UNDERSTANDING THE QUANTUM BEHAVIOUR OF MATTER AS A DERIVED PROPERTY. I. A COSMOLOGICAL IMPLICATION OF STOCHASTIC ELECTRODYNAMICS

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ABSTRACT
An old hope to get a better physical understanding of the quantum behaviour of matter has been connected with the observation that it is natural to consider the zeropoint radiation field as a real entity, instead of the virtual field considered by quantum electrodynamics. This random electromagnetic field pervades the entire universe and is in permanent interaction with matter. An order-of-magnitude estimate, considering the matter-field system to be in dynamical equilibrium at zero temperature, allows to establish a relation between Planck's constant –which determines the scale of the field fluctuations- and cosmological constants.

I. INTRODUCTION

No physicist on Earth would doubt that quantum theory gives a right description of those parts of the world that belong to its domain; that this domain extends much beyond the mere atomic scales which the theory originally was intended to address, and that the descriptions is not only excellent and can attain admirable precision, but has never failed to give the right answer as yet. However, a good part, if not all, of these same practicing physicists will also agree, openly or reluctantly, that the mysteries of the quantum world have not been cleared up, and that many of them remain on stage despite the considerable efforts invested in trying to get a clear understanding of what is going on in the real world.

Of course, whether or not one subscribes to the last sentence essentially depends on what one understands by *understanding*, as happens so often in physics. A well known historical example of what we have in mind is the Newtonian theory of gravitation: the clarity, simplicity and high precision of this theory made of it a paradigm, indeed a grandiose paradigm, and the theory reigned undisputed for over two centuries. The universal gravitational force soon became the accepted central element for innumerable terrestrial and celestial facts; no physicist could doubt of it. And this occurred despite the shortcomings of the theory in more than one essential aspects. Not only did it rest on the ageing concept of action at a distance, but the specific form of the force was selected *ad hoc*, with no theoretical support that could justify or explain it. Thus, from this more demanding point of view, what one can say at most is that the classical theory gives a precise and simple description, good enough for almost all of our daily (non-cosmological) requirements; but it hardly constitutes an explanation of those events. Just to get such an explanation the whole of general relativity was proposed. Nowadays we explain the falling of bodies as a causal event directed by the local structure of space-time; no more actions at a distance nor *ad hoc* properties are needed. We know that for all simple applications the predictions of both theories agree; but nevertheless, they are entirely different conceptual structures, so different that one could even say that general relativity explains the Newtonian theory.

Is not something similar happening today with quantum theory? We can calculate delicate corrections to some transition frequencies to within a hundred- or a thousand-millionth part, and carry out refined applications of the quantum properties of matter and the radiation field to construct marvelous and powerful devices that characterize our present day civilization. But have we got a real understanding of what is happening deep-down in the quantum world? A glance at the quantum literature dedicated to the discussion of its fundamental aspects, or even to some of its direct applications, is sufficient to perceive the tremendous confusions and uncertainties that trouble our present-day knowledge. Of course, if the number predicted by the theory is taken as the test, just as was the case with Newtonian gravitation and has become customary among physicists due to the pragmatic viewpoints that pervade the scientific atmosphere, there seems to be no problem at all. But, for instance, what is the physical explanation of atomic stability, the origin of uncertainty, or of quantization, or of the so called wave-particle duality? The theory correctly predicts that the ground state is there; but it tells nothing about the mechanism that brings about such stability, ar just the right energy. In more general terms, it would be difficult to express our feeling about quantum theory better than Bell has already done,[1] by saying that quantum mechanics is a FAPP theory -alright *f* or all practical purposes- about measurements and observables, not *beables*.

As an example of the kind of essential doubts related to basic questions that are under active discussion in the current literature, take the problem of the calculation of the time that particles spend inside the a well or a potential barrier. Not only a number of mutually inconsistent definitions have been proposed, at least one of them giving complex times, but unbounded velocities are predicted and even alleged to have been measured and used to transmit useful information ar superluminal speed.[2]

Since the creation of quantum mechanics there has been a flood of papers and essays discussing these and related questions, and almost any conceivable argument or answer has been proposed or attempted, both from within physics and outside it, principally from the philosophy of science. And this has not been the endeavor of idle physicists or philosophers, since names as Einstein, Dirac, de Broglie, Dirac, Landé, Popper and Schrödinger enter in the unending list. Some of the more representative attempts of these unorthodox efforts have been reviewed in books, as those of Ballentine,[3] Jammer[4] or Wheeler and Zurek.[5] We do not intend in this talk to enter into such matters, due to the obvious lack of time and space, so we leave here our general considerations and go over to more specific questions, directly related to our work.

In the two parts of the present contribution, we deal with specific aspects of a theory that has been proposed since long ago in an attempt to get a causal and realistic understanding of quantum mechanics, known as *stochastic electrodynamics* (SED). This theory starts from the observation that the assumption that atomic electrons move in an empty space, occupied only by the Coulomb field of the nucleus, is contrary to the spirit of quantum theory itself. For we know from quantum theory that it would be inconsistent to ascribe a well defined value to the vacuum state of any (quantum) field, including very particularly the radiation field. Indeed, in quantum theory the fields are represented by operators, to which no definite value can be ascribed, and this should remain true even for the ground or vacuum state. This is recognized to be the case in QED, where it has become customary to recognize that the vacuum can produce observable effects (it contributes its bit, for instance. to the atomic Lamb shift), without, however, itself being observable.

This is the point where SED departs from the usual views, by considering the vacuum not as a virtual field, but as a *real* entity, as real as the electron itself. Hence, in SED one visualizes the atom as immersed in this pervasive stochastic electromagnetic background, with which it interacts continuously, thus acquiring a restless stochastic motion. Qualitatively speaking, one immediately perceives here a possibility to explain atomic stability, as was envisaged long ago by Nernst[6]: the idea is to prove whether the average rate of energy radiated by the moving electrons can compensate the mean energy absorbed during a given time interval, leading thus to an average stationary condition. Elementary calculations considering only circular orbits validate this conclusion; however, more detailed calculations lead to difficulties. A detailed discussion of this and related matters, with an ample list of references, can be seen in de la Peña and Cetto.[7]

A revision of this literature shows that there are many positive results of the theory –among others the quantum properties of the harmonic oscillator, the diamagnetism of electrons, Casimir and other long-range forces, the kinematics of the Compton effect, the blackbody radiation spectrum and the specific heat of solids- indicating that its physical contents are by no means negligible. In essence, as is discussed in detail in Ref. [7], one can conclude that SED has not been refuted –contrary to what has been said so many times in different forms-, but that in its original form it was beset with problems that can be associated to the extra postulates introduced along its development. A careful revision of its detailed postulates seems indeed to correct the theory in the right sense, leading in particular to a stable atom with the whole set of its random orbital motions. Some aspects of this issue are the subject of part II of the present work, while in this first part, we take as granted the legitimacy of SED as a fundamental theory of quantum matter in principle, and use it – or rather, its basic principle- to reach an interesting conclusion about the fundamental constants of nature.

II. A COSMOLOGICAL IMPLICATION

An interesting article published recently by Calogero[8] has moved us to disentomb an estimation which we made many years ago,[9] just when the above mentioned difficulties with SED started to become apparent. Having to face those difficulties at the time, we left aside the calculation and almost forgot about it; stimulated now by the new form of SED referred to above that frees us from the difficulties of principle, and by the results of Calogero that parallel our old estimations, we come back to our neglected work.

Let us consider a world made of harmonic oscillators, representing both matter and the radiation field. Such a crude model should be appropriate for the purpose of performing only an order-of-magnitude estimate of certain quantities. Matter and field oscillators, taken in equilibrium at zero temperature, are nevertheless interchanging energy, in such a form that in the mean the oscillators absorb as much as they radiate. Under the assumption that all oscillators of a given frequency, irrespective of their nature, are equivalent, they all must have the same mean ground state energy. Thus, the matter oscillators are radiating and contributing to the random field component, and the random fiel so generated should coincide with the vacuum field of that frequency; the background field is thus maintained. This is a kind of Cosmological Principle associated with SED, or, if preferred, a kind of Electromagnetic Mach Principle: the field produced at a given point by all dipoles should equal the random field acting at that point on the particles themselves. This requirement establishes a relationship between cosmological and atomic constants; in other words, the scale of quantum fluctuations, Planck's constant, becomes determined by cosmological parameters.

A similar reasoning, but dealing entirely with the gravitational field, is the subject discussed by Calogero in his recent work, where, restricting himself to order-of-magnitude considerations, he shows that the identification of the un-avoidable gravitational fluctuations with the quantum fluctuations of atomic systems leads indeed to a relationship between atomic and cosmological constants. Here one should recall also a similar attempt made by Puthoff some years ago[10] within SED, on the basis of a self-regenerating model, to prove that the zeropoint field is due to radiation from the zeropoint field-driven particle motion throughout the rest of the universe. Indeed, the basic ideas of Puthoff's paper are very much in line with the present ones, although in our roungh estimate we refrain from resorting to a specific cosmological model. Also, we leave aside any problem related with the infinite gravitational effects of the zeropoint field, just as is done in QED with all vacuum fields, simply because nobody knows how to escape this problem (a detailed discussion can be seen in the review by Weinberg[11]). By equating the radiation field predicted by the model at a given point with the corresponding component of the zero-point field, we obtain a prediction for the baryonic mass density of the universe, which gives the pursued relation between atomic constants and the Hubble constant. This relation happens to correspond essentially to the one discussed in Weinberg's book[12] (§16.4), which is usually taken as a numerical coincidence, of unknown meaning.

Consider the dipole α(α = 1,2,...,N) of frecuency ω, at a distance r_α from us, i.e. from the origin of coordinates; the Fourier amplitude of the electric field produced by this oscillator at the origin is

$$\mathbf{E}_\alpha(\omega) = -k^2 \mathbf{n}_\alpha \times (\mathbf{n}_\alpha \times \mathbf{p}_\alpha)\frac{e^{ikr_\alpha}}{r_\alpha}, \quad k = \frac{\omega}{c}, \tag{1}$$

where $\mathbf{p}_\alpha = (e/2)(\mathbf{q}_{0\alpha} + i\dot{\mathbf{q}}_{0\alpha}/\omega)$ is the (complex) amplitude of the dipole moment $\mathbf{p}_\alpha e^{-i\omega t}$ and $\mathbf{n}_\alpha = \mathbf{r}_\alpha / r_\alpha$ is the unit vector in the direction of $\mathbf{r}_\alpha$. Since the mean energy of the oscillator is $\frac{1}{2}\hbar\omega$, one has $\left\langle \mathbf{q}_{0\alpha}^2 + i\dot{\mathbf{q}}_{0\alpha}^2/\omega^2 \right\rangle = \hbar / m\omega$, where the average is taken ober the set of oscillators of frecuency ω, so that we write

$$\mathbf{p}_\alpha = \frac{e}{2}\sqrt{\frac{\hbar}{m\omega}}\,\mathbf{B}_\alpha \tag{2}$$

and consider the amplitudes $B_{\alpha i}$ to be statistically independent complex stochastic variables with zero mean and second moments given by

$$\langle B_{\alpha i} B^*_{\beta j} \rangle = \delta_{\alpha\beta}\delta^*_{ij}, \quad \langle B_{\alpha i} B^*_{\beta j} \rangle = 0. \tag{3}$$

With these assumptions the mean square of equation (1) is (we omit the index α)

$$\langle |E(\omega)|^2 \rangle = \frac{\hbar e^2}{4mc^4} \frac{\omega^3}{r^2} \langle |n \times (n \times B)|^2 \rangle = \frac{\hbar e^2}{2mc^4} \frac{\omega^3}{r^2}, \tag{4}$$

since $\langle |n \times (n \times B)|^2 \rangle = \langle B \cdot B^* - (n \cdot B)(n \cdot B^*) \rangle = 2$. Here we have taken into account that the field amplitudes produced by statistically independent oscillators are uncorrelated. To evaluate the average energy content of the radiation field of frequency ω at the origin, we integrate equation (4) over a spherical volume of radius *R*, assuming an isotropic and homogeneous distribution of oscillators, of which there are $n(\omega)$ of frequency ω and a total number $N = \Sigma\, \omega n(\omega)$:

$$\langle \varepsilon(\omega) \rangle = \frac{n(\omega)}{4\pi} \int_V \langle |E(\omega)|^2 \rangle dV = \frac{\hbar e^2 \omega^3 R}{2mc^4} n(\omega). \tag{5}$$

The Cosmological Postulate of SED asserts that this energy should correspond to the zero-point field energy of frequency ω, $\frac{1}{2}\hbar\omega$, one thus obtains

$$n(\omega) = \frac{mc^4}{e^2 \omega^2 R}. \tag{6}$$

To estimate the total number of oscillators we integrate over all frequencies, using the rule $\frac{1}{V}\sum \varpi \rightarrow (2\pi^2 c^3)^{-1} \int d\omega \omega^2$, which gives

$$N = \sum \omega n(\omega) = \frac{mc^4}{e^2 R} \sum \omega \frac{1}{\omega^2} \rightarrow \frac{mcV}{2\pi^2 e^2 R} \int_0^\Omega d\omega = \frac{mc\Omega V}{2\pi^2 e^2 R}. \tag{7}$$

Since the integral is divergent we have introduced a cutt of frequency for the material oscillators. Indeed, the material oscillators are transparent at arbitrarily high frequencies, and one can take a cutt of around the pair-creation frequency $\Omega = 2mc^2/\hbar$ as physically meaningful, so that (7) becomes

$$\frac{N}{V} = \frac{m^2 c^2}{\pi^2 \alpha \hbar^2 R}, \tag{8}$$

where $\alpha = e^2/\hbar c$ stands for the fine-structure constant. Here V must be taken as the volume of the visible universe, as this is the part that contributes to the radiation field, and thus N/V is to be identified with the cosmological density of charged particles, which multiplied by m_N (the nucleon mass or any typical baryon mass) gives for the baryonic density of the universe the following estimate:

$$\rho \cong \frac{m^2 m_N c^2}{\pi^2 \alpha \hbar^2 R}. \tag{9}$$

Before going further let us add a couple of remarks with regard to this expression. Firstly, we have not taken into account any absorption process, the reason being that we are dealing with the *zeropoint* field, a field that is not absorbed by matter in equilibrium with it. Of course it is scattered by matter, but for a uniform and homogeneous universe the final distribution remains the same. Thus equation (9) needs *no* correction from Thomson scattering.

The second comment refers to the naivete of the model. As already stated, the idea is to make a qualitative test of the SED Cosmological Principle, and for such purpose the present rough estimate should suffice. For example, a somewhat more realistic model would take into account the expansion of the universe, which produces a redshift, so that instead of the original frequency ω radiated when the universe had a scale factor R(t), we see the frequency

$$\omega_0 = \frac{R(t)}{R_0}\omega, \tag{10}$$

where the subindex 0 refers to the present moment and place of observation. Thus, if $\nu(\omega)$ represents the spatial density of oscillators of local frequency ω at a distance r from us, instead of equation (5) we would write

$$\langle\varepsilon(\omega)\rangle = \frac{e^2\hbar}{2mc^4}\omega_0^3 R_0^3 \int_0^{R_0} \frac{\upsilon(\omega_0 R_0/R(t))}{R^3(t)r^2} r^2 dr, \tag{11}$$

where, using Weinberg's notation,[12] one must put $dr = (\sqrt{1-kr^2}/R(t)dt$. To go further one would have to specify the cosmological model; however, no fundamental qualitative change seems to ocurr, although there appear of course numerical factors, which do not alter the essential contents of equation (9). Thus, up to such numerical factors we take our former result (9) as a reasonable relation among the relevant constants of nature.

Let us investigate now how well equation (9) works. For this purpose we introduce an auxiliary mass defined by

$$\overline{m} = \left(\frac{m^2 m_N}{\pi^2\alpha}\right)^{1/3} \cong 30m. \tag{12}$$

Equation (9) can then be rewritten in the form (observe that $R = R_0$, so we add the subindex 0 to mark the present values of the cosmological parameters)

$$\frac{\rho_0 R_0^3}{\overline{m}} = \frac{\overline{m}^2 c^2 R_0^2}{\hbar^2} = \left(\frac{R_0}{\lambda_{\overline{m}}}\right)^2, \tag{13}$$

where $\lambda_{\overline{m}}$ is the Compton wavelength (divided by 2π) associated with the mass $\overline{m}, \lambda_{\overline{m}} = \hbar/\overline{m}c$. We recognize in each side of equation (13) one of the 'large numbers' of cosmology, namely (H_0 is the present value of Hubble constant, $H_0 = c/R_0$)

$$N_1 = \frac{\hbar c}{G m_N^2} \sim \frac{1}{6}10^{39}, \tag{14}$$

$$N_2 = \frac{mc^2}{\hbar H_0} = \frac{mcR_0}{\hbar} = \frac{R_0}{\lambda_m} \sim \frac{1}{3}10^{39}, \tag{15}$$

$$N_3 = \frac{\rho_0 c^3}{m_N H_0^3} = \frac{\rho_0 R_0^3}{m_N} \sim 10^{79}, \tag{16}$$

Except for the differences in the masses, equation (13) reads

$$N_3 = N_2^2, \tag{17}$$

which is one of the well-known numerical coincidences among these large numbers. The surprising content of this expression is that it relates cosmological parameters with Planck's constant, which is a highly non-trivial result (recall that Weinberg[12] qualifies it as mysteriuos). The second independent relation among these numbers, which can be taken to be $N_1N_2 \cong N_3$, relates cosmological parameters only and can be obtained from cosmological models, as the Friedmann model.

We conclude that the SED Cosmological Principle, namely that the energy of the vacuum fluctuations corresponds to the energy radiated by all dipoles of the universe, seems to hold and serves to explain the relation $N_3 = N_2^2$ up a constant factor of at most a few orders of magnitude.

Let us now recast equation (9) in a different form. In terms of the dimensionless gravitational coupling constant $\alpha_G = Gmm_N/\hbar c$ equation (9) becomes

$$\alpha_G R_0 \cong \frac{3\pi}{8}\alpha\lambda_m,$$

which we write simply as

$$\alpha\lambda_m \cong \alpha_G R_0, \tag{18}$$

where the value of the common length $l = \alpha\lambda_m = e^2/mc^2$ equals the classical electron radius. Equation (18) can be extended by observing that for the nuclear forces one can take $\alpha_N \cong 1$ and $R_N \cong \hbar / m\pi c \cong \alpha\lambda_m / 2$ (numerically), so that

$$\alpha_G R_0 \cong \alpha\lambda_m \cong \alpha_N R_N. \tag{19}$$

Equation (18) explains why Calogero's gravitational arguments and the present electromagnetic ones lead to equivalent results, and equation (19) extends this equivalence to nuclear forces, suggesting a kind of universality of the vacuum effects on matter. This is, in our view, another form of saying that it should be feasible to represent the effects of the zero-point field as a fluctuating metric field, a possibility that was already studied by Einstein himself.[13] Some additional comments on this subject and related references can be seen in the cited book on SED.[7] It is interesting to observe that equation (17) (or Ed. (18)) cannot be obtained solely from the usual quantum formalism; it is within the conceptual frame of SED where the cosmological principle leading to equation (17) finds its natural place.

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