The quantum field theory interpretation of quantum mechanics

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It is shown that adopting the Quantum Field —extended entity in space-time build by dynamic appearance propagation and annihilation of virtual particles—as the primary ontology the astonishing features of quantum mechanics can be rendered intuitive. This interpretation of quantum mechanics follows from the formalism of the most successful theory in physics: quantum field theory.

Keywords: quantum mechanics, interpretation, quantum field theory

I. INTRODUCTION

After more than one century that Planck and Einstein made the first quantum postulates\cite{1, 2} and after 80 years that the mathematical formalism of quantum mechanics was established\cite{3}, the challenge posed by quantum mechanics is still open. For many decades the situation was well described by R. Feynman when he said “nobody understands quantum mechanics”\cite{4}. This is is perhaps no longer true due to the achievements of the last decades. The lack of understanding was compensated by the development of an extremely precise and esthetic mathematical formalism; we did not know what quantum mechanics is but we knew very well how it works. The development of the very successful axiomatic formalism had the consequence that many physicists where satisfied with the working of quantum mechanics and did no longer tried to understand it. This attitude was favoured by the establishment of an orthodox instrumentalist “interpretation” which, if we are allowed to put it in a somewhat oversimplified manner, amounts to say “thou shall

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not try to understand quantum mechanics”. Only a few authorities like Einstein, Schrödinger, Planck, could dare not to accept the dogma and insisted in trying to understand quantum mechanics[5]. Fortunately the situation changed and the search for an interpretation of quantum mechanics became an acceptable research subject. The roots for this change are found in the pioneering work of Einstein Podolsky and Rosen[6] which pointed out to some peculiar correlations in the theory, followed by the work of Bell[7] that established measurable consequences of them that were confirmed experimentally[8].

The increased activity in the field resulted in a very large number of “interpretations” but, unfortunately, also in much confusion on the precise meaning of producing an interpretation for quantum mechanics. So, besides the Copenhagen or Complementarity interpretation we can find Schrödinger’s field interpretation, the de Broglie pilot wave interpretation, the hydrodynamic interpretation, the many world interpretation, the modal interpretation, the transactional interpretation, the coherent histories interpretation, the Path Integral interpretation, the causal (Bohmian) interpretation, the stochastic interpretation, the statistical interpretation, the hidden variables interpretation, and many other with ephemeral life. For more confusion, we should add to the list the no interpretation interpretations including many instrumentalist claims that quantum mechanics does not need an interpretation and just has to provide an algorithm for predicting the results of experiments.

A study of the proposals shows that there is some confusion about what exactly is an interpretation. Unfortunately, it seems that any new idea about some general feature of the theory, or some metaphorical model, or an alternative mathematical formalism, is called “an interpretation”. This situation may result in a sterile proliferation of interpretations. In order to limit this growth and to clarify this issue, we can choose set of quite reasonable minimal requirements that a proposal should fulfill in order to be called an interpretation.

**Realism** *Every interpretation of quantum mechanics must be realist.* This amounts to the philosophical postulate of the objective existence of reality independent of any observation, although any act of observation may produce strong, or even unpredictable, effects.
The objects of study of quantum mechanic, the *Quantum Systems*, is an abstraction of reality defined by a set of observables that we use to build models of reality. The knowledge that physics has provided about these models of reality forces us to accept that the quantum system may have properties by far more sophisticated than the ones detected by our sense perception, and that their behaviour may contradict our classical intuition. In other words, physics has shown that *naive realism* is wrong.

Any interpretation must be realist because in an interpretation we associate the results obtained from the theory or from the experiments with some existent objects. An interpretation of a theory becomes meaningless without the existence of the objects to which it is applied. Many physicist may be surprised by the necessity to state such a postulate because they may take it as obvious. However it is convenient to state it explicitly because there are ideologies and epistemological schools that question the postulate of realism.

The search for an interpretation of quantum mechanics implies the acceptance of another philosophical postulate: *Nature not only exists but it can also be known, at least in an ever increasing approximation, by means of physical theories.* That is, quantum mechanics can give us information about reality, even if it is affected by inherent uncertainties or indeterminacies. Therefore, quantum mechanics is telling us something about nature and not merely about the observations that we make of nature.

**Physical Space-Time** Every existent physical system is embedded in space-time and is associated to a domain of it according to the equations of motion of the theory. This space has some geometrical structure allowing the assignment of coordinates and there are mathematical transformations of coordinates relating different frames of reference. These transformations may depend on several physical constants in a way that, under the appropriated limit, Poincaré, Lorentz or Galilei transformations are obtained.

It is important to notice that this requirement *does not* say that physical space is a four dimensional Minkowski space or a Riemann space with curvature or
a three dimensional Euclidian space and a one dimensional time. The dimension and geometrical structure of physical space-time may be anything, provided that in the appropriated limit the spaces of classical physics or of special or general relativity are reached. Considering the difficulties encountered by all attempts to find an interpretation of quantum mechanics in the usual Minkowski or Euclidian spaces, we may expect that, perhaps, the advent of a definite interpretation for quantum mechanics will require a radical proposal of some unexpected geometry for physical space-time. For this reason, it is important that this requirement should not restrict the possible geometrical structures that may be necessary to assign to physical space.

**Primary Ontology** Every interpretation of quantum mechanics must propose a primary ontology. A possible reason for the difficulties in finding an interpretation of quantum mechanics was perhaps a wrong choice of an ontology from the beginning. In many attempts, either a particle or a field ontology was assumed. These two choices are very successful in classical physics but clearly fail with quantum mechanics. In order to overcome these failures, the concepts of particle-wave duality was introduced as a manifestation of the more general principle of complementarity.

The requirement of a primary ontology means that the interpretation must clearly state what are the basic existent things in physical space, that are the carriers of energy and momentum or of other observable properties. In early interpretations, these primary ontology where particles or fields and these entities were endowed with non classical properties like the complementary presence of dual properties. Whatever this primary ontology is, it must exist in physical space as carrier of energy-momentum. This requirement excludes the “histories” or the “correlations” from being the primary ontology. There have been several attempts of interpretations based on different choices for the primary ontology. Without many details we just mention some of them. The well known probability interpretation of the wave function $\psi(x)$ proposed by Max Born favours a particle ontology. In this case $\psi(x)$, a Hilbert space element, does not carry energy and is not really existent in physical space.
Opposite to it, we can find Schrödinger interpretation proposing that only the wave function has objective existence. A hybrid interpretation was proposed by L. de Broglie with his “double solution” suggesting a mixed particle and field ontology. Another idea originated by L. de Broglie is based on a particle ontology with a pilot wave determining its motion. This interpretation was successfully taken by D. Bohm in his causal quantum mechanics (Bohmian mechanics).

These criteria are not satisfied by several proposals mentioned above. In this work we will see that an interpretation of quantum mechanics based on an entity different from particles or fields that we name Quantum Field can be adopted providing a somewhat intuitive understanding. We will try to show that most astonishing features of quantum mechanics can be explained as a natural consequence of the ontology suggested by quantum field theory based on a permanent creations and annihilation of virtual particles and antiparticles. Indeterminacies, nonlocality consequences of superposition, individuality entanglement of identical particles, and many other features of the quantum system, not understood in the particle or in the field ontology, become natural features of the quantum field built by virtual particles.

II. THE ONTOLOGY OF THE QUANTUM FIELD

There exist a set of physical entities, called Elementary Particles, characterized by different values of some observable properties. They are listed in the Standard Model and are identified as electrons, neutrinos, quarks, photons, etc. Associated with each elementary particle we define a physical system called Virtual Particle consisting in the creation of the particle at some space-time point, its propagation with definite energy-momentum and its annihilation at another space-time point. Opposed to virtual reality in computer simulations, virtual particles do exist in reality but with ephemeral live. These virtual particles exist and have observed empirical consequences as in the Casimir effect or in the Lamb shift. They can not be permanent because they do not satisfy the energy momentum relation $m^2 = E^2 - P^2$
(they are off the mass shell) and they can propagate in space-like trajectories. This fact has the astonishing consequence of the necessary existence of antiparticles: for a virtual particle propagating in a space-like trajectory between the times $t_1$ and $t_2$ ($t_1 < t_2$) in a reference system $S$ there is a Lorentz transformation to $S'$ where the corresponding antiparticle is propagating between $t'_2$ and $t'_1$ ($t'_2 < t'_1$).

The Quantum Field is a physical entity extended and evolving in space-time according to specific equations of motion (Schrödinger, Dirac, Klein-Gordon) made by an infinite set of virtual particles. At every space-time point the amplitude of the intensity of the field denotes the existence of particles, and likewise, the field provides the amplitude for realization of every energy-momentum value. The quantum field is the primary ontology with permanent existence; however it is not simple and elementary because it is composed by the superposition of virtual particles. In this view, Feynman graphs represent not only a term in a perturbation expansion but they describe real processes occurring in physical space. All these features are compatible with the mathematical formalism that will be described in the following section.

III. MINIMAL QUANTUM FIELD THEORY

In this section a minimal version of quantum field theory is presented containing only those features required for the understanding of quantum mechanics based on its ontology. For this purpose we don’t need to consider specific spin values of the particles described by the theory neither do we need to describe the details of the interactions between different particles involving advanced mathematical techniques. Therefore we consider only the main features of quantum fields and we avoid the mathematical complications that sometimes blur the essential features of the theory. There are excellent books where quantum field theory is presented in all rigour and details[10].

The physical system that the quantum field describes is an indefinite number of some type of particle (electron, quark, photon, etc.) in its space-time evolution. The state of such a system, that is, that mathematical entity allowing us make any
prediction concerning the observables, is an element of a Fock space $\mathcal{H}$ built as the orthogonal sum of Hilbert spaces

$$\mathcal{H} = \mathcal{H}^0 \oplus \mathcal{H}^1 \oplus \mathcal{H}^2 \oplus \ldots \oplus \mathcal{H}^n \oplus \ldots$$

where

$$\mathcal{H}^n = \mathcal{H} \otimes \mathcal{H} \otimes \ldots$$

is the Hilbert space for an $n = 1, 2, \ldots$ identical particle system and $\mathcal{H}^0$ contains only one element: the (normalized) vacuum state $\psi_0$ (not to be confused with the null element of any Hilbert space).

A useful basis in Fock space is given by the eigenvectors of the position operator of the particles $\{\varphi_{x_1,x_2,\ldots,x_n} \} \forall n$ built as linear combinations of all label permutations of the element $\varphi_{x_1} \otimes \varphi_{x_2} \otimes \ldots \otimes \varphi_{x_n}$ (in $\mathcal{H}^n$) such that the resulting state is totally symmetric or anti-symmetric when the particles described are bosons or fermions respectively.

An interesting feature of quantum field theory, that is absent in non relativistic quantum mechanics, is the possibility of states with an indefinite number of particles, described by a superposition of Hilbert space elements belonging to different subspaces of Eq.(1). An important example of this, appears in the quantum field for photons: a state with an exact number of photons has zero expectation value for the electric and magnetic field observables and only with states that are not eigenvector of the number operator can we observe nonzero values of the electric and magnetic fields. Other interesting states, also with non definite number of particles, are the coherent states (eigenvectors of the annihilation operator) that turn out to be the states closest to the classical behaviour of the system.

A central feature of quantum field theory is the description of spontaneous creation and annihilation of particles by means of operators that connect the Hilbert spaces of Eq.(1) increasing or decreasing the number of particles. More precisely, consider some one particle state $\varphi \in \mathcal{H}^1$ corresponding to some property of the particle, that is, $\varphi$ is an eigenvector of some observable. We define now a creation operator $A^\dagger$ such that $A^\dagger \psi_0 = \varphi$ and when applied to any state of $\mathcal{H}^n$ results in an element of $\mathcal{H}^{n+1}$ (properly symmetrized or anti-symmetrized) with an extra particle
in the state \( \varphi \). Correspondingly, \( A \) is the annihilation operator for a particle in the state \( \varphi \).

If we consider now a set of creation operators \( \{A^\dagger_\alpha\} \) corresponding to a basis \( \{\varphi_\alpha\} \) in \( \mathcal{H}_1 \), then we can obtain any multiparticle state in Fock space by the application of these operators to the vacuum state. Furthermore, not only the states, but also all operators in Fock space can be expressed in terms of creation and annihilation operators making them ubiquitous in the formalism of quantum field theory. For instance, the operator \( A^\dagger A \) is related with the number of particles in the state \( \varphi \) (zero or one for fermions) and therefore \( \sum_\alpha A^\dagger_\alpha A_\alpha \) is the operator for the total number of particles in the system.

The symmetrization requirements of the states imply that the creation and annihilation operators must satisfy commutation (for bosons) or anti-commutation (for fermions) relations:

\[
[A_\alpha, A^\dagger_\beta]_\pm = \delta_{\alpha,\beta} \mathbb{I} , \quad [A^\dagger_\alpha, A^\dagger_\beta]_\pm = 0 , \quad [A_\alpha, A_\beta]_\pm = 0 .
\] (3)

As said before, one of the great achievements of quantum field theory was the prediction of the existence of antiparticles. Furthermore we will see that their existence is necessary in order to satisfy relativistic causality. Therefore, in the formalism, it is necessary to include operators \( \bar{A}^\dagger \) and \( \bar{A} \) for creation and annihilation of antiparticles. Since antiparticles and particles annihilate each other (except when they are identical) the total number of particles in a given state corresponds to the operator \( A^\dagger A - \bar{A}^\dagger \bar{A} \). The question naturally arises whether the creation of an antiparticle is equivalent to the annihilation of a particle, that is, whether \( \bar{A}^\dagger = A \) and \( \bar{A} = A^\dagger \). If this were so, the total number of particles in a given state would be associated with the operator \( A^\dagger A - AA^\dagger \), but this is always \(-1\) for bosons: an absurd result. Therefore for boson fields \( \bar{A}^\dagger \neq A \) and \( \bar{A} \neq A^\dagger \) and we must express the quantum field using both set of operators whereas for fermion fields we may do it with just one type of creation and annihilation operators. There is however an exception in this argument: the case where the bosons are neutral (with respect to electric and all other charges) and identical to the antiparticles (photons, for instance). In this case we can make indeed \( \bar{A}^\dagger = A \) and \( \bar{A} = A^\dagger \).

Consider now the creation and annihilation operators \( B^\dagger_\beta \) and \( B_\beta \) related with a
basis $\{\phi_\beta\}$ in $\mathcal{H}^1$ different from the basis $\{\varphi_\alpha\}$ created by $\{A_\alpha^\dagger\}$. Using the unitary transformation among the bases we readily obtain a relation among creation and annihilations operators:

$$B_{\beta}^\dagger = \sum_\alpha \langle \varphi_\beta, \phi_\alpha \rangle A_\alpha^\dagger, \quad B_\beta = \sum_\alpha \langle \phi_\beta, \varphi_\alpha \rangle A_\alpha,$$

and same equations for antiparticle creation and annihilation.

We are now ready for the presentation of the main tool of quantum field theory: this is, essentially, the equations above but relating the creation and annihilation operators for position eigenstates with those for momentum eigenstates. Let then

$$\Psi(x) = \sum_p \left( u(x, p) A(p) + v(x, p) \bar{A}^\dagger(p) \right)$$

be the annihilation operator for a particle in the space-time location $x = (t, \mathbf{x})$ given in terms of the annihilation of particles (and creation of antiparticle) with all possible energy momentum $p = (E, \mathbf{p})$. The corresponding creation operator is obtained by hermitian conjugation. This general expression is schematic and several comments are due to make it clear.

1. The variables $x$ and $p$, playing the role of the indices $\beta$ and $\alpha$, are continuous and therefore the summation symbol must be understood as an integral with a Lorentz invariant integration measure. Furthermore, this summation should also involve the spin degree of freedom that we have suppressed in this schematic treatment.

2. The operator $\Psi(x)$ and the complex functions $u(x, p)$ and $v(x, p)$ have implicit several components in the different cases: one for scalar (spin zero) particles, three for vector (spin one massive) particles, four for Dirac spinors, sixteen for tensors, etc. and have the appropriate behaviour under Lorentz transformations.

3. In all the cases mentioned above, the operator $\Psi(x)$ satisfy some equation of motion for the field (Klein-Gordon, Dirac, etc.). There are in fact two approaches in the presentation of quantum field theory: in one, as suggested here, we start with particles and obtain the equation of motion of the operator
fields and in the other approach we start from a Lagrangian and find the solutions of the Euler-Lagrange equations to represent the particles.

4. In the cases where particles and antiparticles are identical we can replace $\bar{A}(p) = A(p)$.

5. As mentioned, this expression is schematic and the exact form, suitable for calculations, can be found in appropriate books [11].

6. The commutation or anti-commutation relations Eq. (3) for the fields (adapted for continuous variables) vanish when evaluated at points $x$ and $y$ such that $x - y$ is space-like. This important requirement of relativistic causality could not be satisfied without antiparticles.

The interactions among particles is introduced in quantum field theory by means of gauge fields with creation and annihilation of the carriers of the interactions: photons, weak vector bosons, gluons and gravitons. When possible, Feynman diagrams represent all perturbation orders of the interaction involving creation, propagation and annihilations of gauge bosons and particles.

As suggested above, the formalism of quantum field theory favours the interpretation based on a permanent creation and annihilation of particles and antiparticles at every location with a given intensity. In order to see how the formalism supports this interpretation let us consider the description that quantum field theory makes of some very simple physical systems. Let $\psi \in \mathcal{H}^1$ be the state of a one particle system at some time. If we expand it in the basis $\{\varphi_x\}$ corresponding to the eigenvectors of the position operator, we have $\psi = \sum_x f(x)\varphi_x$. Now we write $\varphi_x$ given by the creation field applied to the vacuum.

$$\psi = \sum_x f(x) \Psi(x) \psi_0 .$$

This suggests the interpretation that $f(x)$ denotes the intensity of the quantum field of the one particle system. That is, at any location $x$, a particle is created from the vacuum with an intensity $f(x)$. In order to support this, let us calculate the number of particles at the location $x$ for this state, that is, the expectation value of
\[ \langle \psi, \Psi^\dagger(x)\Psi(x) \psi \rangle = \left\langle \sum_{x'} f(x') \Psi^\dagger(x') \psi_0, \Psi^\dagger(x)\Psi(x) \sum_{x''} f(x'') \Psi^\dagger(x'') \psi_0 \right\rangle = \sum_{x'} \sum_{x''} f^*(x') f(x'') \delta_{x,x'} \delta_{x,x''} \langle \psi_0, \psi_0 \rangle \].

(7)

Now, using the commutation or anti-commutation relations we can shift all the creation field operators to the left (that is, expressed in “normal order”) and considering that the annihilation operator applied to the vacuum produces the null element, we obtain

\[ \langle \psi, \Psi^\dagger(x)\Psi(x) \psi \rangle = \sum_{x'} \sum_{x''} f^*(x') f(x'') \delta_{x,x'} \delta_{x,x''} \langle \psi_0, \psi_0 \rangle = |f(x)|^2 . \]

(8)

Let us consider a virtual particle created at the location \(x\) with an intensity given by the complex function \(f(x)\). The modulus squared of this function gives then the existential weight (probability) for the particle at \(x\). However, this function must also contain information indicating that the virtual particle belongs to a collective of virtual particles that make up the field for the real particle: it must contain information about all other observables. This information is contained in a holistic way involving all values of \(x\). For instance, the intensity for the creation of a virtual particle with momentum \(p\) is given by \(g(p) = \sum_x f(x) \langle \phi_p, \varphi_x \rangle \) where \(\langle \phi_p, \varphi_x \rangle \) is the internal product between the eigenvectors of position and momentum.

As a generalization of Eq.(6) we have the most general state in Fock space

\[ \psi = \sum_n \sum_{x_1,x_2,\ldots,x_n} F_n(x_1,x_2,\ldots,x_n) \Psi^\dagger(x_1)\Psi^\dagger(x_2)\ldots\Psi^\dagger(x_n) \psi_0 . \]

(9)

Any physically relevant quantity (transition amplitude, scattering matrix, etc.) can be given in terms of internal products among two states like the one above. That is, it will involve the vacuum expectation value of products like \(\Psi(x_1)\Psi(x_2)\ldots\Psi(x_n)\Psi^\dagger(x_{n+1})\Psi^\dagger(x_{n+2})\ldots\Psi^\dagger(x_{n+m})\) for all \(n, m, \) and \(x_i\). In the formalism of quantum field theory, every physically relevant quantity or process is expressed in terms of creation and annihilation of virtual particles and in the proposed ontology this restless activity is assumed to occur in reality.

The commutation and anti-commutation relations of Eq.(3) were motivated by the symmetrization requirements of identical particles states. However, the first of
these relations allows an interesting interpretation in agreement with the proposed ontology for quantum field theory: for any location $x$, the identity operator $\mathbb{1}$ can be written as $\mathbb{1} = \Psi(x)\Psi^\dagger(x) \pm \Psi^\dagger(x)\Psi(x)$, that is, as a combination of creation and annihilation of particles. Applied to any state (including the vacuum), $\psi = \Psi(x)\Psi^\dagger(x)\psi \pm \Psi^\dagger(x)\Psi(x)\psi$, suggesting that any state can be thought as resulting from a permanent creation and annihilation of particles.

IV. INDIVIDUALITY LOSS

One of the fundamental features of reality discovered by quantum mechanics is the *individuality loss*. In our perception of macroscopic objects we take for granted that their individuality is conserved: if we look at a stone, close our eye for a second, and observe it again, we never doubt that we are dealing with *the same* stone. This anthropocentric conviction can not be extrapolated to the microscopic world. Identical classical systems have an individuality that is conserved through the time evolution and interaction with other system (this conservation of individuality corresponds to the concept of *conatus* in antique Greek philosophy). So classical systems, even when they are “identical”, can be assigned an individual identity that is conserved: they can have a name, an ID number, a licence plate. Quantum mechanics requires a drastic conceptual change: *the individuality loss*. A set of five identical “classical” atoms is countable (five in total) and numerable (the atom number one, the number two, . . .) but real atoms, necessarily described by quantum mechanics, are countable but not numerable. The individuality of the particles is entangled with the individuality of all other identical ones in the universe (although “for all practical purposes” a cluster decomposition isolating a particular system from the rest is possible to an extremely good approximation [12]).

Consider, for instance, two different states $\xi$ and $\eta$ belonging to the Hilbert space for one particle system $\mathcal{H}^1$. The state of a two identical particle system belongs to $\mathcal{H}^2 = \mathcal{H}^1 \otimes \mathcal{H}^1$ and the individuality entanglement requires a state proportional to $\xi \otimes \eta \pm \eta \otimes \xi$ symmetric (for bosons) or antisymmetric (for fermions). Notice the formal similarity of this state with EPR-Bell entangled states where two sub-
systems exhibit correlations that have been extensively studied. There are cases, however, where the subsystems are not entangled and a separated treatment is possible. On the contrary, the *individuality* entanglement in identical particle states is a distinctive feature of quantum mechanics that can not be avoided.

It turns out that individuality entanglement is not just an interesting feature but is one of the essential features of quantum physics and therefore any complete interpretation of quantum mechanics must provide a rational explanation or understanding for the individuality entanglement. In the ontology suggested by quantum field theory the individuality loss is very natural because in this interpretation we are not dealing with one, or two, or many particles as individual entities. For instance, the field for a one electron system, or for several electrons system, is made up by the permanent creation propagation and annihilation of virtual particles that are not assigned to any of the individual electrons of the system: in a two electron field there is no way to differentiate one electron from the other because they are both simultaneously made by an active background of ephemeral virtual particles with a mean value of *two* for the particle number observable, but each virtual component of the field is not assigned to any one the electrons.

V. DISTRIBUTIONS IN NONRELATIVISTIC QUANTUM MECHANICS

The predictions of non relativistic quantum mechanics are presented in the form of distributions for the eigenvalues of the operator associated with an observable. That is, for a system in a state $\psi$, the theory provides for any observable $L$ with eigenvectors $\{\varphi_\lambda\}$ (associated with the eigenvalue $\lambda$) the distribution $\rho(\lambda) = |\langle \varphi_\lambda, \psi \rangle|^2$ that can be tested empirically. Unfortunately, the name “probability distribution” is irreversibly installed in quantum mechanics for this function, although this is a misnomer because this quantity does not satisfy all the requirements that the mathematical theory requires for a probability. There are historical reasons for this name in addition to the fact that it is measured experimentally as if it were a probability, that is, by the frequency of appearance of each eigenvalue. Anyway, other names for it have been proposed like "pseudo-probability" or, more recently, "existential
weight” but with little hope for acceptance.

One question that has dominated the research in the foundations of quantum mechanics is the nature of this distribution. There are basically two options: an ontological or a gnoseological interpretation. We say that the existential weight has a gnoseological interpretation if we assume that the system in its reality possesses some definite value for the observable—the putative value—but we are unable to know it because the theory is unable to predict it: the system has a definite value but we can not know it. The indeterminacy resides in our knowledge of the reality of the system that has some hidden features. In this interpretation the question immediately arises about the existence of a better theory that can predict the exact value, the so called hidden variable theories. In the opposite interpretation, the ontological, we accept that the observables are diffuse by nature and do not assume precise values: quantum mechanics is a complete theory and the indeterminacies are in the reality of the system and not in our knowledge if it.

At first sight, the gnoseological interpretation appears to be less traumatic and was intensively investigated after the appearance of the crucial paper of Einstein, Podolsky and Rosen. However, theoretical and empirical developments put severe restrictions in the theories with hidden reality and many experts today favour the ontological interpretation of the indeterminacies. In fact, the Bell and Kochen-Specker theorem show that the existence of non contextual putative values for commuting observables enters in contradiction with the formalism of quantum mechanics. Much more definitive, the experimental violation of Bell inequalities show that the existence of such non contextual putative values is in contradiction with reality. Context independence means that the putative value of an observable does not depend on what other commuting observables are being considered; a very reasonable assumption because the context can be decided by theoretician at his office and this should not change the reality of a physical system.

In the quantum field theory interpretation of quantum mechanics the indeterminacies are ontological: the quantum field of a particle is extended in space with an existential weight for the location of the particle at any position given by the amplitude of the intensity for the creation of particles at that point. Similarly every
momentum value is realized with an existential weight given by the corresponding
intensity of the field. Position and momentum of the system described by the quan-
tum field are diffuse and are related by Fourier transformation that is a realization of
a symmetry arising from the equivalence of the description of the system by means
of its location or its movement (being and becoming symmetry)\[16\].

VI. POSITION-MOMENTUM CORRELATIONS

The interpretation of the quantum field as permanent creation and annihilation of
virtual particles provide a very intuitive view of the position-momentum correlations
of a particle\[17\]. In order to see this, let us consider the simplest system consisting
of one free particle moving in one dimension. The position-momentum correlation
is defined as

\[ C = \frac{1}{2}(XP + PX) \]  \hspace{1cm} (10)

with commutation relations

\[ [X, C] = i\hbar X \quad \text{and} \quad [P, C] = -i\hbar P \ . \]  \hspace{1cm} (11)

Let us imagine the virtual components of the quantum field created at a location
at “the right” of the one dimensional distribution for position \( \rho(x) \), that is, with
a \textit{positive} value for the observable \( X - \langle X \rangle \). If these components are moving with
momentum smaller than the mean value, that is, with \textit{negative} value for \( P - \langle P \rangle \)
the relative motion will be towards the center of the field and the distribution will
shrink. Similarly, the components created at the left and moving to the right have
the two offsets \( X - \langle X \rangle \) and \( P - \langle P \rangle \) with different sign, that is, their (symmetrized)
product is negative.

For simplicity, let us assume that in this state we have \( \langle X \rangle = \langle P \rangle = 0 \) (the
general state is obtained with the translation and impulsion operator). Therefore,
the product of the two offsets in position and momentum is precisely the correlation
observable and the previous argument means that if the correlation is negative then
the space distribution shrinks. We can prove this with rigour: let us calculate the
time derivative of the width of the distribution \( \Delta^2 x = \langle X^2 \rangle \). In the Heisenberg
picture, assuming a nonrelativistic hamiltonian $H = P^2/2m$, we have

$$\frac{dX^2}{dt} = -\frac{i}{\hbar}[X^2, H] = \frac{-i}{2\hbar m}[X^2, P^2] = \frac{1}{m}(XP + PX) = \frac{2}{m}C.$$  \hspace{1cm} (12)

Taking expectation values we conclude that states with negative correlation shrink and states with positive correlation expand, as expected from the heuristic argument given above based on the reality of the virtual components of the field.

The momentum distribution for a free particle is time independent and if the field is shrinking, that is, with negative correlation, we are approaching the limit imposed by Heisenberg indeterminacy principle. This principle will not be violated because the correlation will not remain always negative: at some time it will become positive and the state will begin to expand. In fact, we can prove that the correlation is never decreasing in time:

$$\frac{dC}{dt} = -\frac{i}{\hbar}[C, H] = \frac{-i}{4\hbar m}[XP + PX, P^2] = \frac{1}{m}P^2 = 2H,$$  \hspace{1cm} (13)

and this is a nonnegative operator. If the field is shrinking, at some later time it will be spreading. Gaussian states of this sort have been reported \cite{18} in a very comprehensive paper.

**VII. SUPERPOSITION**

The principle of superposition establishes that if $\psi_1$ and $\psi_2$ are two possible states of a system then $\psi \propto \psi_1 + \psi_2$ is another possible state. This principle is a necessary consequence of the linear structure of the Hilbert space of states and of the linearity of the causal evolution of the system that preserves the superpositions. Another way of looking at it, is to think that any state $\psi$ can be decomposed in an infinite number of ways into components involving all Hilbert space element not orthogonal to the given state, that is, related to all properties not incompatible with the one fixing the state. In this way, the state contains information about all possible properties of the system. A useful application of the principle of superposition corresponds to the mathematical possibility of expanding any state in a basis. Physically, this expansion provides the content of the state concerning all eigenvalues of an observable. Notice however that states are superposed but not the properties of the system associated
with them. In fact, if $\psi_1$ and $\psi_2$ are eigenvectors of some observables corresponding to two different properties of the system, then $\psi$ is not an eigenvector corresponding to any one of these properties.

Let us consider the quantum field of a particle in a state $\psi_1$. According to the ontology proposed, this field is build by a permanent creation and annihilation of virtual particles. The same can be said for the state $\psi_2$. Let us assume now that these two states correspond to quantum fields separated in physical space. In this case, the superposition $\psi \propto \psi_1 + \psi_2$ corresponds to a quantum field where virtual particles are created somewhere and annihilated far away providing some sort of “quantum rigidity” or non-separability that played a relevant role in the EPR argument.

An other interesting consequence of the superposition of states of compound systems is entanglement that will be mentioned next.

**VIII. ENTANGLEMENT**

Entanglement is one of the most remarkable features of nonrelativistic quantum mechanics exhibiting strong correlations between unrelated observables in compound systems. Most physical systems are compound, in the sense that they can be decomposed in subsystems, sometimes corresponding to separate physical systems (like an electron and a proton in a hydrogen atom) or to different degrees of freedom of one system (like spin and location of the same particle, or different space coordinates).

The Hilbert space for the states of the compound system $S = (S_A, S_B)$ is a tensor product structure $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. Consider two different properties of the subsystem $S_A$ (for instance, spin 1/2 in two different orientations) denoted by $A_1$ and $A_2$ corresponding to the states $\phi_1$ and $\phi_2$ that may, or not, be orthogonal. Consider also another unrelated pair of properties $B_1$ and $B_2$ of $S_B$ associated with $\phi_1$ and $\phi_2$ (for instance, located here or there). Furthermore, imagine two possible states of the system: $\phi_1 \otimes \phi_1$, corresponding to the simultaneous appearance of the properties $A_1$ and $B_1$ and the other state, $\phi_2 \otimes \phi_2$, corresponding to the appearance of the properties $A_2$ and $B_2$. The superposition, $\phi_1 \otimes \phi_1 + \phi_2 \otimes \phi_2$, is an entangled state of the system. In this state, none of the properties $A_1, A_2, B_1, B_2$ are objective (in the
sense that the state is \textit{not} an eigenvector corresponding to any of these eigenvalues) but there are strong quantum correlations among them because the observation of one property, say $A_1$, forces the appearance of $B_1$ although they may be totally unrelated (like spin and location). In entangled states all sort of astonishing quantum effects appear, like violations of Bell’s inequalities, Einstein-Podolsky-Rosen (so called) paradox, Schrödinger cat, nonlocality, teleportation, quantum cryptography and computation, etc. The principle of superposition, that generates the entanglement, contains perhaps the central essence of nonrelativistic quantum mechanics and almost all pondering concerning its foundations involve entangled states.

IX. MEASUREMENT

The understanding of the measurement process in quantum mechanics is very controversial but can be described following the scheme devised by von Neumann\[3\] and the London Bauer theory\[19\] without intervention of the observer conscience and with the physical process of decoherence\[20\] replacing the unnecessary “collapse”.

In order to describe the measurement process let us consider a physical system $S$ in a state expanded in the eigenvectors $\varphi_\lambda$ of an observable $L$ to be measured: $\psi = \sum_\lambda f(\lambda) \varphi_\lambda$. The measurement apparatus is another quantum system $S_A$ that can be in a set of states $\{\phi_\lambda\}$ corresponding to the reading $\lambda$ in its display. During the measurement, both system interact and the compound system $(S, S_A)$ is set in an entangled state $\sum_\lambda f(\lambda) \varphi_\lambda \otimes \phi_\lambda$. Although the apparatus is treated as a quantum system, it is macroscopic, has a large energy $E_A$ and could be treated classically. This means that after the interaction, in an extremely short decoherence time that can be estimated as $\frac{\hbar}{E_A}$, the system makes a transition from the pure state to a mixed state with \textit{classical} probabilities:

$$\sum_\lambda f(\lambda) \varphi_\lambda \otimes \phi_\lambda \rightarrow \sum_\lambda |f(\lambda)|^2 P_\lambda,$$

where $P_\lambda$ is a projector in the state $\varphi_\lambda \otimes \phi_\lambda$.

In the decoherence of the system the resulting state is a sum of classical probabilities: the ontological indeterminacies of the pure state become gnoseological
uncertainties of the mixed state. In each instance of measurement the apparatus stays in one of the states $\phi_\lambda$ with probability $|f(\lambda)|^2$.

X. CONCLUSION

Lead by our classical macroscopic expectations we are conditioned towards an ontology based on fields or particles. These views failed in the microscopic world and a compromise ontology was developed mixing particles and field properties in a complementary way. However this last option implies an ontology difficult, or impossible, to imagine because reality should simultaneously have contradicting properties of particles and fields. The proposal that reality is made by Quantum Fields—extended entities in space-time build by dynamic appearance propagation and annihilation of virtual particles—is compatible with the astonishing features of quantum mechanics and can be rendered intuitive. This interpretation of quantum mechanics follows from the formalism of the most successful theory in physics: quantum field theory.

[1] M. Planck. “Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum”. Verhandlungen der Deutschen Physikalischen Gesellschaft, 2, 237-245 (1900).
[2] A. Einstein. “Uber einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtpunkt”. Annalen de Physik (4), 17, 132-148 (1905); A. Einstein. “Theorie der Lichterzeugung und Lichtabsorption”. Annalen de Physik (4), 20, 199-206 (1906).
[3] J. von Neumann. Mathematische Grundlagen der Quantenmechanik. Springer, Berlin (1932).
[4] R. Feynman. Character of Physical Law. MIT Press (1967).
[5] For the historical development of quantum mechanics see M. Jammer. The Philosophy of Quantum Mechanics. Wiley, New York (1974).
[6] A. Einstein, B. Podolsky, N. Rosen. “Can quantum mechanical description of physical reality be considered complete”, Phys. Rev. 47, 777-780 (1935).
[7] J. S. Bell. “On the Einstein Podolsky Rosen paradox”, Physics 1, 195-200 (1964).
[8] S. J. Freedman, J. F. Clauser, “Experimental test of local hidden variable theories”, Phys Rev. Lett. 28, 938-941 (1972).
A. Aspect J. Dalibard and G. Roger. “Experimental test of Bell’s inequalities using time varying analysers”, Phys. Rev. Lett. 49, 1804-1807 (1982).
[9] For more details see Chapter 2 of ref.[5] or Chapter 8 of J. T. Cushing. Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony. The University of Chicago Press, Chicago 1994. Or also relevant chapters of Tian Yu Cao. Conceptual Developments of 20th Century Field Theories. Cambridge University Press, Cambridge 1997.
[10] See for instance S. Weinberg. The Quantum Theory of Fields. Cambridge University Press (1995).
[11] See for instance equations 5.2.11, 5.3.34, 5.5.34, 5.7.31, 5.9.23, 5.9.34 in the book of ref.[10]
[12] A. C. de la Torre, H. O. Martín. “Distinguishing identical particles and the correct counting of states” Eur. J. Phys. 30, 467-475 (2009).
[13] A. C. de la Torre. “On Randomness in Quantum Mechanics” Eur. J. Phys. 29, 567-575 (2008).
[14] J. S. Bell. “On the problem of hidden variables in quantum theory,” Rev. Mod. Phys. 38, 447-452 (1966).
[15] S. Kochen and E. P. Specker. “The problem of hidden variables in quantum mechanics,” J. Math. Mech. 17, 59-88 (1967).
[16] A. C. de la Torre. “The position-momentum symmetry principle” arXiv: 1311.2454
[17] A. C. de la Torre. “A quantum arrow of time” arXiv: 1411.2178
[18] R. W. Robinett, M. A. Doncheski, L. C. Bassett. “Simple examples of position-momentum correlated Gaussian free-particle wavepackets in one-dimension with the general form of the time-dependent spread in position” Found. of Phys 18, 455-475 (2005).
[19] F. London, E. Bauer. La théorie de l’observation en mécanique quantique. Hermann, Paris (1939).
[20] E. Joos, H. D. Zeh. “The emergence of classical properties through interaction with the environment” Z. Phys. B 59, 223-230 (1985).

W. H. Zurek. “Decoherence and the transition from quantum to classical” Phys. Today 44, 36 (1991).

M. Schlosshauer. “Decoherence, the measurement problem, and interpretations of quantum mechanics” Rev. Mod. Phys. 76, 1267-1305 (2005).