# On Extracting Energy from the Quantum Vacuum



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**Chapter 19**

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## I. Introduction

Quantum theory predicts that the vacuum of space throughout the universe is filled with electromagnetic waves, random in phase and amplitude, propagating in all possible directions, and with a cubic frequency distribution. This differs from the cosmic microwave background radiation, and is referred to as the electromagnetic quantum vacuum, which is the lowest energy state of otherwise empty space. When integrated over all frequency modes up to the Planck frequency, $\nu_P$ (~ $10^{43}$ Hz), it represents an energy density of as much as $10^{113}$ J/m$^3$ which is far in excess of any other known energy source, even if only an infinitesimal fraction of it is accessible. Even if we are constrained to integrate over all frequency modes only up to the nucleon Compton frequency (~ $10^{23}$ Hz, the characteristic frequency associated with the size of nucleons), this energy density is still enormous (~ $10^{35}$ J/m$^3$). In addition, the electromagnetic quantum vacuum is not alone; it intimately couples to the charged particles in the Dirac sea of virtual particle-antiparticle pairs, and thereby couples to the other interactions inherent in the Standard Model (weak and strong force vacua). Therefore, all the numbers just mentioned are subject to further refinement. However, it should be noted that we can safely ignore any coupling of the quantum electromagnetic vacuum to the quantum chromodynamic (QCD) vacuum in the context of this chapter because the latter coexists in two phases: 1) the ordinary vacuum exterior to the hadron, which is impenetrable to quark color, and 2) the vacuum interior of the hadron in which the Yang-Mills fields that carry color (gluons) propagate freely. Both vacuum phases are separated by a boundary at the surface of the hadron on which the Yang-Mills and quark fields satisfy boundary conditions.

Even though this zero-point field (ZPF) energy seems to be an inescapable consequence of quantum field theory, its energy density is so enormous as to make it difficult to reconcile. Instead, many quantum calculations subtract away the ZPF energy by ad hoc means (e.g., renormalization). However, we observe the effects of the quantum vacuum ZPF that are responsible for a variety of well known physical effects, such as:

1. Lamb shift
2. Spontaneous atomic emission
3. Low-temperature van der Waals forces
4. Casimir Effect
5. Source of photon shot and fluctuating radiation-pressure noise in lasers
6. Astronomically observed cosmological constant (a.k.a. dark energy; a form of Casimir energy according to the Schwinger-DeWitt quantum ether prescription[1-4]).

Rather than eliminate the ZPF energy (a.k.a. ZPE) from the equations, there is much left to be learned by exploring the possibility that it is a real energy. From this perspective, the ordinary world of matter and energy is like foam atop the quantum vacuum sea. If the ZPF is real, then there is the possibility that it can be tapped as a source of power or be harnessed to generate a propulsive force for space travel. This notion, of exchanging energy with the quantum vacuum, is the focus of this chapter.

The propeller or the jet engine of an aircraft can push air backwards to propel the aircraft forward. A ship or boat propeller does the same thing in water. On Earth there is air or water to push against. But a rocket in space has no material medium to push against, and so it needs to carry propellant to eject in order to provide momentum. A deep

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space rocket must start out with all the propellant it will ever require, and this quickly results in the need to carry additional propellant just to propel the propellant. The breakthrough one wishes to achieve in deep space travel is to eliminate the need to carry propellant at all. How can one generate a propulsive force without carrying and ejecting propellant?

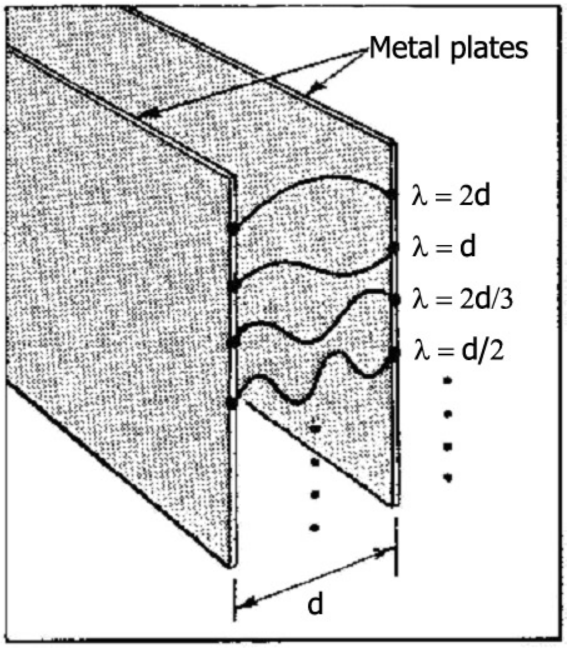


**Figure 1. Schematic of Casimir Effect Cavity.**

## II. Early Concepts for Extracting Energy and Thermodynamic Considerations

The Casimir force is a force associated with the electromagnetic quantum vacuum.[5] This force is an attraction between parallel uncharged metallic plates that has now been well measured[6-8] and can be attributed to a minute imbalance in the ZPE density inside the cavity between the plates versus the region outside the plates as shown in Figure 1. As shown in the figure, the vacuum is full of virtual photons, but photons with wavelengths, $\lambda$, more than twice the plate separation, $d$, are excluded from the space between them, which causes the imbalance that pushes the plates together. However, this is not useful for propulsion since it symmetrically pulls on the plates. If some asymmetric variation of the Casimir force could be identified, then one could in effect sail through space as if propelled by a kind of quantum fluctuation wind. This specific notion is explored in Chapter 13.

The other requirement for space travel is energy. It is sometimes assumed that attempting to extract energy from the vacuum ZPF would somehow violate the laws of thermodynamics. Fortunately, it turns out that this is not the case. A thought experiment published by Forward[9,10] demonstrated how the Casimir force could in principle be used to extract energy from the vacuum ZPF. Forward showed that any pair of conducting plates at close distance experiences an attractive Casimir force that is due to the electromagnetic ZPF of the vacuum. A “vacuum-fluctuation battery” can be constructed by using the Casimir force to do work on a stack of charged conducting plates as shown in Figure 2. By applying a charge of the same polarity to each conducting plate, a repulsive electrostatic force will be produced that opposes the Casimir force. If the applied electrostatic force is adjusted to be always slightly less than the Casimir force, the plates will move toward each other and the Casimir force will add energy to the electric field between the plates. The battery can be recharged by making the electrical force slightly stronger than the Casimir force to re-expand the foliated conductor.

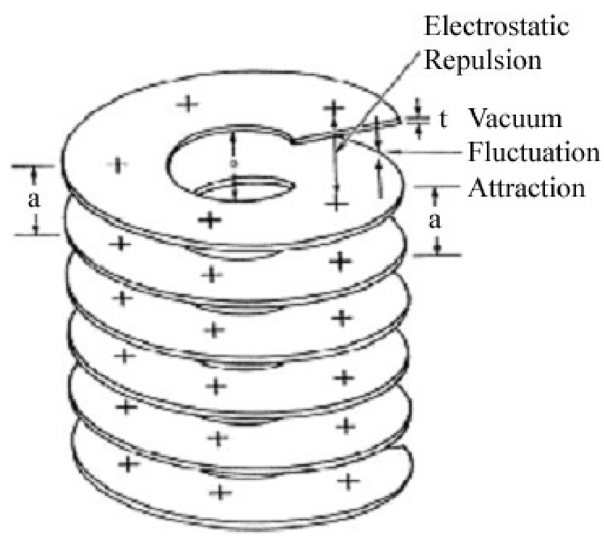


**Figure 2. Vacuum-Fluctuation Battery.[9]**

Cole and Puthoff[11] verified that (generic) energy extraction schemes are not contradictory to the laws of thermodynamics. For thermodynamically reversible processes, no heat will flow at temperature $T = 0$. However, for thermodynamically irreversible processes, heat can be produced and made to flow, either at $T = 0$ or at any other $T > 0$ situation, such as by taking a system out of mechanical equilibrium. Moreover, work can be done by or done on physical systems, either at $T = 0$ or $T > 0$ situations, whether for a reversible or irreversible process. However, if one is considering a net cyclical process on the basis of, say, the Casimir Effect, then energy would not be able to be continually extracted without a violation of the second law of thermodynamics. Thus, Forward’s process cannot be cycled to yield a continuous extraction of energy. Here, the recharging of the battery would, owing to frictional and other losses, require more energy than is gained from the ZPF. There is no useful engine cycle in this process; nonetheless, the plate-contraction phase of the cycle does demonstrate the ability to cause "extraction" of energy from the ZPF. It does reflect work done by the ZPF on matter.

Another illustrative example of an early scheme for extracting energy from the ZPF is described in a patent by Mead and Nachamkin.[12] They propose that a set of resonant dielectric spheres be used to extract energy from the ZPF and convert it into electrical power. They consider the use of resonant dielectric spheres, slightly detuned from each other, to provide a beat-frequency downshift of the more energetic high-frequency components of the ZPF to a more easily captured form. Figure 3 shows two embodiments of the invention. The device includes a pair of dielectric structures (items 12, 14, 112, 114 in the figure) that are positioned proximal to each other and which intercept incident ZPE radiation (items 16, 116 in the figure). The volumetric sizes of the structures are selected so that they resonate at a particular frequency of the incident radiation. But the volumetric sizes of the structures are chosen to be slightly different so that the secondary radiations emitted from them (items 18, 20, 24, 118, 120, 124 in the figure) at resonance interfere with each other, thus producing a beat frequency radiation that is at a much lower frequency than that of the incident radiation, and that can be converted into electrical energy. A conventional metallic antenna (loop or dipole type, or a RF cavity structure; items 22, 122 in the figure) can then be used to collect the beat frequency radiation. This radiation is next transmitted from the antenna to a converter via an electrical conductor or waveguide (items 26, 126 in the figure) and converted to electrical energy. The converter must include: 1) a tuning circuit or comparable device so that it can effectively receive the beat frequency radiation, 2) a transformer to convert the energy to electrical current having a desired voltage, and 3) a rectifier to convert the energy to electrical current having a desired waveform (items 28, 30, 32, 34, 128, 130, 132 in the figure).

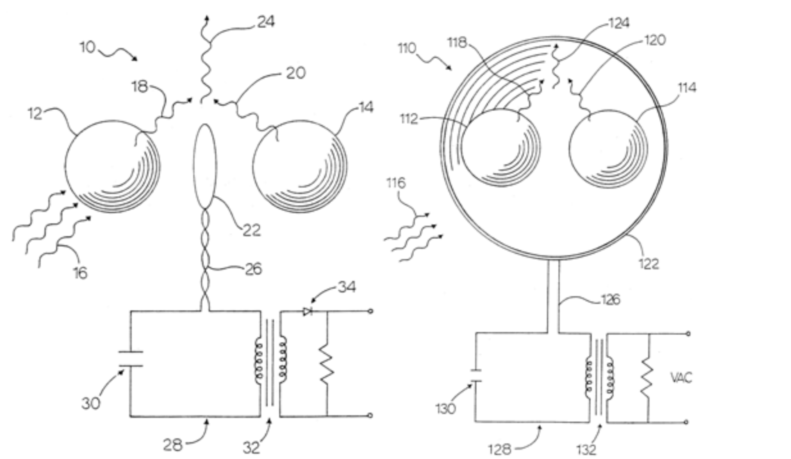


**Figure 3. ZPE Resonant Dielectric Spheres Electrical Power Generator.[12]**

The receiving structures are composed of dielectric material in order to diffract and scatter the incident ZPE radiation. The volumetric sizing requirements for the receiving structures are selected to enable them to resonate at a high frequency corresponding to the incident ZPE radiation, based on the parameters of frequency of the incident ZPE radiation, and the propagation characteristics of the medium (vacuum or otherwise) and the receiving structures. Since the ZPE radiation energy density increases with increasing frequency, greater amounts of electromagnetic energy are potentially available at higher frequencies. Consequently, the size of the receiving structures must be miniaturized in order to produce greater amounts of energy from a system located within a space or volume of a given size. Therefore, the smaller the size of the receiving structures, the greater the amount of energy that can in principle be produced by the system.

Although a computer model study performed at the Air Force Research Laboratory (Edwards AFB, CA) indicates that the invention could work, no experimental study has been performed to validate this in the lab (F. B. Mead, private communication, 2002). Regarding critiques, it is not clear how the beat frequency can be picked up by the receiving loop antenna. There is no nonlinear method in the invention showing that an electromagnetic beat frequency can be generated and coupled to the loop. Without a nonlinear coupling method there will be no sidebands, one of which would be frequency down-shifted and called the beat frequency. The coupling method requires the generation of sidebands in the mixing of two different frequencies via a nonlinear technique. However, an easy resolution to this potential deficiency is that the resonant dielectric spheres could be constructed of a nonlinear dielectric material.

Although several novel ZPF energy extraction mechanisms have been proposed in the popular and technical literature, no practicable technique has been successfully demonstrated in the laboratory. To better understand how ZPE extraction methods might work, it is necessary to characterize the physics of the ZPF and proposed energy extraction techniques, and to evaluate their feasibility for application to space power and propulsion systems. In what follows, we summarize the physics of the ZPF and the experimental investigations being pursued to address the question of extracting energy from the quantum vacuum.

## III. Origin of Zero-Point Field Energy

### A. QED Theory

The basis of the ZPF is typically attributed to the Heisenberg Uncertainty Principle. According to this principle, $A$ and $B$ are any two conjugate observables that we are interested in measuring, and they obey the commutation relation $[A,B] = i\hbar$ ($i$ is the unit complex number and $\hbar$ is Planck's reduced constant, $1.055 \times 10^{-34}$ J·s). Their corresponding uncertainty relation is $\Delta A \Delta B \geq \hbar/2$, where $\Delta A$ is the variance (a.k.a. uncertainty) of observable $A$ and $\Delta B$ is that of the conjugate observable $B$. This relation states that if one measures observable $A$ with very high precision (i.e., its uncertainty $\Delta A$ is very small), then a simultaneous measurement of observable $B$ will be less precise (i.e., its uncertainty $\Delta B$ is very large), and vice versa. In other words, it is not possible to simultaneously measure two conjugate observable quantities with infinite precision. This minimum uncertainty is not due to any correctable flaws in measurement, but rather reflects the intrinsic fuzziness in the quantum nature of energy and matter. Substantial theoretical and experimental work has shown that in many quantum systems the limits to measurement precision is imposed by the quantum vacuum ZPF embodied within the uncertainty principle. Nowadays we rather see the Heisenberg Uncertainty Principle as a necessary consequence, and therefore, a derived result of the wave nature of quantum phenomena. The uncertainties are just a consequence of the Fourier nature of conjugate pairs of quantities (observables). For example, the two Fourier-wave-conjugates time and frequency become the pair of quantum-particle conjugates time and energy and the two Fourier-wave-conjugates displacement and wavenumber become the pair of quantum-particle conjugates position and momentum. For more on this see, e.g., Reference 13.

Radio and microwaves, infrared light, visible light, ultraviolet light, X-rays, and gamma rays are all forms of electromagnetic radiation. Classically, electromagnetic radiation can be pictured as waves flowing through space at the speed of light. The waves are not waves of anything substantive, but are in fact ripples in the state of a field. These waves carry energy, and each wave has a specific direction, frequency and polarization state. This is called a "propagating mode of the electromagnetic field." A useful tool for modeling the propagating mode of the electromagnetic field in quantum mechanics is the ideal quantum mechanical harmonic oscillator: a hypothetical charged mass on a perfect spring oscillating back and forth under the action of the spring's restoring force. The Heisenberg Uncertainty Principle dictates that a quantized harmonic oscillator (a.k.a. a photon state) can never come entirely to rest, since that would be a state of exactly zero energy, which is forbidden by the commutation relation outlined above. Instead, every mode of the field has $\hbar\omega/2$ ($\omega$ is the mode or photon frequency and $\hbar\omega$ is the energy of a single mode or photon) as its average minimum energy in the vacuum. (This is a small amount of energy, but the number of modes is enormous, and indeed increases as the square of the frequency. The product of this minuscule energy per mode, multiplied by the huge spatial density of modes, yields a very high theoretical energy density per unit volume.) This ZPE term is added to the classical blackbody spectral radiation energy density $\rho(\omega)d\omega$ (i.e., the energy per unit volume of radiation in the frequency interval $[\omega, \omega + d\omega]$):[14]

$$\begin{aligned} \rho(\omega)\,\mathrm{d}\omega &= \frac{\omega^2}{\pi^2 c^3}\left[\frac{\hbar\omega}{\exp(\hbar\omega/kT)-1} + \frac{\hbar\omega}{2}\right]\mathrm{d}\omega \\ &= \frac{\hbar\omega^3}{2\pi^2 c^3}\coth\left(\frac{\hbar\omega}{2kT}\right)\mathrm{d}\omega \end{aligned}, \qquad (1)$$

where $c$ is the speed of light ($3.0 \times 10^8$ m/s), $k$ is Boltzmann's constant ($1.3807 \times 10^{-23}$ J/K), $T$ is the absolute temperature, and $\omega = 2\pi\nu$ is the angular frequency. The factor outside the square brackets in the first line of Eq. (1) is the density of mode (or photon) states (i.e., the number of states per unit frequency interval per unit volume); the first term inside the square brackets is the standard Planck blackbody radiation energy per mode; and the second term inside the square brackets is the quantum zero-point energy per mode. Equation (1) is called the Zero-Point Planck (ZPP) spectral radiation energy density. Planck first added the ZPE term to the classical blackbody spectral radiation energy density in 1912, although it was Einstein, Hopf, and Stern who actually recognized the physical significance of this term in 1913.[14] Direct spectroscopic evidence for the reality of ZPE was provided by Mulliken's boron monoxide spectral band experiments in 1924, several months before Heisenberg first derived the ZPE for a harmonic oscillator from his new quantum matrix mechanics theory.[15]

Following this line of reasoning, quantum physics predicts that all of space must be filled with electromagnetic zero-point fluctuations (a.k.a. the zero-point field) creating a universal sea of zero-point energy. The density of this energy depends critically on where the frequency of the zero-point fluctuations ceases. Since space itself is currently thought to break up into a kind of "quantum foam" at the Planck length, $\ell_P$ (~ $10^{-35}$ m), it is argued that the ZPF must cease at the corresponding $\nu_P$. If true, then the ZPE density would be ~ $10^{113}$ J/m$^3$, 108 orders of magnitude greater than the radiant energy at the center of the Sun! Formally, in Quantum Electrodynamics (QED) theory, the ZPE energy density is taken as infinite; however, arguments based on quantum gravity considerations yield a finite cutoff at $\nu_P$. Therefore, the spectral energy density is given by $\rho(\omega)d\omega = (\hbar\omega^3/2\pi^2 c^3)d\omega$, which integrates to an energy density, $\rho_E = \hbar\nu_P^4/8\pi^2 c^3 \approx 10^{113}$ J/m$^3$. As large as the ZPE is, interactions with it are typically cut off at lower frequencies depending on the particle coupling constants or their structure. Nevertheless, the potential ZPF energy density predicted by quantum physics is enormous.

### B. SED Theory

An alternative to QED, stochastic electrodynamics (SED) identifies the origin of the ZPF as a direct consequence of a classical ZPF background. SED begins with the ordinary classical electrodynamics of Maxwell and Lorentz, but instead of assuming the traditional homogeneous solution of the source-free differential wave equations for the electromagnetic potentials, one instead considers that due to multiple charged particles moving throughout the universe, there is always a random electromagnetic radiation background present that affects the particle(s) in any experiment. This new boundary condition (random radiation background) replaces the prior null background of traditional classical electrodynamics. Moreover, the principle of relativity dictates that identical experiments performed in different inertial frames must yield the same result, and that this random classical electromagnetic radiation must be isotropic in all inertial frames; it is invariant under scattering by a dipole oscillator, invariant under redshift (Doppler, cosmological, gravitational, no Einstein-Hopf drag force), and must therefore have a Lorentz-invariant energy density spectrum. The only energy density spectrum that obeys such conditions is one that is proportional to the cubic power of the frequency. Interestingly, this is exactly the same frequency dependence as that of the QED spectral ZPF energy density described above, when the temperature $T$ is set to zero in Eq. (1). Thus in SED, the random radiation assumes the role of the ZPE of QED, and is termed the classical electromagnetic ZPE. Planck's constant appears then in SED as an adjustable parameter that sets the scale of the ZPE spectral density.

The formulation of the SED model has evolved over time, beginning with the work of Nernst in 1916 and the later foundational work of Marshall and Boyer in the 1960s.[14] The original Standard SED model was based on random phases with fixed electric-field mode amplitudes. The more recent Modified SED model employs random phases with random electric-field mode amplitudes and a full probability distribution for the ground state amplitude, in agreement with quantum theory.[16] A comparison of SED with quantum theory shows that the first and second moments of the spectral energy distribution are identical, but beyond that, the distributions diverge widely. Nevertheless, several quantum theory results have been reproduced by means of the SED approach, such as:[14,17]

1. Quantum mechanical harmonic oscillator
2. Lamb shift
3. Blackbody radiation
4. Van der Waals forces
5. Casimir forces
6. Diamagnetism
7. Davies-Unruh Effect.

The strength of the SED model is that it is heuristically appealing, with transparent derivations, and it is applicable to linear systems. SED calculations have also been shown to be in one-to-one correspondence with the expectation values of the Heisenberg quantum equations of motion for linear systems. Both SED and QED will play a role in the discussions to follow.

## IV. Review of Selected Experiments

In what follows, we outline each of the proposed experimental concepts that were selected for theoretical and laboratory investigation. A subset of our proposed concepts has undergone preliminary evaluation by Lockheed-Martin review panels involving both internal R&D personnel and outside experts on theory and experimentation (V. Teofilo, private communication, 2005).

### A. Voltage Fluctuations in Coils Induced by ZPF at High Frequency

In a series of experiments, Koch et al.[18-20] measured voltage fluctuations in resistive wire circuits that are induced by the ZPF. The Koch et al. result is striking corroboration of the reality of the ZPF and proves that the ZPF can do real work (cause measurable currents). Although the Koch et al. experiment detected minuscule amounts of ZPF energy, it shows the principle of ZPF energy circuitry to detect vacuum fluctuations and opens the door to consideration of means to extract useful amounts of energy. The secondary consequences on other phenomena, if energy can be successfully extracted, have not yet been investigated.

Blanco et al.[21] have proposed a method for enhancing the ZPF-induced voltage fluctuations in circuits. Theoretically treating a coil of wire as an antenna, they argue that the antenna-like radiation resistance of the coil should be included in the total resistance of the circuit, and suggest that this total resistance should be used in the theoretical computation of ZPF-induced voltage fluctuations. Because of the strong dependence of the radiation resistance on the number of coil turns (quadratic scaling), coil radius (quartic scaling), and frequency (quartic scaling), any enhanced ZPF-induced voltage fluctuations should be measurable in the laboratory at readily accessible frequencies (100 MHz compared to the 100 GHz range necessary in the Koch et al. experiments).

In the theory of Blanco et al., random voltage fluctuations are conveniently described by their frequency spectrum. That is, given a sufficient time interval of measured voltages, the measurements are Fourier transformed to the frequency domain to determine how the voltage fluctuations are distributed (e.g., quantity of low-frequency, long duration fluctuations relative to high-frequency, short-duration fluctuations). Theoretically, the spectrum of voltage fluctuations, $S(\omega,T)$, of a resistive circuit is given by:[21]

$$S(\omega,T) = \frac{R(\omega,T)}{\pi}\frac{\hbar\omega}{2}\coth\left(\frac{\hbar\omega}{2kT}\right), \tag{2}$$

where $R(\omega,T)$ is the total resistance (ohmic plus radiative), $\omega$ is the (angular) frequency, and $T$ is the absolute temperature. The resistance $R(\omega,T)$ is temperature dependent through its ohmic contribution (the radiation resistance depends only on frequency). Note the similar hyperbolic cotangent functions appearing in Eq. (2) and in the second line of Eq. (1). The postulate of Blanco et al. is that the total resistance must include the radiation resistance of the circuit:[21]

$$R(\omega,T) = R_{\text{ohmic}}(\omega,T) + R_{\text{rad}}(\omega)\,. \tag{3}$$

Under the assumption that the wavelengths of the ZPF modes of interest are larger than the dimensions of the circuit, the radiation resistance of a coil is given by:[21]

$$R_{\text{rad}}(\omega) = \frac{2}{3}\frac{\pi^2 N^2}{c}\left(\frac{a\omega}{c}\right)^4, \tag{4}$$

where $N$ is the number of coil turns, and $a$ is the radius of the coil winding.

According to Blanco et al., large enhancements in ZPF-induced voltage fluctuations are possible. By reducing the temperature to minimize ohmic resistance, making the coil of many turns and large radius, and performing measurements at high frequency, it should be possible to investigate this amplification effect. The predicted coil-enhanced voltage spectrum can readily be computed. The result is shown in Figure 4 for a 1 cm diameter coil of 2000 turns, made of 38 AWG tungsten wire, and kept at a temperature of 3 K. In Figure 4, the upper (dotted) curve represents the predicted voltage spectral density for the combined ohmic plus radiation resistance. The lower (solid) curve is the predicted result when radiation resistance is ignored. If the postulate of Blanco et al. is correct, the enhancement in voltage fluctuations due to the antenna-like nature of the coil should be easily measured at frequencies as low as 100 MHz (where the coil enhancement effect is ~ 100-fold for tungsten).

To successfully measure the ZPF-induced voltage fluctuations, the requirements of low temperature, large coil, and high frequency must be met. The low-temperature requirement is met by performing the experiment in a cooled dewar. Existing high-quality cryogenic dewars (pumped down to 3 K) and sensitive laboratory instruments are suitable for the measurements. The cold spot in one particular dewar under consideration is cylindrical, 2.5 cm in both diameter and height. The largest coil that can be installed will thus have a coil radius of approximately $a$ = 1 cm. To keep the linear dimension of the coil small will require a small wire thicknesses, perhaps $b$ = 0.01 cm (gauge 38 AWG). By winding the coil in a number of layers (10 or 12 layers), a large number of turns can be accommodated, perhaps $N$ = 2,000 turns. To minimize ohmic resistance, wire made of tungsten (W) is preferred; however, copper (Cu) is a suitable alternative.

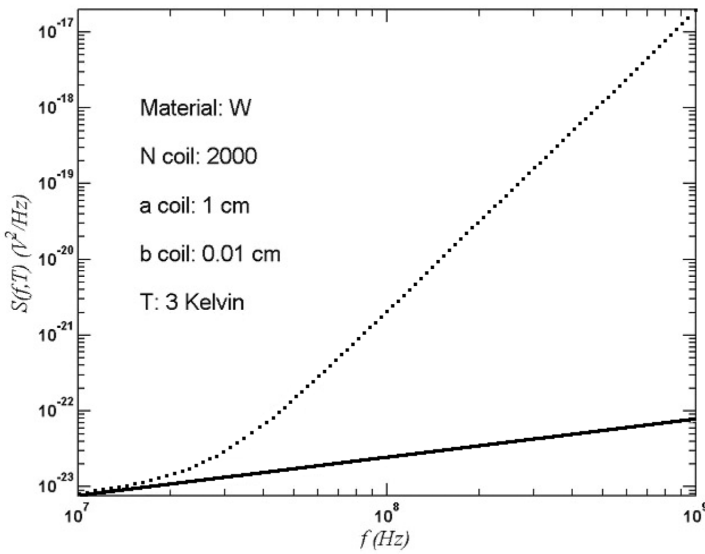


**Figure 4. Theoretical Voltage Spectral Density of a Tungsten Coil.**

Voltage fluctuations in the 100 MHz range are easily detected using commercially available laboratory equipment; hence this experiment could be performed using tungsten without resorting to the more sophisticated Josephson junction techniques required by Koch et al. for their higher frequency measurements. For a copper wire coil, the magnitude of the enhancement effect is reduced somewhat compared to the tungsten results shown in Figure 4. But for frequencies approaching the GHz regime, the radiation resistance enhancement effect in copper wire is still predicted to be over four orders of magnitude larger. Commercial equipment readily allows measurements of the voltage spectrum in the GHz regime. Therefore, given a cost tradeoff of copper vs. tungsten coil fabrication, the use of copper coils may be preferred. Suitable coils can be fabricated by a custom coil-winding vendor. A second coil can be used in a control experiment constructed with the same parameters as the first coil, but with half of its turns wound in the reverse direction. This will make the coil non-inductive so that its voltage spectral density should correspond to the lower solid curve in Figure 4.

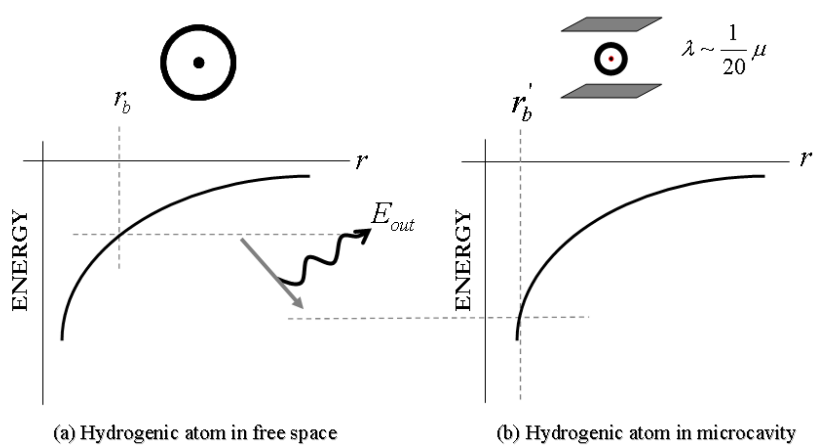


**Figure 5. Energy Released from Ground State Suppression of Hydrogenic Atom in a Microcavity.**

**B. ZPF Energy Extraction by Ground State Energy Reduction**

As first analyzed by Boyer,[22] and later refined by Puthoff,[23] the following paradox was addressed: even though atomic ground states involve electrons in accelerated motion, such states are nonetheless radiationless in nature – even though it is well known from classical electrodynamics that charged particles undergoing acceleration must always emit radiation. For the standard Bohr ground state orbit of the hydrogen atom, this was interpreted as an equilibrium process in which radiation by the electron in its ground state orbit was compensated by absorption of radiation from the background vacuum electromagnetic ZPE. This interpretation has recently been strengthened by the analyses of Cole and Zou[24,25] using a SED model for the vacuum ZPE. Since the balance between emitted orbital-acceleration radiation and absorbed ZPE radiation is modeled as taking place primarily at the ground state orbital frequency, one can consider the possibility of using this feature in some type of mechanism to extract energy from the ZPF. One fundamental difference between the SED interpretation and that of quantum mechanics is that in quantum mechanics the 1*s* state of the electron is regarded as having zero angular momentum, whereas in the SED interpretation the electron has an angular momentum of $m_e c r_e/137$ ($m_e$ = electron mass, $r_e$ = electron radius, atomic fine structure constant $\alpha = 1/137$, and $c/137$ is the classical orbital velocity of the ground state electron).

The Bohr radius of the hydrogen atom in the SED view is 0.529 Å. This implies that the wavelength ($\lambda$) of zero-point radiation responsible for sustaining the orbit is $2\pi \cdot 0.529 \cdot 137 = 455$ Å (or 0.0455 μm). It has been conjectured by Puthoff and Haisch (private communication, 2004) that suppression of zero-point radiation at this wavelength (and at shorter wavelengths) inside a Casimir microcavity could result in the decay of the electron to a lower energy state determined by a new balance between classical emission of an accelerated charge and absorption of zero-point radiation at $\lambda < 455$ Å, where $\lambda$ depends on the microcavity plate separation ($d$). Since the frequency of this orbit is $6.6 \times 10^{15}$ Hz, no matter how quickly the atom were to be injected into a Casimir microcavity, one would assume that the decay process would be a slow one as experienced by the orbiting electron. Figure 5 shows a schematic representation of a hydrogenic atom in free space and inside a microcavity (note in the figure that $r_b$ = free-space Bohr orbit radius, $r_b'$ = suppressed Bohr orbit radius, $\lambda$ = resonant wavelength of Bohr orbit, and $E_{out}$ = released energy).

Consider the possibility that the decay to a new sub-Bohr ground state would involve gradual release of energy in the form of heat, rather than a sudden optical radiation signature. Since the binding energy of the electron is 13.6 eV, it is estimated that the amount of energy released in this process could be on the order of 1 to 10 eV for injection of the hydrogen atom into a Casimir cavity of $d = 250$ Å. Furthermore, consider the possibility that when the electron exits the cavity it would reabsorb energy from the zero-point field and be re-excited to its normal state. If these conjectures were to be verified by experiment, then the energy extracted in the process comes at the expense of the zero-point field, which in the SED interpretation propagates at the speed of light throughout the universe. In effect the energy would be extracted locally and replenished globally. The secondary consequences on other phenomena, if this energy conversion were to succeed, have not yet been investigated. However, on a cautionary note, the conflicts between SED and QED theories (discussed in Sect. V) raise questions as to whether the conjectured approach discussed here is viable. This issue is perhaps best addressed by experiment for its resolution.

In terms of an experimental test, consider using monatomic gases or liquids flowing in a block with Casimir tunnels, which has the following attributes: 1) no dissociation process is required for monatomic gases or liquids, 2) heavier element atoms are approximately two to four times larger than hydrogen and thus can utilize and be affected by a larger Casimir cavity, 3) heavier elements have numerous outer shell electrons, several of which may be simultaneously affected by the reduction of zero-point radiation in a Casimir cavity.

All of the noble gas elements contain *ns* electrons. He ($Z = 2$, $r = 1.2$ Å) has two 1*s* electrons. Ne ($Z = 10$, $r = 1.3$ Å) has two each of 1*s* and 2*s* electrons. Ar ($Z = 18$, $r = 1.6$ Å) has two each of 1*s*, 2*s*, and 3*s* electrons. Kr ($Z = 36$, $r = 1.8$ Å) has two of each of 1*s*, 2*s*, 3*s*, and 4*s* electrons. Xe ($Z = 54$, $r = 2.05$ Å) has two of each of 1*s*, 2*s*, 3*s*, 4*s* and 5*s* electrons. Larger Casimir cavities would also be expected to have an effect on the energetics of the outer electron shells (at larger radii). One could therefore expect that a Casimir cavity having $d = 0.1$ μm could have an effect on reducing the energy levels of the outermost pair of *s* electrons, and possibly also *p* electrons and intermediate shell *s* electrons as well.

Continuing with this model, it is reasonable to expect that a 0.1 μm Casimir cavity could result in a release of 1 to 10 eV for each injection of a He, Ne, Ar, Kr or Xe atom into such a cavity. According to Maclay,[26] a long cylindrical Casimir cavity results in an inward force on the cavity walls due to the exclusion of interior ZPF modes. In the "exclusion of modes" interpretation of the Casimir force, this implies that a cylindrical cavity of diameter 0.1 μm could yield the desired decay of outer shell electrons and subsequent release of energy. If we let the length of the cylinder be 100 times the width, this results in $\ell = 10$ μm for the length of the Casimir tunnel. Taking advantage of this effect, Puthoff and Haisch (private communication, 2004) propose a segmented tunnel consisting of alternating conducting and non-conducting materials, each 10 μm in length. In a length of 1 cm, there could be 500 such pairs in segments, resulting in 500 energy releases (each yielding 1 to 10 eV) for each transit of an atom through the entire 1 cm-long Casimir tunnel.

Now consider a 1 $cm^3$ block that is built up of 10 μm thick alternating layers as described above. Assume that tunnels of 0.1 μm diameter could be drilled through the cube perpendicular to the layers (this is not physically possible, of course; tunnel manufacture must be done differently). If 10% of the cross section comprises entrance to some 1.3 billion tunnels, then the amount of energy released would be proportional to the flow rate of the gas through the tunnels (for the number of entrances and exits through Casimir segments). A flow rate of 10 cm/sec through a total cross sectional area of 0.1 $cm^2$ yields 1 $cm^3$ of gas per second flowing through the tunnels, which at

STP would be $2.7 \times 10^{19}$ atoms. A very simple sealed, closed-loop pumping system could maintain such a continuous gas flow. Since each atom interacts 500 times during its passage, there would be $1.3 \times 10^{22}$ transitions/s in the entire cube of 1 $cm^3$. An energy release of 1 to 10 eV per transition corresponds to 2,150 to 21,500 W of power released for the entire Casimir cube of tunnels. However, again, all of this assumes that the chain of conjectures detailed above is correct. Fortunately, this can be experimentally tested.

Microcavity fabrication to match the atomic ground states is daunting because there will potentially be fabrication irregularities that cause edge and surface effects which act upon the particles as they enter or exit the Casimir region. And it is not possible to drill 1.3 billion tunnels having diameters of 0.1 μm. However, it should be feasible to use microchip technology to etch holes into the individual layers first and then assemble the stack. Extremely fine coregistration and alignment of stacks would be an issue, but a surmountable one. A much smaller number of layer pairs and tunnels would suffice for a measurable demonstration of release of ZPE by this process. If such a small-scale demonstration succeeds, larger versions that convert more energy could be built that also take advantage of more efficient thermal-to-electrical energy conversion methods. Also if successful, such apparatuses could be used to explore for secondary effects of converting quantum vacuum energy into thermal, then electrical energy.

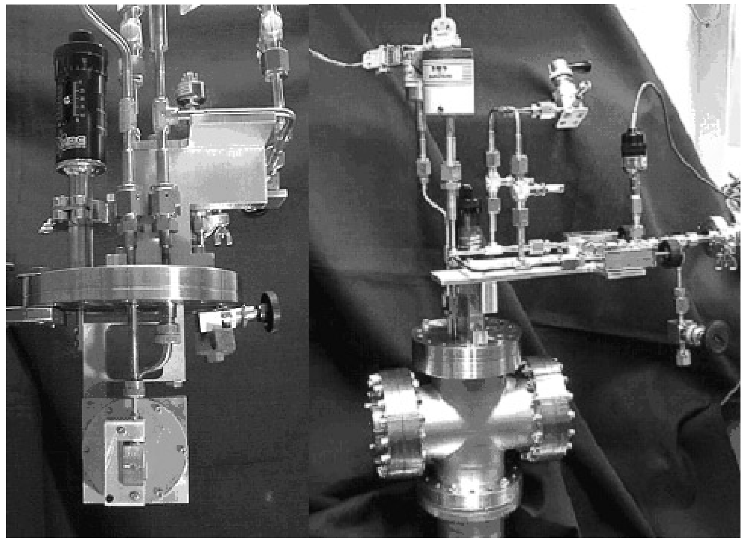

**Figure 6. Experimental Apparatus for Ground State Energy Reduction Tests.**

Further investigation by Puthoff et al.[27] was based on the premise that the above principle is broadly applicable to other than just atomic ground states. In their experiment, $H_2$ gas was passed through a 1 μm Casimir cavity to suppress the ZPE radiation at the vibrational ground state of the $H_2$ molecule. The anticipated signature for such a process would be an increase in the dissociation energy of the molecule. Initial experiments, shown in Figure 6, were carried out at the Synchrotron Radiation Center at the University of Wisconsin at Madison, where an intense UV beam is available to disassociate gas molecules. Further experimentation to investigate this hypothesis has yet to be completed. See Chapter 21 in this text for additional details.

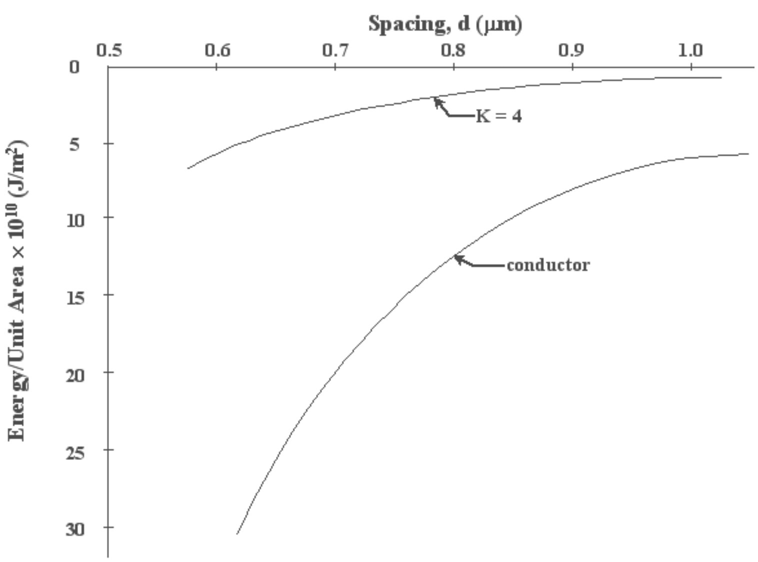


**Figure 7. Tunable Casimir Effect: Conductor vs. Dielectric.**

### C. Tunable Casimir Effect

As previously discussed, the Casimir Effect is a unique ZPF-driven quantum force that occurs between closely-spaced conductive cavity walls (or plates). If left unfettered, the plates will collapse together and energy is converted from the ZPF into heat (or other forms of energy) in accordance with the expression $E/A = -\pi^2 \hbar c/720\, d^3$, where $E/A$ is the energy per unit area of the plates and $d$ is the plate separation. Investigation of this mechanism by Cole and Puthoff[11] showed that this process fully obeys energy conservation and thermodynamic laws.

Although the Casimir force is conservative, and thus the Casimir device might appear to be a one-shot device, the fact that the attractive Casimir force is weaker for dielectric plates compared to conductive plates raises the possibility of the use of thin-film switchable mirrors to obtain a recycling engine.[28-30] Figure 7 shows a comparison of the strength of the Casimir force in a conductive cavity with that in a dielectric cavity. In such an application the plates are drawn together by the stronger force associated with the conducting state and withdrawn after switching to the dielectric state. The engine cycle for this concept is shown in Figure 8. Assuming optimistic conditions for practical devices (negligible energy required for switching; plate separation oscillations between 30 nm and 15 nm for 1 $cm^2$ plates; driving circuit ≈ 10 times the weight of the Casimir plates, etc.), an estimate of the achievable power might be obtained. Based on the described parameters, and assuming a switching from a purely conductive state to a dielectric constant of $K = 4$, yields a figure of merit of ≈ 35 × $f$ (MHz) W/kg ($f$ = switching rate) for the power density.[28] This can be compared to the power density of ≈ 5 W/kg achieved by current radioisotope thermoelectric generators. The predicted output power per unit area for this experimental device is ≈ $10^{-6}$ $f$ (MHz)/4[$d$(μm)]$^3$ W/$cm^2$.

Another "tunable" conductive-type plate experiment under consideration involves the use of plates consisting of three-dimensional photonic crystals, with the bandgap of the photons that can transmit through the structure being a "tunable" value. Using microelectro-mechanical processing methods, Sandia National Laboratories has produced such crystals and are researching methods of actively modifying the structures while in use.[31] The technology requirements for this concept are the nano-fabrication of microcavities with thin-film deposited surfaces, RF-driven piezoelectric mounts for cavity oscillation, mirror-switching modality (e.g., hydrogen pressure modulation), and calorimetric measurement of energy/heat production.

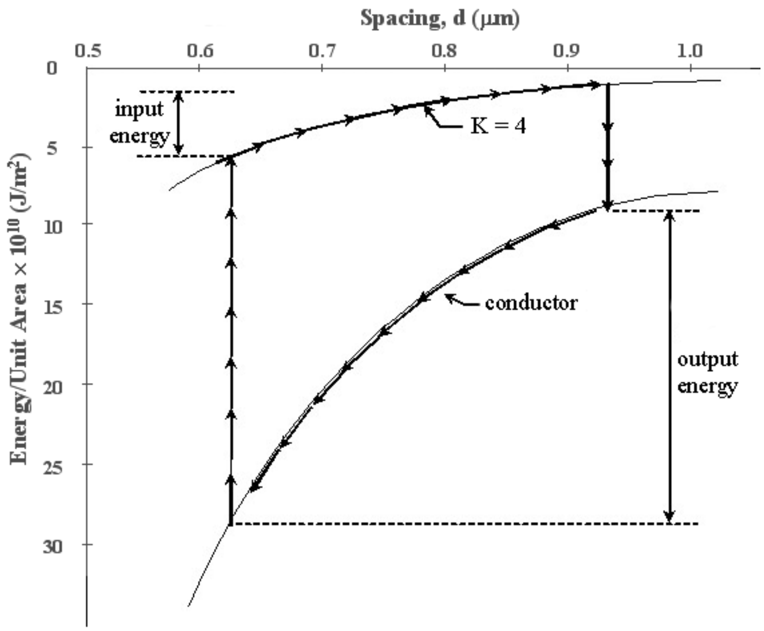


**Figure 8. Tunable Casimir Effect: Engine Cycle.**

An initial experiment to explore this concept was recently performed by Iannuzzi et al.[32] They investigated the effect of hydrogen switchable mirrors (HSMs) on the Casimir force. HSMs are shiny metals in their "as deposited" state. However, when they are exposed to a hydrogen-rich atmosphere, they become optically transparent. Because the electromagnetic ZPF depends on the optical properties of the surfaces, the Casimir force of attraction between two HSMs in air should be different than the attraction between the same HSMs immersed in a hydrogen-rich atmosphere. That is because one expects that the Casimir force will be much weaker when the HSM is in the transparent state rather than in the reflective state. The experiment tested this for plate separations of 70 - 400 nm.

Iannuzzi et al.'s experimental results showed that the Casimir force did not noticeably decrease after filling the experimental apparatus with hydrogen. This may have occurred for two reasons. First, the dielectric properties of the HSMs used in the experiment are only known only in a limited range of wavelengths spanning 0.3 - 2.5 μm, while the experiment measured the transparency of the HSMs over a wavelength range of 0.5 - 3 μm. This narrower wavelength span excludes the rest of the electromagnetic ZPF modes having wavelengths shorter than 0.5 μm and longer than 3 μm. The ZPF modes lying outside this narrow wavelength span were not affected by the hydrogenation-induced transparency of the HSMs, hence their contribution to the total Casimir force acting between the HSMs was not included. One would expect to see a significant decrease of the Casimir force if the hydrogenation-induced transparency of the HSMs had affected all of the ZPF mode wavelengths ranging from IR to UV (ZPF modes with $\lambda >> 2.5$ μm will not give rise to large contributions to the force). Second, the experiment demonstrated a property of the Lifshitz theory (see Ref. 32 for more detail), that in order to significantly change the Casimir force between surfaces at separations on the order of 100 nm it is not sufficient just to change their optical (IR and visible) reflectivity, but it is necessary to modify their dielectric functions over a much wider spectral range. This comports with the first reason, and indicates that more theoretical and experimental work is needed to overcome the shortcomings of this experiment, and allow for the design and testing of new experiments that can achieve Casimir plate transparency over a wider spectral range.

A notion similar to the tunable Casimir Effect involves changing the dimensions of a rectangular "Casimir box." Forward[33] proposed a paradox in which energy could be extracted by altering the aspect ratio of a conductive rectangular Casimir cavity over a specific cycle of dimension changes (e.g., varying width while holding length constant). It was subsequently shown by Maclay,[26,34] that the Casimir energy inside the box is not isotropic, varying in such a way that more work is expended in cycling the box dimensions than can be extracted. It appears that no net gain of energy is theoretically possible in this scheme. Whether such considerations apply to the tunable Casimir cavity concept remains to be assessed.

### D. EV Phenomenon

Shoulders[35] developed an experimental program to explore the physics of microscopic plasma vortices (a.k.a. force-free plasmoids), which are thought to be a form of ball lightning.[36] This study was motivated by the earlier experimental work of Wells at the Princeton University Plasma Physics Laboratory, Bostick and Nardi at the Stevens Inst. of Technology, and their collaborators.[37-44] Shoulders became interested in the possibility of stable, quantized force-free structures that could be taken apart by some process to yield a net energy gain for power generation. The foundation for this speculation was Nardi et al.'s[44] observation of strange electron concentrations they called vortex filaments that formed in an electron beam made by plasma focus or relativistic electron beam machines, which exhibited electron concentrations that appeared to violate the space charge law. Furthermore, Nardi et al. observed that the vortex filaments were striking exposed materials (metals, dielectrics, ceramics, glass, etc.), boring smooth channels straight through them, and sometimes exploding with such a large force that they created impact craters or holes in the materials. Piestrup et al.[45] performed more recent experiments to investigate this unusual phenomenon. This discovery inspired Shoulders to consider vortex filaments as a potential new source of energy, and hence he named them electromagnetic vortices or "EVs." However, given that he could not experimentally verify the vortex nature of the phenomenon, he later redefined EV to mean Electrum Validum (roughly translated as *strong electron*).

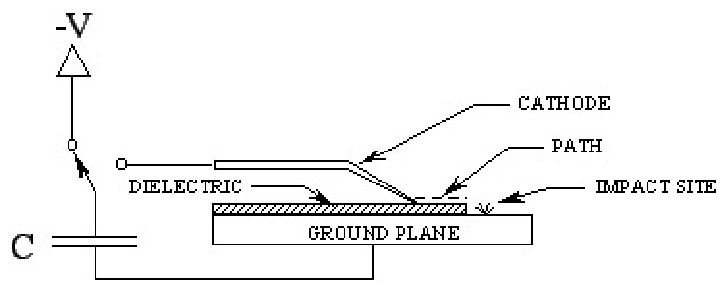


**Figure 9. Schematic of EV (Pulse Discharge Source) Device.[46]**

Bostick and Shoulders began collaborating and realized that EVs were much easier to generate and observe using micro-arc discharge devices because they are usually obscured in large high-power plasma machines by surrounding plasma. This led Shoulders to design a series of low-voltage, low-power micro-arc discharge (or condensed-charge emission) devices to produce EVs in the lab. Figure 9 shows a schematic diagram for one embodiment of an EV (pulse discharge source) device. The EVs are generated at the cathode tip and then follow the path (dashed line above the dielectric) to the impact site on the ground plane (in the figure, C = capacitor and V = voltage). The EVs generated by such devices were able to reproduce the material damage observed in Nardi et al.'s earlier experiments. Figure 10 shows a scanning electron microscope (SEM) photograph of the damage inflicted by a single EV burst fired along an aluminum-oxide ceramic plate. The EV bored through the ceramic forming a smooth symmetrical channel along its path.

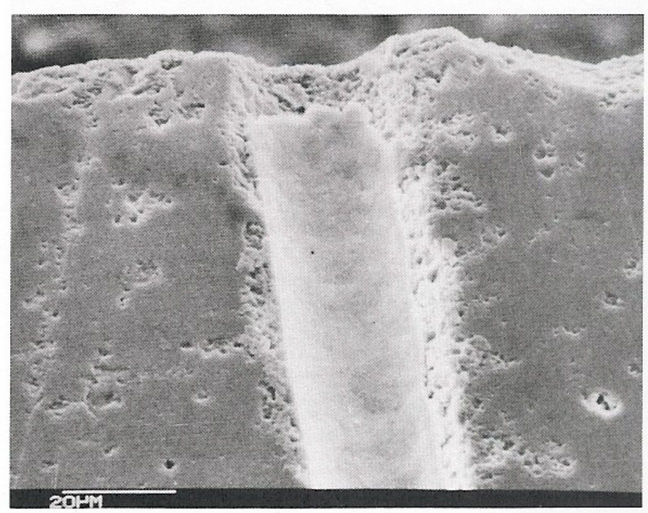


**Figure 10. SEM of EV Damage to Ceramic Plate (20 μm scale).[35]**

Shoulders' experimental studies claim that EVs have physical characteristics corresponding to the phenomenon observed by Nardi et al. His conclusions were that EVs are compact spherically shaped balls (diameter ≈ 1 - 20 μm) of condensed high-density charge (~ $10^{30}$ electrons/m$^3$) with an internal electric field > $10^8$ V/m, a charge-to-mass ratio of 1.7588 × $10^{11}$ Coulomb/kg (≈ electron's charge-to-mass ratio), and a surface current density of 6 × $10^{15}$ Amps/m$^2$.[35] Shoulders also reported that EVs are a source of (copious) X-rays; a single EV discharge gun can produce multiple EVs in which the coupling between adjacent EVs produces quasi-stable structures (chains); and EVs respond like an electron under deflection by external fields of known polarity.

Since electrons would not be expected to bind together due to their mutual Coulomb repulsion, a speculative model based on the vacuum electromagnetic ZPF was formed to explain the existence of EVs. The emerging laboratory evidence led them to consider the hypothesis that the Casimir Effect may be a major contributing mechanism to the formation of EVs in micro-arc discharges. This conjecture is based on models by Casimir[47] and Puthoff and Piestrup[48] suggesting that the generation of a relatively cold, dense, non-neutral (charged) plasma results in charge-condensation effects that may be attributable to a Casimir-type pinch effect (i.e., ZPF-induced pressure forces) in which the inverse square-law Coulomb repulsion is overcome by an attractive inverse fourth-law Casimir force to yield a stable configuration of bound charges at small dimensions. This is a derivative of Casimir's semi-classical model of the electron in which a dense shell-like distribution of charge might suppress vacuum fields in the interior of the shell.[47] However, initial application of Casimir's model found that the vacuum field inside the modeled electron was found to augment rather than offset the divergent Coulomb field thus rendering the electron's self-energy divergent. Puthoff[49] later resolved this problem by developing a self-consistent vacuum-fluctuation-based model in which the net contribution to the point-like electron's self-energy by its Coulomb and vacuum fields vanishes thus rendering a stable finite-mass electron.

Shoulders and collaborators subsequently investigated different approaches to extracting useful energy from the vacuum ZPF by way of exploiting EV phenomenon. Even though EVs can be easily produced in the lab, efforts to test this hypothesis have not met with success due to technical problems (see Chapter 21 in the text for more details). However, this topic is ideal to pursue for future research.

## V. Additional Considerations and Issues

### A. The QED Vacuum Revisited

#### *1. The QED Vacuum as a Plenum*

Continued theoretical and experimental research has revealed that the vacuum constitutes an active agent that contributes to a host of phenomena ranging from microscopic level shifts of atomic states to possible connections to the cause of cosmological expansion.[14,50] As more of its attributes are explored, the vacuum has been found to exhibit phenomena characteristic of an optical medium, such as induced birefringence in the presence of an applied magnetic field,[51] and breakdown (decay) in the presence of external electric fields.[52-54] The current view is that the vacuum has structure, and can be considered much like a medium of classical physics. However, the vacuum differs significantly from that of a classical medium due to the existence of quantum fluctuations. A primary attribute of quantum theory is the concept of matter and field fluctuations, rooted in Heisenberg's Uncertainty Principle.

In second-quantized QED theory, the theory that applies to the electromagnetic vacuum, the canonical approach to representing fluctuations of the free vacuum electromagnetic field is to express the field distribution in terms of standing- or traveling-wave normal modes. Section I suggested that the large value of the integrated ZPE density fuels the concept of potentially useful vacuum energy conversion to other forms, should even some small part of the spectral distribution be accessible for conversion by technological means.

#### *2. The QED Vacuum as a Mathematical "Placeholder" for Fluctuating Matter Fields*

The treatment of the QED vacuum as a fluctuating plenum with (formally) infinite energy density has caused some physicists to call into question the viability of the second-quantized QED formalism. Jaynes, for example, in considering the consequences for calculation of the Lamb shift of the 2*s* level of the hydrogen atom under the assumption of a much more modest electron Compton frequency cutoff (~ $10^{21}$ Hz), calculates a fluctuating power flow for the Poynting vector of 6 × $10^{20}$ MW/cm$^2$ – comparable in every square centimeter to the total power output of the sun – and states that "real radiation of that intensity would do a little more than just shift the 2*s* level by 4 microvolts."[55] However, despite alternatives to the formalism of QED that have been suggested (more on this later), second-quantized QED cannot be lightly dismissed; and this is so even though the infinities that must be dealt with by such procedures as renormalization caused even one of its founders, Paul Dirac, to remark: "This is just not sensible mathematics. Sensible mathematics involves neglecting a quantity when it turns out to be small – not neglecting it because it is infinitely great and you do not want it!"[56]

A second argument that can be raised against using the QED formalism to further explore vacuum fluctuation physics is that, despite the magnitude of the energy density potentially associated with vacuum electromagnetic fluctuations, observation of the cosmological constant – a measure of net vacuum energy density – has a value that is only on the order of the average energy density of matter in the universe $\approx 10^{-9}$ J/m$^3$.[57,58] This leads to what is often referred to as the 120 orders-of-magnitude problem, or "cosmological coincidence." In the mainstream view, rather than the QED value being discounted, the resolution of this problem is thought to lie in the domain of infinity (or divergent integral) cancellations, requiring instead an accounting for the fine-tuning requirements of such cancellations.[59,60]

Again, the root cause of the difficulties that accompany second quantization of the vacuum field is that an unbounded plenum possesses an infinite number of degrees of freedom, each with its assigned ground-state fluctuation energy. In an attempt to circumvent the difficulties associated with an unbounded, second-quantized plenum, alternative approaches to QED have been explored in the literature in some detail, a few of which are discussed in Sect. V(E). A number of these alternative viewpoints interpret the second-quantized QED vacuum with its infinite degrees of freedom as simply an over-idealized mathematical placeholder for "real" fields that originate in matter fluctuations whose number of degrees of freedom is necessarily always limited. Nevertheless, though the alternative formalisms and associated interpretations differ significantly from the canonical approach, detailed calculations yield results identical to those generated by the second-quantized field formalism. As a result, even treated as a mathematical placeholder for matter fluctuation fields, at this point in our discussion the QED value must be taken seriously. The proposed corollary concerning the potentially significant conversion of QED vacuum energy to other forms is further evaluated in the sections that follow.

### B. The Casimir Effect Revisited

The most-quoted quintessential configuration for the conversion of vacuum energy to other forms of energy is the Casimir Effect. As previously discussed, when parallel conducting plates are placed in a vacuum, they attract one another by a very weak force that varies inversely as the fourth power of the distance between them. First computed by Casimir in terms of van der Waals forces (a matter-fields approach – see below), he soon realized that, because the force turns out to be independent of the molecular details of the conductors, it could be computed as a problem in vacuum energy, and that is the way it is now generally presented in the literature (the "plenum approach").[5,61]

#### *1. Casimir Effect in the Plenum Picture*

One begins with the free quantum vacuum electromagnetic field fluctuations, and then determines their modification due to the insertion of two parallel plane conductors (i.e., plates) as additional boundary conditions, which constrain a discrete set of intra-cavity modes of integer half-wavelengths. Aside from an unobservable, high-frequency-cutoff-dependent, free-field term that remains from the mathematical regularization procedure, the resulting (renormalized) vacuum stress-energy tensor is given by $\langle T^{\mu\nu}\rangle_{vac} = (\pi^2\hbar c/720d^4)\mathrm{diag}(-1,1,1,-3)$, where the angular brackets denote the quantum (vacuum state) expectation value of the tensor $T^{\mu\nu}$, $d$ is the plate separation, and diag(–1,1,1,–3) denotes the diagonal elements of a 4×4 matrix.[1-3,61] (For this derivation, the vacuum fluctuations of other quantum fields are essentially undisturbed by the presence of the conductors or are affected only in the immediate vicinity of the atomic nuclei that they contain.) $\langle T^{\mu\nu}\rangle_{vac}$ represents the real physical stress carried by the vacuum field fluctuations in the presence of the parallel plane conductors, and it encodes the Casimir Effect in terms of (1) an interaction energy per unit area, $E/A = -\pi^2\hbar c/720d^3$, and (2) a corresponding force per unit area, $F/A = -\pi^2\hbar c/240d^4$. If free to move in response to the attractive Casimir force, the motion of the plates toward each other is understood in the plenum approach to progressively eliminate intra-cavity modes, converting their associated ground-state energies first into kinetic energy, and then, upon collision of the plates, into heat. In Sect. II we described the Casimir-force-driven collapse of Forward's charged slinky as a Casimir-type configuration for building up an electric field to charge a battery, and how such processes were shown not to violate either conservation of energy or thermodynamic constraints.

#### *2. Casimir Effect in the Fluctuating Matter Fields Picture*

Complementary to the vacuum mode description (plenum approach), the Casimir effect can be described, like van der Waals attraction, as arising from correlations in the state of electrons in the two plates through the intermediary of their coupled fields. From this standpoint (matter-fields approach) there is no requirement for the high energy density vacuum field of the plenum approach to reside throughout all space.

Unfortunately with regard to energy generation, though the Casimir forces involved can be of significance for MEMS applications,[62] the associated Casimir energies involved are too small to be considered of significance for energy applications, so if the possibility for vacuum energy conversion exists, one must look elsewhere to other types of matter-vacuum interactions.

### C. Type I (Transient) and Type II (Continuous) Machines

A key feature of the Casimir process just described, regardless of viewpoint (plenum or matter-fields), is that it is a "one-shot," transient, energy-producing machine. That is, after delivering its energy, $E$, the matter that comprises the machine is in a "used" state (we commonly refer to this used matter as "ash") and cannot be restored to the original state without an input of energy that is greater than or equal to $E$. This "one-shot" feature can be generalized to define a category of machine we call a Type I transient machine, with the Casimir machine constituting the prototypical representative. Should gravitation eventually be traced to a vacuum ZPF origin as proposed by Sakharov,[63] then the fall of an object of mass $m$ through a height $h$ in a gravitational field ($g$ = acceleration of gravity at Earth's surface), delivering its gravitational energy $mgh$ upon impact with the ground, would constitute another example.

In contrast, one can envision a Type II (continuous) machine in which vacuum ZPF energy is converted to a useful form on a recycling basis without net alteration to its own matter state. A hypothetical example is the tunable Casimir device that we reviewed in Sect. IV(C). The cycle of energy generation would consist of the collapse of conducting plates with delivery of energy, followed by separation of plates switched to insulating mode for which the attractive force is considerably weaker, only to be switched back to conducting mode for the next cycle, etc. Provided the input switching energy required per cycle is less than the output energy delivered per cycle, a continuous generation of energy without a net change in matter configuration would result. A second example would be a nonlinear oscillator that continuously, on a steady-state basis, down-shifted high-frequency components of the vacuum ZPF spectrum to lower frequencies for convenient collection and application, without a net change in its own operation.

Clearly a Type II machine would be far more useful than a Type I machine for energy extraction. Type II machines would constitute a fuel-less energy source, with the ambient vacuum ZPF providing essentially unlimited energy. For this to be the case, however, another requirement needs to be satisfied, which we address in the next section.

### D. Degradability of the Vacuum

The possibility of continuous conversion of vacuum ZPE to other forms (i.e., by a Type II machine) requires that, in principle, vacuum energy must be degradable (i.e., continuously consumable), not just that there be a surfeit of energy in place to harvest. This perspective leads to a remarkable question for deeper explorations of QED. It turns out that the mathematical structure of QED is based on a formalism in which the vacuum mode structure and vacuum fluctuation energy per mode are quantized in what could be called a "hard-wired" fashion, i.e., they possess fixed immutable values. Therefore, at the end of a cycle of a hypothetical Type II machine, in which both matter and vacuum mode structure have been returned to their original states, the vacuum modes must of necessity contain at a minimum the same, "hard-wired," energetic content as before the cycle. Therefore, assuming local detailed-balance energy conservation, continuous conversion of vacuum ZPE to other forms via a Type II machine is, from the QED viewpoint, forbidden in principle since the vacuum as described by the QED formalism is non-degradable. (Globally, vacuum energy is not conserved during cosmological expansion, with work being done by the negative vacuum pressure to maintain positive constant vacuum energy density and therefore increasing the vacuum energy.[64]) This outcome of second-quantized QED theory permits of but two interpretations with regard to continuous vacuum energy conversion: 1) QED theory, despite criticisms that can be leveled against it, is correct in its description of vacuum fluctuation dynamics, and even though vacuum ZPE exists, it cannot be continuously converted to other forms, or 2) the axiomatic inconvertibility is an artifact of an over-idealized mathematical structure, and therefore the possibility of conversion remains an open question.[‡] What is not in question, however, is that QED, as an axiomatic, quantum formalism based on the concept of an immutable, non-degradable vacuum, does not support the concept of continuous vacuum energy conversion.

### E. Alternatives to QED

As noted in Sect. V(A1), despite its successes the second-quantized QED formalism with its infinite vacuum degrees of freedom and associated infinite energy density has been the subject of criticism and, as a result, alternatives have been proposed and investigated in the literature. The alternatives run the gamut from neoclassical

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[‡] A number of publications by E. T. Jaynes, A. O. Barut and their collaborators are based on the premise that second quantization is an unnecessary artifact of an over-idealized formalism.

theories in which matter is quantized but the fields are not (e.g., the voluminous work of E. T. Jaynes), through classical theories where both matter and fields are treated classically, with vacuum fluctuations fields taken to be real but of a classical nature (e.g., SED), to formalisms which eliminate the concept of vacuum fields altogether (e.g., direct-action approaches investigated by A. O. Barut and others; see the references cited below). We examine each of these briefly with regard to the possibility of useful "vacuum energy conversion."

***1. Neoclassical Theories of QED Vacuum Fluctuation Effects***

A major proponent of the neoclassical approach has been E. T. Jaynes, who has questioned whether the quantized vacuum field is physically real or merely an artifice of the second-quantized QED formalism. Based on the fact that the QED formalism permits expression of effects in terms of quantized "self" or "source" fields as an alternative to expression in terms of quantized vacuum fluctuation fields, Jaynes advanced the hypothesis that QED effects can be attributed to the self-fields of quantized matter without considering independent quantization of the vacuum fields, expressions in terms of the latter just being a placeholder for the former. Pointedly, with regard to QED being "the jewel of physics because of its extremely accurate predictions," Jaynes' position is that "those accurate experimental confirmations of QED come from the local source fields, which are coherent with the local state of matter," and that "the quantized free field only tags along."[65] Jaynes nonetheless arrived at a conclusion that we might call Jaynes' Axiom, namely, "This complete interchangeability of source-field effects and vacuum-fluctuation effects… shows that source-field effects are the same as if vacuum fluctuations were present." Applied to the case of a radiating atom, Jaynes provides a specific example of his conclusion with the statement "The radiating atom is indeed interacting with an electromagnetic field of the intensity predicted by the zero-point energy, but this is just the atom's own radiation reaction field."[66] As a result, with the axiomatic second-quantized field formalism set aside, in the neoclassical approach any consideration of the conversion of vacuum ZPE for use must be displaced to consideration of the conversion and degradability of source or matter-fields fluctuation energy for use, issues yet to be addressed in the literature.

***2. The SED Model Revisited***

SED is a classical (i.e., non-quantized) theory of particle-field interactions that assumes the existence of classical particles and a classical random background electromagnetic field distribution whose Lorentz-invariant spectral energy density is chosen to match that originally appearing in second-quantized QED. Given SED's heuristic value of classical-like modeling and ease of calculation and its seeming ability to address many quantum mechanical problems with success (as outlined in Sect. III(B)), the SED approach has been employed in the literature to explore vacuum energy conversion. In the absence of a formalism for vacuum field quantization, there are no fundamental immutability constraints that would mitigate against vacuum energy degradability, so that issue is not testable under this formalism.

Investigations to date have included the use of cavity-QED techniques to suppress atomic or molecular ground states,[27] and evaluation of the use of a nonlinear oscillator to continuously downshift high-frequency components of the vacuum fluctuation spectrum to lower frequencies for convenient collection and use. With regard to the latter, the result of a nonrelativistic SED analysis is that the downshifting process acts to convert an initial hypothetical cubic-frequency vacuum fluctuation spectrum towards a Rayleigh-Jeans rather than a Planck heat spectrum (the former being a low energy approximation of the latter).[67,68] Extension of the analysis to the relativistic regime does not alter this conclusion.[69,70] Though further work remains, these considerations lead us to conclude that SED in its present form is incomplete, and may not be useful for the assessment of the potential conversion of vacuum energy to other forms; its predictions concerning such must be treated with caution.

Additional shortcomings of the SED model include convoluted attempts to derive interference effects or Schrödinger's equation, and the difficulty in explaining sharply-defined stationary states (i.e., sharp atomic spectra), though there have been many attempts.[17] QED and SED do not in general yield the same results for nonlinear systems, although they are in agreement for the range of linear systems examined. The apparent disagreements between SED and QED are quite serious, and occur in areas in which QED is highly successful. Perhaps the source of these difficulties lies in accurately dealing with the nonlinear stochastic differential equations in SED for these problems. Even still it is likely that differences will remain, which should clearly be testable by experimental means.[71] For a very thorough, detailed and scholarly review of SED, see Ref. 17 and the corresponding review by Cole and Rueda.[72]

Given the heuristic value of certain aspects of SED modeling, but with the shortcomings outlined above noted, SED theorists de la Pena and Cetto have proposed a modification to SED they call LSED (linear SED).[73] The modification consists of the addition of three new constraining principles that result in a form of convergence with nonrelativistic quantum mechanics while retaining some of the appealing attributes of standard SED (e.g., quantum states being stable on the basis of a dynamic balance between absorption and emission of background vacuum fluctuation fields). The added constraints (for example, an added constraint that invokes detailed energy balance for separate frequencies) result in correcting several known problems with standard SED. For example, now the equilibrium spectrum is Planck's, not Rayleigh-Jeans, and wavelike behavior of matter and nonlocality issues can be addressed, etc. The issue of continuous vacuum energy conversion has yet to be addressed in this new formalism, however, so that remains for the future.

***3. QED Without Second-Quantized Fields***

As yet another alternative to canonical second-quantized QED, Barut[74] has proposed that effects attributable to vacuum ZPF can be derived with a theory in which there are source (matter) fluctuation fields but no vacuum fluctuation fields, and that even the former can be eliminated. Barut's approach is developed in considerable detail as an independent, self-consistent, formulation of QED in its own right. Barut argues that effects normally attributed to vacuum fluctuations in the second-quantized, linear theory of the radiation field can be equally well computed within the framework of a non-second-quantized, nonlinear theory which is based entirely on matter wave functions alone. His program is to assess how far one can go in understanding radiative processes without second quantization or vacua that fluctuate. Barut and his collaborators have successfully applied the theory to the Lamb shift and spontaneous emission,[75,76] problems of cavity QED,[77] Casimir-Polder and van der Waals forces,[78] calculations of the electron's $g_e$-2 (gyromagnetic ratio, $g_e$) factor,[79-81] and the Davies-Unruh effect[82] among others.

Given that the formalism of second-quantized field operators are not used at all in the Barut approach, the seemingly quantized properties of fields are taken to simply reflect first quantization of the sources. Therefore, in the absence of the independent existence of second-quantized field fluctuations, the QED arguments concerning immutability and nondegradability of quantized vacuum fluctuation fields, and the corollary proscription against potential conversion of energy from such fields, do not apply. As in the neoclassical approach, the question of the conversion of quantum ZPE to other forms must be diverted to consideration of the global properties of matter fluctuation interactions in the as-yet-incomplete development of the Barut approach.

**F. Examples of a Degradable Vacuum**

In closing, we review three examples of a degradable vacuum that are predicted by the quantum field theory of curved spacetime and the Standard Model of elementary particle physics.

***1. Gravitational Squeezing of the Vacuum***

In their study of traversable wormholes, Hochberg and Kephart[83] discovered that the gravitational field of any astronomical body produces a zone of negative energy around it by "dragging" some of the virtual quanta (a.k.a. vacuum ZPF) downward. They applied their discovery to the problem of creating and stabilizing traversable wormholes. Their quantum optics analysis showed that there is a distortion of the vacuum electromagnetic ZPF due to the interaction with a prescribed gravitational background, which results in "squeezed" vacuum states that possess a negative energy density. Squeezing of the vacuum is a quantum process that is roughly analogous to the compression of an ordinary fluid (see Sect. II in Chapter 16 of this text for details). This means that as the vacuum field is continuously being squeezed by the gravitational field of a body, its energy is continuously being degraded with respect to the undisturbed remote vacuum field.

The magnitude of the gravitational squeezing of the vacuum can be estimated from the quantum optics squeezing condition for given transverse (to direction of gravitational acceleration) momentum and (equivalent) energy eigenvalues, $j = 8\pi r_S/\lambda$, of two electromagnetic ZPF field modes, subject to $j \to 0$, where $\lambda$ is the ZPF mode wavelength and $r_S$ is the Schwarzschild radius of any astronomical body under study.[§83] This condition simply states that substantial gravitational squeezing of the vacuum occurs for ZPF field modes with $\lambda \geq 8\pi r_S$ of the mass under study (see Table 1 in Chapter 16 of this text for a quantitative discussion).

It is not clear whether this mechanism can be exploited to extract energy from the vacuum. Conservation of energy suggests one of two possible outcomes: 1) the lost energy is injected into the gravitational energy of the body, or 2) the lost energy reappears as an accumulation of positive energy density ZPF modes elsewhere in the universe. Further research will be needed to address this question.

***2. Redshifting the Vacuum***

Calloni et al.[84,85] explored the possibility of verifying the equivalence principle for the zero-point energy of QED. They used semi-classical quantum gravity theory to evaluate the net force produced by the quantum vacuum ZPF acting on a rigid Casimir cavity in a weak gravitational field which is modeled using the standard

[§] $r_S = 2GM/c^2$ is the critical radius at which a massive body of mass $M$ collapses into a black hole, used here as a convenient radial distance parameter to simplify the inequality, but there is no actual black hole collapse involved in this mechanism ($G$ is Newton's universal gravitation constant, $6.673 \times 10^{-11}$ Nm$^2$/kg$^2$).

Schwarzschild spacetime metric geometry.** They evaluated the regularized (or renormalized) stress-energy tensor $\langle T_{\text{vac}}^{\mu\nu} \rangle_{\text{ren}}$ of the quantized vacuum electromagnetic field between two plane-parallel ideal metallic plates lying in a horizontal plane. $\langle T_{\text{vac}}^{\mu\nu} \rangle_{\text{ren}}$ encodes the Casimir Effect, which has a negative energy density and a negative pressure along the vertical (gravitational acceleration) axis between the plates. Bimonte et al.[86,87] also studied this problem using Green-function techniques in the Schwinger-DeWitt quantum ether prescription for $\langle T_{\text{vac}}^{\mu\nu} \rangle_{\text{ren}}$ in a curved spacetime. The results from these studies agreed with the equivalence principle and proved that quantum vacuum ZPF does gravitate since the energy of each ZPF mode is redshifted by the factor $(-g_{00})^{1/2} = [1 - (2GM/c^2r)]^{1/2}$ even though the modes remain unchanged (here $M$ is the mass of a gravitating body, $r$ is the radial distance from the body, and $g_{00}$ is the time-time component of the Schwarzschild metric tensor).

These studies suggest that cavity electromagnetic vacuum states are continuously degrading inside a background gravitational field. But can we extract energy from this mechanism? The answer to this question is not known at present, but consideration of the conservation of energy suggests that the same two possible outcomes given in the previous section would seem to apply: 1) the lost energy is injected into the gravitational energy of the body, or 2) the lost energy reappears as positive energy density ZPF modes elsewhere in the universe. Further research will be needed to address this question as well.

### *3. Melting the Vacuum*

In their study of the structured vacuum, Rafelski and Müller[53] (see also, Ref. 54) analyze the nature of the strongly interacting (QCD) vacuum and elucidate its character from the Standard Model of particle physics and high energy particle accelerator data. They concluded that in addition to the electroweak vacuum (i.e., the unified electromagnetic and weak force vacua) there exists a dual QCD vacuum structure: one vacuum structure that is everywhere in space and consists of a complicated soup of interacting gluons which confine the quarks – this is called the ordinary or "frozen" vacuum; and another vacuum structure that is found inside elementary particles (e.g., hadrons), and which behaves like the dielectric vacuum of electrodynamics. In this second vacuum structure, particles that have a strong charge (such as quarks or gluons) can move freely, but are confined by the frozen vacuum that is everywhere else. This is called the perturbative, or gluon, or "melted" vacuum, which can also be pictured as a quark-gluon plasma. They estimate that there is a "latent heat" of ~ 1 GeV/fm$^3$ (or $10^{35}$ J/m$^3$) associated in the phase change of transforming from one vacuum structure to another when the gluonic structures of the perturbative vacuum are melted.†† It is important to point out here that this is a degradable vacuum structure.

This unusual dual vacuum structure led Rafelski and Müller to speculate on a mechanism for the "burning of matter" as the ultimate source of energy in which it might be possible that the energy contained within baryons could be converted into useful energy. Their idea is to remove or destroy the three quarks residing inside a baryon in order to gain energy, the latent heat, from the melted vacuum inside the baryon. This process also entails the decay of the quarks via lepton-quark interactions, which is a topic that is beyond the scope of this chapter. They suggest that it might be possible that producing a quark-gluon plasma in high energy nuclear collisions could be a very efficient source of energy. In this process atomic nuclei would be collided at high energy in order to form a compressed high density zone in the region where the two nuclei overlap. This would lead to the melting of the vacuum and the subsequent direct conversion of matter into radiation, thus releasing ~ $10^{35}$ J/m$^3$ of energy density. This magnitude of energy density would be very useful as a source of energy for space propulsion applications.

Rafelski and Müller point out that the commonly held view that the centers of neutron stars are dead and cold, due to their nuclear fuel having burnt out and the energy of gravitational collapse having been expended for the conversion of the collapsed star into a gigantic atomic nucleus, is not the complete story. They hold open the possibility that the entire rest-mass of all the baryons inside neutron stars might become available and converted into heat. In their scenario, the core of a neutron star is actually composed of condensed quark matter, and the rest-mass of baryons is burnt up into radiation inside the quark core. They also point out that supernovae explosions, gamma ray bursts, positron emission from the center of our galaxy, quasars, and galactic nuclei have been observed to emit extreme amounts of thermal energy, the mechanisms of which are still not understood today.

Theoretical and laboratory studies of the dual QCD vacuum have been underway for over 20 years. The progress in experimental particle physics is such that one gains an order of magnitude in the resolution (i.e., energy) of elementary particle structures roughly every decade. It is hoped that the commissioning of the Large Hadron

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** A spacetime metric is a Lorentz-invariant distance function between any two points in spacetime, which is defined in terms of a metric tensor, $g_{\mu\nu}$, that encodes the geometry of spacetime (Greek indices $\mu,\nu = 0\ldots3$ denote spacetime coordinates, $x^0\ldots x^3$, such that $x^1\ldots x^3 \equiv$ space coordinates and $x^0 \equiv$ time coordinate).

†† 1 eV = $1.602 \times 10^{-19}$ J; 1 GeV = $10^9$ eV; 1 fm = $10^{-15}$ m.

Collider in 2008 will lead to higher resolution probing of the dual QCD vacuum structure, and help to determine whether there are deeper grand unified and/or Higgs vacuum structures residing within quarks. This topic is a rich area for future research, in which investigators can explore ways to exploit the energy residing within new vacuum structures for space power and propulsion applications.

***4. ZPF Modes and Vacuum Field Energy***

The above examples illustrate how the vacuum becomes degradable when perturbed under certain conditions. In each of the examples, the vacuum ZPF modes were perturbed in such a way as to drive the QED field's vacuum state energy below zero, or the vacuum undergoes a phase shift as in the QCD case. The Casimir Effect is another example in which certain ZPF modes are excluded by boundary conditions which perturb the free-space vacuum ZPF modes, thus driving the QED field energy below zero inside a Casimir cavity. In accordance with the discussion in Sections III(A) and V(D), the ZPF modes serve only as a placeholder for a quantum field's vacuum state calculations. Therefore, the "hardwired" ZPF modes cannot be driven below the ground state. It is only a quantum field's overall vacuum state energy that can be driven below zero. So we conjecture that the key to exploring the possibility of extracting energy from the vacuum is to discover or invent additional mechanisms that perturb the ZPF modes of a quantum field, which could then be technologically implemented and tested in laboratory experiments.

## VI. Discussion and Conclusions

What are the conclusions that can be drawn from the considerations presented here regarding the concept of continuous conversion of energy from the vacuum electromagnetic ZPF?

First, we see that although the original inspiration for the concept of continuous vacuum energy extraction came from second-quantized QED theory, it must be acknowledged that QED, as an axiomatic, quantized formalism based on the concept of an immutable, non-degradable vacuum, does not support the concept of continuous vacuum energy conversion. Given that second-quantized QED is our most comprehensive quantum theory to date, its lack of support for continuous vacuum energy conversion must be given serious consideration.

Second, SED as an alternative theory, whose formalism has been taken to support the concept of continuous vacuum energy conversion, has enough shortcomings in its current state of development that one must conclude that it is not at present an adequate tool for the assessment of potential vacuum energy conversion. SED predictions must thus remain suspect in the absence of experimental confirmation. The purpose of the experimental program outlined in Sect. IV is meant to address this need.

Third, the concept of the conversion of energy from vacuum fluctuations is in principle not falsifiable, given the unknowns which present theory has yet to resolve (e.g., dark energy), and the numerous approaches currently being brought to bear in the development of quantum theory.

Finally, even though experimental efforts at energy extraction from the vacuum have been proposed or are already under way at various laboratories, definitive theoretical support underpinning the concept of useful extraction of energy from quantum fluctuations is not yet in place. Such support awaits theoretical developments that either posit a plenum that (unlike second-quantized QED) can be shown to be degradable, or posit conversion of energy associated with matter fluctuations, also in a degradable fashion. Since the quantum fluctuations of interest are associated with quantum ground states, what is minimally required are particle-vacuum or particle-particle interactions that result in the formation of alternate lower-energy, ground states of matter/field configurations. Suggested approaches to be explored are those which are known to yield results consistent with the existence of vacuum fluctuation fields, but without the formalism of independently postulated second-quantized vacuum fields. Whether useful conversion of energy from quantum fluctuations can be accomplished, and identifying the unequivocal conditions under which this can be achieved, are yet to be determined.

It has been argued that the QED vacuum is degradable under the action of gravitation-induced quantum squeezing or redshifting. However, it is not known whether these effects can be exploited for the extraction of energy from the vacuum. The concept of a dual, degradable vacuum structure in QCD can possibly lead to the generation of useful energy via the release of latent heat from melting the QCD vacuum. The new generation of high energy particle colliders coming online in the very near future may yield new information about the complex vacuum structure of the universe, allowing us to find ways to exploit its energy content for revolutionary space propulsion applications.

## Acknowledgments

The authors wish to thank our colleagues, V. Teofilo (Lockheed Martin), B. Haisch (ManyOne Networks), L. J. Nickisch (Northwest Research Assoc.), A. Rueda (California State University-Long Beach), D. C. Cole (Boston

University), M. Ibison (Inst. for Advanced Studies at Austin), S. Little (Inst. for Advanced Studies at Austin), and M. Little (Inst. for Advanced Studies at Austin) for their extensive technical contributions to this chapter. We would also like to thank J. Newmeyer (Lockheed Martin), E. H. Allen (Lockheed Martin), T. Kephart (Vanderbilt Univ.), P. C. W. Davies (Arizona State Univ.), M. Millis (NASA-Glenn), and M. LaPointe (NASA-Marshall) for their very useful comments.

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