Assessment of proposed electromagnetic quantum vacuum energy extraction methods

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Abstract

In research articles and patents several methods have been proposed for the extraction of zero-point energy from the vacuum. None has been reliably demonstrated, but the proposals remain largely unchallenged. In this paper the feasibility of these methods is assessed in terms of underlying thermodynamics principles of equilibrium, detailed balance, and conservation laws. The methods are separated into three classes: nonlinear processing of the zero-point field, mechanical extraction using Casimir cavities, and the pumping of atoms through Casimir cavities. The first two approaches are shown to violate thermodynamics principles, and therefore appear not to be feasible, no matter how innovative their execution. The third approach does not appear to violate these principles.

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I. INTRODUCTION

Physical effects resulting from zero-point energy (ZPE) are well established.[1] This has led to several proposals and reviews discussing the extraction of ZPE to use as a power source.[2, 3, 4, 5, 6, 7, 8, 9] To someone reading these research papers and patents it may not be clear which of these approaches might have merit and which would violate fundamental physical law. The purpose of this paper is to analyze ZPE extraction proposals to determine whether the extraction approaches describe are, in principle, feasible. The methods are divided into three classes, and the underlying principle of operation of each is assessed.

The ZPE extraction methods usually involve ZPE in the form of electromagnetic zero-point fields (ZPFs). The energy density of these ZPE vacuum fluctuations is[10]

$$\rho(h\nu) = \frac{8\pi\nu^2}{c^3}\left(\frac{h\nu}{\exp(h\upsilon/kT)-1} + \frac{h\nu}{2}\right) \tag{1}$$

where ν is the frequency, and k is Boltzmann's constant. The first term in the large brackets describes Planck radiation from a black body at temperature T. As T approaches zero or at room temperature at frequencies above 7 THz, the energy density is dominated by the second, temperature-independent term, which is due to zero-point energy. For high frequencies this energy density is huge, but how large depends upon the frequency at which the spectrum cuts off, a matter that is not resolved.

Two physical manifestations of the ZPF that will be discussed in this paper are zero-point noise fluctuations and the force between Casimir cavity plates. The available noise power in a resistance R per unit bandwidth is[11]

$$\frac{\Delta V^2}{4R} = \frac{h\nu}{\exp(h\nu/kT) - 1} + \frac{h\nu}{2} \quad . \tag{2}$$

The first term on the right-hand side is the thermal noise, which is approximated at low frequencies by the familiar Johnson noise formula. The second term, usually called quantum noise, is due to zero-point fluctuations. This physical manifestation of the ZPF dominates the noise at low temperatures and high frequencies.

A second physical manifestation is evident with a Casimir cavity, which consists of two closely-spaced, parallel reflecting plates.[12] As a result of the requirement that the tangential electric field must vanish (for an ideal reflector) at the boundaries, limits are placed on which ZPF modes are allowed between the plates, and those modes having wavelengths longer than twice the gap spacing are excluded. The full spectrum of ZPF modes exterior to the plates is larger than the constrained set of modes in the interior, with the result that a net radiation pressure pushes the plates together. The resulting attractive force between the plates is[13]

$$F(d) = -\frac{\pi^2 \hbar c}{240 d^4} \tag{3}$$

where d is the gap spacing. For this force to be measurable with currently available experimental techniques, d must be less than 1 μm.

The benefits of tapping ZPE from the vacuum would be tremendous. Assuming even a conservative cutoff frequency in Eq. (1), if just a small fraction of this energy were available for extraction the vacuum could supply sufficient power to meet all our needs for the foreseeable future. Cole and Puthoff[14] have shown that extracting energy from the vacuum would not, in principle, violate the second law of thermodynamics, but that is not equivalent to stating that extraction is feasible, nor do they attempt to describe how it could be accomplished. There is no verifiable evidence that any proposed method works.[15]

In this article, I assess different methods that have been proposed to extract usable ZPE. I do not examine proposed methods to use ZPE forces as a means to enhance or catalyze the extraction of energy from other sources, such as chemical or nuclear energy. I separate the different vacuum energy extraction approaches into three classes: nonlinear extraction, mechanical extraction, and pumping of gas. I analyze each to see if the underlying principles of operation are consistent with known physical principles, and then draw conclusions about the feasibility of the ZPE extraction.

II. ANALYSIS

A. Nonlinear processing of the zero-point field

1. Rectification of zero-point fluctuations in a diode

Several suggested approaches to extracting energy from the vacuum involve nonlinear processing of the ZPF. In general, a nonlinear process is irreversible, i.e., once a signal undergoes a nonlinear change there is no direct way for it to revert to its original state. For that reason, it is attractive to consider applying a nonlinear process to the ZPF because it is then converted from its high-frequency form, and hence is available to do work. One particular nonlinear process is electrical rectification, in which an alternating (AC) waveform is transformed into a direct (DC) one.

Valone[9] describes the electrical noise in resistors and diodes that results from zero-point fluctuations. He discussed the use of diodes to extract power from these ambient fluctuations, and compares this to diodes used for thermal energy conversion. For example, in thermophotovoltaics radiation from a heated emitter is converted to electricity. In Valone's case, however, the source is under ambient conditions. Valone is particularly interested in the use of zero-bias diodes used for zero-point energy harvesting, so as to rectify the ambient fluctuations without having to supply power in providing a voltage bias to the diodes.

This nonlinear extraction represents a sort of Maxwell's demon.[16] In 1871 Maxwell developed a thought experiment in which a tiny demon operates a trapdoor to separate gas in equilibrium into two compartments, one holding more energetic molecules and the other holding less energetic ones. Once separated, the resulting temperature difference could be used to do work. This is a sort of nonlinear processing, in which the system, consisting of the demon and the compartments, operates differently on a molecule depending upon its thermal energy. In the fourteen decades since its creation, innovative variations on the original demon have been proposed and then found to be invalid. Despite the best efforts of Maxwell's demon and his scrutineers,[17] there still is no experimental evidence for the demon's viability.

It is generally agreed that the demon cannot carry out his fiendish act of separation with thermal noise fluctuations, because such fluctuations are in a state of thermal equilibrium with their surroundings.[18] These thermal fluctuations are described by the first term on the right-hand side of Eq. (2). In equilibrium, the second law of thermodynamics applies and no system can extract power continuously. All processes in such a system are thermodynamically reversible. A detailed balance description of the kinetics of such a situation was developed by Einstein to explain the relationship between the emission and absorption spectra of atoms,[19] and generalized by Bridgman.[20]

The difference between detailed balance and steady state is illustrated with the three-state system shown in Fig. 1. Each arrow represents a unit of energy flux. In the steady-state case shown in Fig. 1(a), the total flux into any state equals the total flux out of it. Under equilibrium, however, a more restrictive detailed balance must be observed, in which the flux between any pair of states must balanced. This is depicted in Fig. 1(b).

This concept of detailed balance can be applied to the extraction of thermal noise from a resistor at ambient (equilibrium) temperature. To optimally transfer power from a source, in this case the noisy resistor, to a load the load resistance should be adjusted to match that of the source. In that case, the load generates an equal noise power to that of the source, and an equal

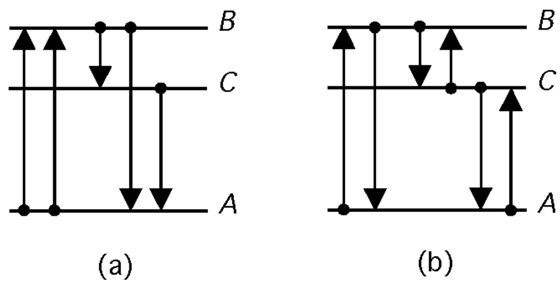

Fig. 1. Illustration of detailed balance. In this three-state system each arrow represents one unit of energy flux. The system in (a) is in steady state, such that the total flux into each state equals the total flux out of it. In system (b) not only does the steady-state condition apply, but the more restrictive detailed balance applies, in which the flux between each pair of states is balanced.

power is transferred from the load to the source as was transferred from the source to the load. Because of this detailed balance, no net power can be extracted from a noisy resistor.

To analyze the case of extracting energy from thermal noise fluctuations in a diode, consider the energy band diagram for a diode shown in Fig.2, where transitions among three different states are shown. For simplicity, five other pairs of transitions are not shown and are assumed to have negligible rates.[21]

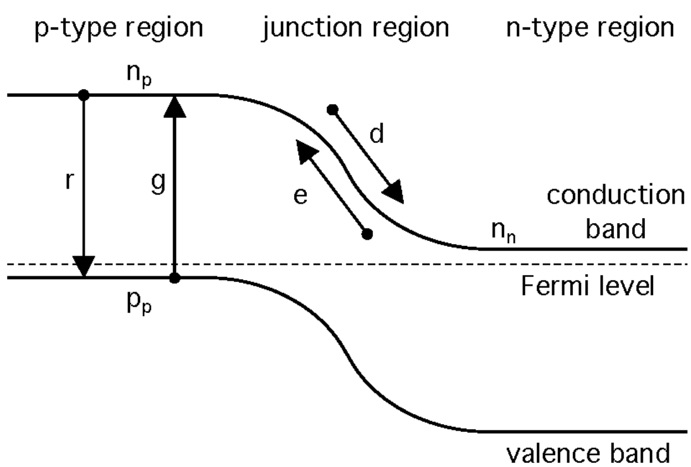

Fig. 2. Diode energy band diagram. Shown are electron transitions between the conduction and valence bands in the p-type region, corresponding to generation rate *g*, and recombination rate *r*. Also shown are electron transitions between n-type and p-type conduction band states, corresponding to excitation rate *e*, and drift rate *d*. This diagram is used in the text to illustrate photovoltaic carrier collection, rectification of thermal fluctuations, and also rectification of zero-point energy fluctuations as proposed by Valone.[9]

I first consider the case of photovoltaic power generation. If the diode operates as a solar cell, light absorbed in the p-type region generates electron-hole pairs, promoting electrons to the conduction band at a rate g that depends upon the light intensity and other factors. The photogenerated electrons diffuse to the junction region, where the built-in electric field causes them to drift across the junction to the n-type region at rate d. The recombination rate, r, and the excitation rate, e, are also shown. Because $g >> r$ and $d >> e$ under solar illumination, i.e., the system is far from equilibrium, there is a net flow of electrons to the n-type region, where they are collected to provide power.

The diode would operate in much the same way for rectifying thermal fluctuations under equilibrium, except that now g would represent the thermal generation rate. In this case, however, the generation rate and drift rate across the junction would be much smaller than under solar illumination. Under thermal equilibrium and in the absence of a Maxwell's demon to influence one of the processes, a detailed balance is strictly observed, such that $g = r$ and $d = e$. The second law of thermodynamics does not allow power generation.

Valone's proposal[9] makes use of power generation in a diode from ZPE fluctuations described by the second term on the right-hand side of Eq. (2). Whether this is feasible becomes a question of whether the zero-point energy in a diode is in a state of true equilibrium with its surroundings. It has been generally accepted that the "'vacuum' should be considered to be a state of thermal equilibrium at the temperature of T = 0."[14] Recently, using the principle of maximal entropy, Dannon has shown explicitly that zero-point energy does, in fact, represent a state of thermodynamic equilibrium.[22] Therefore it is clear that the detailed balance argument presented above for the case of thermal fluctuations also applies to ambient zero-point energy fluctuations, and a diode cannot rectify these fluctuations to obtain power.

2. Harvesting of vacuum fluctuations using a down-converter and antenna-coupled rectifier

A somewhat different approach to nonlinear processing of the ZPF for extracting usable power would be to use an antenna, diode and battery. The radiation is received by the antenna, rectified by the diode, and the resulting DC power charges the battery. In the microwave engineering domain, this rectifying antenna is known as a rectenna.[23] Because of its ν^3 dependence, shown in Eq. (1), the ZPF power density at microwave frequencies is too low to provide practical power. Therefore to obtain practical levels of power, a rectenna must operate at higher frequencies, such as those of visible light or even higher. There are diodes that operate at petahertz frequencies. One example is metal/double-insulator/metal tunneling diodes[24] but the rectification power efficiency at such high frequencies is generally low.[25] The first question about ZPF rectification is how it can be made practical. The second, and more important question here, is whether this is feasible from fundamental considerations. I address these in turn.

A nonlinear processing method to extract ZPE is proposed in a 1996 patent by Mead and Nachamkin,[4] which describes an invention to down-convert high-frequency ZPF to lower frequencies where it is more practical to rectify. The invention includes resonant spheres that intercept ambient ZPF and build its intensity at their resonant frequency. The high-intensity oscillation induces nonlinear interactions in the spheres such that a lower-frequency radiation is emitted from them. This down-converted radiation is then absorbed by an antenna and rectified to provide DC electrical power. The invention is depicted in Fig. 3.

Mead and Nachamkin's approach can be broken down into three steps:

a) Down-conversion of the ambient ZPF;
b) Concentration of the down-converted radiation at the diode by the antenna;
c) Rectification of the down-converted, concentrated radiation by the diode.

Step (a) is a nonlinear process like that performed by the diode described in the previous section, except that in the current case the ZPF is down-converted to an intermediate frequency whereas in the previous case the ZPF fluctuations in a diode were down-converted to DC. Therefore this step must observe a detailed balance of rates. Regarding steps (b) and (c), under equilibrium a source, antenna and load are in detailed balance, such that the power received by the antenna from the source and transferred to a load is equal to the power transmitted back to the source.[26]

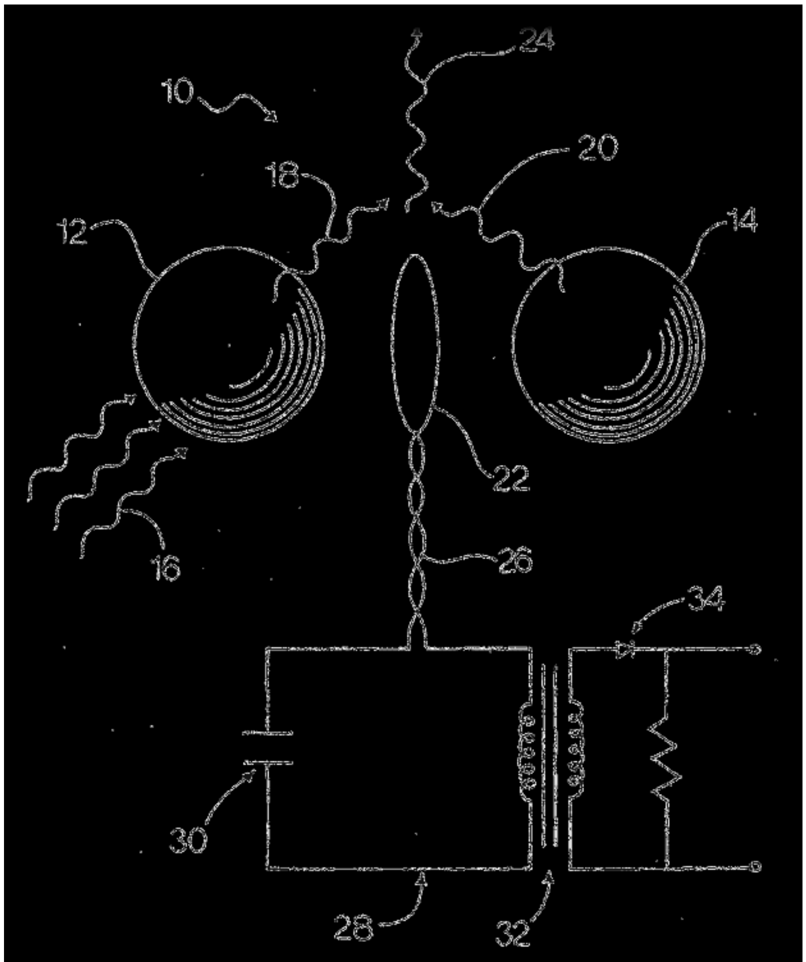

Fig. 3. Mead and Nachamkin's invention[4] for down-converting, collecting, and rectifying zero-point field radiation. The non-identical resonant spheres interact with ambient zero-point fields to produce radiation at a beat frequency. This radiation is absorbed in the loop antenna and rectified in the circuit.

If steps (a) and (b) could provide a greater-than-equilibrium concentration of power to the diode, then the diode in step (c) would no longer be operating under equilibrium and would not be constrained by the second law of thermodynamics to a detailed balance of rates, so that power could in principle be harvested. However, as argued above, the concentration of power at the diode cannot occur under equilibrium. In summary, when applied to the harvesting of vacuum fluctuations each of the three steps in the ZPF down-converter system is subject to a detailed balance of rates, and therefore the system cannot provide power.

3. Nonlinear processing of background fields in nature

If nonlinear processing of ZPF were sufficient to extract energy, one would expect to see the consequences throughout nature. Naturally occurring nonlinear inorganic and organic materials would down-convert ZPF, for example, to the infrared. The result would be constant warmth emanating from these nonlinear materials. Such down-conversion may exist, but through detailed balance there must be an equal flux of energy from the infrared to higher-frequency background ZPF.

For ZPF to provide usable power an additional element must be added beyond those providing nonlinear processing of ambient fields.

B. Mechanical extraction using Casimir cavities

The attractive force between two closely spaced conducting, i.e., reflecting, plates of a Casimr cavity was predicted by Casimir in 1948,[12] and is given by Eq. (3). This attractive force was later shown to apply also to closely spaced dielectric plates,[27] and becomes repulsive under certain conditions.[28] The potential energy associated with the Casimir force is considered next as a source of extractable energy.[5, 6]

The simplest way to extract energy from Casimir cavities would be to release the closely spaced plates so that they could accelerate together. In this way, the potential energy of the plate separation would be converted to kinetic energy. When the plates hit each other, their kinetic energy would be turned into heat. The Casimir cavity potential would be extracted, albeit into high-entropy thermal energy. If this energy conversion could be carried out as a cyclic process, electrical power obtained from this heat would be subject to the limitations of the Carnot efficiency,

$$\eta_{\max} = \frac{T_h - T_c}{T_h} \tag{4}$$

where T_h is the temperature of hot source and T_c is the temperature of the cold sink.

1. Energy exchange between Casimir plates and an electrical power supply

In 1984 Forward described a different concept[2] for extracting energy from the mechanical motion of Casimir plates, one that maintains the low entropy of the Casimir cavity's potential energy through the extraction process. A coiled Casimir plate is shown in Fig. 4. The attractive Casimir force between spaced-apart coils of the Casimir plates is nearly balanced by the injection of electric charge from an external power supply causing the plates to repel each other. As the plates move together due to the attractive Casimir force, they do work on the repulsive charge, resulting in a charge flow and transfer of energy to the power supply. In this way, the coming together of the Casimir plates provides usable energy, and maintains the low entropy of the original attractive potential energy. Forward made no attempt to show how this would provide continuous power, since once the plates came together all the available potential energy would be used up.

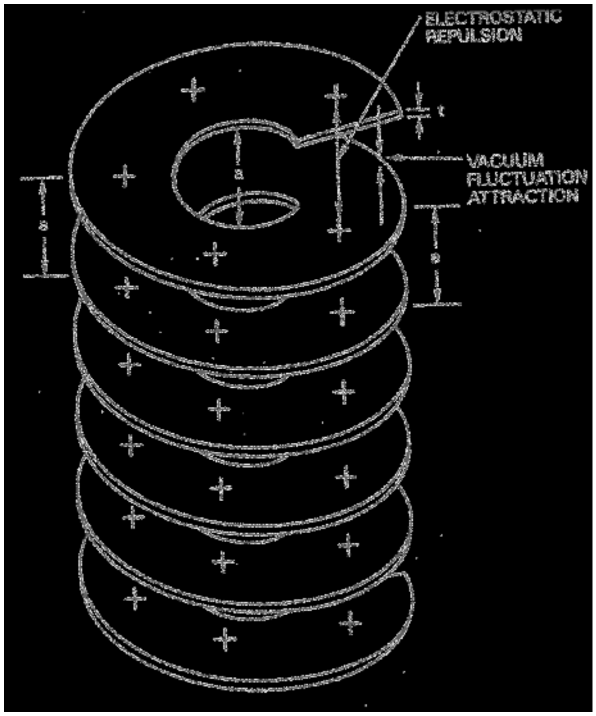

Fig. 4. Slinky-like coiled Casimir cavity, as conceptualized by Forward.[2] He used this device concept to demonstrate how one might convert the vacuum fluctuation potential energy from Casimir attraction to electrical energy. As the plates approach each other the repulsion of positive like-charges results in a current that charges up an external power supply.

2. Cyclic power extraction from Casimir cavity oscillations

In a series of publications, Pinto proposed an engine for the extraction of mechanical energy from Casimir cavities.[6] His concept makes use of switchable Casimir cavity mirrors. A schematic depiction of the process is shown in Fig. 5. In step (a) the Casimir cavity plates are allowed to move together in response to their attraction, and the reduction in potential energy is extracted (for example, by the Forward method). In step (b) one of the plates is altered to change its reflectivity. Because of the altered state, the attractive Casimir force is reduced or reversed and the plates can then be separated using less energy than was extracted when they came together, as depicted in step (c). After they are separated, the plates are restored to their original state, and the cycle is repeated. Puthoff analyzed a system of switchable Casimir cavity mirrors and calculated the potential power that could be produced by Casimir plates as a function of vibration frequency and mass.[29]

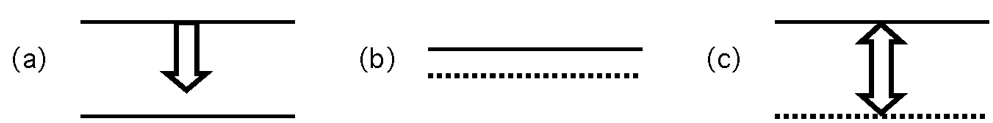

Fig 5. Casimir cavity engine for the cyclic extraction of vacuum energy, similar to system proposed by Pinto.[6] In step (a) the Casimir plates move together in response to Casimir attraction, producing energy that is extracted. In step (b) the lower plate is altered to reduce its reflectivity and hence reduce the Casimir attraction. In step (c) the plates are pulled apart, using less energy than was obtained in step (a), and then the cycle is repeated.

Pinto's approach cannot work if the Casimir force is conservative. If so, no matter what process were used to separate the plates, it would require at least as much energy as had been extracted by their coming together. For example, in step (b) shown in Fig. 5, electrical charge might be drained from at least one of the plates to modify its reflective property. This would reduce the Casimir attraction and allow the plates to be pulled apart with minimal force, after which charge would be injected back into the plates to reestablish the Casimir attraction. For a conservative force, the minimum energy required for this draining and injecting back of the electrical charge is the energy that could be obtained from the attractive force of the plates moving together. Alternatively, exposing a plate to hydrogen may be used to change its reflectivity[30] and hence the attraction between plates. If the force is conservative then the hydrogenation/de-hydrogenation cycle would require at least as much energy as could be extracted from the Casimir-plate attraction, and the system cycle could not produce power. A similar situation to that of Casimir force exists with standard electric forces, which clearly are conservative. The electric attraction induced by opposite charge on two capacitor plates cannot produce cyclic power.

In one analysis, a Carnot-like cycle was used to show that the Casimir force did not appear to be conservative,[6] so that it would be possible to extract cyclic power. However, from an analysis of each of the steps in the cycle, Scandurra found that the Casimir force is conservative after all, consistent with the general consensus, and that the method cannot produce power in a continuous cycle.[31]

Generalizing from the conservative nature of the Casimir force, it appears that any attempt to obtain net power in a cyclic fashion from changing the spacing of Casimir cavity plates cannot work.

One might ask if it is possible to use ZPE to do the work on the Casimir plates necessary to reduce the attractive force or to convert it to a repulsive force. In this way, could a continuous cycle provide power? If such a ZPE-powered process were developed, net power could be extracted. However, the power would then be coming from the process that modified the Casimir plates rather than from cycling the spacing of the Casimir cavity plates.

C. Pumping atoms through Casimir cavities

1. Zero-point energy ground state and Casimir cavities

There is a fundamental difference between the equilibrium state for heat and for ZPE. It is well understood that one cannot make use of thermal fluctuations under equilibrium conditions. To use the heat, there must be a temperature difference to promote a heat flow to obtain work, as reflected in the Carnot efficiency of Eq. (4). We cannot maintain a permanent temperature difference between a hot source and a cold sink in thermal contact with each other without expending energy, of course.

Similarly, without differences in some characteristic of ZPE in one region as compared to another it is difficult to understand what could drive ZPE flow to allow its extraction. If the ZPE represented the universal ground state, we could not make use of ZPE differences to do work. But the entropy and energy of ZPE are geometry dependent.[32] "The vacuum state does not have a fixed energy value, but changes with boundary conditions."[33] In this way ZPE fluctuations differ fundamentally from thermal fluctuations. Inside a Casimir cavity the ZPF density is different than outside. This is a constant difference that is established as a result of the different boundary conditions inside and out. A particular state of thermal or chemical equilibrium can be characterized by a temperature or chemical potential, respectively. For an *ideal* Casimir cavity having perfectly reflecting surfaces it is possible to define a characteristic temperature that describes the state of equilibrium for zero-point energy and which depends only on cavity spacing.[31] In a real system, however, no such parameter exists because the state is determined by boundary conditions in addition to cavity spacing,[34] such as the cavity reflectivity as a function of wavelength, spacing uniformity, and general shape.

The next approach to extracting power from vacuum fluctuations makes use of the step in the ZPE ground state at the entrance to Casimir cavities.

According to stochastic electrodynamics (SED), the energy of classical electron orbits in atoms is determined by a balance of emission and absorption of vacuum energy.[35] By this view of the atom, electrons emit a continuous stream of Larmor radiation as a result of the acceleration they experience in their orbits. As the electrons release energy their orbits would spin down were it not for absorption of vacuum energy from the ZPF. This balancing of emission and absorption has been modeled and shown to yield the correct Bohr radius in hydrogen.[36] Accordingly, the orbital energies of atoms inside Casimir cavities should be shifted if the cavity spacing blocks the ZPF required to support a particular atomic orbital.

A suitable term for this is the “Casimir-Lamb shift”. The energy levels of electron orbitals in atoms are determined by sets of quantum numbers. However the electromagnetic quantum vacuum can change these energies, as exhibited in the well known Lamb shift. In the case of the Lamb shift the nucleus of the atom (a single proton for hydrogen) slightly modifies the quantum vacuum in its vicinity. The result is that the $2P_{1/2}$ and $2S_{1/2}$ orbitals, which should have the same energy, are slightly shifted since they spread over slightly different distances from the nucleus, and hence experience a slightly different electromagnetic quantum vacuum. The electromagnetic quantum vacuum can be altered in a much more significant way in a Casimir cavity. Hence the term, Casimir-Lamb shift.

Currently, only a semi-classical analysis using SED has been used to predict this shift of orbital energies. Although much of SED theory has been applied successfully in producing results that are consistent with standard quantum mechanics, there have not been any reports yet in which this Casimir-Lamb shift has been replicated using quantum electrodynamics. An exploratory experiment to test for a shift in the molecular ground state of H_2 gas flowing through a 1 μm Casimir cavity was carried out, but without a definitive result.[37]

2. The extraction process

In a 2008 patent,[8] Haisch and Moddel describe a method to extract power from vacuum fluctuations that makes use this effect of Casimir cavities on electron orbitals. The process of atoms flowing into and out from Casimir cavities is depicted in Fig. 6. In the upper part of the loop gas is pumped first through a region surrounded by a radiation absorber, and then through a Casimir cavity. As the atoms enter the Casimir cavity, their orbitals spin down and release electromagnetic radiation, depicted by the small outward pointing arrows, which is extracted by the absorber. On exiting the cavity at the top left, the ambient ZPF re-energizes the orbitals, depicted by the small inward pointing arrows. The gas then flows through a pump and is re-circulated through the system. The system functions like a heat pump, pumping energy from an external source to a local absorber.

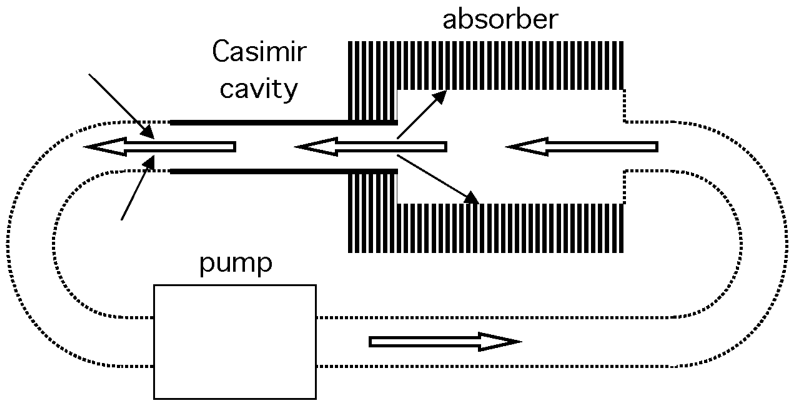

Fig. 6. System to pump energy continuously from the vacuum, as proposed by Haisch and Moddel.[8] As gas enters the Casimir cavity the electron orbitals of the gas atoms spin down in energy, emitting Larmour radiation, shown as small arrows pointing outwards. The radiant energy is absorbed and extracted. When the atoms exit the Casimir cavity, the atomic orbitals are recharged to their initial level by the ambient zero-point field, shown by the inward pointing small arrows.

3. Violations of physical law

In examining whether this process violates any physical laws, I first ask whether it conflicts with the conservative nature of the Casimir force. It does not because although Casimir plates are used, they do not move as part of the process. Therefore, this process differs from the mechanical process described earlier which does make use of cyclic Casimir plate motion in an attempt to extract power from Casimir attraction.

Next comes the question as to whether there is a detailed balance that would render the process invalid. If the gas were stationary, then we would expect a detailed balance of radiation to exist between the atoms and their environment at the entrance and exit to the cavity. However, the gas is flowing and in such a dynamic situation there is no requirement for detailed balance.

Might there be a different sort of balance, in which the energy that is radiated as the gas enters the cavity is simply reabsorbed as the gas exits, leaving no net energy to do work? The asymmetry of the system prevents that from occurring. The local absorber at the entrance intercepts the emitted radiation, while the lack of a local absorber at the exit allows the gas to interact with more distant ZPFs. A potential flaw in this argument of a separation between emission and absorption might be that vacuum fluctuations are non-local and connect distant locations. Not enough is known about ZPF to determine whether this is a serious possibility, and there is no evidence at this time that it is non-local.[38]

Another question is whether the radiated power extracted at the entrance to the Casimir cavity is used up in pumping gas through the system. There are two parts to the pumping power requirement, the power required to pump the gas through the cavity, and the power required to pump into and out from the cavity:

a) The power required to pump the gas through the cavity is known from studies of gas flow through nanopores,[39] and shown in the patent[8] to be less than 1% of the power that may be obtained from the process.
b) There are two consideration regarding the power required to pump the gas into and out from the cavity:

i. Given that the atoms are in a lower energy state inside the cavity than outside, there may be a force required to pump the gas out from the cavity. Since that same force presumably would attract the gas into the cavity these two forces should cancel in steady-state operation.

ii. According to SED, the atoms about to enter the cavity have fully energized electronic orbitals, whereas the atoms about to exit have lower energy orbitals. This difference in the state of the atoms might contradict argument made just previously that the pumping force in and pumping force out cancel each other. On the other hand, the orbital energetics of the atoms should have no direct effect on the inter-atomic forces of the gas,[40] and so should not increase the power required to pump the gas through the system.

There are some ambiguities here, but taken as a whole it does not appear that the radiated power extracted at the entrance to the Casimir cavity is required to power the circulation pump.

In summary, the gas-flow process does not require Casimir plates to move, is not subject to detailed balance, provides asymmetry to separate emission from absorption, and does not require substantial pumping power. There appear to be no fundamental violations of physical law that would preclude the pumping of gas through Casimir cavities from being used to extract ZPE from the vacuum. Whether this approach will work in practice is not yet known.

III. CONCLUSIONS

The tremendous energy density in the zero-point field (ZPF) makes it very tempting to attempt to tap it for power. Furthermore, the fact that these vacuum fluctuations may be distinguished from thermal fluctuations and are not under the usual thermal equilibrium make it tempting to try to skirt second law of thermodynamics constraints. However, zero-point energy (ZPE) is in a state of true equilibrium, and the constraints that apply to equilibrium systems apply to it. In particular, any attempt to use nonlinear process, such as with a diode, cannot break thermodynamic reversibility in a system in equilibrium. Detailed balance arguments apply.

The force exhibited between opposing plates of a Casimir cavity makes it temping to make use of the potential energy to obtain power. Unfortunately, the Casimir force is conservative. Therefore in any attempt to obtain power by cycling Casimir cavity spacing the energy gained in one part of the cycle must be paid back in another.

We treat thermal fluctuations, usually thought of as an expression of Planck's law, and ZPE vacuum fluctuations, usually associated with the ground state of a quantum system, as if they were separate forms of energy. However, the ZPE energy density given in equation (1) may be re-expressed in the form[41]

$$\rho(h\upsilon) = \frac{4\pi\upsilon^2}{c^3}\coth\frac{h\upsilon}{2kT} . \tag{5}$$

The fact that these two seemingly separate concepts can be merged into a single formalism suggests that thermal and ZPE fluctuations are fundamentally similar. More rigorously, Planck's law can be seen as consequence of ZPE,[42] and is "inherited" from it.[43] In more than a century of theory and experimentation we have not been able to extract usable energy from thermal fluctuations, and it might seem that we are destined to find ourselves in a similar situation with attempts to extract usable energy from ZPE.

There is, however, a distinction that can be drawn between the two cases, which has to do with the nature of the ZPE equilibrium state. The equilibrium ZPE energy density is a function of the local geometry. Two thermal reservoirs at different temperatures that are in contact with each other cannot be in equilibrium; heat will flow from one to the other. Two ZPE reservoirs having different energy densities that are in contact with each other can, however, be in equilibrium. For example, a Casimir cavity can be in direct contact (open at its edges) with the free space surrounding it such that the ZPE density inside and outside the cavity are different without any net flow of energy between the two regions. Furthermore, extracting ZPE from the vacuum does not violate the second law of thermodynamics.[14]

Our apparent lack of success in extracting energy from the vacuum thus far leads to two possible conclusions. Either fundamental constraints beyond what have been discussed here and the nature of ZPE preclude extraction, or it is feasible and we just need to find a suitable technology.

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