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ON THE INTERPRETATION OF QUANTUM MECHANICS

Abstract If interpretation is a metacognitive process, interpreting a physical theory means identifying the metaphysical concepts suitable for representing its theoretical terms. From this perspective, given the linearity of the formalism of quantum mechanics, its natural interpretation is the one suggested by W. Heisenberg, according to whom quantum mechanics governs the potential level of physical reality, not its actual level.

> Metaphysics is a restaurant that offers a thirty-thousand-page menu and nothing to eat.
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> ROBERT PIRSIG [Pirsig, 1992]
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> Those who have made discoveries in physics have distinguished themselves from ordinary scientists, not by having no metaphysics in their heads, but by having new metaphysical ideas, […] and by connecting their metaphysics with revolutionary theories, instead of keeping the two separate.
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> JOHN WATKINS [Watkins, 1958]

Introduction From a physical point of view, quantum mechanics is fully satisfactory, both in terms of the experimental tests to which it has been subjected and from an applied perspective. Therefore, the interpretation of quantum mechanics is a philosophical problem. However, as A. Einstein observed [Einstein, 2014], physicists must also contribute to its solution.

> It has often been said, and certainly not without justification, that the scientist is a mediocre philosopher. Wouldn't it be better, then, for physicists to leave the philosophizing to philosophers? This might indeed be the best thing in an age in which the physicist believed he had at his disposal a solid system of concepts and basic laws so well-founded as to be inaccessible to doubt; but it cannot be the best thing in an age in which, as in the present, the very foundations of physics have become problematic. In an age like the present, in which experience compels us to seek a new, more solid foundation, the physicist cannot simply leave the critical consideration of theoretical foundations to the philosopher; for it is he who knows best and feels most clearly where the shoe hurts. In seeking a new foundation, he must strive to clarify for himself the extent to which the concepts he uses are well-founded and constitute *something irreplaceable*.

Referring to the difficulties of interpreting quantum mechanics, A. Zeilinger [Zeilinger, 1996] observed that "interpretation means an analysis of what the theory implies for our general worldview ("Weltbild"). It involves questions about the deeper meaning of the theory." If one agrees with this consideration of the Austrian Nobel Prize winner, it seems reasonable to believe that "a deeper meaning" of quantum mechanics, and more generally of a physical theory, must be sought within a conceptual framework different from that used by physics.

If interpretation is a metacognitive process, interpreting a physical theory means identifying the metaphysical concepts suitable for representing its theoretical terms. To the physicist who views metaphysics with suspicion, all this might appear of little use, if not downright inappropriate. It should be noted, however, that physics commonly uses metaphysical concepts, and that it is precisely through these concepts that we are able to construct a physical image of the world. Consider, for example, the concept of matter. In physics, we commonly speak of "material bodies," "matter and antimatter," "dark matter," and so on. The relationship between the metaphysical concept of "matter" and the physical concept of "mass" plays a crucial role in making classical mechanics intuitive, even in its relativistic form. Had we not naturalized this relationship, classical mechanics would be no less counterintuitive than quantum mechanics.

Based on these preliminary considerations, this paper addresses the interpretative problem of quantum mechanics not by distancing itself from metaphysics—which represents the natural metalevel within which to seek the interpretation of a physical theory—but by identifying the metaphysical concepts best suited to providing its conceptual framework.

The experiment is merely a trivial tool. The true goal remains: understanding the world. Limiting the scope of quantum mechanics solely to accounting for the trivial operations we perform in our laboratories is tantamount to betraying the great enterprise.

JOHN BELL [Bell, 2010]

In experiments on atomic events, we deal with things and facts, with phenomena that are exactly as real as the phenomena of everyday life. But atoms and elementary particles themselves are not so real; they form a world of possibilities and potentialities rather than a world of things or facts.

WERNER HEISENBERG [Heisenberg, 2013]

Levels of Physical Reality One of the things generally taken for granted is that physical reality is structured on a single level. This assumption rests on a sound principle: the injunction "not to multiply entities beyond necessity" (Occam's razor). However, one cannot rule out a priori the possibility that this assumption hinders progress in our understanding of the physical world. This is because, as Albert Einstein observed, "everything should be made as simple as possible, but not simpler." Is considering only one level of physical reality an oversimplification? "To what extent," Einstein asks at the end of his reflection in the previous section, do assumptions like this constitute "something irreplaceable"?

Throughout the history of philosophy, various thinkers have felt the need to introduce a second level of reality to account for events within the realm that frames our experience. Examples include the Platonic world of ideas, Aristotelian potentiality, and the Kantian noumenon. W. Heisenberg [Heisenberg, 1955]—who first formulated quantum mechanics and possessed a solid philosophical background—argued that the laws of quantum mechanics "govern the possible and not the actual." For Heisenberg, therefore, physical reality is structured across these two levels. When he asserts that quantum mechanics governs "the possible," he certainly does not mean that the theory he pioneered regulates something merely linguistic or conceptual—that is, something existing only on our lips or in our minds. It is evident that, for Heisenberg, "the possible" constitutes a genuine level of physical reality; indeed, the German physicist maintains that it is governed by a physical theory—quantum mechanics. This is clearly implied in the quotation that opens this section.

Treating "the possible" as a level of physical reality might seem like a rather exotic choice. Yet, one might ask: if a die is rolled, is there a possibility that a 3 comes up? The answer is obvious: yes, there is a possibility that a 3 comes up. What is less obvious is how seriously one should take that "there is"—that is, the "being" of this possibility (the substance of the argument remains the same if one simply says "it is possible for a 3 to come up"). It is worth noting that all players agree that this possibility "exists"; thus, this answer fully satisfies the criterion of reality adopted by science—namely, intersubjective shareability (upon which, for instance, the peer-review process is based). Therefore, the two levels identified by Heisenberg must both be considered real for methodological reasons, even before considering the authority of the person who identified them and argued for their reality. In the following discussion, these will be referred to as the potential level and the actual level of physical reality.

Naturally, "the possibility that a 3 comes up" exists in a different way and sense than the die itself. The latter can be seen and touched by all the players; "the possibility that a 3 comes up," however, can be neither seen nor touched by any of them—and yet they agree that it exists, and not just the player who bets a certain sum of money on the 3. If, then, one adheres to the criterion of reality adopted by science—and by physics in particular—one must conclude that what is physically possible is real, albeit in a different way and sense than that in which the actual is real. It is precisely this difference that defines the gap between the possible and the actual discussed by Heisenberg, thereby structuring physical reality into two levels: the potential and the actual.

Quantum mechanics is worthy of all respect. But an inner voice tells me it's not yet the real solution. The theory says a lot, but it doesn't bring us any closer to the secret of the 'Old

> Man.' I, in any case, am convinced that He doesn't play dice.
>
> ALBERT EINSTEIN [Einstein, 1926]

Power and Chance If we agree with Heisenberg that quantum mechanics governs the realm of the possible, we might ask what governs the actual—that is, the level of physical reality that encompasses our experience. The answer to this question is implicit in the term "possible." What is possible cannot become actual through a cause or a causal chain, even if the causes of this evolution remain unknown (as in the case of hidden variables). Indeed, if the possible were causally linked to the actual, it would not be "possible" in the true sense; instead, it would simply be an unknown actual state causally linked to a known one—in which case, distinguishing between two levels of physical reality would be neither necessary nor possible. In fact, it is precisely the absence of causal links between the potential level of physical reality and its actual level that renders them two physically distinct levels. Therefore, the transition from the possible to the actual must occur in an intrinsically random manner. It follows that the "actual" discussed by Heisenberg is governed by chance—understood here in the non-epistemic sense, meaning chance not attributable to our ignorance. Naturally, this does not imply that the actual—that is, what we experience—is devoid of order or regularity. Randomness does not imply an absence of structure. On the contrary, since event distributions are determined for a statistical ensemble, the actual is indeed governed by chance regarding elementary, microscopic events, yet it is deterministic at the level of composite, macroscopic events. These latter events involve statistical ensembles of elementary events and thus depend on the distributions of those elementary events rather than on the outcome of any single elementary event. It is perhaps in this sense that one can understand the observation by Einstein that opens this section.

> As long as wave packet reduction is an essential component, and as long as we do not know exactly when and how it replaces the Schrödinger equation, we will not have an exact and unambiguous formulation of our most fundamental physical theory.
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> JOHN BELL [Bell, 2010]

> A system cut off from the outside world is potential, not actual.
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> WERNER HEISENBERG [Heisenberg, 1955]

Power and Causality Consider a system S. If it is isolated—meaning it does not interact with other systems—S is subject only to its own internal constraints, those that define it as such (consider, for example, the constraints defining the possible values of an electron's intrinsic angular momentum, and thus the corresponding states of the electron itself). Consequently, S cannot discriminate between its possible states—that is, assume one of them while excluding the others, even though the latter satisfy the same internal constraints. Precisely because it is isolated, S superimposes its possible states and thus exists in a potential state, as Heisenberg observes in the quote opening this section.

Now consider system S and a second system S', initially isolated from one another and thus both in a potential state. When they interact, they form a more complex system, SS', which encompasses them as parts. The possible states of SS' are the possible pairs formed by a possible state of S and a possible state of S' (unless SS' imposes additional constraints beyond those to which S and S' were subject separately—i.e., before interacting—in which case not all pairs would be possible, as occurs with the pair of spin-correlated electrons discussed later). It follows that the interaction between S and S' selects a possible state for S and a possible state for S', and that these are relative, not absolute, states.

Based on the discussion in the previous section, the selection of the pair of states for S and S'—actualized by their interaction—is intrinsically random. The interaction between two otherwise isolated physical systems is thus the cause that leads both to assume just one of their possible states; yet, it is a cause whose effects are purely random. This implicitly requires that the interaction between S and S' not be continuous over time (as is indeed the case if the interaction is mediated by the exchange of interaction carriers). Indeed, if it were so, it would continuously select only one of the possible pairs—that is, one of the possible states of SS'—which would contradict the fact that the other pairs of states of S and S' (i.e., the other states of SS') are also possible states.

> If one thinks of the word "state" as a description of potentiality rather than of actuality, then the concept of coexisting potentialities is quite plausible, since a potentiality can involve overlap with other potentialities.
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> WERNER HEISENBERG [Heisenberg, 2013]

> Questo concetto di probabilità è strettamente legato al concetto di filosofia naturale degli antichi come Aristotele; è, in una certa misura, una trasformazione del vecchio concetto di "*potentia*", da un'idea qualitativa a una quantitativa.
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> WERNER HEISENBERG [Heisenberg, 1955]

Power and Probability In terms of the linearity of its formalism, quantum mechanics describes a physical system by superimposing its possible states. Compared to the description classical mechanics would provide for the same system, the one offered by quantum mechanics may appear rather peculiar. However, to provide a complete description of a physical system, it is not only possible but necessary to consider and combine all the system's possible states. From this perspective, the quantum-mechanical description of a physical system—expressed by its wave function—is arguably more natural than the description provided by classical mechanics.

This brings us to the crucial question of the present work—and indeed of any study aiming to propose an interpretation of quantum mechanics. The wave function of a physical system, which formally expresses the superposition of its possible states, is the pivotal theoretical element of quantum mechanics: how should it be interpreted? It is worth reiterating here that, if interpretation is a form of metacognition, then interpreting an element of a physical theory means relating it to a metaphysical concept capable of representing it "in a deeper sense"—to use Zeilinger's words. From this standpoint, seeking a *physical* interpretation of quantum mechanics would be pointless, as the best one could hope to find is a tautological interpretation. It is also worth recalling A. Einstein's dictum: "No problem can be solved without changing the level of consciousness that created it."

It is possible that the metaphysical concept needed to give "a deeper sense" to the values (of the squared modulus) of the wave function has not yet been provided by philosophers; in that case, one would have to ask them to coin a neologism. Yet, were this the situation, one might spare them the trouble, for neologisms take a long time to become evocative—that is, to suggest or conjure up the very thing for which they were coined. Fortunately, however, the natural metaphysical concept to be linked with the linear combination of a system's possible states has long been available in metaphysical discourse: it is precisely the concept of "potentiality" identified by Heisenberg. Indeed, what is the superposition of a physical system's possible states if not its potential condition?

Since its inception, physics has adopted the concept of "matter" into its vocabulary, borrowing it from the matter-spirit dichotomy that had long been a subject of philosophical debate. Physicists aligned this metaphysical concept with the physical concept of "mass." Mass is a physical quantity—a measurable value—that expresses quantitatively what the metaphysical concept of "matter" expresses qualitatively. Indeed, the mass of a material body is defined as the amount of matter constituting it. It was precisely this relationship between the qualitative and quantitative aspects of bodies that made classical mechanics immediately intelligible—so much so that the question of its interpretation never even arose.

> All elementary particles can, at sufficiently high energies, be transmuted into other particles, or they can simply be created from kinetic energy or resolved into it, for example, into radiation. And this is the final proof of the unity of matter.
>
> WERNER HEISENBERG [Heisenberg, 2013]

Power and Energy Human laws do not predict human actions; rather, they establish what individuals are permitted (or forbidden) to do, depending on the legal system. We have assigned an analogous role to physical laws regarding the physical world—hence the name "laws." They do not dictate what *does* happen, but rather what *can* happen—what is physically possible—and, conversely, what cannot happen—what is physically impossible. Indeed, physical laws express the constraints to which physical systems are subject.

From this perspective, it is entirely natural to expect a physical theory that incorporates such constraints to govern "the possible" rather than "the actual"—precisely as quantum mechanics does, according to

Heisenberg. Of course, this does not make quantum mechanics the "science of the possible" in the sense that "anything is possible"—on the contrary, the constraints quantum mechanics imposes on possibility are quite strict and rigorous—but rather in the sense that "everything possible *exists*," albeit at a level of physical reality distinct from that of the actual.

The principle of conservation of energy is the most significant of these constraints. Indeed, ever since Albert Einstein formulated the mass-energy equivalence, energy can effectively be regarded as the underlying basis—the *substance* (from the Greek for "that which stands beneath")—of everything we experience, as Heisenberg suggests in the opening quote of this section. For the purposes of the interpretation proposed here, it is important to note that energy is a physical quantity that typically manifests in both potential and actual forms. These latter points can be summarized by stating that at the foundation of all our experience lies something that typically takes on both potential and actual forms. From this perspective, distinguishing the potential level of physical reality from its actual level does not appear to be a stylistic choice, but rather a theoretical necessity dictated by the dual nature of the foundation of physical reality itself.

While it is true that in physics a body's potential energy is that which it possesses by virtue of its position within a force field, it is equally true that this type of energy is termed "potential" precisely because it is latent—unmanifested. The gravitational potential energy stored in a high-altitude artificial lake can be neither seen nor touched, much like the possibility of certain events occurring—such as rolling a three on a die or the occurrence of an accident. Yet it is considered real—so real, in fact, that vast sums are invested to safely convert it into electrical energy. The possibility of certain events occurring is likewise considered real; indeed, betting agencies and insurance companies base their business models upon it.

Like potential energy, the *potency* of an event can also be measured: probability is the quantitative, measurable expression of what the metaphysical concept of "potency" expresses qualitatively—just as mass is the quantitative expression of what the metaphysical concept of "matter" expresses at a qualitative level. Naturally, within the context of this work, the term "potency" is employed in its metaphysical sense, rather than in the physical sense of energy exchanged per unit of time.

The interpretive proposal advanced here—following Heisenberg—suggests introducing and naturalizing the metaphysical concept of "potency" within the language of physics. R. Feynman [Feynman, 2007] famously stated, "I think I can safely say that nobody understands quantum mechanics today"—a remark that likely included himself. Normalizing the relationship between the metaphysical concept of "potentiality" and the physical concept of "probability" would make it possible, at the very least, to construct a mental model of certain quantum phenomena.

> We will choose a phenomenon [the double-slit experiment] that is impossible, absolutely impossible, to explain in any classical way, and which contains within itself the heart of quantum mechanics. Indeed, this phenomenon contains the only mystery. We cannot eliminate the mystery by "explaining" how it happens. We will simply describe how it happens, and in doing so, we will have described the main features of quantum mechanics.
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> RICHARD FEYNMAN [Feynman, 2007]

Power and Quantum Phenomena The hypothesis that there exists a potential level of physical reality, governed by quantum mechanics, renders intuitive and intelligible various physical phenomena that otherwise remain difficult to grasp—such as the phenomenon observed in the double-slit experiment. Yet, despite the authority of Heisenberg, who first proposed it, this hypothesis has not been taken into consideration. Proof of this lies in the fact that, even today—as quantum mechanics marks its centenary—attempts to explain the experiment's outcome still resort to statements that are nonsensical (let alone counterintuitive), such as "the particle interferes with itself" (a particle is indivisible by definition, whereas interference requires, by definition, at least two interfering entities).

From an operational standpoint, distinguishing the potential level of physical reality from its actual level means regarding both the potential forms of physical systems and their actual forms as real, and acknowledging that these forms can interchange. Specifically, based on what has been discussed so far, the potential form of a physical system is expressed by its wave function, which—from a physico-mathematical perspective—describes a field.

Consequently, the squared modulus of the wave function will henceforth be referred to as the "power field" of the physical system it describes. After all, taking the formalism of quantum mechanics seriously implies—

or perhaps primarily entails—recognizing a degree of reality not only in physical systems as they appear to our experience (i.e., their actual forms, or particles) but also in the forms described by the wave function (i.e., their potential forms, or fields).
The objection generally raised against interpretive proposals suggesting that the wave function describes a physical field is that the wave function of a system of N particles depends on 3N spatial coordinates; therefore, in general, the wave function does not "inhabit" ordinary three-dimensional space but rather configuration space—that is, an abstract space. This objection cannot be upheld within the framework of the interpretation proposed in this work. Indeed, structuring physical reality according to the two levels identified by Heisenberg means, in concrete terms, recognizing a particle and its field of potentiality as the poles of a dynamic equilibrium—that is, a reversible process in which the field of potentiality emits and reabsorbs particles, thereby "creating" and "destroying" its own actualized forms. In this physical scenario, which mirrors the one outlined by quantum field theory, the phrase "set of N particles" is meaningless. In other words, the objection must be rejected because it implicitly assumes that particles are persistent, whereas, according to the proposed interpretation, they are ephemeral.
Based on the foregoing, the dynamic field-particle equilibrium is an inherently stochastic process; consequently, the position at which the field emits a particle is unpredictable, even in principle. Naturally, this does not imply that all emission positions are equally probable. In fact, the field is more likely to emit particles where the field of potentiality is more intense, and more likely to reabsorb them where it is less intense.
The dynamic field-particle equilibrium model is consistent provided that the particle's field of potentiality preserves not only its energy but also its information. In other words, precisely because it is a dynamic equilibrium, the process must be reversible, as only then can the field reconstitute the particle. Based on this model, several characteristically quantum phenomena are discussed below.

The Double-Slit Experiment L'esito dell'esperimento della doppia fenditura si spiega facilmente ipotizzando che la sorgente a monte delle fenditure non emetta particelle, ma il loro campo di potenza, cioè il campo oscillante che risolve l'equazione di Schrödinger per la particella libera. I due treni d'onda diffranti dalle fenditure interferiscono a valle delle fenditure, alternando frange di interferenza costruttiva a frange di interferenza distruttiva. Ma la lastra fotografica a valle delle fenditure è sensibile alle particelle, non al loro campo di potenza. L'emissione di particelle da parte del campo di potenza è più probabile dove questo è più intenso, cioè in corrispondenza delle frange di interferenza costruttiva, mentre il loro assorbimento è più probabile dove il campo è meno intenso, cioè in corrispondenza delle zone di interferenza distruttiva. Ne consegue che, quando il fronte dell'interferenza raggiunge la lastra, in corrispondenza dei massimi del campo di potenza è più probabile che la lastra venga impressionata. Viceversa, in corrispondenza dei minimi del campo è meno probabile che la lastra venga impressionata. Ogni tentativo di stabilire "da quale fenditura è passata la particella" costringe il campo di potenza ad assumere la propria forma attuale, la particella, e dunque interrompe l'interferenza.

Tunneling effect Quantum tunneling is another example of a quantum phenomenon that is easily explained if one considers the potential level of physical reality to be real, and agrees with Heisenberg that this level is governed by quantum mechanics. Experimentally, the probability of finding a particle beyond a finite potential barrier is observed to be greater than zero, even when the incident particle's kinetic energy is lower than the potential energy it would need to acquire to overcome the barrier classically. This paradox ceases to be one if, instead of thinking in terms of an "incident particle," one hypothesizes that it is the particle's power field that propagates from the source to the barrier. Indeed, solving the Schrödinger equation governing this field reveals that it is partially reflected and partially transmitted. Since the field preserves the particle's energy and information, the transmitted portion of the field reconstitutes the particle beyond the barrier with a probability greater than zero.

Entanglement A final example of a quantum phenomenon that can be readily explained by considering the two levels of physical reality identified by Heisenberg is entanglement. Consider a calcium atom undergoing double ionization. The pair of electrons lost by the atom is subject to the Pauli exclusion principle, and the conservation of momentum dictates that the two electrons move away from the atom in opposite directions and at the same speed. If a spin measurement is performed on one of them, the other immediately assumes the opposite spin.

In this case, too, the phenomenon can be explained by hypothesizing that it is not two particles moving away from the calcium atom, but rather their field of potentiality propagating outward. Since the particles in dynamic equilibrium with this field are spin-correlated, the condition for equilibrium reversibility is satisfied if the field preserves not only the energy but also the information regarding the particles themselves—which, in the case at hand, includes the spin correlation of the two electrons. Crucial to explaining this phenomenon is the observation that the hypothetical field of potentiality propagating from the calcium atom is not a superposition of the individual potentiality fields of the two electrons; rather, it is a single field of potentiality preserving the energy and information of both—a field whose actualized form is a pair of spin-correlated electrons. Therefore, the spin measurement simply actualizes this physical system, which—as the field propagates—may meanwhile have assumed the (actual) form of two electrons separated by a significant distance. From this perspective, there is no transfer of information from the electron being measured to the other. This is not because the process—being instantaneous—would violate relativistic constraints, but because the two electrons transition simultaneously from the potential level to the actual level of physical reality; this occurs precisely because what propagates from the calcium atom is the potentiality field of a pair of spin-correlated electrons, rather than the potentiality fields of two electrons whose intrinsic angular momenta are mutually unconstrained. In other words, the phenomenon's instantaneous nature stems from the fact that a physical system's potential state and actual state are mutually exclusive. When a spin measurement restores the system's actual state—namely, a pair of spin-correlated electrons—its potentiality field instantly ceases to exist everywhere. This is not a "collapse," but rather a transition of the system from the potential level of physical reality to its actual level. Conversely, once the interaction mediating the measurement ceases, the system's actual state immediately ceases to exist, and its potentiality field propagates, once again diffusing across the space of its possible states (with respect to the measured dynamic variable).

> Dark energy is incredibly strange, but it actually makes sense to me that it has gone unnoticed […] after all, it doesn't accumulate in galaxies, it's everywhere and it's uniform.
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> ADAM RIESS [Riess, 2011]

Power and Dark Energy The dynamic field-particle equilibrium model—which gives concrete expression to the two levels of physical reality identified by Heisenberg—predicts, when applied on a cosmological scale, that the universe's energy is distributed partly across one level and partly across the other. The portion of potential energy—understood here as energy distributed across the hypothetical potential level of physical reality—cannot be directly experienced, not even in principle. Indeed, direct detection is impossible, not so much due to the intrinsic limitations of observational instruments, but for the same reasons that the gravitational potential energy stored in a high-altitude artificial reservoir cannot be directly experienced: unlike the actual, the possible is, by definition, not directly experienceable.

The picture emerging from the theory of general relativity and currently available astronomical observations is consistent if one hypothesizes that the amount of energy (including mass) detected through observation represents 5% of the total. If the remaining 95% of the energy were indeed distributed across the potential level of physical reality, and if this percentage were destined to increase over time, the universe would still be quite young—meaning that, to date, it would have manifested only one-twentieth of its potential.

> The electron can no longer be conceived as a single, tiny particle of electrical energy; it must be associated with a wave, and this wave is not a myth; its wavelength can be measured and its interference predicted.
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> LOUIS DE BROGLIE [de Broglie, 1929]
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> In the dominant conception, the only mechanisms of communication between molecules are close encounters in which molecular forces can operate, whose range of action does not exceed a couple of molecular diameters. In water vapor at the point of liquefaction, the average distance between molecules is a few dozen molecular diameters, and collisions involve only a few molecules at a time and do not produce aggregates that remain stable, waiting for other partners to join the primitive aggregates, due to the long timescales of collision-based dynamics; in fact, during this wait, they have already disintegrated. What, then, is the mechanism that allows the transformation of vapor into liquid in a short timescale over extended spatial regions?
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> EMILIO DEL GIUDICE [del Giudice, 2001]

Power and Particles The dynamic equilibrium between a particle and its power field is consistent provided that the particle and its power field are substantially identical yet formally different. To clarify the meaning of these two conditions, one can consider the phenomenon of fog: the water droplets forming it are continuously emitted and reabsorbed by the humid air—at a frequency dependent on the relative humidity level—while the total quantity of water is conserved.

The droplets and the moisture in the air are substantially identical yet formally different: both are composed of the same substance—water—but whereas the droplets are discrete bodies (occupying a limited region of the available space), the atmospheric moisture is a field (occupying the entire available space) whose intensity is expressed precisely by the relative humidity level. Moving beyond the metaphor, the frequency at which a particle is emitted and reabsorbed by its power field depends on the intensity of the power field itself—specifically, the squared modulus of the wave function—and the process conserves total energy.

The hypothesis that a particle's power field is a physical field suggests a model for the particle itself. Since the power field is oscillatory, requiring the particle to be substantially identical to its power field implies that the particle is, in turn, an oscillatory field. Conversely, requiring the particle to be formally different from its power field—which is an open field (meaning its phase varies over an open support) and a progressive wave—implies that the particle's own oscillatory field is closed (meaning its phase varies over a closed support) and stationary. Indeed, the oscillation of a field can be supported either by a closed support (with a dimension at least equal to half its wavelength—in which case the particle possesses spinorial properties that its power field must preserve) or by an open support, representing the periodic extension of the closed support.

From this perspective, the phenomenon of quantization would originate in the closure of the oscillating field characterizing the particle—even prior to any constraints to which its power field might be subject, such as in the case of the atom. Furthermore, from a physical standpoint, the transitions between the potential level of physical reality (field) and its actual level (particle)—and vice versa—which render their equilibrium dynamic, can be understood as phase transitions of the oscillating field constituting both; specifically, transitions from a phase varying on an open support to one varying on a closed support, and vice versa.

The particle model—a closed, stationary oscillating field—suggested by the hypothesis that its power field is a physical field (albeit one existing at a different level of reality than that where physics situates other fields) can model different particles depending on the geometry and topology of the closed support characterizing them. String theory might perhaps be viewed as an attempt in this direction.

> Are you really convinced that the Moon only exists when you look at it?
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> ALBERT EINSTEIN [Einstein, 1986]

> That one body can act on another at a distance through a vacuum, without the mediation of anything else, is to me such an absurdity that I believe no man, with a competent faculty of thought in philosophical matters, could ever fall into it.
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> ISAAC NEWTON [Newton, 1693]

> The electron is kept within a certain distance from the nucleus of the atom by the exchange of photons with the proton.
>
> RIHARD FEYNMAN [2010]

Power and Motion Early atomic models, based on electromagnetism and classical mechanics, predicted that the hydrogen atom would be extremely unstable. Indeed, due to electromagnetic radiation from the electron—which must necessarily follow a curved trajectory to remain near the proton—and the resulting loss of kinetic energy by the electron itself, it would inevitably follow a spiral trajectory that would lead it to fall into the nucleus. Furthermore, such a mechanical system would be extremely sensitive to perturbations. Experience, however, shows that the hydrogen atom is stable within a broad and varied spectrum of physical conditions. With the enunciation of Heisenberg's uncertainty principle, it became definitively clear that the concept of "trajectory" was unsuitable for theoretically exploring the world, at least on the atomic scale, because particles move within it without following trajectories (or following all possible trajectories, as assumed when calculating the Feynman path integral). The following problem therefore arises.

Two successive position measurements find a particle of mass *m* at points A and B respectively: describe the motion of the particle knowing that it moved from A to B without following a trajectory (or following all possible trajectories), and that in the meantime no other position measurements have been performed.

The only logically acceptable solution to this problem is for the particle to disappear at A and reappear at B. While this solution appears to lack logically sustainable alternatives, it seems physically unacceptable. Indeed, if the body of mass *m* were to disappear after the initial position measurement, the principle of conservation of energy would be violated by an amount equal to (at least) mc^2. The only way to reconcile this logical necessity with a physical principle for which no violations are known is to hypothesize that the body does not disappear in the sense of ceasing to exist entirely, but rather ceases to exist as a body in order to assume a different physical form – one that conserves its energy without possessing a specific position.
If we wish to avoid "multiplying entities beyond necessity"—and given that physical entities consist of bodies and fields—we must hypothesize that, between position measurements, the body takes the form of a field. This hypothesis satisfies the aforementioned conditions, as a field can conserve energy while lacking a specific position (instead encompassing all possible positions the particle might occupy—that is, all points where a position measurement could restore it). Unlike a body, it does not follow a single trajectory but propagates (following all possible trajectories); consequently, it can reach point B without traversing a specific path.
In the scenario described, the particle assumes its actual form only during position measurements. This is a logical necessity from a relativistic standpoint, even prior to any quantum-mechanical considerations. Indeed, a particle's position is not an intrinsic property—unlike its mass—but rather a relationship with a reference frame. For this relationship to hold physical significance, it must be understood as a physical interaction; this, in turn, requires the reference frame to be not merely an abstract system of spatial coordinates, but an actual physical system with which the body interacts. In the absence of such interaction, the concept of position loses its physical meaning. ...and with it, the concept of a “particle”—and, more generally, that of a “body”—loses its physical significance.
Are the consequences of this loss of physical significance confined to the conceptual realm, or do they manifest primarily on the physical level? A body is defined as a physical entity occupying a limited region of the available space, whereas a field is defined as a physical entity occupying the entire available space. The former has a position; the latter does not. For this reason, in the absence of interaction with a reference system, the field would physically—even before conceptually—replace the body. This is why Heisenberg [Heisenberg, 1955] can state that “a system cut off from the outside world is of a potential, not actual, nature.” In the absence of interactions—for instance, during the interval between two successive position measurements—the body would cease to exist as such (at the actual level) and begin to exist as a field (at the potential level).
It is not, therefore, a transformation—in the sense of a shift from one form to another, both belonging to the same level of physical reality—but rather a transition between two distinct levels thereof. After all, if the transition from body to field (and from field to body during position measurements) were a transformation of one into the other within the same level of physical reality, this process would have to be governed by quantum mechanics. However, since the only process governed by that theory is the unitary evolution of the state vector—or wave function, understood here as the body’s *potentiality field*—and given the strong reasons to believe that quantum mechanics is a complete theory, it is reasonable to conclude that this transition does not entail a transformation.
From a physical standpoint, a particle's power field must be understood as a distribution of the relative energy density of the energy the field is tasked with conserving—namely, that of the particle itself (relative energy density is the ratio of energy density to particle energy and has dimensions of the reciprocal of volume, just like the wave function). Consequently, the emission of a particle by the power field does not entail a "collapse"—understood here as an "instantaneous concentration" of its energy density (a process otherwise forbidden by the theory of relativity)—but rather a decrease in the field's total energy (i.e., the potential level of physical reality) and the simultaneous appearance of a particle at its actual level.
According to current physics, interactions are mediated by the exchange of interaction carriers, making them temporally discontinuous. In the case of a macroscopic body, such interactions occur very frequently; the body thus oscillates between its actual state (a body interacting with other bodies) and its potential state (a field interfering with other fields) at an extremely high frequency—matching the frequency of its interaction with the environment—leaving its power field no time to diffuse appreciably. This is also because the diffusion coefficient appearing in the Schrödinger equation is inversely proportional to the body's mass, rendering the diffusion of a macroscopic body's power field particularly slow. It follows that the field fails to

revert to its pure state; that is, between one interaction and the next, it remains—to a good approximation—a statistical mixture of possible positions with minimal dispersion.
Therefore, the position of the body's center of mass remains virtually unchanged, in the sense that the dispersion of the successive positions it assumes due to environmental interactions is negligible compared to the body's dimensions (whereas, for microscopic bodies in isolated environments, the body's dimensions are negligible compared to the dispersion of successive positions). This applies unless the macroscopic body is subject to potentials; in that case, the dispersion remains negligible transverse to the potential gradient but spreads out longitudinally relative to it, moving as predicted by classical mechanics—albeit discontinuously, meaning without following trajectories consistent with quantum mechanics. This interpretation of the motion of bodies draws no boundary between the classical and quantum worlds, because, for all practical purposes, the motion of macroscopic bodies can be regarded as continuous, and the bodies themselves as persistent.

> The Aharonov-Bohm effect demonstrates that the vector potential A is a "real" physical reality. In classical mechanics, only the E and B fields matter, but in quantum mechanics we must admit that the potential has a direct influence on the phase of the wave function, even where the magnetic field is zero.
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> RICHARD FEYNMAN [Feynman, 2007]
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> A scientific theory should not be required to be capable of being chosen, once and for all, in a positive sense; but it should be required that its logical form be such that it can be highlighted, by means of empirical tests, in a negative sense: an empirical system must be capable of being refuted by experience.
>
> KARL POPPER [Popper, 1970]

Confirmations and Falsifiers The proposed interpretation is corroborated by the Aharonov-Bohm effect if one accepts that potentials—including electric and magnetic ones—do not pertain to the actual level of physical reality but rather to its potential level; consequently, they influence measurement outcomes by acting upon that potential level rather than the actual one.
Generally, the discussion regarding the falsification of physical theories focuses on the theories themselves rather than their interpretations. However, this work proposes not merely an interpretation of quantum mechanics but also an extension of the theory. Indeed, the considerations discussed thus far suggest that a body—whether elementary or composite, microscopic or macroscopic—exists in dynamic equilibrium with a physical field (the "power field") that preserves its energy and information. This hypothetical field is "richer" than the material body’s wave function—that is, the solution to the governing Schrödinger equation—and is therefore, in principle, distinguishable from it.
In the standard formulation, an electron and a fullerene molecule are treated identically, as they differ only in the mass term appearing in the Schrödinger equation. From the perspective presented here, however, the oscillating field solving that equation should be viewed as a "carrier wave" (a term borrowed from radio transmission); this wave must be appropriately modulated in terms of parameters such as amplitude, phase, and helicity to encode information about the body with which it is in dynamic equilibrium. Thus, under the proposed conceptual framework, a fullerene’s power field would differ from an electron’s not only in wavelength but also in the modulations encoding its information.
In principle, this would allow for an experimental distinction between the standard formulation of the theory and the extension proposed here. From a practical standpoint, the experiment might involve producing particularly detailed interference patterns in the presence of potentials capable of revealing any modulations of the wave function. The experiment would likely need to be conducted using molecules distinguished by global properties (such as chirality), because decoding local properties potentially encoded in their force field might require a level of resolution that an interference pattern cannot provide.

> Many of the abstractions that characterize modern theoretical physics were discussed in the philosophy of past centuries. In those days, these abstractions could have been dismissed as mere mental exercises by scientists whose sole concern was reality, but today, the advancement of experimental results forces us to take them seriously.
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> WERNER HEISENBERG [Heisenberg, 2016]

Heisenberg drew from quantum mechanics a profound and radical metaphysical thesis: that the state of a physical object is a collection of potentialities. But his discovery is incomplete, as the transition from potentiality to actuality remains mysterious.

ABNER SHIMONY [Shimony, 1990]

Conclusions The following table summarizes the prerogatives of the two levels of reality identified by Heisenberg, between which the characteristic entities between which the present work identifies a relationship of dynamic equilibrium.

Level of physical reality	*Characteristic physical entity*	*Characteristic condition*	*Characteristic regime*	*Experienceability*
potential	field	insulation	deterministic	indirect
actual	body	interaction	casual	direct

Regarding the interpretation of quantum mechanics, Heisenberg is generally associated with the interpretative orthodoxy established by the Copenhagen school. However, if interpretation is a metacognitive process, the one developed by Bohr cannot even be described as such, precisely because it fails to identify relationships between the theoretical elements of quantum mechanics and metaphysical concepts.
Therefore, in the author's view, Heisenberg's interpretation of quantum mechanics is the one that can be readily inferred from the observations presented in this work and summarized in the preceding table. Indeed, when Heisenberg asserts that quantum mechanics governs the potential level of physical reality, he interprets quantum probability as the quantitative expression of metaphysical *potency*—understood not in the Aristotelian sense, but simply as the coexistence of a plurality of alternatives.
During the same years that the first formulations of quantum mechanics emerged, Max Born realized that the values of the squared modulus of the wave function express the probability density—distributed across the space of possible states of a physical system—that the system will present itself to our experience in one of those states. It was Heisenberg who recognized that the physical concept of "quantum probability" finds its natural metaphysical counterpart in the concept of "potency." However, this insight never fully developed into a comprehensive interpretation of quantum mechanics, even though the German physicist revisited the idea on several occasions.
Perhaps due to the historical period between the two world wars, as well as the prestige of Niels Bohr and the influence his Copenhagen school exerted on physicists of the time, the interpretation of quantum mechanics took different paths; these led the orthodoxy to draw a boundary—at once implausible and arbitrary—between the quantum world and the classical world. However, the primary reason Heisenberg did not pursue his own intuition—and thus did not formally translate it into an interpretation of mechanics distinct from those emerging at the time—was perhaps caution. To maintain that mechanics governs "the possible, not the actual" is tantamount to saying that the possible is real—that it constitutes a genuine level of physical reality, even though it cannot be directly experienced, not even in principle. This is a delicate position to uphold, especially for a physicist like Heisenberg, who had a reputation to safeguard during the years when the "Short Twentieth Century" was undergoing its most dramatic phases—events in which the German physicist was personally and professionally involved. Based on these personal impressions, the author of this article has taken the liberty of revisiting this idea and attempting to develop it further. From this perspective, direct experience of the behavior of quantum systems should be interpreted as indirect experience of the potential level of physical reality; the intrinsically statistical nature of the wave function—corroborated not only by countless independent experimental checks but also by the difficulties encountered in various attempts to attribute a different nature to it—supports this thesis. Yet the most compelling argument remains the linearity of the formalism, whereby the quantum-mechanical description of a physical system is presented as a superposition of its possible states, and thus as a potential state of the system itself.
A. Einstein [in Bell, 2010]—famously critical of certain crucial aspects of quantum mechanics (to which he himself made fundamental contributions)—nevertheless maintained that "the formal relations contained in this theory—that is, its entire mathematical formalism—will likely have to be contained, in the form of logical deductions, within any viable future theory." If the linear nature of the formalism is considered one of the theory's indispensable aspects, then abandoning the metaphysical concept of "potentiality" within quantum mechanics might be tantamount to abandoning the metaphysical concept of "matter" in classical

mechanics. Were this to happen, to paraphrase Feynman, we would likely eventually reach a point where no one understood classical mechanics anymore either.
In this regard, it can be observed that the metaphysical concept of “matter”—closely linked to that of a “material body” and, consequently, to that of a (massive) “particle”—renders the actual level of physical reality intelligible, whereas the concept of “potentiality” plays the same role with respect to the potential level of that same reality. These are, therefore—to use a term favored by Niels Bohr—two complementary metaphysical concepts, in the sense that understanding physical reality requires employing both, albeit at different levels of physical reality itself.
The concept of “potentiality” was introduced on a logical basis, whereas the concept of “matter” entered physics from the outset on an empirical basis. In this sense, the complementary use of these two metaphysical concepts reflects reasoning and observation—the tools of science—respectively.
During a conference on quantum mechanics held at the University of Cambridge in 1999, the ninety participating physicists were asked which interpretation of quantum mechanics they found most convincing. Fifty of them declared themselves undecided or stated that they found none of the interpretations under consideration convincing. Thirty [respondents] pointed to the "many-worlds" interpretation proposed and developed by H. Everett III [Everett III, 1957] and subsequently by B. DeWitt. Four chose the Copenhagen interpretation. The "many-worlds" interpretation differs significantly, on the surface, from the one proposed here. Consider, however, a physicist performing a spin measurement on an electron. According to the Everett-DeWitt view, two worlds arise: one corresponding to positive spin and the other to negative spin. These worlds are not causally connected; otherwise, they would constitute a single world rather than two. The physicist who performs the measurement and notes a positive spin regards their own world as actualized, whereas the world in which they recorded a negative spin—from their perspective—existed merely in potentiality. The same applies to the physicist who notes the negative spin. Thus, the "many worlds" of Everett and DeWitt can be understood as the level of potentiality that Heisenberg introduces into physical reality, while each actualized world can be viewed—from its own perspective—as the level of actuality within that same reality. I thank the philosopher Stefano Pianese for drawing my attention to this interpretive convergence.

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