

# Real vacuum fluctuations, the clue to understand quantum physics

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## 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 the fields existing in nature. Planck's constant appears as the parameter fixing the scale of the noise. Hints for an intuitive explanation are offered for some typical quantum features, like the uncertainty principle

## 1 Towards a model of the microworld

### How to understand quantum mechanics

“Nobody understands quantum mechanics” wrote Feymann[1], and many people still agree. I think that a realistic interpretation and a physical model of quantum mechanics are needed. This opinion is not new, it was supported by Einstein, Podolsky and Rosen[2] whose celebrated 1935 article begins: “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*”. (My emphasis). In summary I believe that 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

but the physical model is also necessary in order to *reach a picture* of the world. For instance, a clear model should say whether an electron is a wave (extended) or a particle (localized). Saying that it is neither, or it is both is not a clear answer.

### **The logical path to a theory of the microworld**

The concept of isolated system is the cornerstone of classical physics. But, is isolation possible in our universe? I think not. The universe is so complex and dynamical that some amount of noise is unavoidable. Furthermore, the assumption of an universal noise leads 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 know 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 further this example, my purpose being to convince the reader that the existence of a “universal 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.

The universal noise is actually accepted in standard quantum mechanics, 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 unavoidable in order to reach 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,  $Z_0$ ,  $W^\pm$  or Higgs, are (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 a “noise” filling the whole space. In the case of fields that noise consists of random fluctuations similar to the zeropoint fluctuations of the

electromagnetic radiation to be studied below. In the case of particles the noise corresponds to the existence of a dynamical “Dirac sea” of particles and antiparticles with some random motion. Quantum commutation (anticommutation) rules provide a disguised form to state the properties of the noise in the case of fields (particles). There should be also a “noise” of spacetime itself in the form of metric fluctuations.

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

### **Planck’s constant $h$ fixes the scale of the universal noise**

For the sake of clarity let me consider just a kind of noise, the 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 proof is not difficult but I shall give an argument which may be traced back to Wien’s work in 1894. An advantage of that 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 is implicit in the use of electromagnetic theory. Now if there are ZPF present even at zero Kelvin, the function  $f(\nu/T)$  should have a finite (not zero) limit for  $T \rightarrow 0$ . It is obvious that the constant involved in that expression should play a fundamental role in quantum physics. It must be fixed by appeal to the experiments and the result is

$$\rho(\nu) d\nu = \frac{4\pi}{c^3} h \nu^3 d\nu. \quad (1)$$

Thus Planck’s constant,  $h$ , appears here with a transparent meaning, it fixes the scale of the universal noise or *quantum noise*[3] (but remember, I consider it *a real fluctuating field*.) The ZPF spectrum eq.(1) is ultraviolet divergent, but we should expect that at high frequencies it would be cut-off by creation or annihilation of particles and gravitational (general relativistic) effects.

The spectrum eq.(1) corresponds to an *energy  $\frac{1}{2}h\nu$  per normal mode* of the radiation. Up to here I have considered the electromagnetic field, but it is plausible that a similar noise exists for all 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, the fundamental assumption of the physical model behind quantum theory, supported in this essay, should be the existence of a (real) universal noise, even at zero Kelvin, consisting of fluctuations of all force fields existing in nature with an average energy  $\frac{1}{2}h\nu$  for every normal mode (except at very high frequencies.)*

The natural extension of the belief in a random electromagnetic radiation with spectrum eq.(1) filling the whole space is stochastic (or random) electrodynamics. That theory assumes that the vacuum electromagnetic zeropoint field is a real radiation, and it studies systems of electrically charged particles immersed in it. A summary has been given by Boyer[3], and a review of the work made until 1995 is the book by de la Peña and Cetto[4].

### **Quantum vs. classical probabilities**

It is currently assumed that quantum probabilities are different from classical, ordinary life, probabilities. The current wisdom is that quantum probabilities derive from a lack of strict causality of the natural laws. That is, people assumes that to the same cause different effects may follow. This is usually called the *fundamental or essential probabilistic* character of the physical laws. Einstein disliked that assumption and strongly criticized it, as shown in his celebrated sentence “*God does not play dice*”. I agree with Einstein. In my opinion there are strictly causal laws in nature, but there is also an universal noise which permeates everything and prevents any practical determinism. Strict causality combined with stochasticity (randomness) is in practice indistinguishable from essential probability, and the former is to me more palatable. Actually the belief in essentially probabilistic laws derives from an excessive esteem of the completeness of quantum mechanics. Indeed the ensemble interpretation[2] offers a natural explanation for the probabilities.

## **2 Consequences of the quantum fluctuations**

### **Heisenberg uncertainty relations**

Let us consider a charged 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  $\nu$ . 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

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

It is possible to get a relation independent of the frequency by taking into account that the mean square velocity may be related to the mean square displacement via

$$\langle v_x^2 \rangle \approx 4\pi^2\nu^2 \langle (x - \langle x \rangle) \rangle^2 \equiv 4\pi^2\nu^2 \Delta x^2. \quad (3)$$

Hence, taking eq.(2) into account we get

$$\Delta x \Delta p_x \simeq \frac{\hbar}{2}, \hbar \equiv \frac{h}{2\pi}, \Delta p_x^2 \equiv m^2 \langle v_x^2 \rangle. \quad (4)$$

Of course our argument has been made for a charged particle, but we may assume that other fields would contribute to the random motion of any particle, e. g. a fluctuating metric, producing a similar effect.

This provides an intuitive interpretation of the Heisenberg uncertainty relation as follows. *Due to the quantum noise, with the peculiar spectrum eq.(??), it is imposible to localize a particle in a region of size  $\Delta x$  without the particle having a random motion with typical momentum dispersion  $\Delta p \gtrsim \hbar/2\Delta x$ .* 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 a device with a microscopic system has 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.

### **A picture of the quantum world 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 in the standard interpretation that distribution does not mean that the electron has an actual position at any time.

Let us consider now a water molecule. As is well known it consists of two hydrogen atoms and one oxygen atom placed in the vertices of an isosceles triangle with an angle of  $104^\circ$  at the oxygen nucleus and some precisely measured hydrogen-oxygen distances. Now quantum mechanics states that the ground state of an isolated water molecule possesses zero angular momentum. Indeed it contains an even number of spin-1/2 particles coupled to zero total spin angular momentum and zero orbital angular momentum. Accordingly the quantum formalism states that the molecule possesses spherical symmetry in the ground state. How could we understand this?. The standard wisdom is that the (angular) 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 there is a picture rather intuitive: the molecule retains its form at any time, but changes position randomly. Of course, here we confront one of the typical assumptions of (standard or orthodox) quantum mechanics which makes an intuitive picture impossible. In fact, the quantum prediction for a zero angular momentum is that both, the system state is spherically symmetric and the (zero) angular momentum is dispersion-free. In my opinion this is a case where the standard interpretation of the quantum formalism should be changed.

### **Particle behaviour of fields**

I assume that in nature there are particles and fields (waves). 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 a possible understanding. 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. 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 quantum noise, 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 them also.) The counter behaves like an alarm system. If it has low sensitivity it may not detect some relevant perturbation, 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 efficiency loophole in the optical tests of Bell's inequalities.

### **Wave behaviour of particles. L. de Broglie waves**

It is attractive the hypothesis that the wave behaviour of particles derives from the existence of the quantum noise. Thus we might assume that, in the interference of electrons or atoms, it is the case that the said waves interfere and some of them couple strongly to the particle, guiding it to the screen where the interference pattern appears. The idea that any particle has an associated wave was put forward by L. de Broglie. His proposal is usually understood as if every particle possesses one wave, an understanding reinforced by the quantitative relation between the particle's momentum,  $\mathbf{p}$ , and the wavevector,  $\mathbf{k}$ . The picture of a unique wave associated to every particle is untenable. For instance, how the (extended) wave may follow the (localized) particle? It is more plausible to assume that there is some background of waves in space able to interact with particles. This leads again to the idea that the waves are, actually, those of the quantum noise. The problem is then 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.

### **Dark energy**

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

$$\rho_{DE} \simeq -p_{DE} \simeq 10^{-26} \text{ kg/m}^3. \quad (5)$$

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 the order of Planck's density, that is about 123 orders of magnitude larger than eq.(5). However it is known[7] that a much better fit to eq.(5) may be obtained if we use a combination of the fundamental constants  $G, \hbar$  and  $c$  plus a mass parameter  $m$  of the order of typical fundamental particles. That is

$$\rho_{DE} \sim G \frac{m^6 c^2}{\hbar^4}. \quad (6)$$

In fact the observed value, eq.(5), is obtained if the mass  $m$  is about 80 times the electron mass. This is a satisfactory value for a weighted average of the elementary particle masses taking into account that light particles excitations should be more probable than excitations of more massive particles. The proposal of Zeldovich[7], leads to the relations

$$\rho_{DE} c^2 \sim G \frac{m^6 c^4}{\hbar^4} = \frac{G m^2}{\lambda} \times \frac{1}{\lambda^3}, \lambda \equiv \frac{\hbar}{mc},$$

which suggests that dark energy density eq.(5) does not correspond to the mean vacuum energy, which is likely zero, but to (small) effects associated to the quantum vacuum fluctuations. Indeed an explicit calculation[8] within general relativity leads to eq.(5) with a single free parameter, the mass  $m$  in eq.(6).

### 3 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 fields present in nature.



An attempt at explaining every quantum phenomena from the vacuum fluctuations via an intuitive picture seems formidable. A better approach is to try to get a picture derived from the quantum formalism, in particular to understand the commutation and anticommutation rules as a form of characterizing the randomness associated to quantum mechanics. An attempt in this direction has been published[5].

A problem for the understanding of 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 almost 50 years. For me this failure is an indication that quantum mechanics is compatible with local hidden variables *for real experiments*, even if some *ideal (gedanken) experiments* violate the Bell inequality[6].

## References

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