Calculations on Electromagnetic Zero-Point Contributions to Mass and Perspectives

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The present article discusses material to be presented at a conference entitled, "Breakthrough Propulsion Physics Workshop," in August, 1997, at NASA. Three topics involving electromagnetic zero-point (ZP) radiation will be discussed here that appear to be of interest to the workshop, namely, the possible relation of electromagnetic ZP fields to inertial mass and gravity and a proposed process involving extracting energy from the vacuum. All three topics have been discussed in the literature in relatively recent years. In particular, a proposal was made [H. E. Puthoff, Phys. Rev. A **39** 2333 (1989)] that the electromagnetic ZP fields are the fundamental basis for the gravitational interaction; later, a related proposal was made [B. Haisch, A. Rueda, and H. E. Puthoff, Phys. Rev. A 49, 678 (1994)] that these fields are also the origin for inertial mass. As summarized here, unfortunately, a detailed examination of the specific steps in the calculations supporting these two proposals show that several of the critical steps in the analyses have severe problems. Regarding the third topic, however, of extracting energy from the vacuum, this process does seem feasible. The main question here is whether a fresh perspective on ZP energy will enable viable energy extraction processes to be developed that are not already in existence.

I. INTRODUCTION

Three areas of research will be described here that appear to be of close interest to the present conference entitled, "Breakthrough Propulsion Physics Workshop." These three areas are: (1) the reaction force of electromagnetic zero-point (ZP) radiation on an accelerated electric dipole oscillator, (2) the asymptotic analysis of the van der Waals forces between electric dipole oscillators, and (3) the thermodynamics of physical operations involved with extracting energy from electromagnetic ZP radiation. Most of the present article will concentrate on the first topic of the reaction force from ZP radiation.

What relation do these three apparently very distinct topics have to each other and what relation do they have to "propulsion physics?" All three areas are related to proposals by others for constructing alternative physical means for space travel [1], [2]. As I have recently learned when approached about this workshop, to seriously consider interstellar travel within one's lifetime, significant breakthroughs in the use of new physical ideas and methods are required. More specifically, the types of propulsion for space travel that the scientific community is familiar with, or even the types that at least seem reasonably feasible given our present level of knowledge, such as propulsion via chemical, fission, or fusion methods, would all require far, far longer times than a typical human lifetime to travel from our solar system to the next nearest star (Alpha Centauri). Moreover, the present known methods for propulsion would all require incredibly enormous quantities of fuel, making such a trip essentially impossible for any reasonable flight time that one might want to consider.

The first two of the three topics that will be discussed here involve my investigations on proposed ideas by others who have attempted to explain gravity and inertia as arising from the effects of electromagnetic ZP radiation acting on matter [3], [4]. Other people [1] have some hopes that such a connection, if true, might enable means to be found for manipulating gravity via methods more familiar from electromagnetic work [5]. The third topic that will be discussed here on energy extraction from ZP radiation has been stated to be of interest to this workshop since there is a need to "discover fundamentally new on-board energy production methods to power propulsion devices." [6]

In this article I will cover these three topics sequentially, then at the end give some concluding remarks. Briefly, however, my outlook at this point is that for the first topic involving the reaction force from electromagnetic ZP radiation on an accelerated system, there is indeed some very interesting physics to report, and more to explore, but this mechanism does not appear to provide the fundamental explanation for inertia proposed in Ref. [4]. For the second topic, Puthoff [3] has proposed that gravity may be explained as the result of a van der Waals like mechanism between distant particles, due to a correlated jiggling motion caused by electromagnetic ZP radiation. Likewise, as with the first topic, this proposed mechanism looks doubtful to me. Finally, regarding the third topic of energy extraction from the vacuum [7], [8], [9], this concept seems quite reasonable. The question here, however, will be whether or not viewing energy extraction in this manner will prove to provide new practical energy extraction methods.

II. STOCHASTIC ELECTRODYNAMICS

Before covering these three topics, I need to mention that my work has all been addressed using the methods of a theory often called "stochastic electrodynamics," and usually abbreviated as "SED". The first two topics I will report on certainly rely on the calculational methods of this theory, while the third topic of "energy extraction" does not. Stochastic electrodynamics is a theory that treats the movement of classical charged particles via conventional classical electrodynamics, namely, via Maxwell's equations and the relativistic generalization of Newton's second law of motion. However, one additional feature is included, namely, the assumption is made that as the temperature of a thermodynamic system is reduced to zero, the thermal electromagnetic radiation present does not simply reduce to zero, but rather to what is called the "zero-point" spectrum given by: $\rho(\omega) = \frac{\hbar\omega}{2}\left(\frac{\omega^2}{\pi^2 c^3}\right)$.

The following reasoning provides one of the main motivating factors behind the theory of SED, namely, that one should not consider the equilibrium behavior of classical charged particles in isolation from the thermal equilibrium behavior of electromagnetic radiation. As classical charged particles interact with each other, they naturally accelerate and deaccelerate during their trajectories, thereby radiating electromagnetic radiation. Indeed, as two oppositely charged point charges rapidly approach each other, the radiated energy roughly rises inversely proportional to the distance between them. Hence, radiation must be a very key component of any system that might constitute a thermal equilibrium situation for classical charged particles. Indeed, because of Earnshaw's theorem [10], we know that a system of classical charged particles cannot exist in static, stable equilibrium. Thus, if an equilibrium situation for classical charged particles is at all possible, then the charges must be following a fluctuating, oscillating trajectory in space. A self consistent picture is then obtained when one realizes that the electromagnetic radiation arising from this fluctuating trajectory must effect the trajectory of other particles and must be an integral part for enabling thermal equilibrium to be obtained between particles and radiation. This concept is actually a fairly natural one for most people when they think of a system at a temperature $T > 0$; i.e., it is commonly accepted to think of a thermal fluctuating system with an average energy of the fluctuations dictated by T. Since the early 1900s, experimentally we know that fluctuations also exist even at $T = 0$. Combining this observation with the ideas about Earnshaw's theorem, and the other remarks above, leads SED proponents to believe that fluctuations between classical particles and fields are also a key feature even at $T = 0$.

A number of very interesting properties have been established for classical electromagnetic ZP radiation, including that the spectrum exhibits Lorentz invariance [11], [12] and that it satisfies the thermodynamic definition of $T = 0$ by resulting in no heat flow during reversible thermodynamic operations for several simple electrodynamic systems that have been examined [13]- [16]. What makes the theory of SED particularly interesting is that besides reexamining the age-old problem of whether equilibrium can exist for classical charged particles, which at some level might be viewed as purely an exercise of academic interest, one finds that SED actually predicts the correct quantum mechanical properties of simple electrodynamic systems. Indeed, many people working in the area of SED have hoped that SED might prove sufficiently powerful to provide a very deep understanding and microphysical basis for quantum mechanical phenomena.

Unfortunately, to date, this hope has not materialized. Agreement has been found for linear systems. However, for nonlinear systems found in nature, SED has so far been found to yield physically incorrect predictions. Whether this disagreement is the final story for SED, or whether there are inaccuracies in the basis for the calculations carried out to date, has not been fully settled yet [17]. Certainly, however, it is safe to say that only a very small minority of physicists believe that SED is the correct approach to adequately describe nature.

The natural question must then arise as to why would one use SED for the calculations reported in this article? At least three simple answers exist. First, provided one stays in the regime where only a linear system is considered, in particular a simple harmonic oscillator (SHO), then the results of these calculations should be accurate. Such is the case for the results reported here. Second, the physical concepts in SED are very clear; one doesn't run into the complications of quantum electrodynamics (QED) where it is difficult to keep straight what is physically real and what is not. In QED, such questions become increasingly more difficult when dealing with accelerated systems, such as what will be discussed here. Third, for some types of calculations the techniques of SED are considerably easier than those of QED. Indeed, a number of calculations in SED have preceded ones in QED, such as with the analysis of the behavior of simple electrodynamic systems accelerated through the vacuum (simple, but more complicated than a single particle) [18], or with regard to some van der Waals force calculations carried out at $T > 0$ and at all distances [21], [13].

For those interested, Refs. [22]- [27] provide further background on SED.

III. INTRODUCTORY REMARKS ON RELATING GRAVITY AND INERTIA TO THE VACUUM

Let us now turn to the first two of the three topics that will be discussed here. In relatively recent years, a line of research has been pursued by a few researchers [3], [4] that has prompted much of the work summarized in the present section and in the subsequent one. The research being referred to here involves the possible relationship between gravity, inertia, and ZP energy. Indeed, Puthoff [28] has proposed that "... gravity is a form of long-range van der Waals force associated with particle *Zitterbewegung* response to the zero-point fluctuations of the electromagnetic field." Puthoff's work contained calculations that he felt showed that one could obtain the Newtonian approximation to the gravitational interaction by considering the effects of the ZP fields on creating a correlated, fluctuating motion between distant particles. The pursuit of this idea was motivated by an article by Sakharov [29] that proposed the gravitational interaction is not a fundamental physical interaction at all, but rather that it results from a "... change in the action of quantum fluctuations of the vacuum if space is curved." [29]

Using somewhat analogous motivating ideas to that of Puthoff's in Ref. [3], Haisch, Rueda, and Puthoff (HRP) have proposed that inertia arises due to the average resistive force that acts on matter when it is accelerated through the vacuum. These researchers proposed, based on lengthy calculations for the behavior of a specific particle model, that the average of the "magnetic component" of the electromagnetic Lorentz force due to electromagnetic ZP radiation acting on the particle is equal to $-m_i\mathbf{a}$, where $\mathbf{a}$ is the acceleration and m_i is the inertial mass. More specifically, they calculated $e\left\langle \frac{\mathbf{v}}{c} \times \mathbf{B}^{ZP} \right\rangle$, where the brackets mean an ensemble average, $\mathbf{v}$ is the velocity of an oscillating particle within the accelerating particle, e is the charge of the oscillating particle, c is the speed of light, and $\mathbf{B}^{ZP}$ is the classical magnetic ZP field acting on the oscillating particle.

Certainly if these proposals are correct, then this work represents very profound physical changes to physicists' conceptions about gravity and inertia. Moreover, if correct, then it seems reasonable to speculate that inertial and gravitational properties of matter might be alterable somewhat by modifying the structure of the vacuum, perhaps very much like what is done in cavity quantum electrodynamic experiments [30]. Although it is far from clear to me how these procedures might provide practical means of aid for improved propulsion schemes, which is one of the main aims of this conference, still, I do recognize that this possible explanation for inertia and gravity, if correct, would open up new possibilities for controlling our environment. The key question then would be to what extent this can be accomplished.

The authors in Refs. [3], [4] supply a number of suggestive arguments as to why ZP radiation should provide an explanation for gravity and inertia. Their calculations attempt to support these arguments. Consequently, it seems critically important to carefully check the accuracy of these calculations. After all, no matter how much one believes or does not believe in the basic physical arguments, the details of sorting through the calculations, their predictions, and whether they agree with physical observation, are ultimately what dictates the usefulness of the theory. Reference [31] examines the calculations in Ref. [4] in considerable detail, carries out some corrections, and extends them by removing some approximations. Here, the results of some of these calculations in Ref. [31] will be reported and summarized. In addition, many of the physical assumptions and limitations in Ref. [4] are examined in some detail in Ref. [32] and are briefly mentioned here.

The calculations in Ref. [4], in particular, were quite lengthy, with a number of approximations made to yield the final results that were obtained. The calculations were sufficiently complex to make it quite difficult to determine the full validity of the approximations, which is what prompted much of the work in Ref. [31]. As will be described here, the results of the detailed calculations that reexamine the work in Refs. [3] and [4] disagree with the major conclusions of these references. Consequently, the point that will be made in the concluding section here (Sec. VI) is that despite the very interesting qualitative ideas in Refs. [3] and [4], the details of the mathematics do not justify them in several critical ways. Unless the detailed calculations back up the general ideas, then we need to conclude that the gravity and inertia ideas involving ZP energy as the source, are not correct as they presently stand.

IV. REACTION FORCE OF ELECTROMAGNETIC ZP RADIATION

Reference [4] considered an electric dipole SHO that was uniformly accelerated through the vacuum. A specific model of a particle was considered that consisted of an overall neutral particle containing an internal oscillating point charge. This point charge was assumed to undergo stochastic oscillations in its trajectory due to the fluctuations of the ZP fields acting upon it. The SHO binding force acting on the oscillating particle essentially connected it to the rest of the composite particle. The entire system was assumed to be uniformly accelerated through space, meaning that as observed in the rest frame of the equilibrium point of the composite particle (*i.e.*, the place where the SHO force equals zero), the equilibrium point was always accelerated at a constant rate given by $\mathbf{a}$.

Although one might wonder why the behavior of such a specific system might be chosen to be analyzed when we know it represents, at best, only a very approximate description for a molecule, an atom, a nucleus, or a subatomic particle, probably the best reason is that for anything much more complicated, the calculations become extremely unwieldy and unmanageable. As with many papers in physics, dating back to the early papers of such people as Einstein and Planck, often difficult calculations are done on the simplest system possible to first demonstrate the intended behavior, and are then generalized if at all possible once the pattern of the underlying physical behavior is understood. I believe this was the intent of Refs. [3] and [4]. Indeed, since then, Rueda and Haisch in Ref. [33] have attempted to generalize the results in [4] to other systems in nature [34].

To calculate $e\left\langle \frac{\mathbf{v}}{c} \times \mathbf{B}^{\mathrm{ZP}} \right\rangle$, the oscillating trajectory of the fluctuating internal particle must be known, which was obtained in Ref. [19] by essentially linearizing the Lorentz-Dirac equation that describes the motion of a classical charged particle. In this way, the velocity v can be expressed in terms of the proper time of the particle and in terms of the ZP fields acting to cause the fluctuating motion of the internal particle. As done in Ref. [4], if the coordinate system is set up so that the uniform acceleration occurs along the $\hat{\mathbf{x}}$ direction and oscillations are constrained to occur in the $x-y$ plane, then the ensemble average of this magnetic component of the Lorentz force, as measured in the rest frame of the equilibrium point of the composite particle, is given by

$$F_{\mathrm{M},x} = \frac{e}{c}\left\langle \frac{dy_{\tau_e}}{dt_{\tau_e}} B^{\mathrm{ZP}}_{\tau_e,z}\left(\mathbf{X}_{\tau_e}\left(t_{\tau_e}\right), t_{\tau_e}\right) - \frac{dz_{\tau_e}}{dt_{\tau_e}} B^{\mathrm{ZP}}_{\tau_e,y}\left(\mathbf{X}_{\tau_e}\left(t_{\tau_e}\right), t_{\tau_e}\right)\right\rangle_{t_{\tau_e}=0} \quad . \tag{1}$$

Here, τ_e represents the proper time associated with the equilibrium point of the composite particle, t_{τ_e} is the time as measured in the instantaneous inertial rest frame of this point, $\mathbf{X}_{\tau_e}$ is the position of this equilibrium point in this inertial rest frame, and y_{τ_e} and z_{τ_e} represent the y and z positions of the oscillating internal particle in this same frame. Upon expressing y_{τ_e} and z_{τ_e} in terms of the ZP fields causing the fluctuating motion and upon recognizing some symmetry properties, one obtains:

$$F_{\mathrm{M},x} = \frac{e^2}{m_0 c}\frac{(-i)}{\pi}\int_{-\infty}^{\infty} d\tau'_e J\left(\tau'_e - \tau_e\right)\left\langle E^{\mathrm{ZP}}_{\tau'_e,y}\left(0,\tau'_e\right) B^{\mathrm{ZP}}_{\tau_e,z}\left(0,\tau_e\right)\right\rangle \quad \text{, where} \tag{2}$$

$$J\left(\alpha\right) = \int_{-\infty}^{\infty} d\Omega \frac{\Omega \exp\left[i\Omega\alpha\right]}{\left[\omega_0^2 - \Omega^2 - i\Gamma\left(\Omega^3 + \Omega a^2/c^2\right)\right]} \quad . \tag{3}$$

Here, $\Gamma = \frac{2}{3}\frac{e^2}{mc^3}$ and m is the mass of the internal oscillating particle. In Eq. (2), the quantity $\left\langle E^{\mathrm{ZP}}_{\tau'_e,y}\left(0,\tau'_e\right) B^{\mathrm{ZP}}_{\tau_e,z}\left(0,\tau_e\right)\right\rangle$ represents the correlation function, or ensemble average, between two components of the electric and magnetic ZP fields at different proper times τ'_e and τ_e along the trajectory of the equilibrium point of the uniformly accelerated particle.

Equation (2) can be shown to agree with expressions in Ref. [4] before certain approximations were made there. What is particularly interesting about this expression is that if one carries out a calculation of $\left\langle E^{\mathrm{ZP}}_{\tau'_e,y}\left(0,\tau'_e\right) B^{\mathrm{ZP}}_{\tau_e,z}\left(0,\tau_e\right)\right\rangle$ in SED for $\tau'_e \neq \tau_e$, then in the no-cut-off limit (*i.e.*, meaning in the limit where the upper frequency limit of the ZP spectrum is assumed to be infinite, so that there is no upper frequency cut-off), one can show that $\left\langle E^{\mathrm{ZP}}_{\tau'_e,y}\left(0,\tau'_e\right) B^{\mathrm{ZP}}_{\tau_e,z}\left(0,\tau_e\right)\right\rangle$ exactly equals zero. This result can be shown to agree exactly with the corresponding quantity in QED [35], [36].

Hence, one's initial reaction to the expression in (2) might naturally be that the force should equal zero. Such was my initial reaction, which was one of the reasons why I strongly suspected that the results in Ref. [4] might be incorrect. Casting the equation for $F_{\mathrm{M},x}$ in terms of an integral over a correlation function is what enables one to make this observation; Eq. (2) is different, but equivalent, to the starting expressions in Ref. [4]. My suspicion was that Eq. (2) did indeed equal zero, although I also suspected that there was another term involving $e\left\langle \mathbf{z} \cdot \nabla \mathbf{E}^{\mathrm{ZP}} \right\rangle$ that needed to be calculated that might contribute in an important manner.

However, Eq. (2) does not equal zero. Although I did not arrive at the same results that HRP did, due to a number of reasons that I will roughly explain here, neither did I obtain a zero answer. The reason for this is that one has to be very careful when carrying out the integral in Eq. (2) over τ_e', as the correlation function does not equal zero when $\tau_e' = \tau_e$. Instead, the correlation function is singular at this point. Consequently, one needs to use more sophisticated techniques for dealing with this singularity while integrating through it. Reference [31] describes how this was carried out. Roughly, though, it involves first evaluating the integrand in Eq. (2) when a finite upper frequency limit is assumed for the ZP spectrum. For a finite upper frequency limit, the integrand is no longer singular, so the integration can then be safely carried out. The result is that $F_{\mathrm{M},x}$ can be expressed as a function of the frequency cut-off, at which point one can then examine taking the no cut-off limit in the spectrum.

Several approximations made in Ref. [4] were removed in [31], including a small velocity approximation involving Eqs. (20) and (21) in Ref. [4], which can be shown to be invalid when carrying out the integral over all τ_e' in Eq. (2). Also, the exact expressions were obtained for $J(\alpha)$ in Eq. (3), from which a full expansion to any order in Γ can be made. Finally, an accurate method was found to express the correlation function [37],

$$C_{\mathrm{M},\sigma}\left(\tau_e' - \tau_e\right) \equiv \left\langle E^{\mathrm{ZP}}_{\tau_e',y}\left(0,\tau_e'\right) B^{\mathrm{ZP}}_{\tau_e,z}\left(0,\tau_e\right)\right\rangle , \tag{4}$$

while integrating over the product of $J\left(\tau_e' - \tau_e\right) C_{\mathrm{M},\sigma}\left(\tau_e' - \tau_e\right)$ in Eq. (2). These steps led to the recognition that the step in Ref. [4] of neglecting the $\tau_e' > \tau_e$ part of the integral in Eq. (2) was not correct [38].

Correcting these steps lead to the result that the average of the ZP Lorentz force, as expanded in the ZP spectrum cut-off parameter σ [37], is given by:

$$F_{\mathrm{M},x} = 0 \cdot a\frac{\Gamma\hbar}{\pi\sigma^2} - \frac{3}{2\,c^2\Gamma}a\frac{\hbar}{\pi} + \left(\frac{1}{c^3\Gamma^2} + \frac{3\,\omega_0^4\Gamma^2}{c^3}\right) a\hbar\sigma + O\left(\sigma^2\right) . \tag{5}$$

If the $\tau_e' > \tau_e$ integral contribution in Eq. (2) was neglected, as was done in Ref. [4], then the first term above that is proportional to $1/\sigma^2$, would not have dropped out, as the $\tau_e' < \tau_e$ contribution to the integral in Eq. (2) equals $-\left(1 - 3\,\left(\omega_0\Gamma\right)^2\right) a\frac{\Gamma\hbar}{\pi\sigma^2}$, while the $\tau_e' > \tau_e$ contribution equals the exact negative of this quantity. This term is closely related to the result of

$$F_{\mathrm{M},x} = -a\frac{\Gamma\hbar}{2\pi\left(c/\omega_c\right)^2} \tag{6}$$

which HRP obtained as their final result of Eq. (109) in Ref. [4], when using their sharp cut-off model that treats the ZP field as being sharply cut off above all frequencies larger than ω_c. Clearly, then, the $\tau_e' > \tau_e$ integral contribution must be retained.

Consequently, unfortunately, despite many of the interesting and suggestive ideas in Ref. [4], at present, the detailed calculations do not support the authors' proposal in Ref. [4]. From Eq. (5), we see that the "magnetic" component of the ZP Lorentz force does cause a resistive force proportional to the acceleration, but this SED result does not become large as the cut-off in the ZP spectrum is removed (*i.e.*, as $\sigma \rightarrow 0$); this result, although quite interesting, hardly seems able to provide a fundamental explanation to inertia. Instead, this result shows that the ZP field can cause mass corrections, a result long known from QED analyses.

My belief is that the SED calculation of the "electric" contribution to the ZP Lorentz force, namely, the contribution from $e\left\langle \mathbf{z} \cdot \nabla \mathbf{E}^{\mathrm{ZP}}\right\rangle$, will prove to be more interesting, but I do not believe that the result will lead to a new fundamental explanation for inertial mass in the manner described in Ref. [4]. Calculations on this term are still in progress.

V. ASYMPTOTIC ANALYSIS OF THE CASIMIR-POLDER EQUATION

The following analysis regarding work in Ref. [3] was contained in a letter I wrote to Dr. H. Puthoff in 1993 [39]. Earlier, I had become aware of the as yet unpublished work in Ref. [4]. While investigating HRP's reasoning, I reexamined Puthoff's proposal in Ref. [3] for explaining gravity based on ZP fields [3], since the possible correctness or incorrectness of that proposal might be tightly coupled to the same outcome for HRP's proposal that the ZP fields were also responsible for explaining inertia. Unfortunately, my analysis of Ref. [3], as outlined here, did not support Puthoff's proposal on gravitation. Since that letter, K. Danley worked with Prof. A. Rueda and wrote a Master's thesis [40] that came to the same conclusions as my letter, although he and Rueda held out hope that a relativistic analysis might yield results in line with Puthoff's original suggestion. Unfortunately, I am unaware of any evidence to either support or not support this hope, so at present I do not share this optimism.

Briefly, Puthoff's work in Ref. [3] referred to the Casimir-Polder potential between polarizable particles as an appropriate starting point for his analysis, where this potential is given by:

$$U(R) = -\alpha^2 \frac{\hbar c}{\pi} \int_0^\infty du \frac{u^4 \omega_0^4}{\left(c^2 u^2 + \omega_0^2\right)^2} \frac{e^{-2uR}}{R^2} \left[1 + \frac{2}{uR} + \frac{5}{(uR)^2} + \frac{6}{(uR)^3} + \frac{3}{(uR)^4}\right] . \tag{7}$$

Here, R is the distance between the two particles, and Puthoff considered the case where the two particles were SHOs with resonant frequency ω_0 and polarizability given by $\alpha = e^2 / \left(m\omega_0^2\right)$. His treatment in Ref. [3] considered only the first term in brackets above [41], in which he substituted $\omega_0 = 0$ into the integrand and then supplied some arguments to support that this term would result in a $1/R$ effective potential between particles. Later, in response [42] to a criticism by Carlip [43] on the mathematical steps used in Ref. [3], he gave some additional arguments and different reasoning to still yield this $1/R$ effective potential, now emphasizing that there should be physical reasons for imposing cut-offs in the integration that enable this $1/R$ form to be obtained.

Some of the points made in Ref. [39] were that (1) one cannot simply extract the first term in Eq. 7, as all of the terms contribute on a roughly equal footing in the large distance regime, and (2) one can directly analyze Eq. (7) without imposing approximations. By making the substitution of $w = uR$ in Eq. (7), one obtains:

$$U(R) = -\alpha^2 \frac{\hbar c}{\pi} \frac{\omega_0^4}{c^4 R^3} I\left(\frac{\omega_0 R}{c}\right) \text{ , where} \tag{8}$$

$$I(b) \equiv \int_0^\infty dw \frac{w^4 e^{-2w}}{\left(w^2 + b^2\right)^2} \left[1 + \frac{2}{w} + \frac{5}{w^2} + \frac{6}{w^3} + \frac{3}{w^4}\right] . \tag{9}$$

Thus, $U(R)$ has a functional form of $1/R^3$ times an integral that depends on $\frac{\omega_0 R}{c}$, where each of the terms in the Casimir-Polder integral make an important contribution. In Eq. 9, one can also replace the upper limit of infinity by an upper cut-off, such as might be imposed if the ZP spectrum was thought to be cut off at sufficiently large frequencies. If a $1/R$ potential is to emerge for the form of $U(R)$, under whatever limiting conditions one imposes (*e.g.*, large R, small ω_0, etc.), then $I(b)$ must result in a b^2 dependence under these conditions.

However, a full evaluation of Eq. (9) does not reveal any such dependency, even if one imposes a reasonable upper ZP spectral cut-off limit. Instead, as shown in Fig. 1, at large $b = \omega_0 R/c$, $I(b)$ is bounded by the asymptotic van der Waals expression of

$$I_r(b) \equiv \frac{23}{4} b^{-4} , \tag{10}$$

yielding an overall $1/R^7$ dependence for $U(R)$ in this regime. At small b, $I(b)$ is bounded by the unretarted van der Waals expression of

$$I_{ur}(b) \equiv \frac{3\pi}{4} b^{-3} , \tag{11}$$

yielding an overall $1/R^6$ dependence for $U(R)$ in this regime. At no point either between these extremes, or at these extremes, is there any behavior that remotely approaches a b^{+2} dependence that would be required to yield a net $1/R$ dependence for $U(R)$. An upper ZP frequency cut-off does not substantially change this analysis.

In Ref. [42], Puthoff added the additional argument that to obtain a net $1/R$ dependence in potential, an upper effective frequency limit of ω_i needed to be imposed in the integration, where $\omega_i < \omega_0$, followed by the condition that the limit of $\omega_0 \rightarrow 0$ was to be taken. In his justification for this reasoning, he used an argument by Boyer in Ref.

[44] that only the low frequency contribution of the interaction between polarizable particles should be effective in yielding the long range attractive force due to correlated motion. This argument is indeed valid; however, applying this reasoning leads to the retarded van der Waals expression in Eq. (10) with its $1/R^7$ dependence, rather than to any $1/R$ dependence. If the *additional* constraints are imposed of an upper limit of ω_i in the integration, with $\omega_i < \omega_0$, as well as that the limit of $\omega_0 \rightarrow 0$ be taken, then this procedure is equivalent to saying that additional physical effects need to be imposed that are not present in the full Casimir-Polder expression. Indeed, after reading Refs. [3] and [42], one might have the impression that the Casimir-Polder expression reduces to a $1/R$ potential if one could only calculate it appropriately under the correct conditions. Instead, the Casimir-Polder expression clearly contains the retarded van der Waals expression with its $1/R^7$ dependence as a limiting case (see Fig. 1). The physical reasoning of the largest contribution to this result being due to the small frequency regime is indeed correct and is not an additional requirement that needs to be imposed when evaluating the integral in Eq. (7). Instead, the requirements of Puthoff in Ref. [42] involving ω_i, $\omega_i < \omega_0$, and $\omega_0 \rightarrow 0$, constitute additional physical impositions that are certainly not contained within the Casimir-Polder equation. Indeed, I am not aware of physical mechanisms that would result in these impositions. Consequently, without additional justification available, I believe it is necessary to conclude that Puthoff's conjecture that the gravitational attraction is due to ZP fields, is incorrect. There may be other ties between ZP fields and gravitation, such as in Sakharov's brief article [29], but this particular connection does not appear to hold.

VI. EXTRACTING ENERGY FROM THE VACUUM

Turning to the last topic of this article, Forward in 1984 first wrote about a possible means for extracting useful energy from the vacuum [7]. He described a relatively simple mechanical mechanism using charged conducting plates that are brought close enough together to allow the Casimir force to overcome the electrostatic repulsion between the plates, thereby enabling charge to be stored at a very high electrostatic potential energy. Indeed, some scientists have speculated that there may be enormous quantities of energy that can be extracted and harnessed from the vacuum, since the energy density of the electromagnetic ZP fields has been estimated to be incredibly large [45]. I am strongly convinced that there is little question that energy can in principle be extracted from the vacuum; Forward's example is one simple method that should clearly work. As for practical means of generating large quantities of energy, that is a separate issue I will discuss in a moment.

Two sets of questions typically arise during discussions about extracting energy from the vacuum. The first set involves the physical legitimacy of being able to extract this energy; *i.e.*, the very concept seems like it must be violating some physical law, such as conservation of energy or the second law of thermodynamics. Indeed, there are a number of subtle issues involving thermodynamic operations at or near $T = 0$, such as regarding the behavior of physical systems under thermodynamically reversible processes (*e.g.*, Casimir plates held apart and then quasistatically displaced toward each other) or irreversible ones (*e.g.*, the same plates initially held apart, then released so that they collide), or whether heat can be generated at $T = 0$ (no it cannot for reversible operations, but yes it can for irreversible ones), and how is energy conserved for these processes (the "vacuum" changes under thermodynamic operations, resulting in the net energy in ZP radiation plus the energy of the system being examined to always be conserved). Although subtle in some cases, at least until one clearly starts examining the issues, all of these concerns appear to be readily understandable and to not constitute violations of physical laws. References [8] and [9] go over many of these concerns in some detail. Reference [22] briefly summarizes some of the work in Refs. [13]- [16] on related thermodynamic issues concerning ZP radiation, as well as specifically addressing the issue of conservation of energy for charged particles and ZP electromagnetic fields.

The second set of questions that typically arise involve the practical issues of how one might extract large quantities of energy from the vacuum. I am aware that there are some technologists actively working on this problem, including Puthoff, who has been working with what he refers to as a charged plasma. Since from a physical standpoint I am convinced that one should be able to extract usable energy, then it seems possible that some of these experiments will be successful, although I have not as yet carried out any specific investigations. Theoretical calculations should also be possible to estimate the quantity of energy possible in specific situations, which should be helpful. In addition, it may be possible to put limits in general on the maximum amount of useful energy one can extract from the vacuum.

I think, though, that the following viewpoint should be kept cautiously in mind when considering ZP energy extraction. The theory of SED has the perspective that the stability of atoms and molecules is due in large part to the balance between "energy pick-up" from the electromagnetic ZP fields and the radiated energy from electrons in their orbits. Although SED has not been shown to hold for nonlinear systems in nature, still, this physical picture is carried over in some ways in quantum theory, where the vacuum field is formally necessary for stability of atoms, otherwise radiation reaction will cause canonical commutators like $[x, p_x]$ to decay to zero unless the fluctuating vacuum is included. Consequently, much phenomena in nature, such as chemical reactions, can possibly be viewed, roughly, as "extractions of energy" from the vacuum, in analogy to the irreversible change of position of colliding parallel plate capacitors. After all, chemical reactions roughly rearrange average "positions" of electrons in atoms as well as atoms in molecules, and typically release electromagnetic energy in the process. Hence, in this sense, extracting energy and heat from the vacuum is not mysterious at all, but is daily observed in common phenomena such as with batteries, combustion, and other chemical reactions [46]. Even fission and fusion may be similar examples, although such operations would then necessarily involve the ZP fields associated with nuclear interactions.

I don't mean to claim that the above is true, but it may be, and one should bear this in mind when trying to construct new ideas for generating energy. If true, then the only real advantage for specific thoughts on energy extraction from the vacuum would be that the deliberate aim of directly attempting this procedure with ZP radiation might enable methods more familiar from electromagnetic work to generate inventive energy extraction methods [5], [1].

VII. CONCLUDING REMARKS

This article briefly covered aspects of the following three topics that appear to be of close interest to the present workshop, namely: (1) a proposal by HRP [4] that electromagnetic zero-point (ZP) radiation may provide a fundamental explanation for inertia, (2) a related earlier proposal by Puthoff [3] that electromagnetic ZP radiation may also provide a fundamental explanation for gravity, and (3) the extraction of energy from the vacuum. As summarized here, and as will be discussed in much more detail elsewhere [32], [31], the calculations in [4] on the first topic have, unfortunately, been found to have some poor approximations in them that when corrected, do not yield results for the average of the "magnetic" component of Lorentz force from the electromagnetic ZP field that fit with the author's proposal for explaining the origin of inertia. In addition, there are a number of more basic issues, other than the details of the calculations, that limit the intended scope and generality of the work in Ref. [4], such as that the use of the Abraham-Lorentz-Dirac equation in arriving at the results already contains the concept of mass embedded in it; these points are discussed in some detail in Ref. [32].

Regarding the second topic, the point was made here that the Casimir-Polder integral can be explicitly evaluated [see Eqs. (8) and (9) and Fig. 1]. The approximations made in [3] and [42] are not valid for examining the asymptotic, long distance behavior of the Casimir-Polder integral. Only if additional physical constraints, not included within the basic physics embodied by the Casimir-Polder integral, are imposed, can the proposed steps made by Puthoff in Ref. [42] be justified. At present, I am unaware of any physical mechanisms that justify these constraints, so Puthoff's gravity explanation appears to be invalid.

Finally, regarding the third topic of extracting energy from the vacuum, and despite what may appear to be in violation of one's common sense, I do not presently see physical reasons that prevent the occurrence of such thermodynamic processes. References [8] and [9] provide explanations here. The real question here will be whether this knowledge will aid the creation of additional practical methods for energy extraction that we do not already know about and indeed make use of presently, such as in the chemical process of combustion. Quite possibly this additional knowledge and insight on the contribution of ZP energy to typical physical processes will be helpful in constructing new processes, but that of course remains to be seen.

As for recommendations for future work, I have several. First, a deeper physical understanding can certainly be gained by continued exploration of the issues on inertial mass contributions from ZP fields. This topic is an important part of the renormalization program in QED and is closely related to investigations by physicists in cavity quantum electrodynamics on effecting the lifetime of excited atomic states and the measured mass of particles. It is far from clear to me that such work should have any relation to advanced space propulsion schemes, but from the standpoint of useful advanced physics, this direction is certainly a good one that should be explored more fully, both theoretically and experimentally. Zero-point fields should clearly provide a contribution to inertial mass, although it seems doubtful that it can be the full explanation. After all, there are certainly other contributions to the measured mass of particles, such as due to electromagnetic binding forces in composite particles and even in models of fundamental particles [48]. The unique transformation properties of ZP fields, in particular with regard to Lorentz invariance, plus their large magnitude, are undoubtedly what enable them to make important inertial mass contributions.

Second, since ZP energy should clearly contribute to inertial mass, there is still work to be done to unravel the relationship of ZP fields and the gravitational interaction. Puthoff made an interesting proposal that does not appear to me to hold, but there is still the curious article of Sakharov [29] and other issues involving energy, mass, gravitation, and ZP fields that are not yet settled. These relationships need to be examined more deeply and pinned down.

Third, further investigations should be carried out on specific examples of proposed energy extraction methods from the vacuum. In particular, detailed calculations should be carried out to pin down the legitimacy of specific proposals and to aid in setting up the best conditions for experimentation, as well as on more general issues involving the maximum energy that could be extracted in idealized thought experiments.

Zero-point fields may well be at the heart of many fundamental problems in physics, including quantum mechanical effects and fundamental understandings of thermodynamics and statistical mechanics [22]- [27]. Regarding a space program, however, here the connection is more difficult. For energy extraction, I can see where a small research effort on this approach might be worthwhile to pursue in a long-range space program, since there may be considerable energy that can be harnessed in this manner. However, this statement should be tempered with the statement that such an effort is considerably less likely to succeed at achieving a technologically useful outcome than continued emphasis on more conventional energy resource approaches. As for pursuing ZP energy related methods to control inertial mass and gravity, the likelihood of those approaches succeeding in a space program seem extremely doubtful to me.

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[38] To see explicitly where in Ref. [4] this approximation was made of neglecting the $\tau_e' > \tau_e$ contribution to the integral in Eq. (2), see Eqs. (82) and (83) in Ref. [4], as well as the statements after Eq. (83) and (90). Equation (90) only contains the $\tau' < \tau$ contribution. Although the approximation for J in Eq. (83) is reasonably good, still one cannot neglect it because $J(\tau' - \tau)$ does not vanish as $(\tau' - \tau) \rightarrow 0$ and $C_{\mathrm{M},\sigma}(\tau' - \tau)$ is singular at $\tau' = \tau$.

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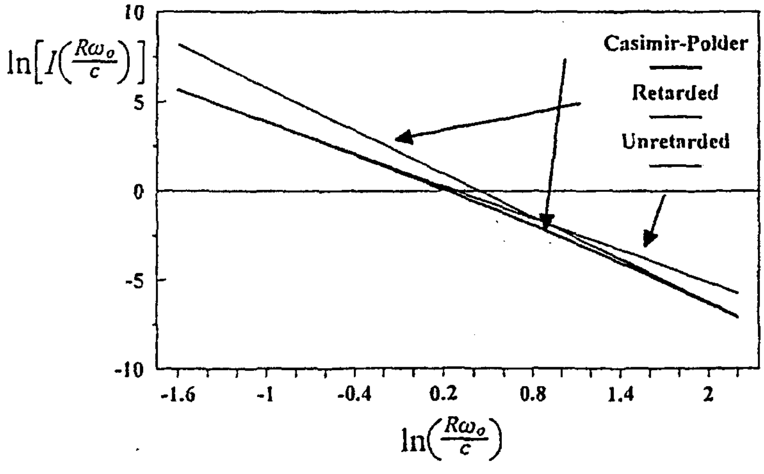

Fig. 1: $\ln(I(b))$, $\ln(I_r(b))$, and $\ln(I_{ur}(b))$ *vs.* $\ln(b) = \ln(R\omega_0/c)$