Nevertheless, the overlapping projections can be separated with optical devices. This quasi-transient nature of free-space overlap can be used to suggest that energy redistribution does not have to be invoked in this case. Fringes are, of course, detectable, but only upon interaction with a detector. Conceivably, the latter can be described as an array of oscillators that absorb and re-emit light. This emission would be impossible when excitatory radiation components are
out of phase, but it should somehow become amplified by resonance during constructive interference. For the sake of consistency, one might even assume that detectors redistribute energy during these interactions from the areas with destructive interference to the areas with constructive interference, whereas the energy of incident radiation is evenly distributed in cross-section. In short, the appearance of fringes might be an effect of the interaction between radiation components and detectors [10], rather than between the propagating radiation components alone. This idea is so simple that one has to wonder: why are people still debating it? Why don’t they just test it? As it is known, interference patterns can become arbitrarily large at sufficient distances from the source. If a fringe is 10 meters wide, then a slit that is 1 meter wide could isolate the central part of a bright fringe, or that of a dark fringe. Given the huge ratio of the slit size to the wave-length of visible light, diffraction can be presumably ignored. Thus, by aiming a telescope at the median point of such a slit, it should be possible to separate the fringe slice into two components. According to the foregoing assumptions, it should be observable that dark fringes and bright fringes actually contain the same amount of energy [13]. In other words, the bright fringes should separate into constituent components without extra energy, while the dark fringes should reveal their hidden energy, without any possibility of mutual trade-off between different regions in the interference volume.

Several variations of this proposal have been advanced recently [18–20], but no empirical verification has been reported. To the best of our knowledge, this is not for lack of trying. In actual experiments, bright fringes cannot be split into components with less total energy, and dark fringes remain dark. Why would that be the case? If a lens with a diameter of 1cm can separate an interference volume into its components (close to the source), why would it be so difficult to separate a 1m slice of the same volume (far from the source)? According to the principle of non-interaction, the two cases should be qualitatively similar, because component wave-packets are supposed to just pass through each other in the same way in both situations. If anything, scattering effects should be smaller in the case of wide slits/aperatures. Could it be that something has been overlooked in this analysis? The answer can be found by reviewing some basic facts in the theory of optical resolution. As it is well-known, a self-luminous point cannot be imaged precisely in the far field with a lens that has a finite diameter (see, for example [13], or any other optics textbook). A point is always imaged as an Airy pattern, whose spread is directly proportional to the wavelength and inversely proportional to the diameter of the lens. The angular size of the central bright disc of the Airy pattern (Fig. 7A) is given by:

$$\sin \theta = \frac{1.22\lambda}{d}. \quad (8)$$

For a given source of light with fixed wavelength, it is only the size of the lens/aperture (d) that can be changed to improve the resolution. When the diameter of the lens is comparable to the wavelength of light, it becomes useless because it cannot resolve any point. A practical consequence of this feature is that radio telescopes need to be very large compared to optical telescopes that work with short wavelengths. Yet, there is an important difference between the absolute limits of resolution of a lens and the constraint of resolving small objects. In most practical situations, the challenge is not to resolve just a single point. Instead, it is to resolve two points that are very close to each other. Lens diameter matters greatly here too, of course. Bigger lenses produce smaller Airy patterns, increasing the resolution power. Yet, a very large lens can still fail to resolve two points if their angular separation is small enough. According to the Rayleigh criterion [21], two points are “just resolved” when their angular separation, as seen from the central point of the lens, is equal to the angular size of the Airy disc (Fig. 7B), such that the central points of each projection overlap with the first dark rings of the other:

$$\sin \alpha = \sin \theta = \frac{1.22\lambda}{d}. \quad (9)$$

This arrangement has a remarkable geometrical property. As shown in Figure 7B, the angular separation of the two sources is equal to the angle of the tilt of the lens between alignment A, when it is normal to the first source, and alignment B, when it is normal to the second source. This is equivalent to the angle between two co-incident plane waves, originating at the same sources. If these waves are in phase at one edge of the lens, they will have a maximal phase delay at the other. When the angular separation between the sources is at the critical value, as specified by equation (9), this phase delay is equal to 1.22 wavelengths. In other words, for any wavelength, and for any lens diameter, two sources are only going to be resolved if they have a range of phase delays in excess of 1.22 wavelengths across the diameter of the lens. As it is well-known, the width of an interference fringe corresponds to the cross-segment in which the range of phase differences between two coherent components is equal to one wavelength. This parameter is fixed, regardless of the size of the fringes. Consequently, it does not matter how far from the sources one places a screen and how big the fringes are. Even with the largest lens in the world, a narrow slice of a single fringe can never be separated into its components, because it can only contain a negligible range of phase delays. The physical significance of this conclusion can be understood by recalling that wavelet phase delays determine the net direction of a wavefront in Huygens’ model. If two wavefronts display negligible variation in their phase differences, they must co-propagate and remain forever indistinguishable, even if they do not interfere.

When linear superposition is analyzed with a particle model such as ray tracing, it is convenient to describe the beams “as if” they pass through each other at every point of intersection. Unfortunately, this assumption
FIG. 7. (Color online) Illustration of the Rayleigh criterion for resolving diffraction limited spots. A) According to Huygens’ Principle, a point-like source of radiation must necessarily produce a spherical front of constructive interference. A finite circular section of a spherical front can only be produced by an emitter with real extension, shaped like a disk with rings. Due to the inbuilt symmetry of this model, convergent projections play back the same process in reverse. A negative spherical front of constructive interference converges onto a single point, as shown in the right side of the drawing. Finite lenses can only capture a circular section of this pattern. Without contributing wavelets or rigid boundaries at the edges, the wave front “opens up” (left side of the drawing). The result is a diffraction (Airy) pattern that looks like a bright disk with faint rings. The angular size of the bright spot, from the central point to the edge of the first ring of destructive interference, is determined by the relationship \( \sin \theta = \frac{1.22 \lambda}{d} \), where \( d \) is the diameter of the lens. B) Two point-like sources of radiation, separated by a very small angle, produce overlapping Airy patterns that may be impossible to isolate. The Rayleigh criterion stipulates that such sources are going to be minimally resolved if their angular separation is equal to the angular size \( \theta \) of the diffraction limited spot from drawing A. The criterion ensures that the peaks of the two Airy patterns fall in each other’s first ring of destructive interference. The drawing B illustrates that the angle \( \theta \) is also equal to the angle \( \alpha \) between two plane waves from the two sources. If these waves are in phase at the right edge of a lens, they must be out of phase by 1.22\( \lambda \) at the left edge. Accordingly, two wave-fronts cannot be resolved if they have a range of phase-differences smaller than 1.22\( \lambda \) across the surface of a lens. For a uniformly illuminated slit, a range of 1.00\( \lambda \) is sufficient. Due to the symmetry of the Huygens model, it follows that radiation from two sources, passing through a single slit, must be subjected to the same restriction. Two coherent laser beams, no matter how far from each other at the source, will not be able to produce separable projections through a slit of any size, unless the width of their interference fringes is smaller than the width of the slit. Even if such a projection were passed through a lens with infinite diameter, the necessary range of phase differences for beam separation cannot be physically available in a small fraction of a single fringe.

A possible loophole might be to assume that scattering effects at the edges of a slit or a lens are hiding the process of rectilinear propagation. The trade-off is to revert to a wave model, because particles do not cause diffraction fringes. Even so, the role of edge scattering becomes less and less compelling as the size of the fringe is allowed to increase with propagation. In order to maintain consistency with known empirical facts, the principle of non-interference can only be applied on the basis of a wave model that is consistent with Huygens’ Principle. In this case, the explanation becomes that different beams obey Huygens’ Principle independently. They are still presumed to be real in the dark fringes. It just so happens that human observers cannot isolate them for technical reasons. The problem with this story is that Huygens’ Principle describes the direction of a wave as a collective process. It also sums up the contributions from different directions onto a point of incidence in a single spherical wavelet. This means that input waves can only pass through each other if indistinguishable components of single spherical wavelets “remember” where they came from and separate accordingly in subsequent interactions. Yet, somehow they still cannot regain their input direction unless dark fringes are allowed to merge with bright fringes.

As a reminder, the starting point of this section was an attempt to show that non-interference is experimentally verifiable. The price was to restrain the validity of this concept to free space interference, excluding all the instances of beam-splitter interference, even though the
same equations are required in both contexts. It is apparent now that free space interference is also too wide a concept for this task. In most cases, when point-like sources radiate light, the outcome is an infinite volume of superposition in which dark fringes persist like infinite projections, without ever mixing with bright fringes, just like in the case of beam-splitter interference. States with new levels of energy do not “naturally” separate back into original components. Moreover, it is even impossible to separate them with optical devices, in another example of similarity with collinear beam-splitter superposition. Thus, energy redistribution during infinite interference in free space is permanent. If the non-interaction principle is used to interpret this observation, then it is necessary to invoke non-locality.

All of the above notwithstanding, the appeal of non-interference comes from the special class of situations where collimated or focused beams intersect with a finite volume of overlap. In this case, fringes are observable in superposition, but the beams are also able to separate without intervening lenses. Can it not be that the concept of energy redistribution is dispensable in this case? Surprisingly, the answer is negative again. If portions of the dark fringes or the bright fringes are isolated with slits, it becomes impossible to observe beam separation, just like in the case of free-space interference with infinite interference volumes, as discussed above. The only exception to this rule happens when several bright fringes are open at the same time, with narrow obstacles at the center of dark fringes. In this case, as shown recently by Afshar [22], beam separation becomes visible, but energy redistribution is a necessary implication because the obstacles do not appear to remove the expected amounts of energy from the superposed beams and do not produce diffraction fringes. Either radiation is flowing around the dark fringes (assuming local energy redistribution in the interference volume), or the apparent beam separation is the outcome of interference between the elements that were diffracted by the slit edges [23] (resulting in non-local energy redistribution beyond the original interference volume) [24]. Consequently, it is not possible to prove the absence of energy redistribution, even when the superposed beams separate without intervening optical devices. Perhaps, this can be explained away as a limitation of our means of observation, by assuming that measurements are always intrusive. Nevertheless, the point remains that the principle of non-interaction does not entail verifiable new physics.

A useful lesson from this discussion is that the observable details of interference are always similar when the quantitative details are similar. Whether we analyze the superposition of radiation in beam-splitters or in free space, the relevant equations are the same and the subtle physical features are also the same. A region with perfect destructive interference is mathematically and physically equivalent to a region without any radiation, no matter what operations we perform over it. In the context of our discussion, this means that the appearance of energy redistribution cannot be avoided in any context. Regions with missing or excessive energy can only revert to their baseline levels if they have the opportunity to mix with each other at later stages of propagation. As a corollary, the principle of non-interaction cannot make predictions that are distinguishable from models that assume real energy redistribution. The only difference is that non-interaction entails non-locality in this process.

In conclusion, modern classical physics interprets wave interactions with concepts that sometimes violate the spirit and the letter of Newtonian mechanics, despite the existence of alternative models. It may seem harmless to assume that waves are transparent to each other. Yet, this entails non-local energy redistribution, transfer of kinetic energy without physical motion, as well as simultaneous motion in multiple directions for single macroscopic bodies. No less importantly, conceptual inconsistencies follow from the differential treatment of single beams and superposed beams. How can it be that a proven classical model violates the principles of classical physics? We suspect that many models in contemporary science are designed to interpret successful equations, rather than actual physical processes. The purpose of formal analysis is to simplify calculations, rather than to capture the whole complexity of the Universe. Sometimes this entails replacing cosmic bodies with point-like objects; sometimes it involves crossing out real forces that balance each other out; and sometimes it leads to the analysis of standing oscillations in terms of running waves that pass through each other unperturbed in opposite directions. What is important to acknowledge is that the same equations can also be interpreted with stories that satisfy the principles of classical physics.

III. SUPERPOSITION: THE TEST OF PARSIMONY

Classical interpretations possess a higher level of intuitive appeal than non-classical alternatives, but this does not prove they are ontologically superior. For all we know, human psychological predispositions could be accidental, even if shared across cultures. Instead, the competition between two equivalent theories can be more conclusively resolved on the basis of the principle of parsimony, otherwise known as Ockham’s razor. If one theory explains a greater number of phenomena with fewer assumptions, it is a more compelling description of reality. This principle is also based on an intuition: it makes little sense to explain something “the hard way” (e.g., one independent theory for each phenomenon), if it is possible to do it “the easy way” (e.g., one common theory for all the relevant phenomena). Though, it has the authority of a long-standing standard of last resort in science, where hallmark discoveries are commonly associated with insights that reduce complex appearances to simple common mechanisms. Accordingly, it is not enough to conclude that one approach to the nature of
wave interference is classical, while the other is not. If the principle of non-interference was found to be more parsimonious, it would be reasonable to treat it as ontologically preferable despite its non-classical features, as long as it did not entail any contradiction with observable phenomena. In any case, this is how modern physics is generally interpreted.

The purpose of this chapter is to determine: which of the two interpretations of linear superposition can survive Ockham’s razor? If waves are assumed to pass through each other unperturbed, associated quantitative tools are often simpler. The question is: do we get a simpler ontology? Do we acquire the ability to explain more phenomena with a common mechanism, when compared to the assumption that wave interference is real? This problem is going to be tackled by reviewing the properties of superposed optical beams distinguishable by polarization, frequency, and direction of propagation. It will be shown that superposition results in observable net states that can be reproduced with single beams as well. The physical properties of these two types of phenomena are identical, quantitatively as well as experimentally. Yet, the principle of non-interference requires different underlying mechanisms for each of them. In contrast, the assumption of real interference requires a single straightforward mechanism. Therefore, the non-classical interpretation is also the one that fails the test of parsimony.

A. Beams with different polarization

The most convenient tool for studying the interaction of polarized beams, in our experience, is the Mach-Zehnder interferometer with collinear output beams in each channel. Consider the set-up shown in Fig. 8, in which linear polarizing filters are installed in each path, as well as in the output channels. Assume that the interferometer is properly aligned, such that the two component beams are in phase in one output channel (towards the filter F3, and out of phase in the other. If the axis of one polarizer (F1) is parallel to the horizontal plane, and the other one (F2) is parallel to the vertical plane, the filtered beam polarizations are orthogonal to each other. What happens when these beams arrive at the analyzer F3? We apply Malus’ Law to predict the amount of light that will be able to pass through. As a reminder, this law states that the proportion of transmitted light must be equal to the cosine squared of the angle between the plane of polarization of the beam (α) and the axis of the analyzer (γ):

\[ I_{\text{out}} = I_{\text{in}} \cos^2(\alpha - \gamma) \]  

(10)

When (α - γ) = 45°, the proportion of transmitted radiation is 50% (ignoring the unavoidable losses at the intervening optical surfaces). Indeed, only half of each beam is transmitted, when they are open one a time. The outcome is the same if the beams are filtered in the diagonal plane, or the anti-diagonal plane, because the absolute value of (α - γ) is the same in both situations. However, things are very different when both beams are open at the same time. Two coherent linear states of polarization produce a net state that is also linearly polarized, in the median plane, if the superposed components are in phase. In this case, the net state corresponds to the diagonal plane. This means that all the radiation must pass through the filter F3, if the latter is aligned in the diagonal plane, and all of it must be blocked if the filter is aligned in the anti-diagonal plane, in accordance with Malus’ Law. This expectation is confirmed by experimental observations. For all intents and purposes, the sum of the two output beams behaves as if it was a single beam with diagonal polarization. At the same time, the net state in the other channel of the interferometer (where the components are out of phase) behaves as if it was polarized in the anti-diagonal plane.
as confirmed by the amount of light reflected by PBS1.

If we assume that interference is real, then component states are not physically relevant. This explains why the net state is able to pass entirely through the diagonally oriented analyzer F3: no radiation is being reflected. In contrast, if interference is assumed to be an illusion, then beam components must behave in the same way, whether present alone or in superposition. During the interaction with F3, only half of the horizontal component must be assumed to pass through, as well as half of the vertical component, but the resulting components with parallel polarization must be assumed to produce the appearance of interference. If the irradiance of beam 1 in the relevant channel is designated as $I_1$, the amount of light that passes a polarizing filter is determined by $I_1 \cos^2(\alpha - \gamma)$. If the irradiance of beam 2 is designated as $I_2$, then the amount of this beam that passes the same filter is given by $I_2 \cos^2(\beta - \gamma)$. Note that both components are polarized in the plane of the analyzing filter at the output. If these values are plugged into the interference equation for beams with parallel planes of polarization:

$$I_t = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \theta$$

the amount of light transmitted by F3 is given by:

$$I_t = I_1 \cos^2(\alpha - \gamma) + I_2 \cos^2(\beta - \gamma) + 2\sqrt{I_1 I_2} \cos(\alpha - \gamma) \cos(\beta - \gamma) \cos \theta \quad (12)$$

where $\theta$ is the phase difference between the component beams in superposition. This expression can also be derived by expanding equation (10) for the net state, where the amplitude of the net state is represented as the vector sum of the two component amplitudes. Hence, the quantitative predictions are necessarily equivalent in either scenario, with or without real interference. In the specific example described above, with two orthogonally polarized beams and a diagonal analyzer, the long expression (12) simplifies to:

$$I_t = \frac{I_1}{2} + \frac{I_2}{2} + \sqrt{I_1 I_2} \cos \theta . \quad (13)$$

Note that Malus’ Law predicts the amount of light that is blocked or reflected by an analyzer as proportional to the sine squared of the original amount. This implies that the amount of reflected light for two beams in linear superposition must be:

$$I_t = I_1 \sin^2(\alpha - \gamma) + I_2 \sin^2(\beta - \gamma) + 2\sqrt{I_1 I_2} \sin(\alpha - \gamma) \sin(\beta - \gamma) \cos \theta . \quad (14)$$

This can be verified empirically by rotating the analyzer F3, or by replacing it with a polarizing beam-splitter. Again, for the specific example considered above, expression (13) simplifies to:

$$I_t = \frac{I_1}{2} + \frac{I_2}{2} - \sqrt{I_1 I_2} \cos \theta . \quad (15)$$

Equations (13) and (15) exhaust all the energy that is present in the channel under consideration, and they are empirically accurate. If they are taken into account together, it is hard not to notice that the same amount is subtracted from one expression and added to the other. This relationship also holds for the outputs of PBS1 in the second channel of the interferometer. In short, we can say that the net state is an illusion, because component interference results in just the right amount of added or missing energy to mimic its behavior. According to the principle of non-interference, each input beam is split by PBS1 in the same way, whether one of them or both are open at any point in time. It just so happens that the net state in the transmitted path cancels out the same amount of energy that is revealed in surplus in the reflected path, when the components are simultaneously present. In the considered example, where $\cos \theta = -1$, we get one dark channel and one bright channel that seems to acquire all the energy. Though, we should assume that this apparent transfer is non-physical, because the two components are presumed to continue their propagation unperturbed in each channel. Also, as discussed in section II, we should pretend that amplitudes are split 50-50 in order to explain this process without interference, even though the equations (11) – (15) work at the level of irradiance.

It might seem that the non-interaction principle is verifiable in this context. In the reflected path of PBS1 (Fig. 8) with the fast axis in the diagonal plane we have the appearance that the energy has doubled, like in any other bright fringe. In the transmitted path we have the appearance that energy has vanished, like in any other dark fringe. Yet, either output beam can be split again with polarizing beam-splitters, in an attempt to reveal the hidden components. For example, the dark projection can be split again with PBS2, aligned with the fast axis in the vertical plane. That should make the energy visible again, effectively extracting energy from a dark fringe. Similarly, by splitting the bright beam into vertical and horizontal sub-components, it should appear to lose half of its energy. Though, if that was the case, then a violation of energy conservation would follow when the dark fringe was split while the bright fringe was not. In actuality, the dark channel remains dark forever, and the bright fringe does not lose energy spontaneously. This can be explained by taking into account the details of the interaction between the input beams and the polarizing beam-splitter. Prior to reaching PBS1, the vertical and the horizontal beams are assumed to be distinguishable. If the PBS1 were rotated with the fast axis in the horizontal plane, the mixture would separate into its components, and we would assume to know where each output comes from. Vertically polarized light must come from F2 and horizontally polarized light must come from F1. (In quantum mechanics, the equivalent of this would be path knowledge). In contrast, the diagonal components from each beam are indistinguishable behind PBS1 (if it is rotated back to transmit diagonally polarized light).
The same holds for the anti-diagonal components in the reflected path. Ergo, PBS2 is still assumed to receive 50% of the beam energy when the channel is dark, but the components with parallel polarization are assumed to cancel out even after being split, producing the appearance of zero energy at each output. Similarly, PBS3 can split the bright channel into two components, one vertical and horizontal. Yet, these components do not revert to lower levels of energy, because they result from indistinguishable diagonal components form both input beams. In other words, we must assume that our measurements of irradiance are wrong, because the energy only appears to be doubled due to interference. Yet, it will stay wrong forever, because the two components cannot be made distinguishable again.

To sum up, the principle of non-interference implies that we can never know what we measure. A linearly polarized beam could be a true single beam, whose measurable energy corresponds to its actual content. Though, it could also be a coherent mixture of two indistinguishable beams with half the “true” total energy. No physical marker is available for distinguishing these states. Indeed, a true linearly polarized beam can also be described as if it was made of indistinguishable components. The only difference between these states is found in their history. One beam is traceable directly to it source, while the other has passed through several optical devices such as to produce a twin beam with zero detectable energy (and half the “true” energy). On the other hand, it is possible to avoid the need for such distinctions, if the interference principle is assumed to be valid. In this case, the net state of two overlapping beams (or more) must always be treated as real. Simultaneous oscillations in different directions at the same point are not possible in this context. So, when the two orthogonally polarized components are mixed at NPBS2, they must suffer the necessary physical transformation, in order to become a single-state beam with linear polarization in the diagonal plane. As such, the net state is reflected unchanged by the PBS1, without anything available for transmission. This state cannot be assumed to contain any path knowledge, because the first filtration is identical to the second. Moreover, there is no need to assume the reality of undetectable dark beams with hidden energy. If two beams appear to be identical, then they must be assumed to be physically identical.

This conclusion is not just a peculiarity of superposition in the MZI. A similar situation emerges if a Young interferometer is used instead. As shown in Fig. a coherent source of light can be blocked by a screen with two slits, where each slit is covered by a linear polarizer. If one filter is oriented vertically, while the other is horizontal, the far-field projection of this double-slit setup appears featureless, without fringes. Still, if the transverse plane of the projection is scanned with a narrow slit and a linear polarizer, it will be observed that some regions are linearly polarized in the diagonal plane (where vertical and horizontal components are in phase), others are anti-diagonally polarized (where they are out of phase), with elliptical states of polarization in-between. This property can be exploited by placing a second screen with two slits in the path of the projection. One slit must be carefully positioned in a region where the output is diagonally polarized, while the other should fall on an adjacent region with anti-diagonal polarization. This time, the slits are not covered with any polarizing filters, but it can be confirmed with additional measurements that output light is linearly polarized, as described, in two orthogonal planes (diagonal and anti-diagonal). The far field projection of the two slits from the second screen will be featureless again, but the whole projection can be filtered with a linear analyzer (F5), revealing fringes in the horizontal plane. Similarly, by rotating the analyzer to the vertical plane, a set of anti-fringes will be discovered. What is the physical process behind this observation? Assuming non-interference, we must take it for granted that diagonal and anti-diagonal polarizations behind the second screen slits are illusory. We must assume that horizontally polarized light from the H slit of the first screen has passed through both slits, producing the appearance of bright fringes. Hence, all the light that is seen in the presence of the horizontal filter must come from that slit. The filter has blocked all the light from the V slit. On the other hand, when the filter is rotated to the vertical plane, the light from the H slit is blocked and we see fringes produced only by light from the V slit of the first screen. Here is the twist: the slits on the second screen can be covered with linear polarizers as well. If a diagonally polarizing filter is placed over the slit that emits diagonally polarized light, the projection remains unchanged, as far as physical observations are concerned. Similarly, the slit with anti-diagonally polarized radiation can be covered with a filter that is oriented in the same plane. After this modification, the far field projection suffers no consequence, and the same types of fringes will be observed with the linear filter used for analysis. Yet, this time we must assume that we are dealing with indistinguishable half-beams with illusory extra energy, like in the MZI set-up described above. Hence, we must describe the same fringes as a result of superposition of diagonal and anti-diagonal polarizations, rather than original vertical and horizontal polarizations. In the absence of filters at the second screen, we are supposed to have path knowledge. In their presence, the situation is radically different, even though every subsequent measurement would produce the same observations. Again, a pure classical interpretation would suggest that we have the same physical process in both situations, because the net state is always the only real state. We do not need to know how the plane of polarization became diagonal or anti-diagonal, because that does not change its nature. As explained in the previous chapter, the net state of two superposed beams cannot be expected to separate into input components behind a slit that is narrower than an interference fringe. Whether we assume that the net state is real or illusory, observable measurement
FIG. 9. (Color online) **Free-space interference between polarized beams.** This is a superposition of two double-slit experiments. The two slits at Screen 1 are covered with orthogonal linear polarizers. The upper slit emits radiation with horizontal polarization. The lower slit projection is vertically polarized. At Screen 2, the lower slit is centered on the point where components from V and H have zero path difference. The center of the upper slit corresponds to a point with a path difference of $\pi$. If the H slit at Screen 1 is open alone, a double slit interference pattern can be seen at Screen 3, in the absence of filters F3, F4 and F5. Similarly, slit V alone produces a complementary fringe pattern. If both slits are open at the same time, a continuous pattern is observed (image [a], to the right). Filter F5 can reveal a set of fringes if it is horizontally aligned (image [b]), and a set of anti-fringes in the vertical alignment (image [c]). If looks as if F5 blocks light from the V slit, or H slit, as the case may be, revealing undisturbed components from each source. Yet, the projection from the lower slit at Screen 2 is linearly polarized in the diagonal plane. 100% of it passes through the filter F4, which has a diagonal axis of polarization. The upper slit projects a beam with anti-diagonal polarization. It also appears to pass entirely through filter F3 (with anti-diagonal axis of polarization). The presence or absence of filters F3 and F4 has no qualitative effect on the observable projections at Screen 3, when both slits are open at Screen 1.

In conclusion, the assumption of non-interference requires a very complex model of superposition for polarized beams. At every interaction with measuring devices, we have to allow for the possibility of unobservable projections with “real” energy, implying that the energy of observable projections is not real. Yet, the unobservable and the observable states are irreversible, suggesting that all the real effect of bright fringes come from unreal energy. More importantly for this discussion, the assumption of non-interference implies that physical observations (and the equations that fit them) are indeterminate. Whenever we detect a beam with linear polarization, we cannot know if it is an “actual” single-mode projection, or a mixture of two components with half the total energy, overlapping in phase. Two different mechanisms are required for the same type of observations. Moreover, we cannot determine which is which by doing measurements, even though this is a classical state. The only way to distinguish the two hypothetical scenarios is by acquiring the full prior history of the projections, all the way to the source. Yet, after all the extra work, we cannot expect a matching compensation, because this interpretation does not entail any new prediction. The subsequent behavior of the beam in question is going to be the same in any experimental setting, regardless of its mechanism of emergence. This is because the outcomes are the same in the alternative scenario, where interference is assumed to be real.

B. Beams with different frequencies

The concept of non-interference appears to be less confusing in the case of interactions between beams with different frequencies. Consider the interaction of two monochromatic laser beams with visible differences in color (for example, red and yellow, as in Fig. 10A), which intersect at a narrow angle. Each beam can be traced visually along its path. Of course, colors are mixed in the volume of overlap, but they are unmistakable before and after the interaction. The red beam is clearly seen going in and coming out unchanged (especially if dust particles are present in the air). The same is true about the yellow beam. How can a beam come out unchanged and not be the same? Furthermore, one beam can be analyzed with a detector while the other is blocked intermittently at the source. The open beam looks the same whether it is present in the interferometer alone or not. For this reason, it seems counterintuitive to even suggest that the beams do not go through each other unperturbed. Yet, the ultimate physical nature of electromagnetic radiation is still not perfectly understood. For all we know, it could be based on a process that involves real waves or is oth-
FIG. 10. (Color online) **Interference between beams with different frequency.** A monochromatic red beam intersects a monochromatic yellow beam. (A) The net state of superposition behaves like a monochromatic orange beam that is variably amplitude modulated in the cross-section. Yet, the output beams look identical to the input beams, as if they just passed through. (B) The same net state of superposition can be generated by passing a monochromatic orange beam through a suitable hologram of intersecting red and yellow beams. The physical role of the holographic plate HP is to modulate the amplitude of the image-forming component of the monochromatic input beam. If the left side of the drawing (B) were covered, it would seem “obvious” that a red beam has passed through a yellow beam. Still, this is impossible, because red and yellow components are not physically present at the input side. This gedanken experiment is based on real findings, some of which are referenced in the text.

Otherwise compatible with the basic principles of classical mechanics. If so, then we have to allow for the possibility that two modes of oscillation are not simultaneously possible in the same point in space, and only the net state of the superposition of two waves is physically real. In other words, the beams may appear identical before and after overlap, but it is not an indisputable fact that the energy in one output comes from a single input. The beams can be assumed to transform into the net state, which then evolves into the observable outputs because of the existing symmetries in the underlying physical interactions. Remarkably, the quantitative aspects of these two models are equivalent. As shown above, and also as demonstrated by Dowling and Gea-Banacloche [2], the two alternative assumptions about interference entail the same macroscopic observations. Hence the problem is not that one model makes better predictions than the other. The question is whether we can increase our interpretive power by invoking non-interference.

The mixture of beams with different frequencies is well understood theoretically and is commonly analyzed in terms of Fourier synthesis. The main features of this process are captured by the following identity:

$$\cos(\omega_1 t) + \cos(\omega_2 t) = 2 \cos(\omega_m t) \cos(\omega_0 t)$$  \hspace{1cm} (16)

where $\omega_1$ and $\omega_2$ are the angular frequencies of two input beams, while $\omega_m = (\omega_1 - \omega_2)/2$ and $\omega_0 = (\omega_1 + \omega_2)/2$ [26]. In other words, whenever we mix two beams with different frequencies, the net state behaves as a new beam with a carrier frequency $\omega_0$ that is equal to the average of the input frequencies. The important feature of this new state is that its envelope is modulated with a beat frequency $\omega_m$ that is equal to half the difference between the input frequencies. Accordingly, if one assumes that non-interference is real, then only the left-hand side of the equation (16) is physically significant. In contrast, the right-hand side of this equation must be assumed to be real if the interference principle is preferred. The identity relationship captures the quantitative equivalence of the two models. Is it possible to tell which model is ontologically accurate, despite their mathematical equivalence? Recently, Lee and Roychoudhuri (L&R) attempted to answer this question with a series of didactic experiments [27]. They reported a remarkable observation. If a mixture of two different frequencies is analyzed with a wide-band photo-detector, the recorded pattern is consistent with the features of the right-hand side of the equation (16). However, if the same mixture is detected with a high-resolution Fabry-Perot spectrometer, the beam is not transmitted at the average frequency ($\omega_0$). Instead, only input frequencies ($\omega_1$ and $\omega_2$) are able to sustain the necessary resonance for passing through the cavity. Moreover, the same mixture was unable to produce fluorescence in a rubidium (Rb) atomic vapor, if the average frequency ($\omega_0$) was centered on a natural Rb transition line, in contrast to the case when input frequencies ($\omega_1$ or $\omega_2$) were centered on the same line. In short, narrow-band detectors could not see the frequency of the net state. Doesn’t this prove that the net state is non-physical? If it was real, why did it not show up in the relevant experiments? If the input states are no longer real, why did they produce the observed resonance?

In order to answer these questions, another group (Gilra et al., [26]) performed a similar series of experiments without mixing two input frequencies. Instead, they used a monochromatic laser beam whose envelope was modulated with an acousto-optical modulator. In this manner, they produced an optical state with the exact properties that would have been possessed by the average frequency of two different beams. Hence, they created a beam that corresponded directly to the right-hand side of the equation (16), and was therefore real. As expected, the carrier frequency was observed with wide-band detectors. Yet, narrow band detectors failed to see it again, just as in the experiments of L&R. Instead, both the Rb vapor and the Fabry-Perot cavity “recognized” the virtual frequencies that would have been required to produce the same net state with two beams. Technically speaking, the right-hand state of the equation (16) was broken down into its left-hand side components, which
is known as Fourier decomposition. Gilra and collaborators also provided a very sound interpretation of the interaction between modulated beams and spectroscopic detectors, demonstrating that Fourier decomposition can be described in a physically meaningful way without violating the principles of classical mechanics. In particular, they explained how amplitude modulation can prevent resonance at the carrier frequency and enable it for down-converted components in narrow-band filters. As a corollary, it does not matter if the complex modulated state is produced by mixing two input frequencies, or by suitably modulating a single input frequency. The products of the two situations are experimentally (and not just mathematically) indistinguishable.

As mentioned at the beginning of this section, the superposition of an ideal red beam with an ideal yellow beam appears exclusively compatible with the principle of non-interference. Yet, this perception is based on partial knowledge. For a proper conclusion, it helps to know that an ideal orange-colored laser beam can be induced to split into a red beam and a yellow beam just by modulating its amplitude, with suitable phase delays between the beat frequencies of adjacent points in the cross-section (Fig. 10). When the superposed state is generated by two beams, it seems “clear” that they just pass through without interaction. Yet, when the same state is produced by a single beam, it is just as “clear” that unperturbed passage is impossible. The two net states are mathematically identical by design, and every detectable property of the output beams is going to be similar in both contexts. Accordingly, the evidence is not exclusively compatible with a single interpretation. A choice must be made on the basis of independent considerations. The interference principle entails a unified model, by treating the net states as if they were physically identical in both cases. Incompatible oscillations cannot coexist at single points in this model. In contrast, the concept of non-interference entails that we are dealing with two different mechanisms of propagation, just like in the case of polarized beams. When two input beams are used, the net state is “really” made of two independent beams. When a single input beam is modulated, the net state is “really” monochromatic. Though, we cannot tell the two situations apart by doing measurements on the superposed or the output states. The only way to distinguish the two scenarios is by learning the prior history of each context. Remarkably, this extra information cannot influence any prediction about the future state of the output beams. Moreover, the limited claim that beams can sometimes pass through each other unperturbed is not necessarily true, even when the presence of two input beams is verified. The evidence is equally compatible with the interference principle, which excludes this possibility.

C. Beams with different directions of propagation

Finally, let us consider a simple experiment, in which two coherent beams are collimated and allowed to intersect at a very narrow angle, producing the appearance of fringes in the interference volume. In the absence of any disturbance, the beams will eventually separate from each other and become clearly distinguishable. According to the principle of non-interference, the fringes in the interference volume are illusory. Light from each beam is uniformly distributed in the cross-section, but the amplitudes of each component add up constructively or destructively. The rays from each source of light simply pass through each other. Next, suppose that the interference volume is blocked with a screen, and only a fringe is allowed to pass through a slit. The size of the slit is carefully selected and the screen is positioned such that the edges of the slit are in the centers of consecutive dark fringes. As far as appearances are concerned, the edges of the slit do not produce any scattering - they are in dark regions. Yet, the light that passes through does not separate clearly into two beams - we are at the boundary of the Rayleigh criterion. If we now repeat the procedure for each bright fringe, it will become obvious that none of the fringes is able to separate into two beams. However, if we put very narrow obstacles at the center of each dark fringe, as if the edges of a slit are still present there, and open all the fringes at the same time (essentially, each bright fringe goes through its own wide slit), we see very good beam separation, as if there are no obstacles at all in the path of the beam. This is the well-known Afshar modification of the double-slit experiment [22, 28]. It has been hotly debated and there are numerous equivalent ways to interpret it [23, 29, 30]. Some of our own results on this topic are summarized in Fig. 11.

For the purpose of this discussion, we must distinguish only two main interpretive approaches. On the one hand, we could assume that the interference principle is real. In this case, we must also assume that there is no energy in the dark fringes, because all of it is channeled through the bright fringes. This explains why there is no diffraction when both beams are open, even though significant diffraction is visible when they are open one at a time. The beams are expected to separate well with or without the obstacles, because the underlying physical mechanism is the same in both situations. Furthermore, beam separation is only possible when all the bright fringes are open, because they have to overlap with each other for this effect. The net state contains all the energy in bright fringes, and it evolves into a pattern with two beam-like projections, as predicted by the Huygens-Fresnel formalism. On the other hand, we could also assume that non-interference is real. In this case, the explanation is a little more intricate, but still plausible [23]. If the reality of interference is denied, we must assume that diffraction at the obstacles for both beams together is the same as in the case when the beams are open one by one. This means that the input beams no longer pass through the
FIG. 11. (Color online) **Several illustrations of the Afshar effect.** A) Two coherent laser beams intersect at a very narrow angle (figure not to scale). The aperture AG contains a single strand of human hair, stretched in the vertical direction. If the obstacle is positioned in the center of a bright fringe, excessive diffraction washes away the separation of the beams (top image on the right) and the strand glows brightly (not shown). There is less diffraction if the beams are open one by one (middle two images). Diffraction becomes negligible if the hairline is placed in the center of a dark fringe (bottom image). B) Similar set-up with convergent beams. This allows for better beam separation and wider fringes in the interference volume. Two 40ga wires are placed across the aperture AG (each in a dark fringe). The power meter PM records the irradiance of a single beam, after separation. The blue trace (right image) shows a square drop in irradiance, observed when the unmeasured beam was momentarily blocked, preventing interference. The red trace shows a continuous variation of irradiance, recorded when fringes drifted across the obstacles due to the displacement of the mirror M at sub-wavelength intervals. Peak irradiance was recorded when the wires were at the center of dark fringes. Notice that the obstacles induced a larger drop in irradiance at the center of bright fringes (red trace), compared to the case of non-interference (blue trace). C) Estimated net energy distribution in the x-z plane of the original Afshar set-up. Each blue dot represents the center of a volume that contains 4% of the input energy of one beam. In ideal conditions, the separated beams look the same with or without the wires in dark fringes (black circles). Yet, the presence of such obstacles makes it impossible to describe output beams as identical to input beams. Even if the underlying propagation of radiation is assumed to be rectilinear, without flowing around the obstacles, output beams have to be described in terms of interference effects, as suggested by the drawing on the right.
volume of superposition unperturbed. If their diffracted projections on a remote screen are summed up, fringe by fringe, taking into account the phase and amplitude of each component at every point of detection, it will turn out that the net state adds up to zero almost everywhere, effectively erasing the appearance of scattering. At the same time, there will be two regions where the components will add up constructively, producing the appearance of two separated beams. If we measure the power of these two “bright fringes”, it will be nearly equal to the power of the input beams, as if the energy has flown around the obstacles in the volume of overlap. In other words, the two output beams must be interpreted as illusory, because the actual radiation is widely scattered in space. The identity relationship between input and output beams is denied, just like in the case of real interference, but for a different reason. When there are no obstacles in the dark fringes, beams are really assumed to pass through. When the obstacles are present, they are really assumed to scatter widely, even though the apparent projections are identical in both cases. It is somewhat ironic that the motivation behind non-interference models was to avoid the complex calculations that are associated with Huygens’ Principle, yet the same model had to be invoked in order to explain the outcome of the Afshar experiment. Not only is non-interference conceptually challenging, it turns out that even its methodological advantages have a limited scope.

To make things even more complicated for this model, the nature of output projections is undefined even if there are no obstacles in the dark fringes. As mentioned already in the preceding sections of this chapter, the net state of two superposed beams can be mimicked by modulating a single input beam. In the case of intersecting coherent beams, this has been demonstrated with holographic tools. When a single reference beam illuminates the hologram of two superposed beams, it can faithfully replicate their properties. Behind the holographic plate, it is possible to observe interference fringes and even beam separation, as if two input beams are passing through. In actuality, the holographic projection is made by light scattered from a single input beam. The plate works as a filter that controls the amplitude and phase profile at every point in the cross-section of the projection. As predicted by the Huygens-Fresnel model of wave propagation, the net state at any front line is sufficient to reproduce the subsequent dynamics, regardless of the conditions that produced it. In some contexts, it is generated by two superposed beams. In others, it can be engendered by modulating a single beam. This phenomenon shows that net states are not just hypothetically real. In many cases, they are undeniably so. Yet, the principle of non-interference forces us to invent two different theories, even though any observable property of these states is identical in both scenarios.

In conclusion, we see that the process of interference can be fully interpreted by two incompatible models. Both of them make the same predictions and often rely on the same (or demonstrably equivalent) mathematical expressions. The two models are only incompatible in the interpretive dimension. The principle of non-interference has become an integral part of classical physics, and it seems to be widely taken for granted as a Newtonian process. As shown at the beginning of this text, it is actually a non-classical mechanism, requiring the assumption of non-locality in the analysis of both motion and energy, and also leads to several conceptual inconsistencies. We asked if these shortcomings were compensated by some unexpected interpretive advantage when particular applications were considered. After reviewing the properties of superposed beams distinguishable by polarization, frequency and/or direction of propagation, this sort of benefit was not found. Quite the opposite: physical observations (and the equations that fit them) became indeterminate in this context. Whenever a beam is measured, it is impossible to tell if it is an actual single-mode projection, or a mixture of two components with illusory energy content, even though it is a classical state. The only way to know the “truth” is by acquiring the full prior history of the projections, all the way to the source. Yet, we cannot extract anything consequential out of such information, because this interpretation does not entail any new prediction. The subsequent behavior of the investigated beam is going to be the same in any experimental setting, regardless of any hypothetical distinction in its nature. In short, we need two explanatory models for a single type of observations, even though it is possible to interpret both scenarios with a single classical mechanism. Moreover, each of the two models of non-interference is more complicated than then single construct that replaces them if interference is assumed to be real. As a corollary, non-interference cannot survive Ockham’s razor.

IV. QUANTUM IMPLICATIONS

The principle of linear superposition tells us that the net effect of two waves on a single point is reducible to the individual contribution of incident components. Though, it cannot help us decide which states are real during overlap: the individual inputs or the net output? We have a mathematical equality between the two alternatives, as well as an experimental equivalence, as shown above. Accordingly, it does not seem to matter which model is chosen: when every detail is taken into account, the final predictions are the same in each case. With this in mind, it is worth asking: what difference does it make if we prefer one story or the other? If we assume that waves do not interact, we get a non-classical picture, as well as many complications, but it still works. This has been the favored model for many generations of scientists. Why do we have to reconsider it? The answer is that interpretations are based on hypotheses about underlying (microscopic) processes. In effect, they are theories about quantum phenomena. The concept of
wave non-interference was part of the mainstream since at least the 19th century, before the development of tools for testing such assumptions. Yet, quantum mechanics is now widely believed to falsify the validity of classical mechanics at the microscopic level. This means that the descriptions of classical processes, such as interference, are not compatible with the known microscopic phenomena. Ergo, prevailing interpretations of classical phenomena are incompatible with quantum observations. What if we tried to interpret classical wave superposition with a truly classical model, in which interference is real? Would we still get a conflict with quantum mechanics?

Many quantum phenomena result from wave-like interactions, and they are predicted on the basis of wave-function analysis. Remarkably, the principle of superposition applies in this context as well, except we have a non-local version. In classical physics, superposition is described as a coincidence between two entities with well-defined states. In quantum physics, we have single entities that are described as undefined, because they occupy multiple states at the same time [41]. This can be illustrated with coherent beams of light that have orthogonal polarization. They can be obtained by splitting a single laser projection in two, and then placing polarizing filters in each path (e.g., one horizontal, and one vertical). At the classical level, the beams are continuous. If they are forced to overlap in phase, the net state is a beam with diagonal polarization (as shown in Fig. 8). So, the beam will be transmitted in full by a polarizing beam-splitter with diagonal fast axis, if both paths are open. In contrast, each component must send 50% of its energy in the reflected path, if it arrives at the analyzer alone. The same type of behavior is observable at the quantum level. If the source is attenuated, it is possible to observe discrete detection events. Various control experiments can be used to show that detection events are most likely produced by indivisible wave-packets [42]. Yet, these single wave-packets display all the features of superposition. When both paths are open, they are always detected in the transmitted path. When one path is open at a time, half of them trigger detections in the reflected path. This shows that single quanta display the properties of a net state that requires two real components (or more) in the context of classical mechanics.

The most remarkable feature of quantum distributions is their similarity with classical detection patterns [43]. Discrete photons are supposed to have a non-classical nature because they are able to reproduce the behavior of continuous beams. To be exact, the problem is not that they are discrete. Rather, it is their undefined nature. Unlike classical particles, they are required to be in several states at the same time. Why are they described like that? The answer is found in the details of classical interpretations of superposition. When the governing assumption dictates that waves do not interfere, the net state can only be described as an illusion. This means that the diagonal polarization in the preceding example is assumed to be produced by the combined effect of two real states of polarization (horizontal and vertical). In other words, the classical beam is in two states at the same time. For this reason, a single photon in the state of the same beam must also be described as if it was polarized in two planes at the same time. Consequently, we have no choice but to describe a quantum with non-local concepts: it has to move in two directions at the same time, be in two places at the same time, and so on. Nevertheless, the mainstream interpretation is not the only one that works at the macroscopic level. As shown above, it also violates the spirit of classical mechanics. In contrast, if we assume that interference is real, then the net state must also be treated as real. This means that the polarization of the output beam is really diagonal in the preceding example, whether we are looking at continuous or discrete states of light. As a corollary, the same single photons can now be described as well-defined, without any change in their quantitative description. Diagonal states of polarization are mathematically equivalent to the sum of two orthogonal states of polarization (assuming equal intensity and phase coherence). This means that we get the same predictions, regardless of the associated interpretive assumptions. On closer inspection, it turns out that this conclusion can be generalized to every quantum phenomenon where multiple states are found in superposition. Wherever it is possible to describe a quantum as if it was occupying multiple states at the same time, it is also possible to say that it belongs to a system that occupies the single net state. Ergo, quanta in “Schrodinger’s cat” states can always be interpreted as entities with well-defined properties. This does not mean that real cats can be in the net state of “dead + alive”. Detection events are never superposed (viz., the measurement problem). It is the net state of a quantum that determines the probability of generating one type of event or another. In short, the nature of our interpretive conclusions at the microscopic level is not determined by the details of our observations, but rather by the interpretive choices at the macroscopic level of analysis. If we switch to a classical interpretation of superposition at the classical level, we also get a classical interpretation at the quantum level.

A similar sensitivity to macroscopic preferences is demonstrable for the principle of quantum complementarity. The latter was developed by invoking explicitly the double-slit experiment [44, 45], which makes it particularly relevant for this discussion. When two beams of light intersect, they seem to go through each other as if they never meet. The principle of non-interaction holds that this is, indeed, the case. Interference fringes are detectable in the volume of overlap, but they are described as mere appearances. By implication, if microscopic bits of light were detected one by one in the interference volume, they would be resolved in their “real” state during overlap and shown to display continuous distributions. These elements of light must continue propagating undisturbed, with rectilinear trajectories, as suggested by the method of ray tracing in geometrical optics, and carry
path knowledge past the interference volume. Unfortunately, quantum experiments falsified this expectation. Populations of single quanta were found to display interference fringes just like classical beams, and also to separate into distinguishable beams after crossing the volume of overlap. Obviously, this was a big problem, and the solution was to introduce the principle of complementarity. According to this new story, single quanta were presumed to produce fringes only when directly observed. Otherwise, they were still assumed to remain unperturbed and to carry path knowledge all the way from the source to the detector. In other words, two complementary realities were assumed to take place, associated with two incompatible observations. The human choice between alternative measurements determined which reality played out. Such an interpretation seems necessary because it is impossible to describe a plausible physical model in which path knowledge and interference knowledge are simultaneously present. Nevertheless, it is possible to describe a physical reality in which quantum interference and beam separation are possible in the same course of events. This is the scenario that follows naturally from the assumption that wave interference is real. In this case, microscopic bits of light are naturally expected to flow through the bright fringes (avoiding the dark ones) and to separate into distinguishable projections afterwards. Of course, path knowledge is no longer assured in this case, and the output beams are only quantitatively similar to the input beams. Still, this interpretation is able to explain quantum phenomena without inconsistencies. Accordingly, any belief about non-classical quantum behavior in this context depends on a commitment to non-classical interpretations of classical wave interference. The Copenhagen interpretation is only meaningful if the principle of non-interference is taken for granted.

These examples suggest that quantum mechanics can be interpreted as a theory with well-defined local objects. Such an outcome is generally perceived as impossible, because of the EPR paradox [46]. Entangled quanta have identical properties. Therefore, one can obtain exact information about incompatible variables by measuring several populations of entangled quanta with different devices. This appears to imply that all of those properties are well-defined prior to measurement, in violation of the uncertainty principle. Yet, well defined entities in such states must necessarily obey Bell’s inequality. The unexpected finding, supported by numerous careful experiments (starting with [47–49]), is that quanta violate this rule. The paradox is that we need entangled systems to reveal the apparent reality of complementary properties, but the same entities violate Bell’s inequality and thereby refute the implication of reality. That is why it does not work to assume that well-defined population components exist in the absence of measurement. For example, when there is a beam with two components of polarization – vertical and horizontal – it is tempting to assume that some photons are vertical while others are horizontal, but this would entail a contradiction with empirical observations. The correct way to describe single quanta of light is by assuming that each of them is in both states of polarization at the same time. This is what makes quantum mechanics so hard to comprehend: a single entity must oscillate in two incompatible directions at the same time, like the classical beam as a whole. Then again, what happens to a classical object, such as a rope, when it is agitated in two orthogonal planes at the same time? It must respond to both actions by oscillating in the diagonal plane (assuming phase coherence). From a mathematical point of view, the rope is in a state of oscillation that is equal to the two input states. Hence, it does contain both states at the same time. However, the physical reality is that the rope cannot oscillate in opposite directions. It must remain well-defined by oscillating in the net state. If two identical ropes were measured simultaneously – one in the vertical plane, and the other in the horizontal plane – it might seem as though the rope had real states of vibration in each plane. Yet, as a physical description, such a conclusion would be wrong. A pair of ropes would also violate Bell’s inequality in terms of oscillation components, because it is the net state that determines the measurement outcomes. Accordingly, a classical photon can also be described as being in a superposition of two states of polarization, if in fact it is polarized in the net state (Fig. [12]). The EPR paradox was produced by the assumption that component states of superposition are real, while the net state is not. Such a belief can only seem necessary if the principle of non-interaction of waves is taken for granted. Even so, this is purely an interpretive preference. If $A + B = C$, then the two equal expressions are interchangeable. It is just as valid, from a quantitative point of view, to assume that the component states are real, or that the net state is real. Accordingly, it is possible to switch to the principle of real interference and avoid the paradox without losing predictive power.

We wish to emphasize that classical interference and quantum interference are formally compatible with each other, as implied by Bohr’s correspondence principle [43]. The gap between macroscopic and microscopic phenomena is not quantitative. We can use the same equations to predict the details of interference fringes in both cases, for large $N$. Continuous beams and discrete populations of photons generate the same types of distributions on detector screens. The gap is rather qualitative: we cannot use the mainstream classical interpretations at the quantum level without running into complications. We are forced to invent incompatible realities and non-local entities in order to fill the conceptual void that is created by the adopted classical interpretive models. Consequently, the experimental record of quantum mechanics does not entail the collapse of classical formal analysis. It only entails a violation of the assumptions that are associated with leading interpretations of classical wave superposition. More importantly, as shown in the preceding chapters, these assumptions are already in conflict with the main principles of Newtonian physics. An equiva-
FIG. 12. Three interpretations of an EPR state. A non-linear source produces low intensity beams of entangled photons pairs. Every photon in the right arm of the set-up has a “twin” with orthogonal polarization in the left arm. For simplicity, the photons in the same arm are assumed to be randomly distributed between two states of polarization only (vertical and horizontal). Also, we assume that even numbers of photons are emitted in phase by the source at any point in time, in order to bring out the differences between interpretations. Every photon is either vertical or horizontal at the source, but the subsequent state can only be determined after measurement. (A): The Copenhagen Interpretation holds that unmeasured indistinguishable photons cannot have well-defined states of polarization. Each propagating photon is assumed to be simultaneously in both states. This property determines the outcome of subsequent measurements for any angle of alignment of PBS1 or PBS2. Bell’s Inequality can be violated in predictable situations. (B) and (C): Classical models hold that single photons have well-defined states at all times, but they can evolve in two different ways. In (B), there is no interference and photons preserve their input states during superposition. Detectors are assumed to resolve individual photons, rather than macroscopic states as a whole. Bell’s Inequality cannot be violated, because the final distributions are produced by unperturbed input states. In (C), interference is assumed to be real, and photons switch from their input states to the plane that corresponds to the net state. In this case, every single photon is assumed to be polarized in the diagonal plane. The distribution of detection events is no longer produced by input states, but rather by the value of the net state, as in (A). Bell’s inequality can be violated. In this context, EPR correlations serve as indicators of real interference. It is not necessary to invoke non-locality for their explanation.
lent interpretation that does not create such difficulties is readily available. We only have to assume that interference is real. When two waves overlap, the net state is real, while the input components lose their physical identity. Of course, this argument does not prove that the Copenhagen interpretation is wrong. It only shows that it cannot be true with necessity. Classical alternatives work at least as well.

V. CONCLUDING REMARKS

Linear superposition and the non-interaction principle have a long common history. In many contexts, it is very convenient to assume that waves can pass through each other unperturbed, with the benefits of simplified algebraic and geometrical representations. Unfortunately, the idea of linear superposition without energy redistribution entails a foundational inconsistency in classical mechanics. If we take it for granted, we need to make several non-Newtonian assumptions about underlying processes (e.g., particles can move in two directions at the same time and transmit momentum without moving at all). Also, we need to use the wrong values for the wave amplitudes in order to make correct predictions (or make additional non-Newtonian assumptions, in order to argue that those amplitude values are correct). In addition, we get the contradictory observation of energy redistribution (despite the starting motivation to avoid it), having to explain it with non-local mechanisms. Furthermore, we end up with indeterminate conclusions in many contexts of observation, because different event histories lead to similar observations. Identical phenomena, described by identical equations, have to be interpreted in different ways, without any compensatory practical benefit. Finally, the microscopic assumptions of this model are contradicted by the quantum-level observations, imposing the necessity to formulate new interpretive models (e.g., the Copenhagen interpretation) for this level of analysis. In order to hold on to the assumption of non-interference, we have to assume that Nature is governed by an inconsistent mixture of laws. This list of difficulties is probably surprising, considering our real life experiences. If waves are examined in a pond, for example, it seems obvious that they pass through each other. Notwithstanding, the Sun also seems to move around the Earth every day. If we take that experience for granted, it is very difficult to unify our Earthly observations with the totality of our knowledge. Likewise, if we take it for granted that waves are transparent to each other, there is little hope of unifying classical mechanics with quantum mechanics.

The main principles of non-classical physics belong to a network of mutually reinforcing assumptions. The latter cannot be proven to be correct or wrong, but their intuitive appeal is heavily influenced by the perceived validity of the non-interaction principle during classical linear superposition. As shown above, quantum superposition and quantum complementarity do not seem plausible otherwise. The strength of these assumptions is also backed by their compatibility with existing formal models that work with unprecedented accuracy. If the equations work so well, how could the interpretations be wrong? Would it not be necessary to invent a better formalism for a better interpretation? The answer is that classical linear superposition provides a common formal backbone for two incompatible interpretations. As soon as we change our story about wave superposition, the same equations in quantum mechanics acquire a radically different meaning. The crucial distinction between “classical” and “non-classical” physics is not found at the boundary between macroscopic and microscopic phenomena. Instead, it is discovered at every level of analysis, where the terms of the most simple equations are mistaken for the most relevant physical elements. More importantly, we do not have to prove that non-classical models are impossible. It is sufficient to acknowledge that classical models are equally compatible with the same equations and experimental data. In our opinion, it should be possible to reclaim quantum mechanics – in its present form – as a classical theory. Our arguments have only covered the direct implications of linear wave superposition, but they justify a wider inquiry into the ontology of quantum mechanics.

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This example will be explained in greater detail in the next chapter.

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