The energetic vacuum: implications for energy research

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> *The existence of an actual vacuum was a subject of debate among scientists from Aristotle into the twentieth century. Since light, magnetic fields and heat all travel through a vacuum,* something *must be there. Borrowing a word from Aristotle, scientists described various kinds of 'aethers' that exist in even the hardest vacuum and that pervade space. Maxwell's theory of electromagnetism reduced these different types to just one, called the ether. Various experiments were developed to detect this ether, of which the most famous was the Michelson–Morley experiment, which failed to find it. Finally, in 1905, Einstein banished the ether by means of special relativity and allowed the true vacuum to exist.*
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> *But not for long. The Heisenberg uncertainty principle of 1927 led particle physicists to predict that particles would arise spontaneously from the vacuum, so long as they disappeared before violating the uncertainty principle. The quantum vacuum is a very active place, with all sorts of particles appearing and disappearing. Careful experiments have demonstrated that the quantum theorists are correct in this interpretation of the vacuum.... Furthermore, starting in 1980 with the theory of the inflationary universe, particle physicists have told us that the entire universe was created as a 'false vacuum', a quantum vacuum that has more energy in its nothingness than it should. The decay of that particular vacuum to an ordinary quantum vacuum produced all the mass in the universe and started the Big Bang.*
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> *The Timetables of Science*
> Simon and Schuster (1988)

Introduction

Modern physical theory, specifically quantum electrodynamics (QED), tells us that the vacuum can no longer be considered a void. This is due to the fact that, even in the absence of matter, the vacuum is neither truly particle nor field free, but is the seat of virtual particle–pair (*e.g.* electron–positron) creation and annihilation processes, as well as zero–point–fluctuations (ZPF) of such fields as the vacuum electromagnetic field, which will be the focus of our study here.

Formally, the energy density associated with the vacuum electromagnetic ZPF background is considered to be infinite. With appropriate high–frequency cutoffs the ZPF energy density is still conservatively estimated to be on the order of nuclear energy densities or greater.[1] The enormity of the figures describing the vacuum electromagnetic zero–point energy raises the question as to whether these numbers should be taken seriously, whether they are due to some defect or misinterpretation of the theory, whether the ZPF fields ought to be considered as 'virtual' or 'real'.[2] There is, however, no question but that the ZPF fields lead to real, measurable physical consequences. One example is the very real Casimir force,[3–6] an experimentally-verified[7–9] ZPF-induced attractive quantum force between closely-spaced metal or dielectric plates. An elegant analysis by Milonni *et al.* at Los Alamos National Laboratory shows that the Casimir force is due to radiation pressure from the background electromagnetic zero-point energy which has become unbalanced due to the presence of the plates, and which results in the plates being pushed together.[10] (We will discuss this effect in more detail later when we address the possibility of ZPF energy extraction.) Other effects which can be traced back to interactions involving the ZPF fields in a fundamental way include the Lamb shift (the slight perturbation of the emission lines seen from transitions between atomic states),[11–13] the van der Waals chemical binding forces,[14] the stabilisation of atomic structure against radiative collapse,[15,16] quantum field mechanisms underlying the gravitational interaction,[17] and spontaneous emission.[18]

Zero-point energy

To understand just what the significance of zero-point energy is, let us begin with a simple harmonic oscillator as shown in Figure 1. According to classical theory, such a harmonic oscillator, once excited but with excitation removed, will come to rest (because of friction losses) as shown in Figure 1(a). In quantum theory, however, this is not the case. Instead, such an oscillator will always retain a finite amount of 'jiggle', as shown in Figure 1(b). The average energy (kinetic plus potential) associated with this residuum of motion, the so-called zero-point energy, is given by $<E> = \hbar\omega/2$, where $\hbar$ is Planck's constant ($\hbar = 1.054 \times 10^{-34}$ joule s^{-1}) and ω is the frequency of oscillation. The meaning of the adjective *zero-point* is that such motion exists even at a temperature of absolute zero where no thermal agitation effects remain. Similarly, if a cavity electromagnetic mode is excited and then left to decay, as shown in Figure 2, the field energy dies away, again to a minimum value $<E> = \hbar\omega/2$ (half a photon's worth), indicating that fields as well as mechanical systems are subject to zero-point fluctuations. It is the presence of such ZPF 'noise' that can never be gotten rid of, no matter how perfect the technology, that sets a lower limit on the detectability of electromagnetic signals.

If we now consider the universe as a whole as constituting a giant cavity, then we approach a continuum of possible modes (frequencies, directions) of propagation of electromagnetic waves. Again, even in the absence of overt excitation, quantum theory has us assign an energy $<E> = \hbar\omega/2$ to each mode. Multiplication of this energy by a density of modes factor[19] then yields an expression for the spectral energy density that characterises the vacuum electromagnetic zero-point energy

$$\begin{aligned}\rho(\omega)d\omega &= [\omega^2/\pi^2 c^3][\hbar\omega/2]\, d\omega \\ &= (\hbar\omega^3)(2\pi^2 c^3)\, d\omega \text{ joules m}^{-3} \qquad (1)\end{aligned}$$

There are a number of properties of the zero-point energy distribution given in (1) that are worthy of note. First, the frequency behaviour is seen to diverge as ω^3. In

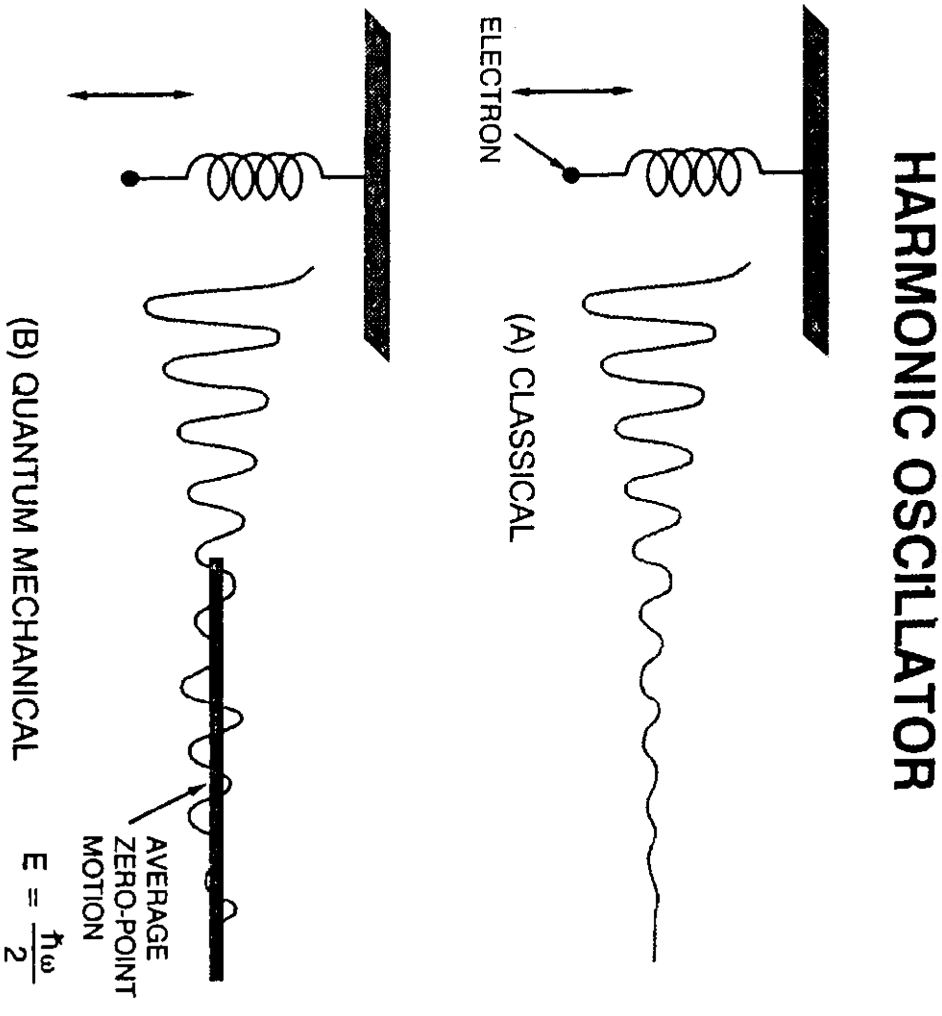

Figure 1 *Harmonic oscillator.*

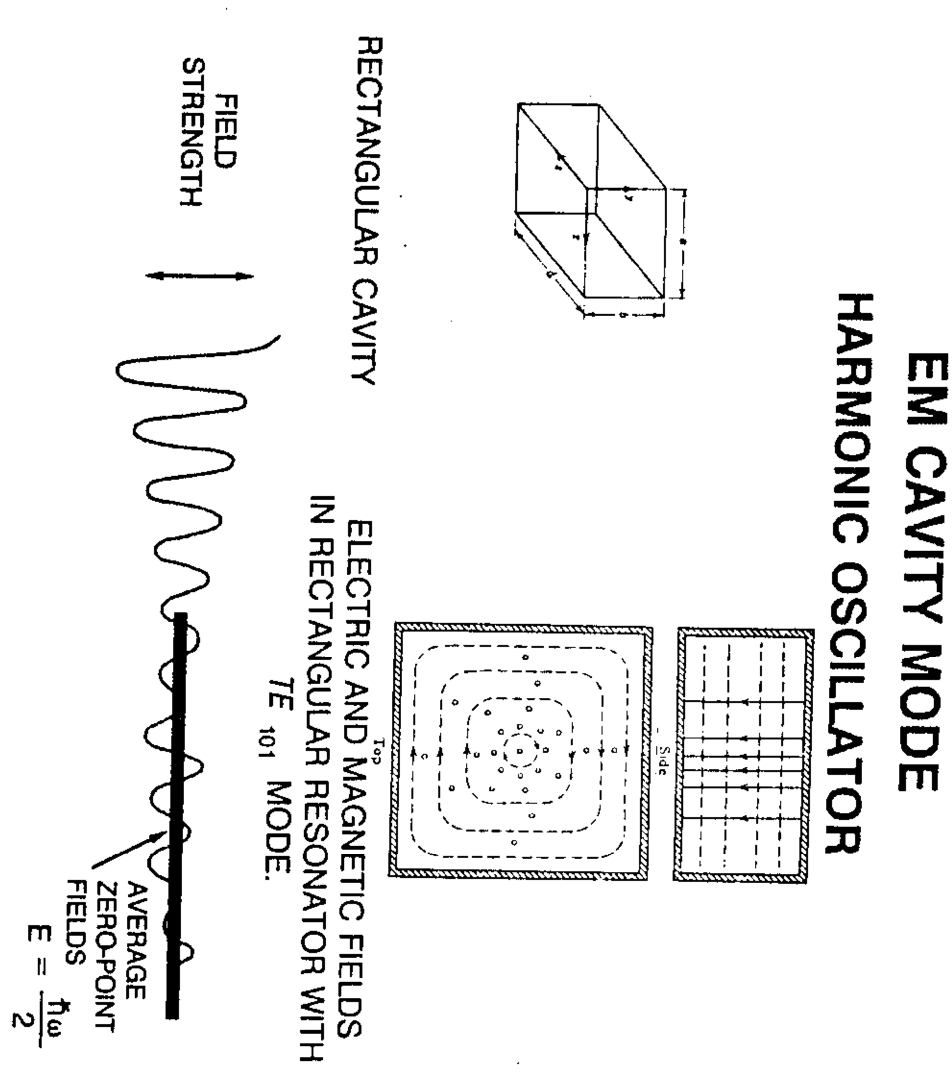

Figure 2 *EM cavity mode harmonic oscillator.*

the absence of a high-frequency cutoff this would imply an infinite energy density. (This is the source of such statements regarding a purely formal theory.) As discussed by Feynman and Hibbs, however, we have no evidence that QED remains valid at asymptotically high frequencies (vanishingly small wavelengths).[1] Therefore, we are justified in assuming a high-frequency cutoff, and arguments based on the requirements of general relativity place this cutoff near the Planck frequency (~ 10^{-33} cm).[17] Even with this cutoff the mass-density equivalent of the vacuum ZPF fields is still on the order of 10^{94} g cm^{-3}. This caused Wheeler to remark that "elementary particles represent a percentage-wise almost completely negligible change in the locally violent conditions that characterise the vacuum.... In other words, elementary particles do not form a really basic starting point for the description of nature. Instead, they represent a first-order correction to vacuum physics."[20] As high as this value is, one might think that the vacuum energy would be easy to observe. Although this is true in a certain sense (it is the source of quantum noise), by and large the homogeneity and isotropy (uniformity) of the ZPF distribution prevent naive observation, and only departures from uniformity yield overtly observable effects.

Contributing to the lack of direct observability is a second feature of the ZPF spectrum; namely, its Lorentz invariance. Whereas motion through all other radiation fields, random or otherwise, can be detected by Doppler-shift phenomena, the ZPF spectrum with its cubic frequency dependence is unique in that detailed cancellation of Doppler shifts with velocity changes leaves the spectrum unchanged. (Indeed, one can derive the ZPF spectrum to within a scale factor by simply postulating a Lorentz-invariant random radiation field.[21,22]) Thus, although any particular component may Doppler shift as a result of motion, another component Doppler shifts to take its place. It is also the case, again unique to the ZPF cubic-frequency-dependent spectrum, that Doppler shifts due to other phenomena (*e.g.* cosmological expansion, gravitation) also do not alter the spectrum.[23] This stands in contrast to, for example, the 3 K blackbody (thermal) microwave background left over from the Big Bang which cools with cosmological expansion.

Yet another feature of the ZPF spectrum, related to its Lorentz invariance and again unique in comparison with all other competitors, is the complete lack of a drag force on a charged particle passing through it. This is because such a drag force (the so-called Einstein-Hopf drag[24]) is proportional to the factor $[\rho(\omega) - (\omega/3)(d\rho/d\omega)]$, and this vanishes identically for $\rho(\omega) \propto \omega^3$.

On the other hand, *accelerated* motion through the vacuum can in principle reveal the presence of the ZPF energy density directly. Unlike uniform motion in which delicate cancellations of Doppler shifts leave the motion undetected, in accelerated motion the Doppler-shift cancellations are no longer sustained. As a result, the Lorentz-invariant spectrum which holds in uniform motion is augmented by additional terms. One factor yields a thermal (Planck) spectrum of temperature $T = \hbar a/2\pi ck$, where a is acceleration, k is Boltzmann's constant and T is temperature. This is known as the Davies-Unruh effect.[25,26] Yet another factor which shows up in the ZPF spectrum of an accelerated observer is found, via the equivalence principle, to reveal a deep connection between zero-point energy and gravity along lines originally proposed by Sakharov[27] (that gravity could be understood as an induced effect brought about by changes in the quantum fluctuation energy of the vacuum due to the presence of matter[17]).

Thus we see that, with its roots in relativity theory which banished the ether, QED has in some sense come full circle to provide us with a model of an energetic vacuum that once again constitutes a plenum rather than a void.

Source of zero–point energy

The fact that the vacuum constitutes an energy reservoir leads naturally to the question as to where the zero–point energy comes from, specifically, the vacuum electromagnetic zero–point energy under discussion here. (This is an especially important issue if one considers the possibility of extracting such energy for use.) Nature provides us with but two alternatives: existence by fiat as part of the boundary conditions of the present universe (like, for example, the 3 K cosmic background radiation left over from the Big Bang), or generation by the (quantum fluctuation) motion of charged particles that constitute matter. This latter possibility was explored in a recent paper by the author, with positive results.[23]

The argument goes as follows. Given charged particles in quantum zero–point motion throughout the universe, a $1/r^2$ dependence of the radiation from such motion, and an average volume distribution of such particles in spherical shells about any given point that is proportional to the area of the shell (that is, proportional to r^2), one could reasonably expect to find at any given point a sum of contributions from the surrounding shells that yielded a high–density radiation field. (Recall a similar argument in astronomy associated with Olbers' paradox.) The high–density ZPF fields would appear to be just such a field.

The details of the calculations examine the possibility that ZPF fields drive particle motion, and that the sum of particle motions throughout the universe in turn generates the ZPF fields, in the form of a self–regenerating cosmological feedback cycle not unlike a cat chasing its own tail. This self–consistent field approach, carried out assuming inflationary cosmology, is found to yield the correct frequency distribution and the correct order of magnitude to match the known ZPF distribution, thus supporting the hypothesis that the ZPF fields are dynamically generated.

As it turns out, there is an additional bonus from the calculations. A derived expression relating the zero–point energy density to such factors as the mass density and size of the universe also yields a precise expression for an observed 'cosmological coincidence' often discussed in the context of Dirac's large–numbers hypothesis: namely, that the electromagnetic–to–gravitational force ratio between an electron and proton is equal to the ratio of the Hubble distance to the size of the classical electron. According to the relevant calculations such a cosmological coincidence is seen to be a consequence of the cosmologically–based ZPF–generation mechanism under consideration that serves to link cosmological and atomic parameters.

The overall picture that emerges, then, is that the electromagnetic ZPF spectrum is generated by the motion of charged particles throughout the universe which are themselves undergoing ZPF–induced motion, in a kind of self–regenerating grand ground state of the universe. In contrast to other particle–field interactions, the ZPF interaction constitutes an underlying, stable 'bottom–rung' vacuum state that decays no further but reproduces itself on a dynamic–generation basis. In such terms it is possible to explicate on a rational basis the observed presence of vacuum zero–point energy.

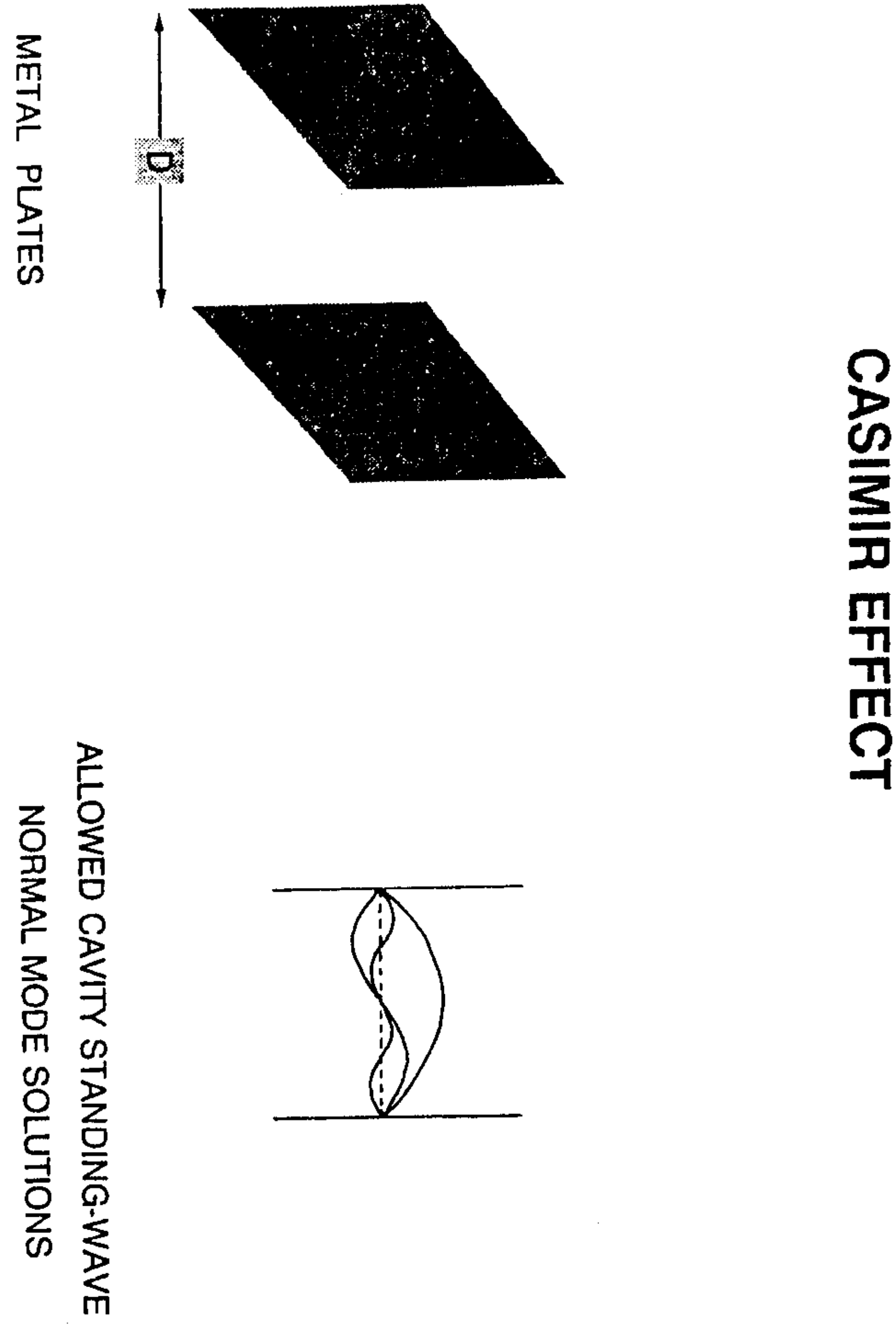

Figure 3 *Casimir effect.*

Vacuum energy extraction?

As we have seen, the vacuum constitutes an extremely energetic physical state. Nonetheless, it is a giant step to consider the possibility that vacuum energy can be 'mined' for practical use. To begin, without careful thought as to the role that the vacuum plays in particle–vacuum interactions, it would only be natural to assume that any attempt to extract energy from the vacuum might somehow violate energy conservation laws or thermodynamic constraints (as in misguided attempts to extract energy from a heat bath under equilibrium conditions). As we shall see, however, this is not quite the case.

The premier example for considering the possibility of extracting energy from the vacuum has already appeared in the literature in a paper by R.L. Forward entitled "Extraction of electrical energy from the vacuum...";[28] it is the Casimir effect. Let us examine carefully this ZPF–driven phenomenon.

With parallel, non–charged conducting plates set a distance D apart, only those (electromagnetic) modes which satisfy the plate boundary conditions (vanishing tangential electric field) are permitted to exist. In the interior space this constrains the modes to a discrete set of wavelengths for which an integer number of half–wavelengths just spans the distance D (see Figure 3). In particular, no mode for which a half–wavelength is greater than D can fit; as a result, all longer–wavelength modes are excluded, since for these wavelengths the pair of plates constitutes a cavity below cutoff. The constraints for modes exterior to the plates, on the other hand, are much less restrictive due to the larger spaces involved. Therefore, the number of viable modes exterior is greater than that interior. Since such modes, even in vacuum state, carry energy and momentum, the radiation pressure inward overbalances that outward, and detailed calculation shows that the plates are pushed together with a force that varies as $1/D^4$, *viz*,[10]

$$F/A = -(\pi^2/240)(\hbar c/D^4) \quad \text{newtons m}^{-2} \qquad (2)$$

The associated attractive potential energy (Casimir energy) varies as $1/D^3$,

$$U/A = -(\pi^2/720)(\hbar c/D^3) \quad \text{joules m}^{-2} \qquad (3)$$

As is always the case, bodies in an attractive potential, free to move, will do so, and in this case the plates will move toward each other. The conservation of energy dictates that in this process potential energy is converted to some other form, in this case the kinetic energy of motion. When the plates finally collide, the kinetic energy is then transformed into heat. (The overall process is essentially identical to the conversion of gravitational potential energy into heat by an object that falls to the ground.) Since in this case the Casimir energy derives from the vacuum, the process constitutes the conversion of vacuum energy into heat, and is no more mysterious than in the analogous gravitational case.

In such fashion we see that the conversion of vacuum energy into heat, rather than violating the conservation of energy, is in fact required by it. And this conversion can be traced microjoule by microjoule as modes (and their corresponding zero–point energies) are eliminated by the shrinking separation of the plates. What takes getting used to conceptually is that the vacuum state does not have a fixed energy value, but changes with boundary conditions. In this case vacuum–plus–plates–far–apart is a higher energy state than vacuum–plus–plates–close–together, and the combined system will decay from the higher–energy state to the lower, in the process creating kinetic energy, then heat, to conserve overall energy. Similar vacuum–decay processes have been discussed within the context of so–called charged vacuum states.[29]

With regard to extracting zero–point energy for use, in Forward's proposed embodiment the two plates in a Casimir experiment are charged with the same–sign charge (*e.g.* electrons). At sufficiently small spacings the Coulomb repulsion between the plates (which goes in an inverse square law $1/D^2$ or less, depending on spacing and geometry) can always be overcome by the stronger $1/D^4$ attractive Casimir force. The plates will therefore be drawn together in a collapsing motion. This confines the charge distribution to a smaller and smaller volume and results in an increased electric field strength in the vicinity of the plates. In such fashion the zero–point energy (Casimir energy) is transformed into stored Coulomb energy, which can then be extracted by a variety of means.

Although demonstrating in principle the extraction of energy from the vacuum, Forward's embodiment is admittedly impractical for significant, continuous energy generation, for a number of reasons. First and foremost is the fact that the generator is a 'one–shot' device. To recycle the generator one must put as much energy into the device to return the plates to their original separated positions as was obtained during the collapse phase, as would be expected in any conservative potential. As a result, given the losses in any real system, not even 'break–even' operation can be achieved, let alone net energy gain.

Let us carry this one step further, however. If one could arrange to have an inexhaustible supply of such devices, and if it took less energy to make each device than was obtained from the Casimir–collapse process, and if the devices were discarded after use rather than recycled, then one could envision the conversion of vacuum energy to use with a net positive yield. Although almost certainly not achievable in terms of mechanical devices, a possible candidate for exploitation along such lines would be the generation of a cold, dense, non–neutral (charged) plasma in which charge condensation takes place not on the basis of charged plates being drawn together, but on the basis of a Casimir pinch effect. (Casimir pinch effects have been explored in the literature, not with regard to energy conversion, but in terms of semiclassical modelling of charge confinement in elementary particles, hadron bag models, *etc.*[30]) Such an approach would constitute a 'Casimir–fusion' process, which in its cycle of operation would mimic the nuclear–fusion process. It would begin, like its nuclear counterpart, with an initial energy input into a plasma to overcome a Coulomb barrier, followed by a condensation of charged particles drawn together by a strong, short–range attractive potential (in this case a Casimir rather than a nuclear potential), and with an accompanying energy release. Should the energy requirements for plasma formation, and electrical circuit and heat losses be kept at a level below that required for break–even operation, then net, useful energy could in principle be generated, as in the nuclear case. Such a proposal is, of course, highly speculative at this point, and further detailed analysis of the energetics involved may yet uncover some hidden flaw in the concept. Nonetheless, known to this author are programs in the United States, the Soviet Union and other countries to explore just such an approach on an experimental basis.

The above provides just one example of the type of concept that can be explored with regard to possible vacuum energy extraction. Other proposals for extracting vacuum energy have been made as well,[31] covering the gamut from the clearly unworkable to the intriguing. To this author's way of thinking, however, there is as yet neither clear-cut evidence of experimental success nor an absolutely unimpeachable theoretical construct. Nonetheless, it is only by continued, careful consideration of such proposals that we can hope to resolve the issue as to whether energy can be extracted from the vacuum, as part of a generalised 'vacuum engineering' concept of the type suggested by Nobel Laureate T.D. Lee.[32] As a caution along the way, the prudent scientist, while generally keeping an open mind as to the possibility of vacuum energy extraction, must of course approach any particular device claim or theoretical proposal with the utmost rigour with regard to verification and validation.

Can the energy crisis be solved by harnessing the energies of the zero–point sea? In the final analysis, given our relative ignorance at this point we must of necessity fall back on a quote given by Podolny[33] when contemplating this same issue. "It would be just as presumptuous to deny the feasibility of useful application as it would be irresponsible to guarantee such application." Only the future can reveal whether a program to extract energy from the vacuum will meet with success.

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2 See, for example, the Closing Remarks section in Boyer, T.H. 1984. *Phys. Rev.*, D **29**, 1089. It can be added that, although the approach developed here involves treating the ZPF fields as real, an alternative viewpoint can be taken in which the results of field–particle interactions traditionally attributed to ZPF are expressed instead in terms of the radiation reaction of the particles involved, without explicit reference to the ZPF. For this viewpoint see Milonni, P.W., 1982. *Phys. Rev.*, A **25**, 1315. Although it is sometimes assumed that the radiation–reaction approach might imply that the ZPF fields do not exist, detailed analysis (see Milonni's paper) shows that even though the interpretation of ZPF effects "can be given exclusively in terms of either radiation reaction or the zero–point field, *both fields are in fact necessary for the formal consistency of the theory*." (Italics his). The interrelationship between these two approaches (ZPF, radiation reaction) can be shown to be complementary on the basis of an underlying fluctuation–dissipation theorem.

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