Advances in the Proposed Electromagnetic Zero-Point Field Theory of Inertia

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ABSTRACT

A NASA-funded research effort has been underway at the Lockheed Martin Advanced Technology Center in Palo Alto and at California State University in Long Beach to develop and test a recently published theory that Newton's equation of motion can be derived from Maxwell's equations of electrodynamics as applied to the zero-point field (ZPF) of the quantum vacuum. In this ZPF-inertia theory, mass is postulated to be not an intrinsic property of matter but rather a kind of electromagnetic drag force (which temporarily is a place holder for a more general vacuum quantum fields reaction effect) that proves to be acceleration dependent by virtue of the spectral characteristics of the ZPF. The theory proposes that interactions between the ZPF and matter take place at the level of quarks and electrons, hence would account for the mass of a composite neutral particle such as the neutron. An effort to generalize the exploratory study of Haisch, Rueda and Puthoff (1994) into a proper relativistic formulation has been successful. Moreover the principle of equivalence implies that in this view gravitation would also be an effect originated in the quantum vacuum along the lines proposed by Sakharov (1968). With regard to exotic propulsion we can definitively rule out one speculatively hypothesized mechanism: matter possessing negative inertial mass, a concept originated by Bondi (1957) is shown to be logically impossible. On the other hand, the linked ZPF-inertia and ZPF-gravity concepts open the conceptual possibility of manipulation of inertia and gravitation, since both are postulated to be vacuum phenomena. It is hoped that this will someday translate into actual technological potential, especially with respect to spacecraft propulsion and future interstellar travel capability. A key question is whether the proposed ZPF-matter interactions generating the phenomenon of mass might involve one or more resonances. This is presently under investigation.

INTRODUCTION

In an article in *New Scientist* science writer Robert Matthews (1995) summarizes the predictions of various scientists: "Many researchers see the vacuum as a central ingredient of 21st century physics." The reason for this is that, despite its name, the vacuum is in fact far from empty. Create a perfect vacuum, devoid of all matter and containing not a single (stable) particle, and that region of seemingly empty space will actually be a seething quantum sea of activity. Heisenberg's uncertainty relations allow subatomic particles to flicker in and out of existence. Similar quantum processes apply to electromagnetic fields, and that is the origin of the electromagnetic zero-point field (ZPF). The entire Universe is filled with a quantum sea of electromagnetic zero-point energy whose properties are the basis of Matthew's predictive statement.

In 1994 we published an analysis which proposed that the most fundamental property of matter — inertia — could be explained as an electromagnetic force traceable to the ZPF (Haisch, Rueda and Puthoff 1994; HRP). The exploratory approach we used had two weaknesses: (1) the mathematical development was quite complex, and (2) the calculations were dependent upon a simplified model to represent the interactions between material objects and the ZPF. But in spite of these two limitations, our analysis yielded a remarkable and unexpected result: that Newton's equation of motion, $\mathbf{f} = m\mathbf{a}$, regarded since 1687 as a postulate of physics, could be derived from Maxwell's laws of electrodynamics as applied to the ZPF. The implication is that inertia is not an innate property of matter, rather it is an electromagnetically-derived force (or quantum vacuum derived force in a future more general derivation). If this proves to be true, the potential exists for revolutionary technologies since the manipulation of electromagnetic phenomena is the basis of most modern technology. In particular, the manipulation of the vacuum electromagnetic fields is today the subject of (vacuum) cavity quantum electrodynamics.

Thanks in part to a NASA research grant, we have made progress in strengthening the basis of the ZPF-inertia hypothesis. We have been able to rederive the ZPF-inertia connection in a way that is mathematically much more straightforward, that is not dependent upon the original simplified matter-ZPF interaction model, and that — importantly — proves to be relativistic (Rueda & Haisch 1998a, 1998b). This increases our confidence considerably in the validity of the ZPF-inertia hypothesis.

We suggest that a change in paradigm regarding our conception of matter is not far off. If inertia proves to be at least in part an electromagnetic force arising from interactions between quarks and electrons and the ZPF, this will do away with the concept of inertial mass as a fundamental property of matter. [a] The principle of equivalence then implies that gravitational mass will need to undergo an analogous reinterpretation. A foundation for this was laid already 30 years ago by Sakharov (1968).

Lastly, the Einstein $E = mc^2$ relationship between mass and energy will also be cast in a different light. As it now stands this formula seems to state that one kind of "thing," namely energy, can mysteriously be transformed into a totally different kind of "thing," namely mass...and vice versa. It is proposed instead that the $E = mc^2$ relationship is a statement about the kinetic energy that the ZPF fluctuations induce on the quarks and electrons constituting matter (Puthoff 1989a). We are used to interpreting this concentration of energy associated with material objects as mass, but in fact this is more a matter of bookkeeping than physics. Indeed the concept of mass itself in all its guises (inertial, gravitational and as relativistic rest mass) appears to be a bookkeeping convenience. All we ever experience is the presence of a certain amount of energy or the presence of certain forces. We traditionally account for these energies and forces in terms of mass, but that appears now to be unnecessary. Interactions of the ZPF with quarks and electrons are what physically underlie all these apparent manifestations of mass. This opens new possibilities.

Only fifty years ago the concept of space travel was regarded by most, including scientists (who should have known better), as science fiction: this in spite of the fact that the basic knowledge was already in place. Details and technicalities, of course, were lacking, but the chief handicap was — more than anything — a mindset that such things simply had to be impossible. Similar prejudices had been at work fifty years prior to that regarding flight. We have come to a new millenium and the first glimmerings of how to go about finding a way to achieve interstellar travel have started to appear on the horizon. A very modest — in terms of cost — but intellectually ambitious program has been established by NASA: The *Breakthrough Propulsion Physics Program* (BPP). The rationale is stated as follows: [b]

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[a] Vigier (1995), a former collaborator of Bohm and de Broglie, recently proposed that the Dirac vacuum (that vast sea of virtual electrons and positrons in the vacuum strongly coupled to the ZPF) also contributes to inertia. We have plans to jointly explore this idea in an extension of our original approach.

[b] The Breakthrough Propulsion Physics website is http://www.lerc.nasa.gov/WWW/bpp/

NASA is embarking on a new, small program called Breakthrough Propulsion Physics to seek the ultimate breakthroughs in space transportation: (1) Propelling a vehicle without propellant mass, (2) attaining the maximum transit speeds physically possible, and (3) creating new energy production methods to power such devices. Because such goals are beyond the accumulated scientific knowledge to date, further advances in science are sought, specifically advances that focus on propulsion issues. Because such goals are presumably far from fruition, a special emphasis of this program is to demonstrate that near-term, credible, and measurable progress can be made. This program, managed by Marc Millis of Lewis Research Center (LeRC) represents the combined efforts of individuals from various NASA centers, other government labs, universities and industry. This program is supported by the Space Transportation Research Office of the Advanced Space Transportation Program managed by Marshall Space Flight Center (MSFC).

The first NASA BPP workshop was held in August 1997 to survey the territory and assess emerging physics concepts. Several invited presentations discussed the ZPF vacuum fluctuations, and this area of research was given a high priority in a ranking process carried out as part of the meeting (Millis 1998 and references therein). In addition to the proposed ZPF-inertia and ZPF-gravitation hypotheses, the possibility of extracting energy and of generating forces from the vacuum fluctuations were discussed. It has been shown that extracting energy from the vacuum does not violate the laws of thermodynamics (Cole and Puthoff 1993). As for ZPF-related forces, the recent measurements of the Casimir force by Lamoreaux (1997) are in agreement with theoretical predictions. Real, macroscopic forces can be attributed to certain configurations of the ZPF, such as in a Casimir cavity. *We are proposing that inertia too is a Casimir-like acceleration-dependent drag force.*

NEWTON'S EQUATION OF MOTION: f=ma

Physics recognizes the existence of four types of mass. (1) *Inertial mass:* the resistance to acceleration known as inertia, defined in Newton's equation of motion, $\mathbf{f} = m\mathbf{a}$, and its relativistic generalization. (2) *Active gravitational mass:* the ability of matter to attract other matter via Newtonian gravitation, or, from the perspective of general relativity, the ability to curve spacetime. (3) *Passive gravitational mass:* the propensity of matter to respond to gravitational forces. (4) *Relativistic rest mass:* the relationship of the mass of a body and the total energy available by perfect annihilation of the mass in the body, that is expressed in the $E = mc^2$ relation of special relativity. These are very different properties of matter, yet for some reason they are quantitatively represented by the same parameter. One can imagine a universe, for example, in which inertial mass, m_i, and passive gravitational mass, m_g, were different... but then objects would not all fall with the same acceleration in a gravitational field and there would be no principle of equivalence to serve as the foundation of general relativity. One can imagine a universe in which active and passive gravitational mass were different... but then Newton's third law of equal and opposite forces would be violated, and mechanics as we know it would be impossible.

Consider inertial mass, m_i. Exert a certain force, $\mathbf{f}$, and measure a resultant acceleration, $\mathbf{a}$. Let this process take place under ideal conditions of zero friction. A nearly perfect example — excluding the very small residual atmospheric drag even at Shuttle altitudes — would be the force exerted by the Space Shuttle engines and the acceleration of the Shuttle that results upon firing. The inertial mass is a scalar coefficient linking these two measureable processes $\mathbf{f}$ and $\mathbf{a}$ (scalar since the vectors $\mathbf{f}$ and $\mathbf{a}$ point in the same direction). However since we perceive a material object in the form of the Shuttle, we reify this m_i coefficient and attribute a property of mass to the object and then say that it is the mass of the object that causes the resistance to acceleration. That is to say, for a given amount of m_i residing in the matter of an object it takes so much force to achieve such a rate of acceleration, which is embodied in $\mathbf{f} = m\mathbf{a}$. We thus attribute mass to all material objects.

It is important to keep in mind that the *actual direct measurement* of the thing we call inertial mass, m_i, can only take place during acceleration... or deceleration which is simply acceleration directed opposite to the existing velocity. We *assume* that an object always possesses something called mass even when it is not accelerating, and proceed to calculate the momentum, $m_i v$, and the kinetic energy, $m_i v^2/2$, of an object moving at constant velocity with respect to us. But there can be no direct evidence that an object possesses mass unless it is being accelerated. The only way we can directly measure the momentum or the kinetic energy that we calculate is by bringing about a collision. But a collision necessarily involves deceleration. It makes for good bookkeeping to assume that an object always carries with it a thing called mass, yielding a certain momentum and kinetic energy, but this is necessarily an abstraction.

The momentum and kinetic energy depend upon relative motion, since no velocity is absolute. Move alongside an object and its momentum and kinetic energy reduce to zero. We argue that in a somewhat analogous fashion, m_i is not something that resides innately in a material object, but rather that it is an electromagnetic reaction force (per unit acceleration) that springs into existence the instant an acceleration occurs, and disappears as soon as the acceleration stops. It is, precisely as defined in Newton's **f**=m**a**, a coefficient linking force and acceleration. It is a force per unit acceleration that arises electrodynamically.

This may be brought into sharper focus by considering Newton's third law. Newton's third law states that for every force there must be an equal and opposite reaction force, i.e. $\mathbf{f} = -\mathbf{f}_r$. For stationary or static phenomena it is impossible to even conceive of an alternative: If the right hand is pressing against the left hand with force **f**, then the left hand must press back against the right hand with the equal and oppositely-directed reaction force, $\mathbf{f}_r$. How could one hand press against the other without the other pressing back? It would violate a fundamental symmetry, since who or what is to say which hand is pressing and which is not. Thus for static or stationary situations the balance of forces is the only imaginable circumstance.

If an agent exerts a force on a non-fixed object, experience tells us that a reaction force also manifests against the agent. But why is this so? The traditional explanation is that matter possesses inertial mass which by its nature resists acceleration by pushing back upon the agent. The discovery that we have made is that, on the contrary, there is a very specific electromagnetic origin for a reaction force $\mathbf{f}_r$. Accelerated motion through the electromagnetic zero-point field (ZPF) of the quantum vacuum results in a reaction force. If one analyses the ZPF using Maxwell's equations of electrodynamics, one finds that $\mathbf{f}_r = -m_{zp}\mathbf{a}$ where m_{zp} is an electromagnetic parameter with units of mass. An electromagnetic reaction force (somewhat like a drag force) arises that happens to be proportional to acceleration. In other words, if one begins with Maxwell's equations as applied to the ZPF, one finds from the laws of electrodynamics that $\mathbf{f}_r = -m_{zp}\mathbf{a}$ and thus if one assumes that the electrodynamic parameter m_{zp} really *is* the physical basis of mass, Newton's third law of equal and opposite forces, $\mathbf{f} = -\mathbf{f}_r$, results in a *derivation* of $\mathbf{f} = m\mathbf{a}$ from the electrodynamics of the ZPF. That being the case, one can, in principle, dispense with the concept of inertial mass altogether. Matter, consisting of charged particles (quarks and electrons) interacts with the electromagnetic ZPF and this yields a reaction force whenever acceleration takes place and that is the cause of inertia.

THE ORIGIN OF THE ELECTROMAGNETIC ZERO-POINT FIELD

There are two views on the origin of the electromagnetic zero-point field as embodied in *Quantum Electrodynamics* (QED) and *Stochastic Electrodynamics* (SED) respectively. The QED perspective is currently regarded as "standard physics" and the arguments go as follows. The Heisenberg uncertainty relation sets a fundamental limit on the precision with which conjugate quantities are allowed to be determined. The two principal conjugate pairs are position and momentum such that $\Delta x \Delta p \geq \hbar/2$, and energy and time such that $\Delta E \Delta t \geq \hbar/2$ where $\hbar$ is Planck's constant, h, divided by 2π. It is a standard derivation in most textbooks on quantum mechanics to work out the quantum version of a simple mechanical harmonic oscillator — a mass on a spring — in this respect.

There are two non-classical results for a quantized harmonic oscillator. First of all, the energy levels are discrete and not continuous. By adding energy one can increase the amplitude of the oscillation, but only in units of $h\nu$, where ν is the frequency in cycles per second. In other words, one can add or subtract $E = nh\nu$ of energy where $n \geq 0$. The second quantum effect stems from the fact that if an oscillator were able to come completely to rest, Δx would be zero and this would violate the $\Delta x \Delta p \geq \hbar/2$ limitation. The result is that there is a minimum energy of $E = h\nu/2$, i.e. the oscillator energy can only take on the values $E = (n + 1/2)h\nu$ which can never become zero since n cannot be negative.

The argument is then made that the electromagnetic field is analogous to a mechanical harmonic oscillator since the electric and magnetic fields, **E** and **B**, are modes of oscillating plane waves (see e.g. Loudon 1983). Each mode of oscillation of the electromagnetic field has a minimum energy of $h\nu/2$. The volumetric density of modes between frequencies ν and $\nu + d\nu$ is given by the density of states function $N_\nu d\nu = (8\pi\nu^2/c^3)d\nu$. Each state has a minimum $h\nu/2$ of energy, and using this density of states function and this minimum energy that we call the zero-point energy per state one can calculate the ZPF spectral energy density:

$$\rho(\nu)d\nu = \frac{8\pi\nu^2}{c^3}\frac{h\nu}{2}d\nu. \tag{1}$$

It is instructive to write the expression for zero-point spectral energy density side by side with blackbody radiation:

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

The first term (outside the parentheses) represents the mode density, and the terms inside the parentheses are the average energy per mode of thermal radiation at temperature T plus the zero-point energy, $h\nu/2$, which has no temperature dependence. Take away all thermal energy by formally letting T go to zero, and one is still left with the zero-point term. The laws of quantum mechanics as applied to electromagnetic radiation force the existence of a background sea of zero-point-field (ZPF) radiation.

Zero-point radiation is a result of the application of quantum laws. It is traditionally assumed in quantum theory, though, that the ZPF can for most practical purposes be ignored or subtracted away. The foundation of SED is the exact opposite. It is assumed that the ZPF is as real as any other electromagnetic field. As to its origin, the assumption is made that for some reason zero-point radiation just came with the Universe. The justification for this is that if one assumes that all of space is filled with ZPF radiation, a number of quantum phenomena may be explained purely on the basis of classical physics including the presence of background electromagnetic fluctuations provided by the ZPF. The Heisenberg uncertainty relation, in this view, becomes then not a result of the existence of quantum laws, but of the fact that there is a universal perturbing ZPF acting on everything. The original motivation for developing SED was to see whether the need for quantum laws separate from classical physics could thus be obviated entirely.

Philosophically, a universe filled — for reasons unknown — with a ZPF but with only one set of physical laws (classical physics consisting of mechanics and electrodynamics), would appear to be on an equal footing with a universe governed — for reasons unknown — by two distinct physical laws (classical and quantum). In terms of physics, though, SED and QED are not on an equal footing, since SED has been successful in providing a satisfactory alternative to only some quantum phenomena (although this success does include a classical ZPF-based derivation of the all-important blackbody spectrum, cf. Boyer 1984). Some of this is simply due to lack of effort: The ratio of man-years devoted to development of QED is several orders of magnitude greater than the expenditure so far on SED.

ACCELERATION AND THE DAVIES-UNRUH EFFECT

The ZPF spectral energy density of Eq. (1) would indeed be analogous to a spatially uniform constant offset that cancels out when considering energy fluxes. However an important discovery was made in the mid-1970's that showed that the ZPF acquires special characteristics when viewed from an accelerating frame. In connection with radiation from evaporating black holes as proposed by Hawking (1974), Davies (1975) and Unruh (1976) determined that a Planck-like component of the ZPF will arise in a uniformly-accelerated coordinate system having constant proper acceleration $\mathbf{a}$ (where $|\mathbf{a}| = a$) with what amounts to an effective "temperature"

$$T_a = \frac{\hbar a}{2\pi ck}. \qquad (3)$$

This "temperature" does not originate in emission from particles undergoing thermal motions. [c] As discussed by Davies, Dray and Manogue (1996):

> One of the most curious properties to be discussed in recent years is the prediction that an observer who accelerates in the conventional quantum vacuum of Minkowski space will perceive a bath of radiation, while an inertial observer of course perceives nothing. In the case of linear acceleration, for which there exists an extensive literature, the response of a model particle detector mimics the effect of its being immersed in a bath of thermal radiation (the so-called Unruh effect).

This "heat bath" is a quantum phenomenon. The "temperature" is negligible for most accelerations. Only in the extremely large gravitational fields of black holes or in high-energy particle collisions can this become significant. This effect has been studied using both QED (Davies 1975, Unruh 1976) and in the SED formalism (Boyer 1980). For the classical SED case it is found that the spectrum is quasi-Planckian in T_a. Thus for the case of no true external thermal radiation ($T = 0$) but including this acceleration effect (T_a), equation (1) becomes

$$\rho(\nu, T_a)d\nu = \frac{8\pi\nu^2}{c^3}\left[1 + \left(\frac{a}{2\pi c\nu}\right)^2\right]\left[\frac{h\nu}{2} + \frac{h\nu}{e^{h\nu/kT_a} - 1}\right]d\nu, \qquad (4)$$

where the acceleration-dependent pseudo-Planckian component is placed after the $h\nu/2$ term to indicate that except for extreme accelerations (e.g. particle collisions at high energies) this term is negligibly small. While these additional acceleration-dependent terms do not show any spatial asymmetry in the expression for the ZPF spectral energy density, certain asymmetries do appear when the electromagnetic field interactions with charged particles are analyzed, or when the momentum flux of the ZPF is calculated. The ordinary plus a^2 radiation reaction terms in Eq. (12) of HRP mirror the two leading terms in Eq. (4).

THE ORIGIN OF INERTIA

Two independent approaches have demonstrated how a reaction force proportional to acceleration ($\mathbf{f}_r = -m_{zp}\mathbf{a}$) arises out of the properties of the ZPF. The first approach (HRP) was based upon a simplified model for how accelerated idealized quarks and electrons would interact with the ZPF. It identified the Lorentz force arising from the stochastically-averaged magnetic component of the ZPF, $< \mathbf{B}^{zp} >$, as the basis of $\mathbf{f}_r$. The new approach (Rueda and Haisch 1998a, 1998b) considers only the relativistic transformations of the ZPF itself to an accelerated frame. We find a non-zero stochastically-averaged Poynting vector $(c/4\pi)$ $< \mathbf{E}^{zp} \times \mathbf{B}^{zp} >$ which leads immediately to a non-zero electromagnetic ZPF-momentum flux as viewed by an accelerating object. If the quarks and electrons in such an accelerating object scatter this asymmetric radiation, an acceleration-dependent reaction force $\mathbf{f}_r$ arises. In fact in this new analysis the $\mathbf{f}_r$ is the space-part of a relativistic four-vector so that the resulting equation of motion is not simply the classical $\mathbf{f} = m\mathbf{a}$ expression, but rather the properly relativistic $\mathcal{F} = d\mathcal{P}/d\tau$ equation (that reduces exactly to $\mathbf{f} = m\mathbf{a}$ for subrelativistic velocities).

In the first approach a specific ZPF-matter interaction is needed to carry out the analysis. We used a technique developed by Einstein and Hopf (1911) and applied that to idealized particles (partons, in the nomenclature of Feynman) treated as Planck oscillators. In the second approach, no specific ZPF-matter interaction is necessary for the analysis. Any scattering or absorption process will yield a reaction force on the basis of a non-zero electromagnetic momentum flux. Presumably dipole scattering of the ZPF by fundamental charged particles is the appropriate representation, at least to first order, since that can be shown to be a detailed balance process in the non-accelerated case, i.e. dipole scattering by non-accelerated

[c] One suspects of course that there is a deep connection between the fact that the ZPF spectrum that arises in this fashion due to acceleration and the ordinary blackbody spectrum have identical form.

charged particles leaves the ZPF spectrum unchanged and isotropic (Puthoff 1989b). *In both approaches it is assumed that the level of interaction is that of quarks and electrons, which would account for the inertial mass of a composite neutral particle such as the neutron (udd).*

The expression for inertial mass in HRP *for an individual particle* is

$$m_{zp} = \frac{\Gamma_z \hbar \omega_c^2}{2\pi c^2}, \tag{5}$$

where Γ_z represents a damping constant for *zitterbewegung* oscillations. [d] This is not to be confused with $\Gamma_e = 6.25 \times 10^{-24}$ s (Jackson 1975) which is used for macroscopic electron oscillations in ordinary radiation-matter interactions. Γ_z is a free parameter and $\Gamma_z \neq \Gamma_e$. In Eq. (5) ω_c represents an assumed cutoff frequency (in radians/s) for the ZPF spectrum and is also a free parameter.

The expression for inertial mass in Rueda and Haisch (1998a, 1998b) *for an object with volume* V_0 is

$$m_{zp} = \left(\frac{V_0}{c^2} \int \eta(\omega) \frac{\hbar \omega^3}{2\pi^2 c^3} d\omega \right) = \frac{V_0}{c^2} \int \eta(\omega) \rho_{zp} \, d\omega. \tag{6}$$

The interpretation of this is quite straightforward. The energy density of the ZPF (Eq. 1) written in terms of $\omega (= 2\pi\nu)$ is $\rho_{zp} d\omega = \hbar\omega^3 d\omega / 2\pi^2 c^3$ which is the second term in the integral. The dimensionless parameter $\eta(\omega)$ represents the fraction of the ZPF flux scattered at each frequency. The total energy involved "generating mass" is determined by the volume of the object, V_0, and the division by c^2 converts the units to mass.

CAN INERTIAL MASS BE ALTERED?

The mass of a proton in energy units is $\sim$ 938 MeV. A proton is composed of two up (u) quarks and one down (d) quark whose individual masses are $\sim$ 5 MeV for the u, and $\sim$ 10 Mev for the d. Thus the mass of the uud combination constituting the proton is about 50 times more massive than the sum of the parts. The same is true of a neutron (udd) whose mass is $\sim$ 940 MeV. This is clearly a naive argument given the conceptual uncertainty of what "mass" actually means for an individual quark which cannot exist in isolation. Nonetheless, taking this paradox at face value does offers a useful perspective for speculation.

The expression (Eq. 5) for m_{zp} of an individual particle as derived by HRP involves two free parameters, Γ_z and ω_c. In HRP we assumed that ω_c was some cutoff frequency dictated either by an actual cutoff of the ZPF spectrum (such as the Planck frequency) or by a minimum size of a particle (such as the Planck length). Let us assume that in place of a cutoff frequency there is a resonance frequency which is specific to a given particle, call it ω_0.

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[d] In the Dirac theory of the electron, the velocity operator has eigenvalues of $\pm c$. The motion of an electron thus consists of two components: some average motion specific to a given physical circumstance plus an inherent highly oscillatory component whose instantaneous velocity is $\pm c$ which Schrödinger named *zitterbewegung* (cf. Huang 1952). The amplitude of this *zitterbewegung* oscillation is on the order of the Compton wavelength. From the perspective of the ZPF-inertia theory, the ZPF can induce such speed-of-light fluctuations since at this level the electron would be a massless point-charge. It is the Compton-wavelength size "electron cloud" that acquires the measured electron inertial mass of 512 keV in energy units via a relationship like Eq. (5). The $\Gamma_e = 6.25 \times 10^{-24}$ damping constant governs the motion of the "electron cloud" whereas the Γ_z applies to the internal *zitterbewegung*. This is an example of an SED interpretation of an apparent quantum phenomeon. The quantum size of the electron is its Compton wavelength. The SED interpretation would be one of a massless point charge driven by the ZPF to oscillate at $\pm c$ within a Compton wavelength-size region of space. More on this is extensively discussed in two articles by Rueda (1993).

One can now imagine that a u-quark has a resonance ω_0(u) yielding $m_{zp} = 5$ MeV and that the d-quark has a different resonance ω_0(d) yielding $m_{zp} = 10$ MeV (assuming the same Γ_z). It would not be surprising that a bound triad of quarks such as the uud or the udd would have a radically different resonance as an ensemble. The resonance of a mechanical system bears no simple relationship to the resonances of its component parts. On this basis it would be easy to see how the same three quarks could have a totally different mass collectively than individually.

This same line of reasoning could be applied to the concept of mass defect. The sum of the masses of two protons plus two neutrons is greater than the mass of a He nucleus. Again, one can easily imagine the resonance of a group of 12 bound quarks in a He nucleus being different than the sum of the resonances of four groups of three bound quarks.

The advantage of this line of reasoning is that one does not have to convert mass into energy and vice versa. The quarks themselves can remain basically unchanged entities, whereas the resonances characterizing the interaction between the quark ensemble and the ZPF vacuum vary. This view would not be at odds with the conventional interpretation that in going from two free protons plus two free neutrons to one bound He nucleus there is simply a change in potential (binding) energy taking place. That interpretation becomes one way to "balance the books" but the change in resonance would serve equally well, yet without the need to convert something material (mass) into something immaterial (energy). One would then interpret the energy released during fusion in terms of a change in the kinetic energy of the *zitterbewegung* motions of the quarks, which are driven by the underlying vacuum. In other words, change in mass becomes instead a change in the amount of energy involved in ZPF-quark interactions resulting from changes in resonance. The energy released in fusion would be coming from the ZPF.

We are suggesting that the mass of a particle is determined by a resonance frequency, ω_0, and that the mass of a composite entity can be radically different from the sum of the individual masses because of changes in the resonances due to binding forces. If that proves to be the case, then one would also expect the mass of an individual particle to be variable if a change in resonance can be induced via external boundary conditions. This would be somewhat analagous to the well-known ability to change spontaneous emission (by more than an order of magnitude) by effectively placing an atom in an appropriate electromagnetic cavity.

We view inertia as a property a particle obtains in relation with the vacuum medium in which it is immersed. We suggest that if one could somehow modify that vacuum medium then the mass of a particle or object in it would change. There is in nature an outstanding anticipatory example of a very analogous feature that is well known. This is the so-called "equivalent mass" or "effective mass" concept that conducting electrons and holes display when immersed in the crystal lattice of a semiconductor. The effective mass parameter was introduced long ago: see for example Smith (1961). If an external agent applies a force to an electron in the conduction band or to a hole in the valence band, the inertia response obtained is not at all the one we would expect for an ordinary electron in empty space, but rather is quite different from it depending on the details of the particular crystal structure of the semiconductor in which the electron (or hole) is immersed. This is why these particles are called "quasiparticles" in this situation with the effective mass being the parameter that characterizes their inertial properties inside the semiconductor medium. *The inertial property of the quasiparticle is due to the complex detailed interaction with the surrounding crystal lattice.* The effective mass is modified if the potentials in the crystal structure change. Moreover if the crystal structure has some anisotropy, the effective mass is no longer a scalar, but a tensor.

We can very reasonably expect that if the vacuum is modified, particularly at high energies, then our proposed inertial mass will also be modified and in particular, if one can manage to introduce an anisotropy in such vacuum by modifying the structure of the vacuum modes in an anisotropic way, the inertial mass may display tensorial properties. Such an anisotropy is not unthinkable: A Casimir cavity is precisely a structure that introduces an anistropy of the ZPF mode structure. It, of course, primarily effects low energy modes. We speculate that we can one day modify the vacuum modes distribution even at high energies (particularly at some particle resonance or resonances if these exist) perhaps by means of strong fields.

Therefore in semiconductors, the response of an electron to a given force is quite different from one material to another. The "effective mass" of an electron in silicon is larger than in gallium arsenide, for example. Although not directly a ZPF-determined effect, it nonetheless provides a cogent example as to how particle masses can depend on environments to which they are strongly coupled. A similar effect has recently been reported for particles produced inside collisions between heavy nuclei. Experimental evidence was reported by Wurm for a change in the effective mass of the ρ-meson during a collision as reported by Schewe and Stein (A.I.P. Bulletin No. 369). The bulletin also states: "According to Volker Koch of Lawrence Berkeley Laboratory, this effect can take place for particles inside any nuclear environment, from the most common atoms to superdense neutron stars."

ZPF-INDUCED GRAVITATION

One of the first objections typically raised against the existence of a real ZPF is that the mass equivalent of the energy embodied in Eq. (1) would generate an enormous spacetime curvature that would shrink the universe to microscopic size. The resolution of this dilemma lies in the principle of equivalence. If inertia is an electromagnetic phenomenon involving interactions between charge and the ZPF, then gravitation must be a similar phenomenon. The mere existence of a ZPF would not necessarily generate gravitation or spacetime curvature. Indeed, preliminary development of a conjecture of Sakharov (1968) by Puthoff (1989a) indicates that the ZPF in and of itself *cannot* be a source of gravitation (see also discussion in Haisch and Rueda [1997]).

Expressed in the simplest possible way, all matter at the level of quarks and electrons is driven to oscillate (*zitterbewegung* in the terminology of Schrödinger) by the ZPF. But every oscillating charge will generate its own minute electromagnetic fields. Thus any particle will experience the ZPF as modified ever so slightly by the fields of adjacent particles. . . and that is gravitation! It is a kind of long-range van der Waals force.

Such a ZPF-based theory of gravitation is only in the exploratory stage at this point. The Puthoff (1989a) analysis that resulted in the calculation of a proper Newtonian inverse-square law of attraction has since been shown to be problematic, e.g. see Carlip (1993) and the reply by Puthoff (1993), also Cole, Danley and Rueda (1998). Moreover at this time there is no accounting for the gravitational deflection of light other than to invoke a variable permittivity and permeability of the vacuum due to the presence of charged matter. However if it can be shown that the dielectric properties of the vacuum can be suitably modified by matter so as to bring about light deflection, this may be a viable alternative interpretation to spacetime curvature since light propagation serves to define the metric.

CONCLUSIONS

A concept has been proposed that attempts to account for the inertia of matter as an electromagnetic reaction force. A parallel gravitation concept along lines conjectured by Sakharov (1968) also exists in preliminary form, and is consistent with the proposed origin of inertia as demanded by the principle of equivalence. On the basis of this ZPF-inertia concept, we can definitively rule out one speculatively hypothesized propulsion mechanism: matter possessing negative inertial mass, a concept originated by Bondi (1957) is shown to be logically impossible. One cannot "turn around" the reaction force an object experiences upon accelerating into an oppositely directed ZPF momentum flux. What you move into comes at you.

Is it proper to regard the ZPF as a real electromagnetic field? The measurements by Lamoreaux (1997) of the Casimir force show excellent agreement — at the five percent level (much better than previous experiments) — with theoretical predictions. One interpretation of the Casimir force is that it represents the radiation pressure resulting from the exclusion of certain ZPF modes in the cavity between the (uncharged) conducting plates (Milonni, Cook and Goggin 1988). There are alternate ways of looking at this (cf. Milonni 1994). We suggest that it is fruitful at this stage to continue exploring the ramifications of a real-ZPF paradigm and that just as a real, measureable Casimir force results upon construction of an uncharged parallel-plate condenser, so too does a real, measureable reaction force result upon acceleration thereby creating the inertial properties of matter.

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