Vacuum fluctuations the clue for a realistic interpretation of quantum mechanics

Emilio Santos
Departamento de Física. Universidad de Cantabria. Santander. Spain

March 10, 2013

Abstract

Arguments are given for the plausibility that quantum mechanics is a stochastic theory and that many quantum phenomena derive from the existence of a real noise consisting of vacuum fluctuations of all fundamental fields existing in nature. Planck’s constant appears as the parameter fixing the scale of the fluctuations. Hints for an intuitive explanation are offered for some typical quantum features, like the uncertainty principle or the particle behaviour of fields. It is proposed that the recent discovery of dark energy in the universe is an argument for the reality of the vacuum fluctuations. A study is made of the compatibility of the model with the results of performed tests of Bell’s inequalities.

1 Introduction

Understanding quantum mechanics presents big difficulties for many people, a paradoxical fact in view of the relevance and the practical success of the theory. For physicists interested in applications understanding is not very relevant if it means getting an intuitive picture of the microworld. In fact, for them the essential purpose of physics is to allow predicting the results of experiments. Other physicists, including most of the workers in foundations, think that the real problem is that, in the attempt to understand quantum mechanics, we should not use concepts of classical physics[21], or we should adhere to a kind of “weak” objectivity[8]. In contrast with those opinions,
in this article it is proposed that quantum mechanics is less different from classical physics than usually assumed, and it might be understood in a similar manner.

Quantum mechanics is extremely efficient for the prediction of experimental results. In almost one century no significant violation of a quantum prediction has been shown. Furthermore the agreement with experiments is truly spectacular, reaching sometimes a precision of one part in $10^{10}$. In contrast the interpretation of the quantum formalism has been the subject of continuous debate since the very beginning of the theory [33] until today. This paradoxical situation, practical success combined with conceptual difficulties, is something new in science. It is true that all previous theories have given rise to controversy, but the conflict is more acute in the case of quantum mechanics. An undesirable consequence has been some confusion between science and pseudoscience in the public opinion. At present some alleged consequences of quantum theory, like the uncertainty principle or the impossible separation between object and subject, have transcended the scientific community and are commented in newspapers and popular writings, frequently presenting quantum mechanics like magic. The situation has been originated, to some extent, by quantum physicists themselves who have sometimes stressed the difficulties of understanding, and even the wonder of that fact. In my opinion the lack of understanding is not wonderful but unfortunate. In any case this state of affairs does not contribute to the popular esteem of true science.

"Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves". With these words begins the celebrated 1935 article by Einstein, Podolsky and Rosen [10]. The paragraph clearly supports a realistic interpretation of any physical theory, which should be able to provide a model of the natural world. Presenting a sketch of such a model for quantum theory is the purpose of this paper. I shall not discuss the philosophical question of whether there is an external world, independent of our mind, which is usually called ontological realism. In any case I support epistemological realism, that is the assumption that science makes assertions about the natural world, and not only about the results of observations or experiments.

In my view there is not yet a clear physical model behind the quantum
formalism, is spite of the numerous interpretations proposed so far. In this respect it is the opposite to general relativity. The latter provides a clear, although strange, physical model: matter produces curvature of spacetime and motion is governed by that curvature. However the calculational tool (the Riemann geometry) is difficult to manage. In quantum mechanics there is a beautiful and relatively simple formalism, that is linear equations involving vectors and operators in a Hilbert space, but there is no clear physical model behind. I would say that general relativity has physical beauty, the quantum formalism has mathematical elegance.

Historically the renunciation to physical models in quantum mechanics came as a consequence of frustration, due to the failure of the models proposed during the first quarter of the 20th. century. This was the case after Bohr’s atomic model, consisting of point electrons moving in circular orbits around the nucleus. That model, generalized with the inclusion of elliptical orbits, produced some progress during the first few years after 1913. However it was increasingly clear that the model was untenable. In 1926 an alternative model was proposed by Schrödinger, with an interpretation of his wave mechanics where the electrons were considered continuous charge distributions. As is well known that model was soon abandoned after the correct criticisms by Bohr, Heisenberg and other people. Independently Heisenberg had proposed a formalisms, with the name of quantum mechanics, which explicitly rejected any model. Indeed he supported the view that the absence of a picture was a progress towards a more refined form of scientific knowledge. The success of the new quantum mechanics in the quantitative interpretation of experiments, toghether with the failure to find a good physical model of the microworld, led to the almost universal acceptance of the current view that models are unnecessary or even misleading.

I do not agree with that wisdom, but support the EPR view[10] that there should be “concepts intended to correspond with the objective reality, by means of which we picture the reality to ourselves”. That is any physical theory should contain two ingredients: a physical model and a calculational tool, the latter including the formalism and rules for the connection with the experiments. The calculational tool is essential because it is required for the comparison of the theory with experiments. Indeed that comparison is the test for the validity of the theory. However the physical model is necessary in order to give satisfaction to the human being, who naturally aspires to have a picture of the world. Furthermore the existence of a physical model might open the possibility for new developments or applications of the theory and
therefore it is not a mere matter of taste.

In the next section I will sketch a physical model of the microworld which is realist and clear and some specific quantum phenomena are analyzed within that model. A warning is necessary. Very probably any quantum physicist reading these two sections will quickly point out many contradictions between the model and known empirical facts, so discarding the model as untenable. I claim that the alleged contradictions are not real, they derive from a common understanding of the quantum formalism which is not fully correct. I will devote the third section of the article to rebut the most relevant of the apparent difficulties of the model, the alleged empirical violations of Bell’s inequalities. Finally I will point out briefly how other difficulties might be solved.

2 The physical model of the microworld

2.1 Vacuum fluctuations, the clue to understand quantum physics

The concept of isolated system is the cornerstone of classical physics. But, is isolation possible in our universe? I think not. The universe is not static and so complex that some amount of noise is unavoidable. Furthermore, the assumption of a fundamental noise may lead from classical physics to quantum physics. Let us give an example, the stability of the hydrogen atom. The atom consists of a proton (say at rest) and an electron moving around. Everybody knows that a classical atom cannot be stable because the electron would radiate, losing energy and falling towards the proton. The argument would be fine if there were an unique atom in space, but if there are many atoms it is natural to assume that the radiation of one atom will eventually arrive at other atoms. Thus every atom will sometimes emit radiation but absorb it other times, possibly reaching a dynamical stationary state with fluctuating energy. I shall not elaborate this example further, my purpose being to convince the reader that the existence of a “fundamental noise” is plausible and might explain, at least, some phenomena taken as purely quantal. Thus classical physics may be seen as an approximation of quantum physics when the said noise may be neglected or, more properly, averaged out.

A fundamental noise is actually accepted in standard quantum theory,
where it is named “quantum vacuum fluctuations”. These fluctuations are qualified as “virtual”, a word whose meaning is not clear. In my opinion the acceptance of the quantum noise as real is what allows reaching an intuitive picture of quantum physics.

This leads me to the following picture of the quantum world. Fundamental fermions, like leptons or quarks, are (localized) particles, but fundamental bosons like photons, gluons, Z₀, W± or Higgs, are actually (extended) fields. Gravity plays a special role, I support the view that general relativity determines the structure of (curved) spacetime and its relation with matter, so that gravity is not a field, at least not in the same sense than the other fields. The wave behaviour of particles derives from the unavoidable interaction with fields, and the particle behaviour of fields derives from the interaction with particles, e. g. during detection. A fundamental property of the universe is the existence of (vacuum, i.e. not involving a finite temperature) fluctuations of all fields. In the case of Bose fields there are random fluctuations similar to the zeropoint fluctuations of the electromagnetic radiation to be studied below in some detail. In the case of particles the fluctuations correspond to the existence of a kind of “Dirac sea” of particles and antiparticles which may be created and annihilated at random. There should be also metric fluctuations of spacetime itself. Quantum commutation (anti-commutation) rules provide a disguised form of stating the properties of the fluctuations in the case of fundamental fields (particles).

The existence of vacuum fluctuations gives rise to two characteristic traits of quantum physics. Firstly quantum theory should be probabilistic. Secondly it should present a kind of wholeness, quite strange to classical physics where the concept of isolated system is crucial. The fact that the vacuum fluctuations at different points may be correlated is the origin of the wholeness. Indeed entanglement may be a consequence of the correlation of quantum fluctuations at different points.

### 2.2 Planck’s constant, the parameter fixing the scale of the fluctuations

For the sake of clarity let me consider just a kind of noise, the zeropoint field fluctuations (ZPF) of the electromagnetic field. What are its characteristics? The most relevant is the spectrum, which may be defined as the energy density, \( \rho(\nu) \), per unit frequency interval, \( d\nu \). It is remarkable that the spectrum
is fully fixed, except for a constant, by the condition of relativistic (Lorentz) invariance. The direct proof is not difficult but I shall replace it by an argument which may be traced back to Wien’s work in 1894. An advantage of that indirect derivation is that it discriminates clearly thermal noise from the ZPF. Combining thermodynamics with Maxwell’s electromagnetic theory Wien derived the displacement law, which states that the spectrum of the black body at a temperature $T$ should be of the form $\rho(\nu, T) = \nu^3 f(\nu/T)$. Lorentz invariance at zero Kelvin is implicit in the use of electromagnetic theory. Now I claim that putting $f(\nu/T) \to 0$ for $T \to 0$ leads to classical physics, but putting the limit equal to a finite constant leads to quantum physics. It is obvious that the constant involved should play a fundamental role. It must be fixed by appeal to the experiments and the result is that at $T \to 0$

$$\rho(\nu) d\nu = \frac{4\pi}{c^3} h \nu^3 d\nu,$$

(1)

$c$ being the speed of light. Thus Planck’s constant, $h$, appears with a transparent meaning, it fixes the scale of the universal noise or quantum noise (but remember, I consider that the noise consists of real fluctuating fields.) The ZPF spectrum eq.(1) corresponding to zero Kelvin, at a finite temperature the fluctuating radiation contains a thermal part with Planck’s spectrum. In cosmology that part is called cosmic background radiation. Actually eq.(1) is strongly ultraviolet divergent, which poses a big difficulty for the model here supported. In standard quantum field theory the same difficulty appears, but it is eliminated by removing it via the “normal ordering rule” in some cases and labelling it “virtual” when a complete removal contradicts the observations. However this solution is not good, it is better to assume that at high frequencies a cut-off should exists due, for instance, to creation or annihilation of particles and/or to gravitational (general relativistic) effects. I do not know how to implement quantitatively this hypothesis but I will point out a possible solution to the divergence problem later on (see section 2.7.)

The spectrum eq.(1) does not fully characterize the ZPF. We must fix the joint probability distribution of the amplitudes of the fields. A natural assumption is that the different modes are statistically independent and each ones has a Gaussian distribution. Thus the ZPF becomes a Lorentz invariant Gaussian stochastic field which may be characterized by a plane waves
expansion of the electric field

\[ E(r,t) = \frac{1}{\sqrt{V}} \sum_j \left[ c_j \varepsilon_j(r) \exp\left(ik_j.r - i\omega_j t\right) + c_j^* \varepsilon_j^*(r) \exp\left(-i k_j.r + i\omega_j t\right) \right], \]

where \( \omega_j = 2\pi \nu_j \), \( \varepsilon_j \) being polarization vectors and \( V \) a normalization volume. A similar expansion may be written for the magnetic field with \( ik \varepsilon_j \) substituted for \( \varepsilon_j \). Then the (complex) coefficients \( \{c_j\} \) and \( \{c_j^*\} \) form a set of independent Gaussian random variables with zero mean and a square mean such that eq.(1) holds true. That is, the probability distribution of the coefficients will be

\[ W(\{c_j, c_j^*\}) d(\text{Re } c_j) d(\text{Im } c_j) = \Pi_j \left[ (\pi \hbar \omega_j/2)^{-1} \exp\left(-\frac{2|c_j|^2}{\hbar \omega_j}\right) \right] d(\text{Re } c_j) d(\text{Im } c_j). \]

Up to here I have considered the electromagnetic field, but I will assume that a similar ZPF exists for all fundamental Bose fields. Indeed all of them should be in a dynamical equilibrium because they may interact exchanging energy. The interaction will be stronger when the frequencies of the excitations of the fields happen to have the same frequency. In summary, a fundamental assumption of the physical model behind quantum theory, supported in this paper, is the existence of a (real) universal noise, present even at zero Kelvin, consisting of Gaussian fluctuations of all fundamental Bose fields of nature with an average energy \( \frac{1}{2} \hbar \nu \) for every normal mode (except at very high frequencies.)

A natural consequence of the belief in a real random electromagnetic radiation with spectrum eq.(1) filling the whole space has been the development of a theory known as stochastic (or random) electrodynamics. It deals with the study of electrically charged particles immersed in the vacuum electromagnetic zeropoint field possessing the spectrum eq.(1). The theory may be traced back to Walter Nernst, who extended to the radiation field the 1912 second radiation theory proposed by Planck for oscillators. That theory consisted of adding the term \( \frac{1}{2} \hbar \nu \) to the oscillator energy at a finite temperature thus giving the second Planck’s law

\[ U(\nu, T) = \frac{1}{2} \hbar \nu + \frac{\hbar \nu}{\exp(\hbar \nu/kT) - 1}. \]
The idea was forgotten after the success of Bohr’s atom, but it has been re-discovered several times and developed by a small number of authors during the last 50 years. A review of the work made until 1995 is the book by de la Peña and Cetto[7]. Stochastic electrodynamics has succeeded in providing a clear intuitive explanation for some phenomena considered as purely quantal, and has been considered as a possible alternative (or reinterpretation) of quantum mechanics by some authors. In my opinion it is a semiclassical theory which reproduces quantum predictions in a limited domain. In any case that theory has been the inspiration of the physical model here presented.

It is here appropriate to sketch the explanation offered by stochastic electrodynamics to the Casimir and Unruh effects[7] because both reinforce the essential idea of this paper: that vacuum fluctuations are real. The Unruh effect is the modification of the spectrum eq. (1) when a radiation (classical) field is seen from an accelerated reference frame. The Casimir effect corresponds to the fact that the normal modes of the (classical) radiation are modified by the presence of two metallic plates. If we ascribe an energy $\frac{1}{2}h\nu$ per normal mode, the energy depends on the distance between plates, leading to an attraction between them which is the Casimir effect. It may be also seen as due to the fact that the radiation pressure on the two sides of a plate is no longer balanced when there is another parallel plate near it, due to the modification of the normal modes.

### 2.3 Heisenberg uncertainty relations

A rather obvious consequence of the reality of the ZPF, proposed in this paper, is that bodies cannot have smooth trajectories. In fact the forces due to the vacuum fluctuating fields give rise to a rapid random motion of any particle. Thus the instantaneous velocity is meaningless, or irrelevant, a situation similar to what happens in the theory of Brownian motion. Only the mean velocity, $v$, during some time interval, $T$, may be a sensible quantity. Still the mean velocity should fluctuate, with a fluctuation $\Delta v$ which would decrease with increasing time. Thus it is plausible to assume that the product $T\Delta v$ should be a function of the variables involved, that is the mass of the body, $m$, the Planck constant, $\hbar$, fixing the scale of the ZPF, and the velocity, $v$, itself. Thus dimensional considerations lead to

$$T\Delta v \simeq const. \frac{\hbar}{mv} \Rightarrow T\Delta v = \Delta x\Delta \nu \simeq \frac{\hbar}{2m},$$
where $\Delta x$ is the distance traveled by the body during the time $T$, and I have chosen the constant in order to agree with the quantum prediction. In summary, due to the vacuum fluctuations, smooth paths do not exist and it is not possible to define both the position and the velocity of a particle with precision beyond the one allowed by the Heisenberg uncertainty relation.

I must point out that the comparison with Brownian motion may be misleading due to the big difference between their spectra. This may be better seen from the selfcorrelation function, which is the Fourier transform of the spectrum, that is

$$\langle x(0)x(t) \rangle = \int_0^\infty S(\omega) \cos(\omega t) \, d\omega. \quad (4)$$

In Brownian motion the spectrum is white (i.e. a constant) so that the integral eq.(4) is zero. This means that the Brownian particle losses quickly any memory of the initial position. In contrast the spectrum of the ZPF increases rapidly, it being zero for $\omega \to 0$ (see eq.(1)). As a consequence the cosinus term effectively cuts-off the spectrum for $\omega \gtrsim 1/t$, but some correlation remains. This means that the memory of the initial position is not fully lost. The picture that emerges is that particles have highly irregular paths which may be seen as the superposition of a smooth one plus strong short-time fluctuations. Actually the effect of the ZPF fluctuations decreases with the particle’s mass so that the classical limit (absence of fluctuations) is obtained for very massive bodies.

Another form of the uncertainty relation appears in a stationary motion. Let us consider a particle in an external potential well. Due to the existence of the ZPF, the particle will perform a more or less periodic motion with a random frequency, say of order $\nu$. (If the particle is charged the electromagnetic ZPF will be relevant field, but in any case the metric fluctuations will play a fundamental role.) As the ZPF has energy $\frac{1}{2} h\nu$ per normal mode of the radiation, we may assume that the particle reaches a dynamical equilibrium with the ZPF when its kinetic energy is similar to half the energy of the appropriate mode, that is

$$\frac{1}{2} m v^2 \approx \frac{1}{4} h\nu. \quad (5)$$

It is possible to get a relation independent of the frequency because the mean square velocity may be related to the mean square displacement via

$$\langle v_x^2 \rangle \approx 4\pi^2 v^2 \langle (x - \langle x \rangle)^2 \rangle \equiv 4\pi^2 v^2 \Delta x^2. \quad (6)$$
Hence, taking eq.(5) into account we get
\[
\Delta x \Delta p_x \simeq \frac{\hbar}{2}, \quad \Delta p_x^2 \equiv m^2 \langle v_x^2 \rangle.
\] (7)

This provides an intuitive interpretation of the Heisenberg uncertainty relations as follows. *Due to the quantum noise (vacuum fluctuations) with the peculiar spectrum* eq.(2), 1) the paths of particles are not smooth but fluctuating, so that velocity and position cannot be defined simultaneously with arbitrary precision, and 2) it is impossible to localize a particle in a region of size \( \Delta x \) without the particle having a random motion with typical momentum dispersion \( \Delta p_x \gtrsim \hbar / 2 \Delta x \). Thus the uncertainty relation appears as a practical limit to the localization of particles in phase space, rather than a fundamental principle of “uncertainty”. However in practice the difference is less relevant than it may appear. For instance as all measuring devices are immersed in the ZPF, the interaction of with a microscopic system gives a random character which necessarily leads to a “disturbance induced by the measurement”. This fact may explain the “Heisenberg microscope” and other effects associated to the uncertainty relations.

### 2.4 A picture of molecules and solids

As is well known the Heisenberg relations allow estimating the size and energy of the ground state of any quantum system. Thus these properties may be interpreted intuitively as due to the fact that all systems are immersed in the universal quantum noise (the vacuum fluctuations.) This suggests a picture of quantum systems which is lacking in standard quantum mechanics. For example, in the ground state of the hydrogen atom quantum mechanics attributes to the electron a well known spherically symmetric probability distribution of positions, but the standard interpretation does not asserts that the electron has an actual position at any time. It only states that “if we performed a measurement of position we would obtain a specific value with some probability predicted by quantum mechanics”. A picture of the reality is therefore lacking. In contrast we offer a clear picture of the electron performing a random motion. The picture may be extended to other atoms provided we add two important ingredients: the spin and the Pauli principle, but I shall not comment on them in this paper.

Let us now explain the model’s picture of molecules. For the sake of clarity I will consider as an example the \( CO_2 \) molecule. As is well known it
consists of three atoms in a straight line with the carbon atom at the center and some precisely measured carbon-oxigen distances. Now quantum theory states that the ground state of the isolated molecule possesses zero angular momentum (say, making a calculation within non-relativistic quantum mechanics, involving the electrons and three spin-zero nuclei taken as point particles.) Indeed the molecule consists of three spin-zero nuclei plus an even number of spin-1/2 electrons coupled to zero total spin angular momentum. Thus a quantum calculation leads to the prediction that the ground state has zero total angular momentum. Now zero angular momentum implies invariance to rotations, that is spherical symmetry. How may we understand the contradictory facts that the molecule is linear and it has spherical symmetry? The standard wisdom is that the linear form of the molecule emerges only as a result of a measurement or in general by the interaction with the environment when the molecule is not isolated. This interpretation is rather counterintuitive, to say the least. In contrast our model offers a transparent picture: the molecule retains its linear form at any time (aside from vibrations,) but changes the orientation randomly with a spherically symmetric probability distribution. This is similar to our model’s picture of the random motion of the electron in the hydrogen atom commented above. In my opinion this is a case where the standard interpretation of the quantum formalism should be reinterpreted. Indeed I propose that the quantum prediction of a dispersion-free zero angular momentum actually means that the dispersion cannot be detected by measurements, but we should not believe that no rotation exists. This is an example of the apparently unsurmountable difficulties for a physical model of the quantum world.

2.5 Particle behaviour of fields

I assume that in nature there are particles and fields (waves). In our model the fundamental Bosons (Fermions) are fields (particles), but composite systems like baryons, nuclei, atoms or molecules, are particles either if they possess integer or half-odd angular momentum. There is no problem to understand the localized detection of particles or the interference of waves, but there are difficulties to get a picture of the wave behaviour of particles or the corpuscular behaviour of waves. Here some hints will be provided for an intuitive understanding of that behaviour.

I shall start with the corpuscular behaviour of fields, discussing only the electromagnetic field although the arguments may be general. The first prob-
lem is why the ZPF, which is very strong at high frequencies, does not activate light detectors. The obvious solution is to postulate that detectors are activated only by the radiation in excess of the ZPF. This assumption is actually the same postulated in standard quantum theory. Indeed the “normal ordering” rule makes exactly a subtraction of the ZPF. For instance if we made a quantum calculation of the vacuum expectation of the energy density, $\rho_{\text{vac}}$, without the normal ordering rule we would get

$$\rho_{\text{vac}}^{(\text{wrong})} = \sum_j \langle \text{vac} | H_j^{(\text{wrong})} | \text{vac} \rangle = \frac{\hbar}{2} \sum_j \nu_j \langle \text{vac} | (a_j + a_j^\dagger)^2 | \text{vac} \rangle = \sum_j \left( \frac{1}{2} \hbar \nu_j \right),$$

where $a_j$ ($a_j^\dagger$) is the annihilation (creation) operator of photons. In the limit of large normalization volume the sum in $j$ becomes a frequency integral of eq.(11), which is clearly divergent. The quantum solution to this problem is to modify the Hamiltonian (and more generally all expressions quadratic in the fields) postulating the “normal ordering rule”, which means putting the annihilation operators to the right. Thus the quantum calculation gives

$$\rho_{\text{vac}} = \sum_j \langle \text{vac} | H_j | \text{vac} \rangle = \frac{\hbar}{2} \sum_j \nu_j \langle \text{vac} | 2a_j \dagger a_j | \text{vac} \rangle$$

$$= \frac{\hbar}{2} \sum_j \nu_j \langle \text{vac} | (a_j + a_j^\dagger)^2 | \text{vac} \rangle - \sum_j \left( \frac{1}{2} \hbar \nu_j \right) = 0,$$

where I have taken into account the standard commutation rules. It may be realized that passing to the normal ordering is equivalent to subtracting the ZPF contribution eq.(8).

In formal quantum mechanics the normal ordering rule may be accepted as a postulate without any further discussion. In contrast if we want to find a physical model behind the formalism, the rule of subtracting the ZPF presents difficulties in the case of photon counters. Remember that in our model there are no “particles of light” (photons), but light consists of a continuous radiation, always including the ZPF. The problem is that in practice the ZPF cannot be subtracted exactly. This fact does not derive from the (divergent) energy associated to the ZPF, but from the fact that the ZPF is fluctuating. If we assume that the ZPF is real, there is always the possibility that some vacuum fluctuations are confused with signals by the detectors, no matter how efficient is the subtraction made. This is explained in the following, where I study three relevant kinds of light detectors.
Firstly we may consider bolometric detection, which is frequently used in astronomy. It consists of a lens system which collects all light arriving at it during some time and it is measured the total energy stored. In this case the ZPF subtraction may be quite accurate because the fluctuations average out if the measurement time is long enough.

The detection of “individual photons” in a photographic plate is due to the atomic nature of the plate. In this case saying that radiation are particles because they give rise to individual blackened grains is like saying that wind is corpuscular because the number of trees falling in the forest is an integer. Of course in both cases, the photo and the forest, there is a random element. It is obvious for the wind but, as explained above, there is also a random element in the radiation: the quantum noise or ZPF.

The detection process in a photon counter may be explained as follows. Inside the detector there are systems, e. g. molecules, in a metastable state. The arriving radiation, with a random element due to the ZPF, has from time to time sufficient intensity to stimulate the decay of the metastable system and this gives rise to a photocount. However the noise alone, being fluctuating, may eventually produce counts in the absence of any signal, which are called dark counts. (Dark counts are usually attributed to thermal fluctuations, but I claim that quantum fluctuations may produce a fraction of them.) The counter behaves like an alarm system. If it has low sensitivity it may fail to detect some relevant signals, but if it is too sensitive it may be activated by accident. The same is likely true for photon counters. This leads me to conjecture that it is not possible to manufacture detectors with 100% efficiency but no dark counts and that this trade-off is the origin of the so-called detection loophole in the optical tests of Bell’s inequalities (see section 3.4 below.) In any case explaining in detail how a detector may subtract efficiently the ZPF is not trivial (it has been called “the needle in the haystack” problem) and naive models predict too many dark counts[9].

There are many more phenomena where light appears as consisting of particles (photons), but might be qualitatively interpreted in terms of waves. I shall mention just two: the atomic emission in the form of needels of radiation and the anticorrelation after a beam splitter.

Firstly I point out that the spontaneous emission of photons by atoms is interpreted, in our model, as an emission stimulated by the ZPF. As a simplified model we may consider that a plane wave with wavevector $\mathbf{k}$, belonging to the ZPF, arrives at an atom in the appropriate conditions to emit radiation with angular frequency $\omega = c|\mathbf{k}|$. If the radiation emitted
is in the form of a spherical wave, far from the atom we will observe the interference between the incoming ZPF plane wave and the emitted spherical wave. It is not difficult to realize that the interference will be constructive mainly within an angle $\theta$ with respect to the forward direction $k$, such that

$$\frac{l}{\cos \theta} - l \sim \frac{\lambda}{2},$$

where $l$ is the distance from the atom to the observation point and $\lambda = 1/|k|$. Thus the emitted radiation will look like a needle having a width about $l \sin \theta \sim \sqrt{l \lambda} << l$, superimposed to the ZPF. That needle is what we may interpret as one photon. Of course that simplified model does not provide an explanation as to why the total energy of the photon is related to the frequency via $E = \hbar \omega$. This would require a detailed study of the structure of the atom and its interaction with light. In any case the needle of radiation should have a well defined energy, $\hbar \omega$, and momentum, $\hbar \omega/c$. After that the Compton effect might be understood as a collision between an electron and a needle of radiation.

The anticorrelation after a beam splitter was first empirically proved by Grangier et al.[15]. The experiment essentially consists of sending individual photons to a balanced beam splitter with two photon counters placed after the two output ports of the splitter. The authors observed that either a count is produced in the first detector or in the second one, but never in both (most times no count was shown in either detector because the efficiency was rather low). This is interpreted as evidence for the particle behaviour of photons, which apparently cross the splitter undivided.

An analysis of that result within our model is somewhat involved[17],[19] but a simplified explanation is as follows. In the input port of the splitter not only the wavepacket (representing) the photon enters, there is also an incoming radiation from the ZPF. We may represent the total electric field at the entrance by the complex amplitude $E_{\text{signal}} + E_{ZPF}$, where I take into account that we should add the amplitudes of signal and ZPF, not the intensities. There is also another input port of the splitter where no signal enters, but some radiation from the ZPF should also enter, which we may represent by $E'_{ZPF}$. The fields in the output ports will correspond to appropriate additions of the incoming amplitudes, that is

$$\frac{1}{\sqrt{2}} (E_{\text{signal}} + E_{ZPF}) + \frac{i}{\sqrt{2}} E'_{ZPF}, \quad \frac{i}{\sqrt{2}} \left( E_{\text{signal}} + E_{ZPF} \right) + \frac{1}{\sqrt{2}} E'_{ZPF}, \quad (9)$$
where \( i \equiv \sqrt{-1} \) and I have taken into account that the transmitted (reflected) radiation does not change the phase (change by \( \pi/2 \)). Thus the corresponding intensities arriving at the detectors will be

\[
I_\pm = \frac{1}{2} |E_{\text{signal}} + E_{ZPF}|^2 \pm \frac{1}{2} |E'_{ZPF}|^2 \pm \text{Im}[\left(E_{\text{signal}} + E_{ZPF}\right)^*E'_{ZPF}]. \tag{10}
\]

Actually only the part of the ZPF in the same mode of the signal (with the same frequency) may interfere with it, and therefore that is the relevant part. Also the corresponding ZPF intensity \( (\frac{1}{2}h\nu) \) is half the intensity of the signal \( (h\nu) \). Thus eq. (10) might be rewritten, after subtraction of the ZPF intensity \( I_0 \),

\[
I_\pm - I_0 = I_{\text{signal}} \left[ \frac{3}{4} + \frac{\sqrt{2}}{2} \cos \phi_1 \pm \left( \sqrt{2} \sin \phi_1 + \sin \phi_2 \right) \right],
\]

where \( \phi_1 (\phi_2) \) is the relative phase between \( E_{\text{signal}} \) and \( E_{ZPF} \) \( (E'_{ZPF}) \); all angles assumed equally probable. The relevant point is that, except for some values of the \( \phi_1 \) and \( \phi_2 \), not very probable, the intensity arriving at one of the detectors is above the ZPF level (therefore detectable), and below the ZPF level (therefore not detectable) at the other detector, which may explain the anticorrelated detection. The full absence of anticorrelation might be explained assuming that for low efficiency detectors (like those used in the commented experiment\[15\]) only radiation well above the ZPF intensity would be detected.

### 2.6 Wave behaviour of particles

There is wide empirical evidence for a wave behaviour of particles. Asides from the early evidence for electron diffraction, the experimental results of neutron interference are really impressive\[22\] and to a lesser degree the atom interference. On the other hand the alleged interference of big molecules, like fullerene, may be less significant\[31\].

It is attractive the hypothesis that the wave behaviour of particles derives from the interplay of the particles and the quantum noise. For instance, in the interference of charged particles we might assume that the electromagnetic ZPF in a periodic arrangement interferes with itself, giving rise to maxima and minima of field intensity in some points, which might guide the particle to the screen where the interference pattern is exhibited. The picture has some similarity with the hypothesis, put forward by de Broglie, that any particle
is always accompanied by an associated wave. L. de Broglie’s proposal is usually understood as if every particle possesses its own wave, a picture reinforced by the quantitative relation between the particle’s momentum, $p$, and the wavevector, $k$. However that picture is untenable. For instance, how the (extended) wave may follow the (localized) particle during the motion of the latter? It is more plausible to assume that there is some background of waves in space able to interact with the particles. This leads to the picture that the waves are, actually, those of the quantum noise or ZPF.

The problem is to explain why the overwhelming interaction of the particle occurs with just one mode of the radiation, that is the one given by de Broglie’s relation. A number of people, in particular this author, have attempted to develop quantitatively that model without real progress till now.

2.7 Dark energy

The observed accelerated expansion of the universe is currently assumed to derive from a positive mass density and a negative pressure, constant throughout space and time, which are popularly known as “dark energy”. The mass density, $\rho_{DE}$, and the pressure, $p_{DE}$, fitting the observations are

$$\rho_{DE} \simeq -p_{DE} \simeq 10^{-26} \text{ kg/m}^3. \quad (11)$$

Many proposals have been made for the origin of dark energy, the most popular being to identify it with the cosmological constant introduced by Einstein in 1917 or, what is equivalent in practice, to assume that it derives from the quantum vacuum. Indeed the equality $\rho_{DE} = -p_{DE}$ is appropriate for the vacuum (in Minkowski space, or when the spacetime curvature is small) because it is Lorentz invariant.

A problem appears because, if the dark energy is due to the quantum vacuum, it should be either strictly zero or of order Planck’s density, that is about 123 orders of magnitude larger than eq.(11). In particular the Planck density is roughly obtained if we integrate the energy density of the electromagnetic ZPF, eq.(11), up to Planck’s frequency (the inverse of Planck’s time.) Thus the hypothesis that the ZPF vacuum energy is real seems flawed, which would make the model of this paper untenable. However there is an alternative which fits in the normal ordering rule of quantum field theory, equivalent to the ZPF energy subtraction as discussed in section 2.5. We
might assume that the vacuum fluctuations of fundamental Bose fields, like the electromagnetic radiation, contribute a positive energy, but fluctuations of fundamental Fermi fields contribute a negative energy, in such a way that the total vacuum energy is strictly zero. A strict cancelation would be quite satisfactory and would justify the subtractions involved in the normal ordering rule.

Nevertheless, even if the mean energy density is zero, as the fields are fluctuating the square mean energy density must be positive (not zero). Indeed for a random variable $x$ the equalties $\langle x \rangle = 0 = \langle x^2 \rangle$ would imply the total absence of fluctuations. The vacuum fluctuations should create a gravitational field. Long ago Zeldovich\cite{34} proposed that this mechanism may be the origin of the dark energy and estimated the gravitational energy density to be

$$|\rho_{DE}| c^2 \sim \frac{G m^6 c^2}{h^4} = \frac{G m^2}{\lambda} \times \frac{1}{\lambda^3}, \lambda \equiv \frac{h}{mc}.$$  \hspace{1cm} (12)

This corresponds to assuming that fluctuations with typical mass $m$ take place with a (positive) correlation length $\lambda$. In fact the observed value $\rho_{DE}$, eq.(11), is obtained if the mass $m$ is close to the pion mass. The sign of $\rho_{DE}$ in eq.(12) might be negative or positive depending on details of the two-point correlation of the vacuum fluctuations.

The Zeldovich calculation of the gravitational energy, eq.(12) follows from Newtonian gravity. An explicit calculation within general relativity\cite{29} shows that vacuum fluctuations lead to a curvature of spacetime equivalent to the one which would be produced by a positive energy and a negative pressure as in eq.(11). That calculation involves a single free parameter, the mass $m$ as in eq.(12). An argument for the value of $m$ follows. We might speculate that the important fluctuations would be those involving hadrons, produced by strong forces, and they would be more probable if the particles created are light, so requiring less energy. This would lead us to assume that the most relevant fluctuations might be those involving the lightest hadron, that is the pion. In fact the pion mass $m$ in eq.(12) fits fairly well the observed dark energy value eq.(11).
3 Quantum mechanics vs. local realism. The Bell theorem

3.1 Are the laws of nature causal?. The debate about completeness

There are strong difficulties to reach a physical model of the microworld from the quantum formalism. Possibly the most relevant are the wave-particle behaviour, above commented, and the violation of the Bell inequalities to be studied below. These difficulties apparently prevent an intuitive picture of the quantum world, e.g. the one provided by our model. But it is a fact that these difficulties have been greatly enhanced by sociological and historical reasons, as I comment in the following.

The early interpretation of quantum mechanics grew on the ground of the philosophical doctrines of positivism and pragmatism. In the positivistic view, physics should lie close to the empirical results, avoiding models which might be wrong. For instance Heisenberg early quantum mechanics rejected models of atoms from the start, using purely mathematical objects (matrices) instead. On the other hand pragmatism states that, the prediction of the experimental results being the unique criterion for the validity of a theory, physical models are not necessary at all. Nevertheless I do not claim that the positivistic and/or pragmatic attitudes were philosophical prejudices without support in the empirical facts. I am aware that people adhered to these doctrines due to the difficulties to understand atomic physics with the realistic epistemology inherited from 19th century physics. In particular, the lack of progress of the old quantum theory resting upon Bohr´s atomic model.

The said philosophical background led Bohr to support the completeness of quantum mechanics, that is to reject the necessity of a more detailed theory able to offer a definite world view. Most people adhered to that view. A consequence of the completeness assumption is that two states of a physical system represented by the same statevector should be identical. But this leads to the unavoidable conclusion that quantum probabilities derive from a lack of strict causality of the natural laws. That is we should assume that different effects may follow from the same cause. For instance two radioactive atoms in the same excited quantum state decay at different times, in spite of been identical according to the formalism. This is usually called the fundamental or essential probabilistic character of the physical laws. Einstein
disliked that assumption and strongly criticized it, as summarized in his celebrated sentence “God does not play dice”. The alternative supported by Einstein\cite{10}, \cite{11} (and other founding fathers like Schrödinger\cite{30}) is that quantum mechanics is not complete. That is the laws of nature are strictly causal, but there is a random element, not explicit in the quantum formalism, giving rise to the statistical character of quantum predictions. According to this realistic approach two atoms in the same quantum state are not identical, what is identical is our (incomplete) information about their real states. This situation led to the well known debate about completeness, confronting Bohr and Einstein positions. The model presented in this paper obviously conforms to Einstein’s view. The debate remained at the philosophical level because it was assumed that strict causality combined with randomness is in practice indistinguishable from essential probability. However a possible empirical discrimination appeared after the work of John Bell, to be commented below.

In my view it is not plausible to assume that a system can be fully isolated from the rest of the world, because the vacuum fields may provide an effective interaction with many other systems. However in order to be able to make physics we should assume that microscopic systems, even if not isolated, may be treated with a formalism which in some form takes account of the interaction with the vacuum fields. For instance, if we represent the state of an atom by a statevector, it is plausible to assume that this representation corresponds to the atom “dressed” by all fields which interact with it. As is well known in quantum electrodynamics the physical electrons are never “bare” but “dressed with virtual photons and electron-positron pairs”. The word “virtual” is just a name for something which has observable effects but is unknown. One of the aims of the model here presented is to give a more clear meaning to the word virtual. One of the reasons for the difficulties to understand quantum mechanics is that it deals with a world where noise (randomness) is crucial, but the noise is hidden because the Schrödinger equation is deterministic (probabilities appear only as a result of the measurement.)

Actually to pretend that a statevector represents faithfully the actual state of an individual system is a rather presumptuous attitude. It is more plausible to assume that the statevector represents the relevant information available about the system, which gives support to the belief in the incompleteness of quantum mechanics. This is the idea behind the ensemble interpretation of quantum mechanics: the state vector should be associated to a statistical ensemble of systems rather than to a single system\cite{10}, \cite{2}. In summary the complexity of even the most elementary quantum system, like a
“dressed electron”, makes the ensemble interpretation of the statevector most plausible.

3.2 Hidden variables

If we accept the ensemble interpretation the obvious question is the following: In view that the information provided by quantum mechanics is incomplete, should we attempt to get additional information? If the answer is yes we should search for a subquantum level which could increase our understanding of the world. That line of research is usually known as the *hidden variables programme*. But the answer may be not, because the experience shows that the programme has failed in spite of the big effort of some (few certainly) people during almost one century. In any case it is my opinion that the rejection of the hidden variables programme is not a sober attitude.

As said above the mainstream of the scientific community has been positioned for the completeness of quantum mechanics and therefore against hidden variables (HV). Possibly the origin of this fact lies in the strong personality of Bohr combined with the comfort produced by the belief that one possesses the final theoretical framework of physics, that is quantum mechanics. With the time the rejection to HV theories was reinforced by the failure to find a useful one. In any case a strong influence had the celebrated von Neumann’s 1932 theorem against hidden variables, which prevented the research on the subject during more than three decades. In 1965 Bell showed that the physical assumptions of von Neumann were too restrictive and that (contextual) hidden variables are possible. Indeed for any experiment it is a simple matter to find a specific contextual hidden variables theory. What is difficult is to get a HV theory valid for the whole of quantum phenomena. The relevant point is that the mere existence of HV has consequences that might be tested empirically. In the following subsection I will derive the most relevant ones following Bell’s work.

The existence of hidden variables is related to philosophical realism, that is the assumption that systems possess *elements or reality* (ontological realism) and that physics should make assertions about that reality and not only about the results of the experiments (epistemological realism.) A necessary condition for realism may be stated as follows. Let us assume that in some experiment we want to measure the observable $A$. Then the value, say $a$, obtained in a measurement will depend on the state, say $\lambda$, of the system...
and the observable which we measure. We should write

\[ a = a(\lambda, \text{context}(A)). \]  

(13)

where we may interpret \( \lambda \) as the elements or reality, i.e. the set of values of the (maybe hidden) variables which faithfully determine the state of the system. The dependence on \( \text{context}(A) \) takes into account that the result of the measurement may depend on the full experimental equipment used for the measurement of the observable \( A \). For some people eq. (13) is a condition for determinism \cite{14}, rather than realism, because the states of the system and the context completely determine the result of the measurement. It is true that eq. (13) excludes the possibility that natural laws are not strictly causal, and therefore the name causality would be more appropriate than determinism, but I shall not discuss this semantical point further. In any case we may replace eq. (13) by the more general one

\[ \Pr(a) = P_a(\lambda, \text{context}(A)), \]  

(14)

with the meaning that the states of system and context only determine the probability of getting the value \( a \). Thus eq. (14) is compatible with both the assumption that natural laws are strictly causal and its denial. We see that realism (whose necessary condition is eq. (14)) is more general than determinism (or deterministic realism, or strict causality) whose necessary condition is eq. (13).

The above construction allows defining two possible kinds of hidden variables theories. In fact let us assume that we measure not one but two observables, \( A \) and \( B \), in the same experiment. Thus eq. (14) leads to the following expectation value for the product of the two observables

\[ \langle AB \rangle = \int \rho(\lambda) d\lambda \sum_a a P_a(\lambda, \text{context}(A, B)) \sum_b b P_b(\lambda, \text{context}(A, B)), \]  

(15)

where I have assumed one continuous hidden variable with probability density \( \rho(\lambda) \). As above the dependence on \( \text{context}(A, B) \) takes into account that the results of the measurement might depend on the full experimental context of the measurement. In other words, we do not exclude that the expectation of the product of two observables, \( \langle AB \rangle \), might lead to a different numerical value if measured with a different equipment. With an assumption as general as eq. (15) it is not strange that, choosing appropriately the functions \( P_a(\lambda, \text{context}(A, B)) \) and \( P_b(\lambda, \text{context}(A, B)) \), we may reproduce any
desired result for $\langle AB \rangle$, in particular a result in agreement with the quantum prediction. HV theories where expectations are given by eq.(15) (or its generalization for more than two observables) are usually named \textit{contextual}, but a more appropriate name would be \textit{general} HV theories. They are obviously compatible with quantum mechanics, but being so general they are not too interesting.

A restricted family of HV theories consists of those \textit{non-contextual}, where the value of the observable $A$ does not depend on the whole experimental context but only on the state of the system under study, and similar for $B$. In non-contextual HV theories eq.(15) is replaced by

$$\langle AB \rangle = \int \rho(\lambda) \sum_a a P_a(\lambda, A) \sum_b b P_b(\lambda, B).$$

We might say that non-contextual theories assume that bodies possess properties independent of any measurement (such properties, represented by $\lambda$, are not the observable quantities, but fully determine them). However eq.(16) involves an assumption far stronger than that, namely that the measurement of property $A$ is not perturbed by the simultaneous measurement of $B$.

John Bell\[3\] introduced local HV theories, which are partially non-contextual. Indeed these theories are non-contextual only for measurements performed at spacelike separation, in the sense of relativity theory. This implies that the expectation values of the products should be calculated via eq.(15) when the measurements of $A$ and $B$ are performed at spacelike separation and via eq.(15) if this condition does not hold true. Spacelike separation is a rather stringent condition. If the measurement of $A$ takes a time between $t$ and $t + \Delta t_a$ and that of $B$ between $t$ and $t + \Delta t_b$, all times defined in an appropriate inertial frame, then spacelike separation requires that

$$\max\{\Delta t_a, \Delta t_b\} < d,$$

$d$ being the maximal distance between the two measuring equipments ($d$ defined in the same frame).

In summary there are three kinds of HV theories fulfilling the following relations of inclusion

$$\text{general} \supset \text{local} \supset \text{non-contextual}.$$  

General HV theories are compatible with quantum mechanics and with experiments as said above. The compatibility of local and non-contextual ones is analyzed in the following.
3.3 Non-contextual and local hidden variables vs. quantum mechanics

Non-contextual HV theories are not compatible with quantum mechanics, a statement known as Kochen-Specker theorem, although Bell proved it independently[4], [20]. A proof goes as follows. We consider four dichotomic observables $A_1, B_1, A_2, B_2$, that is observables which may take only the values $\pm 1$. Calculating the expectations via eq.(16) and making use of the properties of probabilities (i. e. $0 \leq P \leq 1$) it is possible to derive the inequality

$$|\langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle - \langle A_1 B_2 \rangle| \leq 2,$$

which is the most popular form of a Bell inequality[6]. Eq.(17) is violated by the quantum predictions in some cases, for instance in a system of two spin 1/2 particles (say silver atoms) in the singlet spin state, flying in opposite directions, say along the axis $OZ$. Measuring the spin projections on two different directions in the $XY$ plane (say forming angles $\phi_A$ and $\phi_B$ with the $OX$ axis) the quantum prediction for the correlation (as defined in eq.(16)) is

$$\langle AB \rangle = \frac{1}{2} [1 + \cos (\phi_A - \phi_B)].$$

Hence choosing measurements (in different runs of the experiment) with four different positions of the spin analyzers with angles

$$\phi_{A1} = 0, \phi_{B1} = \pi/4, \phi_{A2} = \pi/2, \phi_{B2} = 3\pi/4,$$

the correlations predicted by quantum mechanics are

$$\langle A_1 B_1 \rangle = \langle A_2 B_1 \rangle = \langle A_2 B_2 \rangle = \frac{1}{2} + \frac{\sqrt{2}}{4}, \langle A_1 B_2 \rangle = \frac{1}{2} - \frac{\sqrt{2}}{4},$$

which violates the Bell inequality (17). This ends the proof.

Local theories are incompatible with standard quantum mechanics, which is known as Bell’s theorem. (The word standard in this context will be explained in more detail below). The proof is quite similar to the one for non-contextual theories, with the additional condition that each of the four measurements involved in eq.(17) is performed at spacelike separation. This similarity has been the source of some confusion because some people have believed that any violation of a Bell inequality refutes local HV theories.
whilst the truth is that the violation may only refute non-contextual HV theories (that is if measurements are not performed at space-like separation.)

The physical model presented (or rather sketched) in this paper does not pretend to be a new theory different from quantum mechanics, but rather an interpretation of the quantum formalism. On the other hand the model may be qualified as a HV model, as explained in the following. Consequently it is crucial for the model to know whether it is local because in this case it seems not to be a valid model, in view of Bell's theorem.

The main point of the model, as explained above, is the belief that quantum vacuum fluctuations are real fields. As a consequence the fields at every spacetime point, or the coefficients of their Fourier analysis (like $\{c_j\}$ and $\{c_j^*\}$ in eq.(2)) may be taken as the hidden variables of the model. They may be named hidden because they do not appear explicitly in the quantum formalism. On the other hand the model may be said contextual as may be seen with reference to eq.(15). Indeed the vacuum fluctuations (ZPF) may be influenced by the measurement context, and therefore some correlation between the apparatus measuring $A$ and the apparatus measuring $B$ may be established via the ZPF. Actually the modification of the ZPF by material systems is well known. For instance the Casimir effect is due to the modification of the vacuum fields by the presence of metallic plates, as explained in section 2.2.

However the model, although contextual, is local. In fact the propagation of the vacuum fields is causal in the sense of relativity theory (as shown for instance by eq.(2)). Relativistic causality is what Bell called locality. As a consequence it seems that the model is untenable as an interpretation of quantum mechanics. My rebuttal to this statement is the conjecture that experiments showing a violation of locality are not feasible, and quantum predictions do not (or should not) exist for impossible experiments. The conjecture is reinforced by the history of the attempts at refuting local HV theories via the empirical violation of a Bell inequality. In the next section I shall comment on these attempts, but here I give an example showing the difficulties to perform a real test of local hidden variables theories. So far there has been only one proposal for an experiment able to measure the correlations involved in eq.(20) between the spin projections of two atoms[12]. The experiment is extremely involved as is shown by the detailed proposal published in 1995, and the experiment has never been performed.
3.4 Empirical tests of Bell’s inequalities

During the last 40 years many experiments have been performed with the purpose of testing Bell’s inequalities, but only two kinds of experiments will be commented here, involving either optical photon pairs or entangled atoms. Less significance has been attributed to the remaining experiments.

Until about 1983 optical tests involved entangled photon pairs produced in atomic cascades, the Aspect experiment being the most celebrated of that period. However the authors were aware that the experiments could not really violate the Bell inequalities because the results could not fit the ideal quantum prediction

\[ \langle AB \rangle = \frac{1}{2} [1 + \cos (2\phi_A - 2\phi_B)] . \]  

(In comparison with eq.(20) a factor 2 appears due to the fact that photons have spin 1 rather than 1/2). In fact assuming for simplicity a linear detection probability and labelling \( \eta \) the detection efficiency and \( \varepsilon \) the noise to signal ratio, that is the ratio between dark counts and true photon detections, the quantum prediction with real detectors departs from eq.(21) becoming

\[ \langle AB \rangle = 1 - \eta (1 + \varepsilon) + \frac{1}{2} \eta^2 [1 + \cos (2\phi_A - 2\phi_B)] , \]  

where I have neglected the noise in the coincidence detection (false coincident counts). If we insert the result in the Bell inequality (17) we get

\[ |\langle A_1 B_1 \rangle + \langle A_2 B_1 \rangle + \langle A_2 B_2 \rangle - \langle A_1 B_2 \rangle| \leq \left| 2 - 2\eta (1 + \varepsilon) + \eta^2 \left[ 1 + \sqrt{2} \right] \right| \leq 2 , \]  

where I have taken into account that the left hand side achieves the maximum value if we choose the angles to be half those of eq.(19). Therefore the Bell inequality is fulfilled whenever the following inequality holds true

\[ \eta < 0.82 (1 + \varepsilon) , \]

an inequality fulfilled in all performed optical experiments in the commented period because available detectors had efficiencies below 10%. This difficulty for the tests has been called the detection loophole.

In order to overcome the detection loophole an assumption named no-enhancement was introduced. It may be stated saying that in any HV model
for the experiments (involving measuring the polarization correlation of optical photons) the detection probability of a photon cannot increase by crossing a polarizer. Adding this condition to those used by Bell in his derivation of the inequalities, it is possible to derive new inequalities which were actually violated in the commented (atomic cascade) photon experiments. Of course the HV models refuted were only those fulfilling the no-enhancement assumption. The model presented in this paper does not fulfill that condition, as may be seen by looking at eq. (10), which represents the light intensity at the outgoing channel of a balanced beam splitter. It may be realized that the outgoing intensity can be greater than the incoming one that is $|E_{\text{signal}} + E_{ZPF}|^2$. The action of a polarizing beam splitter is more involved, but again the intensity of signal plus ZPF may increase, whence the detection probability can be enhanced.

There is another difficulty with the empirical tests of Bell inequalities involving photon pairs produced in atomic cascades. In fact the angular correlation of the photon produced is too low to violate a Bell inequality even if ideal, 100% efficient, detectors were used [24]. This is due to the three-body character of the two-photon emission in atomic cascades. In spite of these problems the experiments, in particular Aspect’s [1], is currently quoted in books of quantum mechanics as refuting local HV theories.

During the last decades, entangled photon pairs produced via parametric down conversion are substitutes for those coming from atomic cascades. In this case the problem of low angular correlation does not appear, but the detection loophole remains. The additional assumption of no-enhancement has been abandoned and a hypothesis of fair sampling is used instead. Thus it is assumed that the ensemble of photons actually detected is representative of the full set of photons arriving at the detectors. The assumption allows extrapolating the actual experimental results, in agreement with the quantum prediction eq. (22), to ideal detection where $\eta = 1, \varepsilon = 0$, which would violate the Bell inequality. It is obvious that the violation only refutes the family of local HV models fulfilling the fair sampling assumption. The question is whether there are interesting local HV models not fulfilling fair sampling, and the answer is affirmative. Furthermore HV models not fulfilling fair sampling are most natural. In fact, the purpose of hidden variables is to explain why systems, represented by the same quantum state, behave differently. In particular why some photons are more likely detected than other photons, in spite of being treated as identical in the quantum formalism. Therefore it is quite consistent with the idea of hidden variables to assume that the
photons actually detected belong to a special subset of photons, that is those which are detectable with a probability greater than the average. In such HV models the sample of detected signals is not representative of the full set. The point may be more clearly understood with reference to our model, as explained in the following.

The model presented in this paper fits in a statement by Willis Lamb\cite{16}: “Photons are the quanta of light, but they are not particles”. For us photons are fluctuations of the electromagnetic field, maybe in the form of needles of radiation, superimposed to the ZPF. As a consequence even the sentence “one hundred detection efficiency” is meaningless in our model. Detection efficiency might be defined only as the ratio between the number of photo-counts, excluding (an unknown number of) dark counts, and the radiation energy arriving at the detector after subtraction of the ZPF, the energy being measured in units $h\nu$. If the photon counters used in an experiment have a relatively low detection efficiency, it is most natural to assume that signals having higher intensity will be more likely detected. Thus the sample detected is not representative of the whole set of arriving signals, just because the signals are not identical. And the lack of real equality of the signals is the crucial assumption of HV models. In summary, the detection loophole is not a purely technical problem in the manufacture of detectors, but derives from fundamental reasons according to our model.

In experimental tests of a Bell inequality involving atoms the detection may be quite efficient and the property corresponding to the polarization of photons (i. e. a linear combination of different atomic states) has been also measured with good efficiency in the experiment by Rowe et al.\cite{23}. Thus the Bell inequality\cite{17} has been violated, although some uncertainty exists about the statistical significance of the violation\cite{28}. As a consequence the experiment has refuted non-contextual hidden variables theories (see section 2 for the proof that the violation of a Bell inequality refutes non-contextual HV theories). However the measurements have not been made insuring spacelike separation, and therefore local HV theories have not been refuted. A popular, but misleading, form of the latter statement is to say that “local hidden variables theories have been refuted by the experiment, modulo the locality loophole”. The correct statement is to say that the question whether local HV models are possible is still open. My conjecture, already stated seven years ago\cite{27}, is that local HV models are possible, that is local realism is compatible with experiments. Furthermore I think that it is also compatible with quantum mechanics, provided that we call quantum predictions only those
for real experiments, that is excluding “predictions” for ideal, not feasible, experiments.

3.5 From ideal to real experiments

Asides from the possible difficulties posed by Bell’s theorem, discussed in the previous subsections, there are other reasons making our model apparently untenable, which any well informed quantum physicists could discover. It is impossible to rebutte all possible objection in a single article of limited length and I shall give here only a few general arguments. They may be summarized in the following three points.

1. Quantum mechanics itself introduces many constraints for real experiments which are not taken into account in ideal examples. To mention just one I shall consider the effect of the Heisenberg uncertainty relations for the measurement of the spin correlation of two massive particles like electrons, neutrons or atoms. Let us assume that both particles start at a point and travel a distance \(l\), moving in opposite directions with velocity \(v\). If there is an initial uncertainty in the position, \(\Delta x\), and the velocity, \(\Delta v\), of one of the particles, the length traveled by it will have an uncertainty

\[
\Delta l \simeq \Delta x + \frac{l}{v} \Delta v \geq \Delta x + \frac{\hbar}{2mv \Delta x} \geq 2\sqrt{\frac{\hbar}{2m v}},
\]

\(m\) being the mass of the particle. The former inequality follows from the Heisenberg uncertainty relation and the second one from trivial algebra. If we want to measure the spins of the particles at a spacelike separation we should insure that the uncertainty in their mutual distance should fulfil

\[
\frac{2 \Delta l}{v} \leq \frac{2l}{c} \Rightarrow l \gtrsim \frac{\hbar}{mc} \left(\frac{c}{v}\right)^3,
\]

\(c\) being the speed of light. This means that “locality cannot be violated” until the particles have traveled some distance, macroscopic for plausible values of \(m\) and \(v\). This does not put unsurmountable difficulties for a (loophole-free) test of Bell’s inequality but it is an indication that the experiment is less simple than it might appear.

2. There may be predictions of the quantum formalism which seem to contradict our model. An example, mentioned in subsection 2.4, is the fact that the formalism predicts no rotational zeropoint. That is a system with
total angular momentum $\mathbf{J}=0$ does not rotate. I believe that this quantum result should not be interpreted as the absence of any rotation, but rather as the impossibility to determine the actual fluctuating rotation in real experiments.

3. One of the cherished statements of quantum mechanics is the principle of superposition. It says that if two states $\psi$ and $\phi$ of a system are possible, then any linear combination of $\psi$ and $\phi$ represents other possible state. Of course, the principle is limited by the superselection rules, so that for instance the linear combinations are not realizable states if $\psi$ and $\phi$ corresponds to states with different electric charge. But I think that stronger constraints should exist, that is I do not think that neither all vectors of the Hilbert state may correspond to physically realizable states nor all selfadjoint operators correspond to quantities actually measurable. However I am not in a position to make a more precise statement.

In summary I believe that constraints on the quantum formalism may exist, able to eliminate all apparent difficulties for the physical model of the microworld here presented.

4 Conclusions

An intuitive picture of the quantum world would be useful and possible. The starting point for that picture is to assume that quantum mechanics is a stochastic theory and that typically quantum phenomena are due to an universal noise in the form of real vacuum fluctuations of all fundamental fields present in nature.

An attempt at explaining every quantum phenomena from the vacuum fluctuations with a clear and consistent model seems formidable. A better approach would be to try to get a picture derived from the quantum formalism, in particular via an interpretation of the commutation and anticommutation rules, which I believe represent a characterization of the randomness associated with quantum mechanics. An attempt in this direction has already been made\cite{25}, but a deep understanding is still lacking.

A problem for viewing quantum mechanics as a stochastic theory, along the lines here presented, is the alleged violation of the Bell inequalities. It is the case that a loophole-free violation has not yet been produced in spite of the big effort of many people during more than 40 years. For me this failure is an indication that quantum mechanics is compatible with local hid-
den variables for real experiments, even if some ideal (gedanken) experiments violate the Bell inequality[27].

References

[1] Aspect, A., Dalibard, J. & Roger, G. (1982). Experimental tests of Bell’s inequalities using time-varying analyzers, Physical Review Letters; 49, 1804-1807.

[2] Ballentine, L. E. (1998). Quantum mechanics, a modern development. Singapore: World Scientific.

[3] Bell, J. S. (1964). On the Einstein Podolsky Rosen paradox. Physics, 1, 195-200. (Reprinted in Wheeler & Zurek (1983)).

[4] Bell, J. S. (1966). On the problem of hidden variables in quantum mechanics. Reviews of Modern Physics, 38, 447-52. (Reprinted in Wheeler & Zurek (1983)).

[5] Bohr, N. (1928). The quantum postulate and the recent development of atomic theory. Nature, 121, 580-90. (Reprinted in Wheeler & Zurek (1983)).

[6] Clauser, F. J., Horne, M. A., Shimony, A., Holt, R. A., (1969). Proposed experiment to test local hidden-variable theories, Physical Review Letters, 23, 880-884 (Reprinted in Wheeler & Zurek (1983)).

[7] de la Peña, L. & Cetto, A. M. (1996). The quantum dice. An introduction to stochastic electrodynamics. Kluwer Academic Publishers, Dordrecht.

[8] d’Espagnat, B. (2011). Quantum physics and reality. Foundations of Physics, 41, 1703-1716.

[9] Dechoum, K., de la Peña, L. & Santos, E. (2000). The problem of light detection in the presence of zeropoint fluctuations: A physical model for the vision of weak signals, Foundations of Physics Letters 13, 253-264.

[10] Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete? Physical Review, 47, 777-80 (Reprinted in Wheeler & Zurek (1983)).
[11] Einstein, A. (1949). Remarks concerning the essays brought together in this co-operative volume. In P. A. Schilpp (Ed.), Albert Einstein: Philosopher-Scientist (pp. 665-688). La Salle Illinois: Open Court.

[12] Fry, E., Walther, T., & Li, S. Proposal for a loophole-free test of the Bell inequalities. *Physical Review, A* 52, 4381-4395.

[13] Genovese, M. (2005). Research on hidden variable theories: A review of recent progresses, *Physics Reports, 413*, 319-396.

[14] Gisin, N. (2012). Non-realist Deep thought or soft option?. *Foundations of Physics, 42*, 80-85.

[15] Grangier, P., Roger, G., & Aspect, A. (1986). Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences. *Europhysics Letters, 1*, 173-9.

[16] Lamb, W. (1995). Anti-photon. *Applied Physics B, 60*, 77-84.

[17] Marshall, T. W., & Santos, E. (1987). Comment of Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences. *Europhysics Letters, 3*, 293-296.

[18] Marshall, T. W., & Santos, E. (1993). Can the Stern-Gerlach effect exhibit quantum nonlocality? In P. Bush, P. Lahti and P. Mittelstaedt (Eds.), *Symposium on the Foundations of Modern Physics*. Singapore: World Scientific, pp. 361-368.

[19] Marshall, T. W., & Santos, E. (2002). Semiclassical optics as an alternative to nonlocality. *Recent Results and Developments in Optics, 2*, 683-717.

[20] Mermin, D. N. (1993). Hidden variables and the two theorems of John Bell. *Reviews of Modern Physics, 65*, 803-815.

[21] Mittelstaedt, P. (1998). *The Interpretation of Quantum Mechanics and the Measurement Process*. Cambridge UK: Cambridge University Press.

[22] Rauch, H. & Werner, S. A. (2000). *Neutron interferometry; lessons in experimental quantum mechanics*, Clarendon Press, Oxford.
[23] Rowe, M. A. Kielpinski, D., Meyer, V., Sakckett, C. A., Itano, W. M., Monroe, C., & Wineland, D. J. (2001). *Nature* (London), 409, 791-794.

[24] Santos, E. (1992). Critical analysis of the empirical tests of hidden-variables theories, *Physical Review A*, 46, 3646-3656.

[25] Santos, E. (1992). The physical meaning of quantization, *Foundations of Physics* 22, 371-379.

[26] Santos, E. (2003). Quantum logic, probability and information. The relation with the Bell inequalities. *International Journal of Physics*, 42, 2545-2555.

[27] Santos, E. (2005). Bell’s theorem and the experiments: Increasing empirical support for local realism? *Studies in History and Philosophy of Modern Physics*, 36, 544-565.

[28] Santos, E. (2009). Relevance of a random choice in tests of Bell inequalities with two atomic qubits. *Physical Review, A* 79, 044104.

[29] Santos, E. (2011). Dark energy as space-time curvature induced by quantum vacuum fluctuations, *Astrophysics and Space Science*, 332, 423-435.

[30] Schrödinger, E. (1935). The present situation of quantum mechanics. *Naturwissenschaften*, 23: pp. 807-812; 823-828; 844-849. (English translation reprinted in Wheeler & Zurek (1983)).

[31] Sulc, S., Gilbert, B. C. & Osborne, C. F. (2002). On the interference of fullerenes and other massive particles, *Foundations of Physics*, 32, 1251-1271.

[32] von Neumann, J. (1932). *Mathematische Grundlagen der Quantenmechanik*. Berlin: Springer-Verlag. English translation Princeton University Press, 1955.

[33] Wheeler, J. A., & Zurek, W. H. (1983). *Quantum theory and measurement*. Princeton: Princeton University Press.

[34] Zeldovich, B. Y. (1968). The cosmological constant and the theory of elementary particles, *Sov. Phys. Usp. 11*, 209-230.