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Physics of the zero-point field: implications for inertia, gravitation and mass

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Previous studies of the physics of a classical electromagnetic zero-point field (ZPF) have implicated it as a possible basis for a number of quantum phenomena. Recent work implies that the ZPF may play an even more significant role as the source of inertia and gravitation of matter. Furthermore, this close link between electromagnetism and inertia suggests that it may be fruitful to investigate to what extent the fundamental physical process of electromagnetic radiation by accelerated charged particles could be interpreted as scattering of ambient ZPF radiation. This could also bear upon the origin of radiation reaction and on the existence of the same Planck function underlying both thermal emission and the acceleration-dependent Davies–Unruh effect. If these findings are substantiated by further investigations, a paradigm shift would be necessitated in physics. An overview of these concepts is presented thereby outlining a research agenda which could ultimately lead to revolutionary technologies.

Keywords: zero-point field; stochastic electrodynamics; quantum electrodynamics; quantum vacuum; inertia; gravitation; dark matter; mass; relativity

Introduction and overview

In 1901, Planck was successful in deriving a closed mathematical expression that fit the then recent measurement of the spectral distribution of thermal radiation by hypothesizing a quantization of the average energy per mode of oscillation [1]. This new formulation avoided the so-called 'ultraviolet catastrophe', the unphysical prediction of classical theory readily derivable from energy equipartition that the black-body spectrum should diverge to infinity as ν^3. Planck derived the well-known black-body function,

$$\rho(\nu,\ T)\mathrm{d}\nu = \frac{8\pi\nu^2}{\mathrm{c}^3}\left(\frac{\mathrm{h}\nu}{\mathrm{e}^{\mathrm{h}\nu/\mathrm{kT}} - 1}\right)\mathrm{d}\nu \quad (1)$$

in which the ν^3 catastrophe is overcome by the exponential denominator resulting from his substitution of discrete for continuous energy intervals. The expression is factored here to show the two components of density of modes (i.e. number of degrees of freedom per unit volume) times the thermal energy per mode in the frequency interval $\mathrm{d}\nu$. As discussed in detail in Kuhn's monograph [2], Planck himself remained skeptical of the physical significance of his mathematical assumption and of his apparently new constant, h, for over a decade. In 1913, Bohr [3] made quantization of atomic energy levels a postulate, thereby laying a foundation for quantum physics based upon Planck's unit of quantization.

That same year Einstein and Stern published a paper [4] studying the interaction of matter with radiation using classical physics and a model of simple dipole oscillators to represent charged particles. They remarked that if, for some reason, such a dipole oscillator had a zero-point energy, i.e. an irreducible energy even at $T = 0$, of $h\nu$, the Planck formula for the radiation spectrum would result without the need to invoke quantization. (Several such derivations of the black-body function using classical physics with a real zero-point field but without quantization have been published by Boyer; see [5] and references therein). In 1916, Nernst proposed [6] that the universe might actually contain enormous amounts of such zero-point radiation. In fact, the existence of such a zero-point field (ZPF) had been first envisaged by Planck around 1910 when he formulated his so-called second theory: namely an attempt to derive the blackbody spectral formula with a weaker quantization assumption. It was Nernst who captured the paramount thermodynamic implications and relevance of such a sea of background radiation and became the main proponent of this concept. Both Planck and Nernst used the correct $(1/2)h\nu$ form for the average energy of the zero-point electromagnetic fluctuations instead of the $h\nu$ value assumed later by Einstein and Stern; the $h\nu$ assumption is correct for the sum of interacting harmonic oscillators plus the energy of the electromagnetic fields. The electromagnetic black-body spectrum including ZPF would then be:

$$\rho(\nu,\ T)\mathrm{d}\nu = \frac{8\pi\nu^2}{\mathrm{c}^3}\left(\frac{\mathrm{h}\nu}{\mathrm{e}^{\mathrm{h}\nu/\mathrm{kT}} - 1} + \frac{\mathrm{h}\nu}{2}\right)\mathrm{d}\nu \tag{2}$$

While this once again appears to result in a ν^3 ultraviolet catastrophe, that is not the case because this component now refers not to measurable excess radiation from a heated object, rather to a uniform, isotropic background radiation field that cannot be directly measured because of its homogeneity. This approach to understanding the black-body spectrum was not developed further thereafter, and was, in fact, essentially forgotten for the next 50 years. What happened instead was that with the success of quantum mechanics, and then quantum electrodynamics, the generalization and existence of an equivalent to the ZPF, the quantum vacuum, was taken to be a consequence of quantum laws. In other words, a quantum version of the ZPF became an accepted part of physics whose existence was interpreted as being due to quantum laws.

In recent years, there has been a growing interest in reviving the original semi-classical approach and exploring its ramifications. The motive until recently, besides gaining intuitive insights and calculational ease, has been to see to what extent various quantum phenomena could be explained solely on the basis of classical physics with a random perturbing radiation field – the ZPF – providing quantum-like fluctuations. This would (again) reverse the cause and effect of ZPF *vis-a-vis* quantum physics. This area of physics is known as 'Stochastic electrodynamics', SED. For a recent review see [7] which also refers to other older but thorough reviews. SED is also discussed by Milonni [8]. The general idea that the origin of quantization was to be found in some classical stochastic subquantum background was very much in the air among the founders of modern physics [9]. In 1966, Nelson published a seminal paper [10] stating: "We shall attempt to show in this paper that the radical departure from classical physics produced by the introduction of quantum mechanics 40 years ago was unnecessary. An entirely classical derivation and interpretation of the Schrödinger equation will be given, following a line of thought which is a natural development of reasoning used in statistical mechanics and in the theory of Brownian motion".

Examining the Heisenberg uncertainly principle, Boyer [11] showed that for the harmonic oscillator the fluctuations caused by the ZPF on the positions of particles are exactly in agreement with quantum theory. Recently, Rueda [12] has arrived at the Schrödinger equation, albeit in a somewhat restrictive context that invokes a ZPF-induced Brownian-motion model.

The most optimistic outcome of the SED approach would be to demonstrate that classical physics plus a classical electromagnetic ZPF could successfully replicate all quantum phenomena, a situation which would undermine some of the present ontological basis of quantum physics. While successful up to a point, SED has not yet achieved this.

As dramatic as a substitution for quantum physics would be on the part of SED, recent studies have identified even more profound roles that the ZPF may play in the foundation of physical laws, the constitution of matter, and the structure of the universe.

(1) The inertia of matter may be due to a Lorentz force-like electromagnetic interaction between charge at the quark or fundamental lepton level and the ZPF [13, HRP].
(2) There appears to be an analogous electromagnetic vacuum origin for gravitation – as there would necessarily be from the principle of equivalence – an idea originally proposed by Sakharov [14,15]. It needs to be shown that this can be made mathematically equivalent to curved space-time. The approach that Einstein took in 1911 [16] (with later corrections [17]) involving a speed of light which is dependent on gravitational potential, $c(\Phi)$, suggests a promising avenue.
(3) Matter and the concept of mass would appear to be secondary phenomena arising out of charge–ZPF interactions: energy, charge and electromagnetic fields being primary.
(4) The creation of electromagnetic radiation by accelerated charge may possibly be interpretable as scattering of ambient ZPF radiation. In stationary frames, the scattering of ZPF radiation by a dipole is an equilibrium process [18]; the asymmetry in the scattering process when an accelerated dipole is viewed from a stationary laboratory frame would appear to be the source of what is customarily interpreted as radiation emitted by accelerated charge (see pp. 114 20 of [19]).
(5) In the ideal case of the Bohr atom, the stability of the ground state of the hydrogen atom can be attributed to energy absorption from the ZPF rather than Bohr's postulated quantum prohibition [11,20].
(6) Spontaneous emission can be interpreted at least in part (one half of it to be precise) as emission stimulated by the background ZPF. As McCrea has argued [21], this places the ZPF in the role of a kind of universal clock governing seemingly spontaneous phenomena.
(7) Even within general relativity, non-gravitational accelerations require a frame of rest that is absolute in either the Newtonian or the Machian sense [22–24]. However, owing to special relativity, such a frame cannot be absolute with respect to uniform rectilinear motions. This seemingly impossible requirement is actually met by the ZPF. Owing to its ν^3 spectrum it has a Lorentz invariant energy density spectrum, yet acquires certain asymmetries as viewed from an accelerating frame... which leads, among other things we think, to inertia, thus providing a quantitative, modern version of Mach's principle [HRP].
(8) The structure of the Universe on the largest scale – voids and sheets – can be attributed to the ZPF via an Einstein–Hopf type acceleration process [25–27]. The same acceleration process may also underlie cosmic rays [5,28].

The objective of this paper is not to establish the veracity of these paradigm-shifting possibilities; some are clearly speculative at this time eg. in the case of (8), caveats exist concerning the Einstein-Hopf process. A recent evaluation of this appears in a review published by de la Peña and Cetto after the acceptance of this paper [29]. Our goal is to present an overview of reasonably justified conclusions concerning the ZPF based upon published work and to extrapolate to new research programs that may come about, clearly identifying speculations as such. The intellectual and perhaps even technological rewards that would be forthcoming should such a research agenda succeed may attract innovative scientists to examine these possibilities in sufficient detail so that in a few years we may know whether this approach has been an intoxicating but illusory deadend or the path to a new paradigm for the next millenium.

If the ZPF is real, why is it not detectable?

The most universal real radiation field we are familiar with today is the cosmic microwave background (CMB). While the NASA COBE measurements, published in 1992, finally found minute inhomogeneities, to high precision the CMB can be considered as quite uniform and isotropic, yet readily detectable. That being the case, why is the ZPF not equally evident? The ratio of the two is simply the ratio of the two terms in Equation 2 taking $T = 2.73$ K. At the 53 GHz-frequency middle band of the COBE differential microwave radiometer this ratio would be $\rho_{ZPF}/\rho_{CMB} = 0.77$. Even more dramatically, in the optical spectrum, Equation 2 predicts that the ZPF should be about two orders of magnitude brighter than the Sun. Why are we not blinded by the ZPF?

To first order, in the absence of special conditions (discussed below), the ZPF is isotropic and homogeneous in its spatial distribution. This must be the case even inside matter due to the characteristics of the ZPF that dipole transitions absorb and re-emit this isotropic, ν^3 radiation without change in spatial or spectral distribution [11,18]. Therefore, matter that might ordinarily be considered opaque to radiation of a given frequency effectively passes on the ZPF radiation without attenuation, i.e. the radiation may be absorbed and re-emitted many times, but the net effect is nil. In such a fashion, the ZPF resists direct observation. Only deviations 'above' the ZPF are measurable.

To second order, however, the presence of the ZPF can be registered indirectly, not on the basis of absorption and reemission, but rather by correlation or interference effects. In the case of closely-spaced atoms or molecules, for example, the absorption and reemission of the ZPF radiation results in the generation of secondary short-range fields (even at temperatures of absolute zero) that, because of their correlating effects, result in short-range attractive forces: the so-called van der Waals forces. Similarly, in a macroscopic version of the same phenomenon, a unique attractive quantum force (the Casimir force) between dielectric or conducting plates can be shown to exist on the basis that absorption and reemission of the ZPF radiation by the plates results in interference and cancellation of certain electromagnetic modes between the plates. The result is an imbalance in the associated ZPF radiation pressures interior and exterior to the plates, hence a net force of attraction between the plates; a close parallel can be drawn between this phenomenon and the familiar concept of radiation pressure [30]. Again, the ZPF background is inferred from its consequences rather than from direct observation. Indeed, at a deeper level, the various phenomena listed above in points (1) to (8) can all be taken as confirmation and perhaps even as indirect 'observations of the ZPF' in the sense that their elucidation is most parsimonious in terms of the ZPF interpretation.

Inertia and Mach's principle

That matter should have the property of inertia is so fundamental to our conception of physical reality that it is difficult to imagine how matter could not have such an innate property. How could one have a stable, solid (including liquid and gas in this context) reality without inertia? Put another way, how could $\vec{F} \neq m\vec{a}$? Newton's equation of motion is a good starting point for discussion. Consider a slight variation of it. Some of the largest scale motions in the Universe involve extremely small accelerations: The v^2/r acceleration of the Sun around the Milky Way galaxy amounts to $a \sim 2 \times 10^{-8}$ cm s^{-2} (taking $v \sim 250$ km s^{-1} and $r \sim 10$ kpc). This is typical of rotational accelerations in outer galactic regions. Accelerations of galaxies within clusters are on a similar scale. Such small accelerations would be extremely difficult to create and measure in a laboratory, and to that extent, the $\vec{F} = m\vec{a}$ relation is *terra incognita* in this regime. Without implying any judgement as to the validity of the proposal, we note that an alternate explanation to the existence of dark matter as a cause of non-Keplerian galactic rotation curves, etc., involves hypothesizing a non-linear $\vec{F} = m\vec{a}$ relationship for accelerations in this regime [31]. The point is not to promote this particular hypothesis, merely to point to a conceivable application for a more complex view of inertia. (Should the ZPF inertia theory result in a prediction of a non-linear inertia in the regime hypothesized by Milgrom, this would of course, be a plus for the theory resolving a major astrophysical puzzle – the nature of dark matter – in a quite unexpected way.)

A discussion of Mach's principle could fill volumes [32]; it was an important consideration for Einstein in his development of general relativity (GR) [17,33], and while he initially thought that GR incorporated Mach's principle, a GR-solution for a universe devoid of matter was discovered by Einstein himself [34], and a solution for a rotating universe by Gödel, both demonstrating that Mach's principle was not compatible with GR. Mach argued that all motions must be relative. That being the case, whether one chooses for purposes of analysis a rotating earth or a stationary earth and a counter-rotating universe should not matter. But what would be the origin of centrifugal force in the latter view, deforming the shape of the earth to make it equivalent to the rotating-earth perspective. Mach proposed that the solution lies in the circumstance that the local property of inertia of any material object is caused by the surrounding matter. In this way, a rotating universe could conceivably induce an equivalent of centrifugal force in a stationary earth. This view would also be consistent with the idea that it should not make sense to allow a measurable perception of rotation (again from centrifugal or Coriolis forces) if an object were rotating in an empty universe, i.e. rotating with respect to what? In Mach's view, such rotation would be an absurdity, and without the presence of other matter available to create inertia the conundrum is avoided. The only long-range force available being gravitation, a Machian inertia must somehow be related to gravity. A preliminary Newtonian model of this was proposed by Sciama [34] in which gravitation arises via the usual scalar potential, $\Phi = -\int_V (\rho/r)\mathrm{d}V$, while inertia arises via the next higher extension, a vector potential, $\vec{A} = -(\Phi/c)\vec{v}(t)$. It can readily be shown that in this view matter on a cosmological distance scale would predominate in the origin of (local) inertia. No entirely satisfactory formulation of Mach's principle has been developed [35]. Moreover, asymmetries such as those measured by the NASA Cosmic Background Explorer, the mass-asymmetry due to our location in the Milky Way, etc., do not give rise to a measurable asymmetry in inertia, i.e. mass is not a vector quantity. Remarkable upper limits can be placed on this thanks to the Hughes-Drever experiments: $\Delta m/m \leq 10^{-20}$ [36] whereas Sciama's approach [34] would predict $\Delta m/m \sim 10^{-7}$ due to the Milky Way.

The concept developed by us (HRP) is different. Inertia does result from something external: not other matter but the ZPF, with the effect, at the first level of the analysis at least, being entirely local. In HRP, we analysed the forces on a Planck oscillator when subject to acceleration using the methods of SED. Analytically, we set a point-charge (termed a parton: this could represent a quark or an electron for example) into harmonic motion driven by the random fluctuations of the ZPF. These fluctuations are perfectly symmetrical in stationary or uniform-motion frames. It was discovered by Davies [37] and by Unruh [38] that acceleration-dependent terms arise in the spectral energy density of the ZPF (cf. equation 3 of HRP). One of these is a pseudo-Planckian component of the ZPF involving an acceleration-temperature (cf. equation 2 of HRP), a very small term under ordinary accelerations. The other term is an acceleration-squared modification of the spectral energy density. In HRP we investigated this term. Following the technique of Einstein and Hopf and the identical configuration used by Boyer [39] to derive the Davies–Unruh effect in the context of SED, we investigated the heretofore unexplored $\vec{v} \times \vec{B}^{ZP}$ force that the driven-oscillator would experience in an accelerating frame. The $\vec{v}$ are the oscillatory motions in a plane due to the electric driving forces, $\vec{E}^{ZP}$, of the ZPF. The oscillator; is then forced to undergo a uniform acceleration, $\vec{a}$, in a direction perpendicular to the plane of oscillation; the resulting Lorentz force after proper stochastic averaging turns out to be such that $< \vec{v} \times \vec{B}^{ZP} > \propto \vec{a}$. The Lorentz force resists acceleration in a linear way. We interpret the inertial resistance to acceleration of matter to be this electromagnetic Lorentz force; inertia would thus be electromagnetic in origin. This is, in effect, a derivation of $\vec{F} = m\vec{a}$ from the electrodynamics of ZPF-charged particle interactions. The inertial mass, m_i, is then a function of electrodynamic parameters,

$$m_i = \frac{\Gamma \hbar \omega_c^2}{2\pi c^2} \tag{3}$$

where Γ is a damping constant for the oscillations and ω_c relates to a characteristic frequency of particle–ZPF interactions. In HRP, ω_c was taken to be either a ZPF cutoff frequency (the Planck frequency) or a reflection of the minimum parton size (the Planck length) which would translate into the same cutoff frequency. We speculate that in more refined future versions of the theory this simple ω_c cut-off parameter will actually be replaced by a resonance frequency, ω_o, and that differences in resonance are factors determining differences in masses of fundamental particles, i.e. the factor of ~ 200 difference between an electron and a muon in spite of their identical charge. For a composite particle such as a proton (made of uud quarks) or neutron (made of udd quarks) the inertia-producing interactions would take place with the individual quarks; at very high frequencies quarks would oscillate essentially independently given the nature of the strong interaction, so-called asymptotic freedom (''At close range, jostling around inside a proton, quarks barely notice one another's presence and act like independent particles.'' [40]); differences in the sign of the charge would only change the phase of the oscillations giving rise to the Lorentz force, not the direction, thus making the effect on the individual quarks in a nucleon additive.

The HRP analysis has been criticized for using an Abraham–Lorentz–Dirac (ALD) equation of motion as a basis, the argument being that we are 'using Newton's law to derive Newton's law.' This is not the case since the ALD equation is phenomenologically invoked as an SED resource solely to bring about oscillations in a plane with the Lorentz force arising independently out of the magnetic component of the ZPF in a perpendicularly-accelerating direction. Other justified criticisms involve the use of an ideal parton to represent charged matter and general mathematical complexity.

All of these problems will be addressed and hopefully swept aside by a new approach in which one considers solely the time evolution of the momentum-flux derived from the Poynting vector of the ZPF in a uniformly accelerating coordinate system [41,42]. This new analysis does not concern itself with particle–ZPF interactions other than to assume that ZPF radiation can be scattered by charged matter. Using entirely straightforward Lorentz transformations of the electromagnetic field one can derive the analogous result to HRP: viz, an acceleration-dependent resistance originating in such scattering of radiation. Moreover this analysis has the merit of not only being analytically simpler than HRP, but also of being relativistic, i.e. one can derive the relativistic form of Newton's law in this fashion $f = \mathrm{d}p/\mathrm{d}\tau$, the well-known four-vector form applicable to particles accelerated to high speeds.

Gravitation

All experiments and observations to date are consistent with predictions of general relativity. The mathematical treatment of gravitation as a space-time curvature works well. However if it could be shown that a different theoretical basis can be made analytically equivalent to space-time curvature, with its prediction of gravitational lensing, black holes, etc. this would reopen the possibility that gravitation is a force. Einstein himself "did not think that electromagnetism and gravity should remain separate, and spent the later years of his life searching for a theory of 'electro-gravity' to complete the work begun by Maxwell" [40]. The following points are also worth noting: (1) general relativity and quantum physics are at present irreconcilable, therefore something substantive is either wrong or missing in our understanding of one or both; (2) the propagation of gravitational waves is not rigorously consistent with space-time curvature. (This point is discussed in chap. 3 of [40]. Eddington dismissed the possibility of gravitational waves, declaring that they would have to travel 'at the speed of thought.' The issue revolves around whether gravitational waves can be made to vanish in a properly chosen coordinate system. The discovery of apparent gravitational energy loss by the Hulse–Taylor pulsar provides indirect evidence for the existence of gravitational waves. Calculations have not yet been done to examine whether the Sakharov–Puthoff model would predict gravitational waves, but the coordinate ambiguities of GR should not appear in a ZPF-referenced theory of gravitation.)

If inertial mass, m_i, originates in ZPF–charge interactions, then, by the principle of equivalence so must gravitational mass, m_g. In this view, gravitation is a force originating in ZPF–charge interactions analogous to the HRP inertia concept. Sakharov [14] was the first to conjecture this interpretation of gravity. If true, gravitation would be unified with the other forces: it would be a manifestation of electromagnetism.

Although there were some early attempts to link gravity to the ZPF from a quantum field theoretical viewpoint (by Amati, Adler and others, see discussion and references in [43]) as well as within SED [44], the first step in developing Sakharov's conjecture in any detail within the classical context of nonrelativistic SED was the work of Puthoff [15]. Gravity is treated as a residuum force in the manner of Casimir or van der Waals forces. Expressed in the most rudimentary way this can be viewed as follows. The ZPF causes a given charged particle to oscillate. Such oscillations give rise to secondary electromagnetic fields. An adjacent charged particle will thus experience both the ZPF driving forces causing it to oscillate, and in addition forces due to the secondary fields produced by the ZPF-driven oscillations of the first particle. Similarly, the ZPF-driven oscillations of the second particle will cause their own secondary fields acting back upon the first particle. The net effect is an attractive force between the particles. The sign of the charge does not matter: it only affects the phasing of the interactions.

Unlike the Coulomb force which, classically viewed, acts directly between charged particles, this interaction is mediated by extremely minute secondary fields created by the ZPF-driven oscillations, and so is enormously weaker than the Coulomb force.

The ZPF-driven ultrarelativistic oscillations were named Zitterbewegung ('trembling motion' in German) by Schrödinger [45]. The Puthoff analysis consists of two separate parts. In the first, the energy of the Zitterbewegung motion is equated to gravitational mass, m_g (after dividing by c^2). This leads to a relationship between m_g and electrodynamic parameters that is identical to the HRP inertial mass, m_i, apart from a factor of two. This factor of two is discussed in the appendix of HRP, in which it is concluded that the Puthoff m_g should be reduced by a factor of two, yielding $m_i = m_g$ precisely.

The second part of Puthoff's analysis is more controversial. He quantitatively examines the van der Waals force-like interactions between two driven oscillating dipoles and derives an inverse square force of attraction. This part of the analysis has been challenged by Carlip [46], to which Puthoff has responded [47], but, since problems remain, this aspect of the ZPF-gravitation concept requires further theoretical development, in particular the implementation of a fully relativistic model.

Clearly the ZPF-inertia and the ZPF-gravitation concepts must stand or fall together, given the principle of equivalence. However that being the case, the Sakharov–Puthoff gravity concept does legitimately answer the objection that 'the ZPF cannot be a real electromagnetic field since the energy density of this field would be enormous and thereby act as a cosmological constant, Λ, of enormous proportions that would curve the universe into something microscopic in size.' This cannot happen in the Sakharov–Puthoff view. This situation is clearly ruled out by the elementary fact that, in this view, the ZPF cannot act upon itself to gravitate. Gravitation is not caused by the mere presence of the ZPF, rather by secondary motions of charged particles driven by the ZPF. In this view it is impossible for the ZPF to give rise to a cosmological constant. (The possibility of non-gravitating vacuum energy has recently been investigated in quantum cosmology in the framework of the modified Born–Oppenheimer approximation by Datta [48]).

The other side of this argument is, of course, that as electromagnetic radiation is not made of polarizable entities one might naively no longer expect deviation of light rays by massive bodies. We speculate, however, that such deviation will be part of a fully relativistic theory that properly takes into account the polarization of the vacuum by passing light rays through the particle–antiparticle Dirac vacuum that should act, in effect, as a medium with an index of refraction modified in the vicinity of massive objects. This is very much in line with the original Sakharov concept [14] and with the approach Einstein took in 1911 [16] (with later corrections [17]) involving a speed of light which is dependent on gravitational potential, $c(\Phi)$.

Radiation from accelerated charges

As demonstrated by Boyer [11] and Puthoff [18], dipole scattering of the ZPF is an equilibrium process for stationary scatterers. The rederivation of the inertia effect from considerations of time evolution of the Poynting vector in a uniformly accelerating coordinate system [41,42] points to similarities with the classical derivation of radiation from uniformly accelerated charges [19]. Based upon this, we speculate that the phenomenon of radiation by accelerating charge may be associated with scattering of ambient ZPF radiation. The isotropic scattering of ZPF radiation by an accelerating particle would appear as creation of emitted radiation from the perspective of a stationary laboratory frame. This same process could also be interpreted as the source of radiation reaction. Thermal radiation, of course also originates in accelerated motions in the form of particle oscillations. This may explain why the Davies–Unruh component of the ZPF that appears in accelerated frames and the thermal blackbody radiation have the same spectral form, viz. the Planck function. A major obstacle to such an interpretation of accelerated charge radiation as a ZPF scattering process is that at 'normal frequencies' the energy density of emission may easily be such that $\rho(\nu) \gg \rho_{ZPF}(\nu)$, which would vitiate this interpretation unless there were some process capable of rapidly downshifting energy from higher frequencies, where ρ_{ZPF} can be much larger.

Stability of the Bohr atom

The snowball that triggered the avalanche of quantum physics started with Bohr's resolution of the problem of radiative collapse of the hydrogen atom. SED analysis of this classical problem has yielded a surprising result that motivates a new look at what has appeared to be a long-resolved issue.

Rutherford's discovery of the atomic nucleus in 1911 together with Thomson's previous discovery of the electron in 1897 led to the obvious, but fatally flawed, analogy between atomic structure and planetary orbits about the sun. Electrons, being charged, would radiate away their orbital energy and quickly collapse into the nucleus in this naive analogy. Bohr recognized that Planck's constant, h, could be combined with Rydberg's empirical relationship among the spectral lines of hydrogen to solve the problem of atomic stability by postulating that only discrete transitions are allowed between states whose angular momenta are multiples of $\hbar$. The ground state of the hydrogen atom would then have angular momentum $mvr_o = \hbar$, or equivalently $m\omega_o r_o^2 = \hbar$, and would be forbidden to decay below this 'orbit' by Bohr's fiat. A more complex picture quickly developed from this that substituted wave functions for orbiting point particles, and in that view the orbital angular momentum of the ground state is actually $l = 0$: the wavefunction is spherically symmetric and has a radial probability distribution whose most probable value is r_o. (The expectation value is $(3/2)r_o$.)

Puthoff [20] improved upon an analysis first carried out by Boyer [11] that demonstrated that while a classically circularly orbiting electron would indeed radiate away energy, if one takes into account the ZPF as a source of energy to be absorbed (again via $\vec{E}^{ZP}$-driven oscillations), at the Bohr orbit, r_o, a condition of balance would take place in absorbed and emitted power, i.e. $< P^{abs} >_{circ} = < P^{rad} >_{circ}$. In other words, a classically orbiting and radiating electron would pick up as much energy as it loses, and thus be stabilized. This simple analysis has been shown to work not only for the ground state of hydrogen but for the ground state of the harmonic oscillator as well, and is now being explored with regard to ground states in general [49]. It does not apply, however, to excited states. A more sophisticated analysis to examine whether analogous arguments might apply to those circumstances has not been seriously attempted. (Extensive but unsuccessful attempts were made by Claverie *et al.* [50], but their work, though mathematically accurate, was based upon what, in our opinion, was an inadequate physical model for the situation beyond the ground state of hydrogen. We contend that for such analysis to be successful one has to include a more detailed description of the ultrarelativistic Zitterbewegung oscillations of the electron that give rise to the electron spin in the context of what we call 'SED with particle structure' [12]. A classical non-spinning electron is found to display a nonstationary behaviour that eventually leads to ionization.)

The most speculative interpretation of this peculiar result is that it may eventually be shown that matter is stabilized at the atomic level by the ZPF. Presumably the quantum probability distribution would then have to correspond to some kind of time-average of the fluctuation-induced perturbations of the electron position.

The ZPF as a universal clock and spontaneous emission

In the ninth Milne Lecture, delivered at the University of Oxford in 1985, Sir William McCrea concerned himself with the question of whether there is a need for some mechanism that acts as a kind of universal timekeeper, and his conclusion was that that role can only be played by what is called the ZPF. Consider the situation of spontaneous emission. What triggers such an event, or at even more fundamental level, what is it that informs the atom that time is passing and something should occur?

All one need do is examine the relations among the Einstein coefficients to implicate the ZPF in this:

$$A_{21} = \frac{2h\nu^3}{c^2} B_{21} \tag{4a}$$

$$\rho_\nu = \frac{4\pi}{c} I_\nu \tag{4b}$$

$$B_{21} I_\nu + A_{21} = B_{21}\left(I_\nu + 2I_\nu^{ZP}\right) \tag{4c}$$

Writing the spontaneous emission coefficient, A_{21}, in this fashion indicates that the spontaneous emission appears to be stimulated emission with the stimulating radiation field being the ZPF. The factor of 2 discrepancy has to do with the intimate relationship between the ZPF and radiation reaction, each of which can be interpreted as contributing equally to the spontaneous emission [51,52]. It is now well known and has been frequently verified that spontaneous emission can be altered (both enhanced and reduced) by placing atoms in a cavity [53]. Further discussion of the hypothesized time-keeping function of the ZPF may be found in McCrea's article.

The ZPF as a Lorentz invariant electromagnetic component of Dirac's ether

In 1951, Dirac concluded [54]: "Thus with the new electrodynamics we are rather forced to have an aether." Ether is a loaded term today because it is so widely described as an outmoded, discredited idea. The nineteenth-century ether was an ill-defined 'substance' providing a universal frame of rest and a medium for propagation of light waves. The ZPF is not an ether of this sort. The ZPF is light waves and is therefore not akin to the mysterious substance called ether in the late-nineteenth century. Moreover, the ZPF is Lorentz invariant, a crucially important property. Being Lorentz invariant it cannot and does not act as a universal frame of rest for rectilinear motion (which we do not want in physics). However, it does provide a universal frame of rest *vis-a-vis* acceleration. Contrary to a widespread belief, acceleration in general is not relative in general relativistic mechanics; only gravitational acceleration is relative. This point has been made by Rohrlich [24], Rindler and Mishra [55] and Mashhoon [56]. In today's physics one does need a type of 'absolute space': viz: one that is absolute with respect to acceleration, but not with respect to rest or uniform motion. Mashhoon [56] states: "Absolute space-time must be invoked to explain inertial accelerations....general relativity renders the acceleration of gravity relative while maintaining the absolute character of any nongravitational acceleration''. The Lorentz invariant ZPF provides this, and in providing this also gives rise to inertia thus providing a substantive form for Mach's principle.

This can be rigorously expressed as follows (Mashhoon, priv. comm.). Newton's equation of motion in special relativity can be written:

$$m \frac{d^2 x^\mu}{d\tau^2} = F^\mu \tag{5a}$$

where these are four-vectors and F^μ represents a non-gravitational force. In general relativity this becomes

$$m \left(\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\nu\rho} \frac{dx^\nu}{d\tau} \frac{dx^\rho}{d\tau} \right) = F^\mu \tag{5b}$$

The velocity $dx^\mu d\tau$ is a time-like four-vector; the force F^μ is a space-like-four-vector. The two are orthogonal to each other (see Møller [69]). If the space-like four-vector force $F^\mu \neq 0$ in any coordinate frame, it will be non-zero in all coordinate frames. The $\Gamma^\mu_{\nu\rho}$ represent the gravitional force and indeed can be set equal to zero by a coordinate transformation. The non-gravitational force F^μ cannot be transformed away. Thus, turning the arguments around, the absolute nature of non-gravitational acceleration is demonstrated by the manifestation of a force that cannot be transformed away. It is in this sense that there is a need for a special reference frame that is not perceptible on account of uniform motion, but that is perceptible on account of non-gravitational acceleration. We propose that the (Lorentz invariant) ZPF plays this role.

Cosmic voids and cosmic rays

An important consequence of allowing a real ZPF–matter interaction is the prediction of a systematic growth of the translational kinetic energy of relatively isolated, electromagnetically interacting particles. ZPF acceleration can be intuitively understood as follows. A drag force exists for particle motion in any ordinary radiation field, since in the rest frame of the particle the higher the velocity, the greater will be the opposing radiation pressure owing to the Doppler shift, which increases the opposing drag strength of the radiation field in the direction of motion and decreases it in the opposite direction. The ZPF spectrum, however, is Lorentz invariant, which precludes such a radiation drag force that would otherwise limit the velocity. There is thus no dissipative effect to compensate the excitations of the fluctuating field.

A detailed description of the prediction of the ZPF acceleration and of its implementation in astrophysical environments may be found in the review of Rueda [57]. The thermodynamics of this predicted phenomenon is discussed by Cole [58] in some detail. The acceleration effect is more pronounced on charged particles than on neutral, polarizable particles. This ZPF-acceleration effect is quenched when the ZPF-induced oscillations become relativistic, due to a time-dilation effect [59]. This situation occurs for electrons. Since electrons undergo ZPF-induced Zitterbewegung at relativistic speeds, $< v_{zb} > \approx c$, they are not significantly accelerated, whereas protons and nuclei, oscillating with $< v_{zb} > \ll c$, can be accelerated.

In regions of intergalactic space where densities are extremely low there will be very few particle collisions to damp accelerations. It has, therefore, been proposed that this may be the origin of the most energetic cosmic rays. The highest energy cosmic ray event detected to date was measured to be 3×10^{20} eV [60].

If one assumes the presence of primordial magnetic fields in the Universe, this same ZPF–acceleration mechanism will lead to a second phenomenon. Since the mechanism is most effective where there is the least matter to damp the accelerations via collisions, large regions of low density will be swept out. Primordial magnetic fields will be carried along and wind up being concentrated along with the swept-out matter in regions of higher density which start to aggregate. Eventually the magnetic pressure will build up to the point where it will resist further concentration of the accompanying matter. The end result of this process is proposed to be the formation of the large scale ($d \sim 100$ Mpc) cosmic sheets and voids discovered within the past decade or so [26,27]. As mentioned above, somewhat different assumptions on the stochastic processes that lead to acceleration may vititate this concept [29]. It is too early to decide one way or the other.

Miscellaneous considerations

Classical electrodynamics takes as a boundary condition that all electromagnetic fields originated in some physical process such as the big bang or subsequent circumstances such as thermonuclear energy generation in stars, etc. Stochastic electrodynamics assumes that there is, in addition, a uniform, isotropic background electromagnetic zero-point field. It is postulated that the ZPF is just part and parcel of the Universe. Presumably it originated together with the rest of the universe. This same question can be phrased in a more rigorous way in terms of boundary conditions on Maxwell's equations as discussed by Boyer [11].

The ν^3 ZPF spectrum is the unique spectrum that remains invariant under an adiabatic compression or expansion of a cavity [11,61] thus one may surmise that it should not change as the universe expands.

As to the origin of Planck's constant, h, the ZPF as a real electromagnetic field is completely defined by two properties. First, it must have Lorentz-invariant averaged statistical properties, e.g. the energy density spectrum: This uniquely defines the spectral shape as a ν^3 spectrum. This leaves only the absolute value to be determined, i.e. having the energy distribution defined leaves only the energy density. The energy density is measurable in various ways, for example from the macroscopic Casimir force (poorly measured so far in practice) or from the Lamb shift. The constant that results is Planck's constant, h. In other words, in the SED perspective, h is an empirically determinable scale-factor for the strength of the ZPF. It is no coincidence that this same constant is the fundamental one in quantum physics: In the SED view, the perturbations caused by the ZPF are the source of quantum indeterminacy. That is why the Heisenberg uncertainly relation contains h, because the ZPF fluctuations provide the irreducible stochastic noise that are conventionally interpreted as innate uncertainty.

It is also of interest to consider the size of the electron in this context. As discussed by MacGregor [62], there are arguably seven 'correct values' of the electron radius, ranging from the Compton radius, $R_C = 3.86 \times 10^{-11}$ cm, to the 'real' radius of the electric charge measured by high-energy scattering experiments, $R_e \ll 10^{-16}$ cm, and for all one knows R_e could be truly point-like. The smearing out of the electron charge by the ZPF involves the two phenomena of vacuum polarization and Zitterbewegung. Both of these together yield a radius equal to the Compton radius. Thus one defensible interpretation is that the electron really is a point-like entity, smeared out to its quantum dimensions by the ZPF fluctuations. In the ZPF inertia concept, the electron should be massless at the level of the Zitterbewegung motions; only accelerations of the already oscillating electron give rise to inertia. If one thus sets the

Zitterbewegung velocity to c, the radius that results from the Heisenberg relation is R_C, again consistent with the view of an electron as an oscillating point charge. It was long-ago suggested by Huang [45] and Weisskopf [63] that the spin of the electron could follow from Zitterbewegung, a concept that has received some support from recent work by Rueda [12].

An important point to make is that at the present time the ZPF theory deals only with photons, not the W^+, W^- and Z^0 massive bosons mediating the weak interaction, nor the gluons of the strong interaction. This is certainly a deficiency which a generalization of the ZPF concept in the direction of a unified field embodying the electromagnetic, weak and strong fields should be able to remedy. Also the question of how quantum non-locality could be reconciled with a purely SED explanation of quantum phenomena has barely begun to be addressed (see [64] and references therein).

Tests and applications

These radical new concepts open the door in principle to: (1) modification of inertia and gravity; and (2) extraction of energy from the ZPF. However, even if these possibilities do materialize, the effects may be infinitesimally minute. Take, for example, the credible theoretical quantum electrodynamics prediction that between two conducting (Casimir-type) plates the speed of light perpendicular to the plates should be greater than c [65]. This appears to be a correct prediction, but the most optimistic circumstances for plate separation of 100 Å would yield an excess of only $10^{-24}c$.

In the views presented herein, inertial mass should also change under such circumstances. Indeed, the two effects are not unrelated. If one assumes that the $E = mc^2$ relationship would still hold exactly, m_i would also change, decreasing by 2Δ c/c. We speculate that a more robust possibility would result from understanding the origin of Γ and ω_0 (assuming a resonance in place of a cutoff) determining m_i.

A thought experiment by Forward [66] involving the Casimir force to do work nicely demonstrated the formal possibility of extracting energy from the ZPF. The thermodynamics of energy extraction from the ZPF has now been studied by Cole and Puthoff [67] and there appears to be no obvious impossibility. The ZPF is not a thermal reservoir, and so, in spite of the 'zero-point' name, it does not amount to attempts to extract usable thermal energy from a $T = 0$ reservoir. The mysterious phenomenon of sonoluminescence has been suggested to originate in ZPF-related energy [68].

The possibility of an Einstein–Hopf acceleration of particles discussed above would be an example of energy extraction. Whether this could be utilized in some practical way is entirely unknown, but it does appear that this could serve as a test. Sealed cryogenically cooled vacuum traps have succeeded in confining large numbers of antiprotons. The proposal of Rueda, Haisch and Cole [26] suggests that individual antiprotons should undergo accelerations on the order of 1 keV s^{-1} in a totally collision-free trap of this sort. Injecting antiprotons into such a trap should then result in ZPF acceleration of these particles which would then readily be detectible via annihilation signatures upon striking the walls of the trap. This would constitute extraction of energy from the ZPF, and indeed the acceleration of certain high-energy cosmic rays may be a naturally occurring process of such energy extraction [28]. Unfortunately the gap between a present-day laboratory high-vacuum density (10^8 cm^{-3}) and the intergalactic density (10^{-6} cm^{-3}) is formidable.

The views presented herein involve a radical change in perspective. It is our hope that this article will elicit the interest of other researchers to investigate these possibilities so that we may soon know whether the exciting prospects implicit in this approach are real or illusory.

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