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THE ROLE OF THE QUANTUM VACUUM IN SPACE TRAVEL

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One of the cornerstones of modern physics is quantum electrodynamics (QED), which is the relativistic version of quantum theory. Quantum electrodynamics, which has made predictions experimentally verified to 1 part in 10 billion, makes the surprising prediction that empty space, devoid of all matter and at absolute zero in temperature, contains a random fluctuating virtual photon field of all frequencies that has a nearly infinite energy density. Although it does not appear possible to observe the ground state of the electromagnetic field directly, it is possible to observe its effects, for example, on energy levels and lifetimes of excited atoms and the magnetic moment of the electron. Quantum vacuum forces between nearby neutral surfaces, referred to as Casimir forces, have been measured and found to agree with predictions. If this ground state radiation pressure or energy could be utilized for propulsion, propellantless propulsion would be possible, using a universally available energy source. Vacuum energy density appears to have the same basic properties as other forms of energy except the vacuum energy density. Vacuum energy can be negative, which occurs when surfaces or other means have reduced the energy density so it is below the value corresponding to empty space. The equivalent mass would be negative and be repelled by a gravitational field, leading to interesting possibilities for propulsion. Different approaches to utilizing vacuum energy in propulsion will be outlined. Restrictions due to the conservation of energy and momentum are discussed. To date, all methods of modifying the vacuum deal only with the long wavelength or low energy photons, so the changes in the vacuum energy density are disappointingly small. Before engineers can develop a useful quantum vacuum drive, we need to discover new boundary conditions on the vacuum.

Keywords: Propulsion, Vacuum fluctuations, Casimir force, sails, MEMS, microelectromechanical systems

1. INTRODUCTION

What we know about the quantum vacuum is tantalizing enough to suggest that the quantum vacuum may be an integral part of starship propulsion: 1) Enormous energy is contained within the vacuum, in the form of vacuum fluctuations, according to quantum electrodynamics, which has always agreed with experiment. If we are clever enough, we may be able to utilize this energy in space travel; 2) The quantum vacuum is involved in many fundamental physical processes, including the creation of mass, atomic energy levels, spontaneous emission, the appearance of quantum forces arising from changes in vacuum energy density, such as Casimir forces, and these forces might be involved in propulsion; 3) The quantum vacuum is a link to the fabric of time and space through general relativity. Changes in vacuum energy may be involved in space warp drives or changes in inertia, or in the expansion of the universe (effect of the cosmological constant) and dark energy; 4) Other properties of the vacuum, such as the ability to generate photons from the vacuum by an accelerating surface, and some properties yet to be discovered, may prove important. The role of the quantum vacuum is pervasive in modern physics, and there are many possibilities and many questions. Quantum Electrodynamics or QED predicts the behaviour of the quantum vacuum, including vacuum forces and the presence of a vast energy in empty space due to a fluctuating electromagnetic field [1]. The present state of our knowledge and some possible directions for the future will be discussed.

Other technologies, such as fusion, interstellar ramjet, matter-antimatter annihilation, light sails, particle beams, have been considered for use in the first interstellar mission [2]. One of these technologies is probably more likely to be used than vacuum energy in the first spacecraft to travel to another star system. Although nuclear energy densities are orders of magnitude greater than chemical energy densities, they are small compared to vacuum energy densities. If the properties of the quantum vacuum could somehow be utilized effectively in the production of thrust, that would provide a decided advantage since the vacuum is everywhere with an enormous energy density. It is important to try to distinguish between what appears possible and what appears impossible within the context of our current understanding of quantum physics and the fundamental laws of physics, particularly conservation of momentum and energy [3, 4, 5].

The discussion illustrates many important ideas about the quantum vacuum, and it suggests potential roles of quantum vacuum phenomena in a macroscopic system like space travel. In fact, with a breakthrough in materials, methods, or fundamental understanding, some of the approaches suggested could become practical, and we might be able to realize the dream of space travel as presented in science fiction works. Science fiction writers have written about the use of the quantum vacuum to power spacecraft for decades but no research has validated this suggestion. Arthur C. Clarke described a "quantum ramjet drive" in 1985 in "Songs of Distant Earth", and observed in the Acknowledgement, "If vacuum fluctuations can be harnessed for propulsion by anyone besides science-fiction writers, the purely engineering problems of interstellar flight would be solved" [6]. American science fiction writer Ken Ingle described, with my fanciful suggestions, the Casimir Vacuum Drive in his

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book "First Contact" [7]. There have been numerous papers on space warps and drives that often presuppose the ability to generate material with negative mass, or generate macroscopic gravitational fields by manipulation of vacuum energy [8]. Unfortunately, most of these fascinating possibilities are well beyond any technology that we can foresee for decades.

On the other hand, in the last ten years great progress has been made in understanding and measuring Casimir forces, which arise between closely spaced surfaces due to the quantum fluctuations of the electromagnetic field, the quantum vacuum [9]. Although the forces tend to be small, practical applications of vacuum forces have recently appeared in MEMS (MicroElectroMechanical Systems) devices.

2. PHYSICS OF THE QUANTUM VACUUM

2.1 Historical Background

Quantum mechanics is one of the great scientific achievements of the twentieth century. It provides models that describe many properties of atoms and molecules, such as the optical spectra or transition probabilities. In its original form, as developed by Schrodinger, Heisenberg, Bohr, and others, quantum mechanics is a nonrelativistic theory that makes the ad hoc assumption that light is emitted and absorbed by atoms in bundles, called photons. The electromagnetic field, however, is treated in nonrelativistic quantum mechanics as an ordinary classical field that obeys Maxwell's equations, not as a quantized field with photons. Dirac, Heisenberg, Jordan, Dyson, and others began formulation of a relativistic form of quantum mechanics, called quantum electrodynamics, and made efforts to quantize the electromagnetic field. This quantized field theory of particles and light theory developed over the next few decades with numerous successful predictions.

One of the fundamental notions of quantum theory is the Heisenberg Uncertainty Principle, which demonstrates you cannot know the position and momentum of a particle simultaneously. Applying it to a mass on a spring (or a diatomic molecule) means that in the lowest energy state the mass cannot be stationary at the end of the spring since this would violate the Uncertainty Principle. The mass must maintain a minimum amount of vibratory motion, called the zero point motion, about its average position. Any two complementary quantum operators obey a generalized uncertainty principle. In the formulation of quantum electrodynamics, the electromagnetic field is quantized and the electric and magnetic components of the electromagnetic field are complementary quantum operators which obey a generalized uncertainty principle. Therefore, by the Uncertainty Principle, the electric and magnetic fields cannot vanish simultaneously. In the lowest state of the electromagnetic field, there are fluctuations in both the electric and magnetic fields. For decades physicists knew this prediction that vacuum energy filled empty space, but they thought that the vacuum fluctuations simply shifted the level of zero energy, and believed that there were no measurable physical consequences of the vacuum energy.

In 1948, Willis Lamb tested a crucial prediction of QED, that the 2s and 2p levels of a hydrogen atom would have precisely the same energy. He determined that the 2s and 2p energy levels were in fact split by an energy equivalent to 1000 MHz or about 4 μeV. Within days, Hans Bethe of Cornell realized the problem and published the solution: the theoretical calculation did not consider the effects of the quantum vacuum on the energy levels of the hydrogen atoms. This ushered in the modern formulation of quantum electrodynamics (QED) of Feynmann, Schwinger, and Toyonaka [10, 11, 12].

Quantum field theory implies that only the changes in vacuum energy from the nearly infinite free field values are meaningful experimentally, since it can compute these changes only, not the absolute value of the energy, which generally is divergent. For example, the Casimir energy density for a parallel plate geometry is defined as the difference between the free field vacuum energy density and the vacuum energy density between the plates.

Quantum fluctuations occur in the particle fields as well as the electromagnetic field, so the quantum vacuum is filled with virtual electron-positron pairs, as well as virtual photons. Before Lamb's Nobel Prize winning measurement, most physicists felt comfortable ignoring the effects of the quantum fluctuations. It turns out that quantum fluctuations affect virtually all physical processes, including the mass, charge, and magnetic moment of a particle, the lifetimes of excited atoms or particles, scattering cross sections, and the energy levels of atoms. In general the vacuum corrections are small but important. QED, which describes all the vacuum processes, has made experimental predictions of magnetic moments and energy levels that have been verified by experiment to 1 part in a ten billion, the most accurate predictions of any scientific theory.

2.2 Energy and Momentum in the Quantum Vacuum

Zero-point field energy density is a simple and inexorable consequence of quantum theory and the uncertainty principle [1], but it brings puzzling inconsistencies with another well verified theory, general relativity. The energy in the quantum vacuum in free space at absolute zero, which is the lowest energy state of the electromagnetic field, is due to the presence of virtual photons of energy $(1/2)\hbar\omega_n$ of all possible frequencies:

$$E_0 = \frac{1}{2}\sum_{n=0}^{n\max} \hbar\omega_n \tag{1}$$

Each ground state photon has one half of the energy of an ordinary photon of the same frequency, which is why the photons are described as virtual. Usually a cut off is used for the high frequencies, such as the frequency corresponding to the Planck Length of 10^{-34} *m*, which gives an enormous energy density (about 10^{114} J/m^3 or, in terms of mass, 10^{95} g/cm^3) Such a large energy would, according to the General Theory of Relativity, have a disastrous effect on the metric of space-time, causing an outward zero-point pressure that would rip the universe apart [13]. Astronomical data, on the other hand, indicate that any such cosmological constant must be ~4 eV/mm^3, or 10^{-29} g/cm^3 when expressed as mass [14]. There are numerous approaches to solve this cosmological constant problem, but ultimately the resolution probably requires either a reformulation of QED, in which the infinities are no longer dominant, or the integration of quantum electrodynamics and the general theory of gravitation. Either of these improvements would give us a better model of the vacuum.

Each virtual photon of frequency ω and wave vector $\vec{k}, (k = 2\pi/\lambda)$ has associated with it a momentum $(1/2)\hbar\vec{k}$. Since photons are in random directions, the mean momentum of the vacuum fluctuations vanishes, but, just as there are fluctuations in the electric and magnetic fields consistent with the uncertainty principle, there are fluctuations in the root mean square momentum. At finite temperatures, real photons begin to appear in the quantum vacuum, but their contribution to the total energy is much smaller than that of the virtual photons. The Casimir force between parallel plates arises because the plates establish a preferred direction in space, resulting in a net virtual momentum transfer and a measurable force.

2.3 Casimir Forces Predicted in 1948

About the same time as Lamb's experiment, Heindrick Casimir, director of research at Phillip's Laboratories in the Netherlands, published a paper predicting a macroscopic force due to the quantum vacuum. He showed that two parallel, uncharged, perfectly conducting metal plates in the quantum vacuum would attract each other because the plates change the modes of vibration of the ground state electromagnetic field between the plates. The modes present must meet the appropriate boundary conditions at each surface: the transverse electric field must vanish, so modes with wavelengths greater than half the separation between the plates are excluded. In actual practice, the modes with frequencies above the plasma frequency do not appear to be significantly affected by the metal surfaces since the metal becomes transparent to radiation above this frequency. If the change in vacuum energy is δen when the plate separation changes an amount δa then the vacuum force between the plates is

$$\delta \mathrm{en} = -F\delta a \tag{2}$$

For uncharged parallel plates with a large area A, very close to each other, an analysis of the vacuum modes predicts an attractive or negative force between the plates:

$$F/A = -\mathrm{K}/\mathrm{d}^4 \tag{3}$$

Where $\mathrm{K} = \pi^2\hbar c/240 = 1.3 \times 10^{-27}\ \mathrm{Nm}^2$, where ħ is Planck's constant, and c is the velocity of light. The Casimir force per unit area between perfectly conducting plates is equivalent to about 1 atm pressure at a separation of 10 nm, and so is a candidate for actuation of MEMS (MicroElectroMechanical Systems).

Two decades after Casimir's initial predictions, a method was developed to compute the Casimir force in terms of the local stress-energy tensor using quantum electrodynamics [15]. Many innovations have followed [1, 9, 16, 17]. Vacuum forces have been computed for other geometries besides the classic parallel plate geometry, such as a rectangular cavity, a cube, a sphere, a cylinder, a wedge. For a rectangular cavity, the Casimir force on each face may be inward, outward, or zero, depending on the ratio of the sides [18]. The maximum vacuum energy density due to surfaces appears to be a factor of about 5 to 10 times less than a typical chemical energy density.

It was not until about 1998, that the parallel plate Casimir force was measured accurately [19, 20]. In 1995 the first dynamic MEMS device with the Casimir effect was modelled [21] and built six years later [22]. Other interesting applications of Casimir forces in MEMS have appeared recently [23]. The Casimir force on semiconductors is of potential interest because the plasma frequency can be adjusted electrically, meaning the Casimir force could be controlled electrically [24, 25].

The application of Casimir forces in space propulsion is motivated especially by the interpretation of the parallel plate Casimir force as arising from virtual radiation pressure, the transfer of momentum from the virtual photons in the vacuum to the surfaces [26]. It is this virtual radiation pressure that we propose to explore as a possible driving force to generate net forces on an object, ultimately to propel a spacecraft.

2.4 Dynamic Casimir Effect

In the dynamic Casimir effect the parallel plates are imagined to move very rapidly, which can lead to an excited state of the vacuum between the plates, and the creation of real photons [9, 27, 28, 29]. When a photon is emitted, a back reaction occurs on the moving surface, resulting in a force tending to damp its motion [30]. In principle, this back reaction could be used to propel a spacecraft.

To understand this process from a physical perspective, imagine that in a real moving conductor the surface charges must constantly rearrange themselves to cancel out the transverse electric field at all positions. This rapid rearrangement of charge can lead to radiation. Recently an experiment was reported in which dynamic Casimir effect was observed in a superconducting circuit. The circuit consists of a coplanar transmission line with an electrical length that can be changed at a few percent of the speed of light by modulating the inductance of a superconducting quantum interference device (SQUID) at high frequencies (11 GHz) [31].

3. SPACE PROPULSION IMPLICATIONS

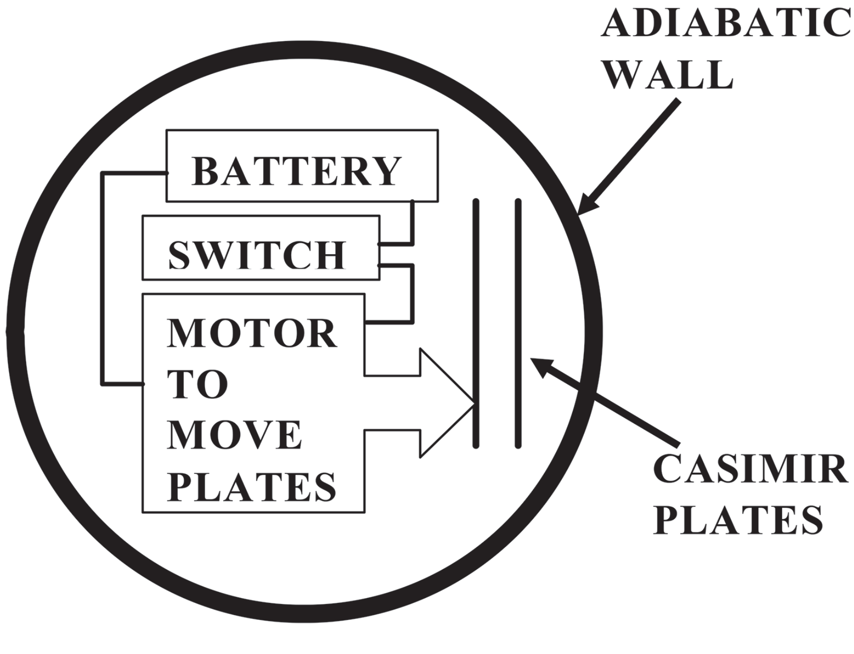
3.1 Properties of Vacuum Energy

Einstein showed using a gedanken experiment that an energy E could be associated with a rest mass m, where $E=\mathrm{mc}^2$. This equation implies that energy and mass are equivalent in their behaviour, for example in how they respond to gravity. Generally it is assumed that the mass m is the inertial mass and that it equals the passive gravitational mass by the Equivalence Principle. Newtonian mechanics and General Relativity assume that the inertial mass m, active gravitational mass, and passive gravitational mass are identical, positive and isotropic, and no experiments to date have contradicted these assumptions [32].

Vacuum energy may appear to be fundamentally different from other forms of energy, but gedanken experiments show that changes in vacuum energy have essentially the same properties as changes in other forms of energy [33], in agreement with several calculations for the parallel plate geometry [34, 35, 36, 37]. From these calculation and the gedanken experiments, it is consistent to conclude that changes in vacuum energy density result in changes in the effective mass.

The gedanken experiments are based on consideration of a device shown in Fig. 1, which illustrates a motor powered by a battery that can change the spacing between the Casimir plates inside [33]. When the plates move quasistatically, energy is exchanged between the quantum vacuum and the battery. We neglect all dissipative forces, and assume that conventional forms of energy cannot go through the adiabatic wall. Assume the sphere is in uniform motion. The question is, does the motion change when the motor moves the plates? Consideration of the equations of motion shows that if no external force acts on the sphere, its center of mass momentum and its energy remain constant, which means the velocity and inertial mass must remain constant. In other words, the chemical energy in the battery and the vacuum energy between the plates both contribute to the inertial mass in the same way.

Fig. 1 Schematic showing apparatus described in gedanken experiment, consisting of a motor/generator to alter the spacing between two parallel plates, and a battery to power the motor, a timer switch, all surrounded by a wall impervious to thermal energy and matter.



This gedanken experiment and other gedanken experiments discussed with the same sphere lead to the following conclusions:

1. Changes in vacuum energy contribute to the inertial mass like any other form of energy.
2. Changes in vacuum energy contribute to the gravitational field like any other form of energy (active gravitational mass).
3. Changes in vacuum energy contribute to the gravitational potential like any other form of energy (passive gravitational mass).

Vacuum energy density in a given region can be negative which simply means it is less than the free field energy density. If the energy is negative, then the associated mass is negative, so the force of gravity on it will be in the opposite direction from normal matter, which has a positive energy density. Thus negative vacuum energy regions will tend to rise in a gravitational field.

3.2 Using Vacuum Momentum and Energy for Propulsion

Conservation of energy and momentum place severe restrictions on what mechanisms may be utilized to propel spacecraft. For example, if a spacecraft is accelerating due to an interaction with the quantum vacuum, then it has to be removing energy from the quantum vacuum. Further the increase in kinetic energy must be equal to or be less than the decrease in energy in the quantum vacuum. In the analysis of any proposed approaches, we need to consider the momentum and energy of the field plus any objects in the field. Consider, for example, a mechanism in a spacecraft that alters the normally isotropic quantum vacuum energy density in a local region surrounding the spacecraft.

Let $E\left(\omega,\vec{r},\vec{r}_s\right)$ be the change in the vacuum energy density as a function of the frequency ω, the position $\vec{r}$ measured with respect to the centre of the sail, given by $\vec{r}_s$, which is measured with respect to some fixed location. If, in actual fact, this function $E\left(\omega,\vec{r},\vec{r}_s\right)$ does not depend on $\vec{r}_s$, but has the same shape no matter where the sail is located, then the change in vacuum energy due to the presence of the sail is constant. By the conservation of energy, the sail is moving at a constant velocity, and cannot experience a force due to its interaction with the quantum vacuum. In conclusion, if the change in vacuum energy does not depend on the position of the spacecraft, then the energy and momentum are constant. In terms of a nautical analogy, to be effective, a propulsion system based on vacuum energy must leave an expanding wake in the vacuum field.

The zero point electromagnetic field is isotropic, so the net mean momentum is zero. In order to make use of the momentum in the quantum vacuum, it is necessary to create an asymmetry in the photon momentum, for example, by parallel plates, so that the mean momentum is no longer zero.

It is possible to extract energy from the quantum vacuum [38, 39]. This can be done, for example, by allowing two parallel plates to slowly come together by the attractive Casimir force. As they approach each other, the motion is used to stretch a spring, which stores the vacuum energy extracted according the conservation of energy. The amount of energy removed is small, but one could imagine many sets of parallel plates oscillating at a high frequency to remove a large amount of energy. The problem with this approach is that when the plates are restored to their original separation, energy is supplied back to the quantum vacuum, so there is no net gain in energy. The electromagnetic field is normally a conservative field, and, to date, no one has developed a method that operates in a cycle and clearly removes a net amount of vacuum energy, well above noise levels. For an excellent review, see [40]. To illustrate the challenges, consider a few approaches that have been suggested. In the parallel plate case, after the plates have come closer together, extracting vacuum energy that is stretching a spring, one could imaging sliding the plates laterally before restoring them to the original separation, in hopes the Casimir force would be reduced since the plates would not be directly overlapping. Unfortunately a lateral Casimir force cancels out any gain, and the net energy extracted in a cycle is still zero [33].

Another approach is to use the fact that the energy levels of an atom are changed when the atom is placed in a cavity because the modes of the vacuum field are changed. Consider a system in which atoms are circulated continuously from one cavity, in which an atomic energy level is raised, to another cavity in which the level is lowered. The atom could be pumped to excite it to the desired atomic level when the level is lowered. Then the atom is moved physically to the cavity in which the energy level is higher. The level increases as expected due to the difference in modes of the vacuum fluctuations. There the atom is allowed to decay, emitting a photon with more energy than the photon used to pump the atom to the original level, so there is a net energy gain from the photon energy. What is the problem with this? One problem is that quantum forces are acting on the atom when it is moved from one region of vacuum energy to another and the work done to move it will cancel the net gain in photon energy. (No one has actually done this calculation, but the result is expected.) In a variation of this approach, the ground state level of the atom is shifted in a cavity.

These failures do not prove that it is impossible to obtain useful amounts of energy from the quantum vacuum. It means no one yet has solved this difficult problem.

3.3 Sails in the Vacuum

A variety of sail concepts have been proposed [41]. As we mentioned earlier, we can view the vacuum as a source of radiation pressure from virtual photons. The challenge is to design surfaces that alter the symmetry of the free vacuum and produce a net force. Consider for example, a sail made of two different materials on opposite sides, which absorb electromagnetic radiation differently. Can we expect a net force on the sail? A simple classical analysis as shown in Fig. 2 suggests the answer to this question [33].

For a given frequency, assume the radiation energy density is proportional to $cf(\omega,T)$, the net momentum transfer ΔP_ω to the top surface is

$$\Delta P_\omega = A_\omega f(\omega,T) + E_\omega f(\omega,T) + 2R_\omega f(\omega,T) \tag{4}$$

where A_ω is the absorptivity, E_ω is the emissivity, R_ω the reflectivity, and T the temperature. For a body in thermodynamic equilibrium, $A_\omega = E_\omega$ and by definition, $1 = A_\omega + R_\omega$. Using these restriction, it follows that $\Delta P_\omega = 2f(\omega, T)$, which is independent of the material properties. Therefore the force on the opposite side of the sail just cancels this force, and there is no net acceleration. This conclusion holds at every frequency. We assumed the temperature of the sail is the same on both sides because of the intimate contact. If the radiation spectrum corresponds to that at zero temperature, the zero point field, then both sides of the sail would be at zero Kelvin. On the other hand, if one made a sail in which a temperature gradient was maintained across the sail, a net force might occur, and it would be a function of the energy required to maintain the temperature difference.

There is a complication to this analysis: what happens if the sail is moving? If the radiation density is due solely to the quantum vacuum at zero temperature ($cf(\omega, O) = \hbar\omega^3/2\pi^2c^3$), then the spectral energy density the sail sees does not change with motion. The invariance of the zero point fluctuations with uniform motion is a special property of the zero point quantum vacuum. Without this property, one could distinguish a unique rest frame for the universe, violating the intent of special relativity. On the other hand, the thermal fields of real photons do not have this unique invariance. Hence uniform motion in a thermal field results in a Doppler shifted spectrum. For a sail, this means that the spectral energy density is different on the opposite sides of the sail, and it would be possible to obtain a net force. This is essentially the situation with a solar sail.

For the most general rigid, unpowered object in the vacuum field at zero temperature, consider that the Hamiltonian H of the object depends on the various internal coordinates corresponding to the objects geometry. We assume that because of the translational invariance of space that the energy of the object does not depend on the location of the centre of mass nor does it depend explicitly on time. It follows from the principles of Hamiltonian mechanics that the centre of mass momentum is conserved. This means either the mass is constant and the velocity is constant, or that the mass is being converted to kinetic energy, as in radioactive decay. The conclusion is that no rigid object will be accelerated by the quantum vacuum. A sail must contain dynamic elements if it is to develop a propulsive force.

By inserting surfaces into the vacuum, we can alter the spectrum of the vacuum fluctuations, which can result in net forces. Indeed, wherever there is an inhomogeneous vacuum energy density, there will be a net force on a polarizable particle given by

$$\frac{1}{2}\alpha\vec{\nabla}\left\langle E(x)^2\right\rangle$$

where α is the fine structure constant $e^2/\hbar c = 1/137$ [42].

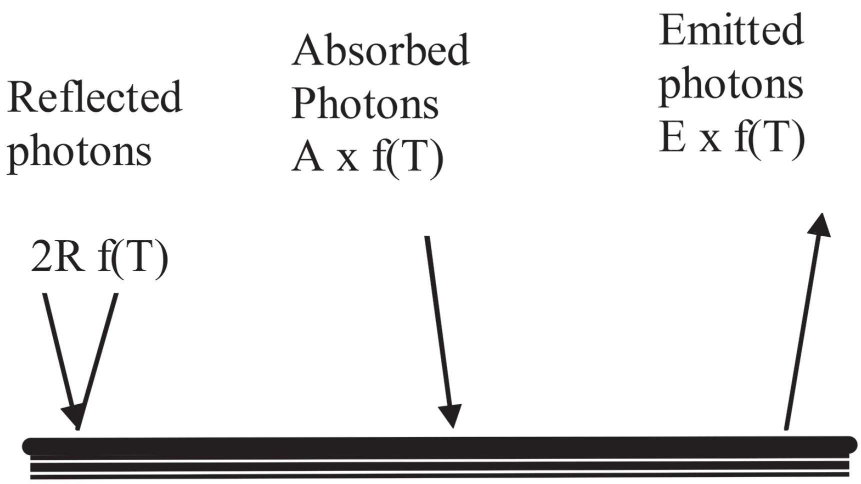


Fig. 2 Schematic of the momentum transfer from electromagnetic radiation to a sail made from different materials on the top and bottom.

Local changes in mode density and therefore vacuum energy density are induced by the presence of curved surfaces, and, depending on whether the curvature is positive or negative, the force between the surface and the particle may be repulsive or attractive [43]. From a propulsion viewpoint, this suggests the possibility of creating propagating regions of negative or positive energy density, or of ejecting particles to generate a propulsive force, among other possibilities.

3.4 Inertia Control by Altering Vacuum Energy Density

Proposals have been made to test the hypothesis that a negative vacuum energy leads to a reduction in mass by constructing stacks of parallel plate capacitors, however the predicted effect is just beyond current measurement capability [44]. From the theory, one can estimate the positive and negative mass contributions for a parallel plate capacitor made from plates that are only one hydrogen atom thick and one atom apart, and still the total energy is positive. Thus it appears that a parallel plate Casimir cavity will always have a positive energy density and cannot be used to create a zero or negative mass spacecraft, or initiate a wormhole. With more effective ways of reducing the vacuum energy, it might be possible to make a negative mass object or to significantly reduce inertia.

There is another variant of a negative mass drive that deserves mention. A system of charges that has a negative electrostatic potential energy ΔE would also, by the principles of general relativity, be expected to have a negative associated mass $\Delta E/c^2$ Thus in a gravitational field, there would be a levitating force, but it appears small in comparison with the total mass [45]. Negative energy drives are discussed more fully in [5].

4. DYNAMIC PROPULSION SYSTEMS

Dynamic propulsion systems, in which something moves, and interacts with the quantum vacuum, have the possibility of extracting energy and momentum from the vacuum. Hence these systems may be able to accelerate a space craft. The movement might be a macroscopic physical motion, or the motion of electrons within a semiconductor, or in a plasma, or possibly altering the plasma frequency or the dielectric constant. Electrically or magnetically controlled effective motion has the benefit of being must faster, possibly in the relativistic regime [31].

One of the major problems designing a dynamic system is that the computations can be very difficult. For many very simple geometries of interest, the vacuum forces have not been computed and in some cases no one yet knows how to compute them. Consider, for example, a small rectangular box but with dimensions of the order of 100 nm. The predicted vacuum energy density inside could be positive, negative or zero, depending on the relative dimensions. Imagine that the top was removed periodically. How would this affect the vacuum field? What would be the energy and momentum balance? It has yet to be calculated.

4.1 Vibrating Cavity Walls in MEMS Cavities

The unexpected behaviour of vacuum forces on the walls of a rectangular cavity predicted by QED allows us to model a cavity with dimensions such that a wall vibrates in part due to the vacuum stress. For example, a cavity that is 2 μm long, 0.1 μm wide, and about 0.146 μm deep will have zero force on the face normal to the 0.146 direction [18]. The zero force corresponds to an unstable energy maximum. Thus a deflection inward leads to an increasing inward (attractive) force and, conversely, any deflection outward (repulsive force) leads to an increasing outward force. This potential is akin to a harmonic oscillator, except the force is destabilizing (F = kx) rather than stabilizing (F = - kx). If we assume that the box is made of real conductive materials, then there will be a restoring force due to the material, and this configuration might become stable if the material force constant exceeds that for the Casimir force (Fig. 3a).These results suggest the intriguing possibility of making a structure that displays simple harmonic motion for small displacements with a frequency that depends on the difference of the material force constant and the vacuum force constant (Fig. 3b). The oscillations could be damped due to the non-ideal properties of the material and the friction with the environment. Experiments with such devices could explore the interchange of energy with the vacuum field and mechanical systems and might lead to greater understanding and useful applications.

4.2 Vibrating Mirror Casimir Drive

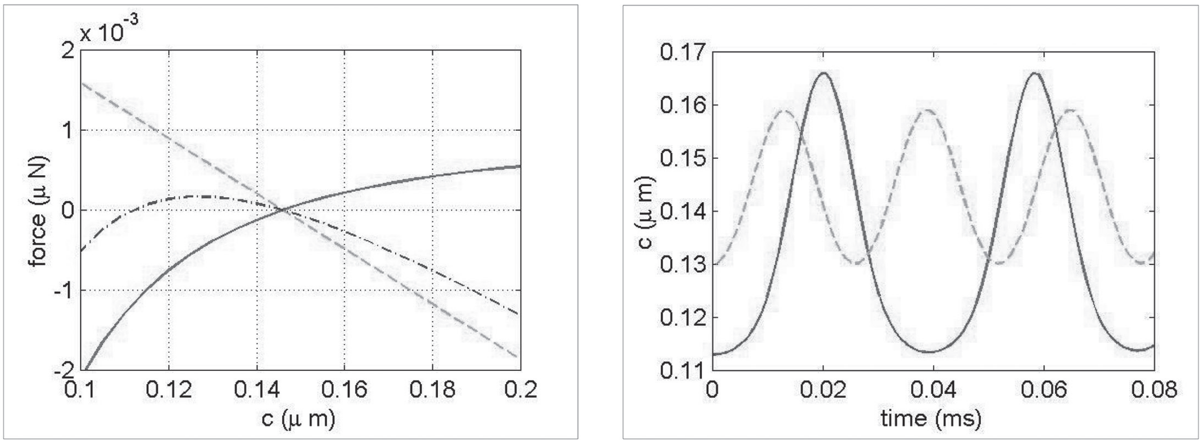
It is possible to conceive of and fully model a vacuum spacecraft that operates by pushing on the quantum vacuum with a vibrating mirror [46]. With a suitable trajectory, the motion of a mirror in vacuum can excite the quantized vacuum electromagnetic field with the creation of real photons. The radiative reaction accompanying the emission accelerates the spacecraft. This model is fully consistent with QED and conservation of energy and momentum. Unfortunately, it is highly impractical, but it does illustrate the possibility of using the properties of the vacuum to propel a spacecraft.

The model is based on an idealized spacecraft that has an energy source, such as a battery, that powers a motor that vibrates a mirror perpendicular to its surface. When the rate of vibration is fast enough, the dynamic Casimir effect will result in the emission of real photons. Friction and other non-ideal forces are ignored in the analysis. The change in energy ΔU of the battery is essentially converted to photon energy plus the kinetic energy $1/2MV^2$ of the space craft. For each photon of frequency ω that is emitted, energy ħω is required and a momentum ħω/c is transferred to the spacecraft. To obtain an upper limit on the acceleration possible, assume all photons are emitted normally from the surface then the velocity of the spacecraft is given by

$$\frac{V}{c} = \frac{\Delta U}{Mc^2} \tag{5}$$

This result is an upper limit for the dynamic Casimir effect, as well as for other mechanisms of propulsion that rely on the emission of light, such as a flashlight, or the electromagnetic radiation from a charged vibrating surface. Because the photon is massless, this is not an efficient way to propel a spacecraft.

A detailed calculation for the dynamic Casimir effect propulsion has been done [30, 46, 47]. The motion is periodic with frequency Ω and amplitude X_o, but with a modified harmonic motion so that a net force results during one cycle. To derive an upper bound numerical estimate, include only the mass of the plate and assume that the plate is made of H atoms and is one Bohr radius a_o thick, so the mass/area is $M/A = m_p/a_o^2$. The change in velocity per second is



(a) **(b)**

Fig. 3 a)The force on the top surface of a closed, perfectly conducting rectangular cavity 2 µm long by 0.1 µm wide, as a function of the depth *c*. The equilibrium position is c_{eq} = 0.146 µm. The dashed line (- - -) is a plot of the linear restoring force from a silicon spring as a function of the deformation of the top of the box, assumed to be made of silicon; the solid line (—) is the destabilizing vacuum force on the top of the box; and the dot-dash line (– ·–) is the total force on the top of the box. Note: The force on the y-axis is actually the total force for 1000 boxes. b) Displacement of the cover plate as a function of time for two starting positions, the solid curve, for 0.113 µm, close to the limit for oscillatory behaviour; the dash is for a smaller initial offset resulting in a more sinusoidal motion.

$$\Delta V_m \Big/ dt = -\frac{\hbar}{15\pi^2} X_o \left(\frac{\Omega}{c}\right)^4 \Omega \frac{a_o^2}{m_p} \qquad (6)$$

If we substitute reasonable numerical values [48], a frequency of 3×10^{10} s^{-1} and an oscillation amplitude of $X_o = 10^{-9}$ m, we find that ΔVm/dt is approximately 3×10^{-20} m/s^2, not a very impressive acceleration. Physically, one would imagine the surface of the mirror vibrating with amplitude of just one nanometer. This conservative limitation in the amplitude arises because the maximum velocity of the boundary is proportional to the elastic deformation, which cannot exceed about 10^{-2} for typical materials. The energy radiated per area is about 10^{-25} W/m^2 . There are a number of proposed methods to increase the acceleration value by over 10 orders of magnitude, the most important being the use of a resonant cavity [48, 49]. With favourable assumptions, after 10 years of operation, the gedanken spacecraft velocity would be approximately 10 m/s .

Eberlein has shown that density fluctuations in a dielectric medium would also result in the emission of photons by the dynamic Casimir effect [50]. Solid state approaches may be of value with further technological developments [31].

5. UNRESOLVED PHYSICS AND FUTURE DIRECTIONS

Vacuum energy effects are typically small and difficult to measure. Almost all measurements to date are for the simplest geometries, variations of the parallel plate geometry or the sphere plate geometry. Only one measurement has been made of the dynamic Casimir effect. Measurements on dynamic systems are needed to explore energy transfer. There are disagreements about the calculation of vacuum forces for non planar surfaces, like spheres, boxes, and disagreements about the behaviour of real metals at different temperatures. It may be possible to focus the fluctuating vacuum electromagnetic field yet no experiments have tested this hypothesis [51]. Both experiment and theory are needed to increase our understanding of the quantum vacuum, and to develop methods to engineer vacuum energy density. There are a number of proposed methods for extracting energy from the vacuum based on QED calculations that have never been tested.

One of the challenges in designing a propulsion system that is based on quantum effects, is that there are no design tools. The calculations of vacuum forces based on QED are very complicated and time consuming. Rather than solve each design problem separately, a design tool needs to be developed. A software tool for simulation would be of great value in exploring the possible utility of different designs and concepts for the practical use of vacuum energy and momentum. Similarly a device that could measure vacuum energy would stimulate great progress.

Looking farther into the future, we need to develop more effective methods to modify the vacuum field, methods that scale as $\hbar^0$ rather than as $\hbar$ and involve large amounts of negative and positive energy, and we need to develop modifications that reduce the randomness of the field, to increase the coherence. Perhaps one day we will even build a vacuum laser.

6. CONCLUSIONS

One objective in this paper is to illustrate some of the unique properties of the quantum vacuum and how they might be utilized in propulsion of a spacecraft. Vacuum energy has the same properties as other forms of energy, except it may be negative, and act like a negative mass. It is not possible to build a rigid sail that will be propelled by the zero point fluctuations; it has to have moving parts or a temperature distribution. Extracting energy or momentum from the vacuum is possible, as in the static Casimir effect, but no one has yet demonstrated how to extract energy or momentum in a continuous manner. We outlined the properties of a spacecraft that was propelled using the dissipative force which an accelerated mirror experiences when photons are generated from the quantum vacuum. With current materials and methods, the acceleration is miniscule, but it does demonstrate proof of principle, which is progress. Hopefully the proven feasibility will stimulate more practical approaches exploiting known or as yet unknown features of the quantum vacuum.

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