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BREAKTHROUGH PROPULSION I: THE QUANTUM VACUUM

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There has been some interest in "breakthrough" or "exotic" propulsion – propulsion that does not involve ejecting a large amount of propellant from a craft to accelerate it – since the mid-twentieth century. To be clear we are not talking about nuclear (fission, fusion, antimatter annihilation) beamed energy propulsion sails, electromagnetic (ion, Hall thrusters, pulsed plasma) rockets or Casimir or Dynamic Casimir effect drives (*referring to work by Jordan Maclay*). These propulsion methods are often referred to as "advanced". Breakthrough propulsion involves either "new" physics, or a new way of understanding well-established physics. For many years, the underlying physics of breakthrough propulsion has been taken to be the physics of the "quantum vacuum". However, the version of the "quantum vacuum" advocated by the majority of exotic propulsion physicists (and engineers) is **not** the standard physics of the vacuum of quantum electrodynamics (QED), electroweak or chromodynamics (QCD) or, more generally, quantum field theory (QFT). Early work of this sort focused upon a stochastic electrodynamics model, developed in the 1980's and 90's, a classical way to treat the quantum vacuum zero-point fluctuations. One application of that model was an attempt to show that inertia could be described as zero-point-field Lorentz force. The implication being that inertia was taken to be electromagnetic in origin, rather than gravitational. This was refuted a decade and a half ago – but is included here for completeness. More recent work, by H. White, on the quantum vacuum has focused on the putative "plasma" of electron-positron (e-p) pairs that allegedly can be "densified" by the action of macroscopic electromagnetic fields on certain materials. We show, by employing only the Heisenberg Uncertainty Principle, that this proposal too leads to incorrect results.

Keywords: Vacuum energy density, vacuum plasma, densification of vacuum, EM-drive, inertia as electromanetism

1. INTRODUCTION

A decade and a half ago, Roger Shawyer proposed a device he called the "EM Drive" as a breakthrough advance in propulsion technology. The device consisted of a conical cavity with flat plates as end caps into which microwave frequency electromagnetic radiation produced with a commercial magnetron was injected at a resonant frequency, see Fig .1. Shawyer claimed that the radiation in the cavity pushed harder on its smaller end plate than on the larger end plate. Shawyer's claims were ignored, for, if true, they would constitute a violation of momentum conservation. Shawyer, nevertheless, soldiered on, attracting enough attention to get several individuals and groups to try to replicate his work. Non-null results have been reported by more than one of these replicators.

While the theory proffered by these replicators to explain the results they obtained may be nonsense, some of the experimental efforts have been done with sufficient care to merit more than casual scrutiny.

Those interested in "breakthrough" propulsion have been generally aware that the physical "forces" that must be dealt with for any propulsion scheme to succeed are gravity and inertia. Actually, gravity and inertia are the same thing in Einstein's general relativity theory, but decades of "sloppy" talk about the relationship between gravity and inertia seems to have left open the possibility that they are not the same thing. So, when people contemplate breakthrough propulsion, some think that there may be two separate paths to their goal. More importantly here, the daunting nature of general relativity theory, our current theory of gravity, encourages some to try to render gravitational and inertial effects in terms of electromagnetic interactions. Electromagnetism, being a vector, rather than second rank tensor field theory is generally much simpler and more extensively studied and understood than general relativity. So it should not be surprising to find that several serious attempts to render gravity and/or inertia as an electromagnetic interaction have been proposed over the years, especially with an eye to creating breakthrough propulsion. This is not a good idea, as we explain here.

1.1 Gravity, Inertia, and Electromagnetism

Until 100 or so years ago, the two fundamental interactions known were gravity and electromagnetism. Some speculated about "inter-molecular" forces, but in an era when the physical atomic theory was not established, such speculations could not be taken as fundamental. In the matter of gravity and electromagnetism, parallels were obvious. In the case of Newtonian gravity the force law is:

$$\mathbf{F} = \frac{Gm_1 m_2}{r^2}\hat{r} \tag{1}$$

where **F** is the mutual force between masses m_1 and m_2 separated by a distance r, their line of centers, and $\hat{r}$ is a unit vector along that line. In the case of electrostatics, Coulomb's law reads:

$$\mathbf{F} = \frac{-kq_1 q_2}{r^2}\hat{r} \tag{2}$$

where the masses m are replaced by electric charges q, the

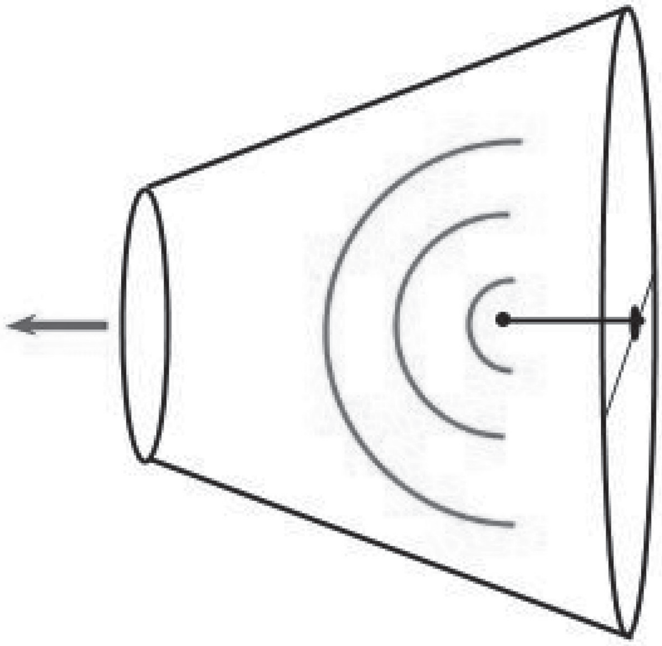

Fig. 1 A reactionless electromagnetic space drive. Consists of a closed metal cavity, with possibly one or two plastic discs at the narrow end. Microwaves are injected into the cavity and thrust is seen in the direction of the blue arrow. The electromagnetic mode patterns depend on the frequency and injection point, which varies from somewhere on the side to large plate shown here.

proportionality constant *k* depends on the choice of units. The minus sign appears as electric charges come in positive and negative, and charges of like sign repel, rather than attract as masses (all positive) do. The formal similarity of these force laws is not surprising as Coulomb used Newton's law of gravity as a guide to the construction of the law named for him.

While the formal similarity of these force laws suggests that gravity and electrostatics are alike and may be related to each other, there are important differences that indicate otherwise. In addition to the opposite directions of the forces between like charges, electrical forces are vastly larger than their gravitational counterparts. And electric charge comes in positive and negative, whereas observed masses are always positive. One need look no further to conclude that gravity and electricity are fundamentally separate interactions. And inertia, a necessary element of any propulsion scheme, an interaction between space and massive entities that causes resistance to accelerations in Newtonian mechanics, doesn't even figure into these considerations.

When inertia was subjected to scrutiny by Ernst Mach toward the end of the 19th century, it became clear that, like gravity, inertia did not display "dipole-like" interactions – those where sources of the field(s) are both positive and negative. When you push on a massive object to accelerate it, the inertial force that arises always acts to resist the acceleration. Were there positive and negative inertial masses, one would expect the direction of the inertial force to depend on the sign of the inertial mass of the object acted upon. So resisting accelerating forces should be the case only part of the time. But they always resist accelerating forces. Just as gravitational forces are always attractive. Since inertia is gravity-like in this regard, and gravity and inertia are universal properties of matter, one might guess that inertia is gravitational in origin. Einstein partially captured this idea in his Equivalence Principle, the equivalence of a homogeneous gravitational field and an accelerating frame of reference (wherein a "gravity-like" field appears). For this and other reasons, Einstein went out of his way to make inertia an integral part of his general relativity theory. At first he thought he had done this; then Willem deSitter showed him that he had not succeeded with his formulation of "Mach's principle" in fully capturing inertia in general relativity theory, for cosmological solutions of his field equations that were clearly anti-Machian existed. Einstein was forced to abandon Mach's principle.

When Einstein first published his general relativity theory, the feature of the theory that attracted the most attention, as now, was its accounting for what had been gravitational forces in the Newtonian world view by distortions – curvature – of the spacetime continuum by the presence of local concentrations of matter. The view became widespread then, as it is today, that curvature is the essence and marker of the presence of a gravitational field. Even Einstein was briefly taken by this interpretational fad. It took Levi-Civita pointing out to Einstein that important physics of general relativity is to be found in the "connection", a piece of mathematics needed to calculate general relativistic results, -- and the connection doesn't vanish in *flat* spacetime when accelerations with their inertial forces are present.

Einstein "got it". The space-like part of space-time is responsible for inertial forces, just as space was in the Newtonian system. In the Newtonian system, however, space was absolute, so inertia was a phenomenon that had no further explanation. In general relativity theory, however, space-time is not absolute. Indeed, the geometrical structure of space-time is determined by the presence and distribution of matter. So gravity is NOT a field that exists IN space-time. Space-time IS the gravitational field. How do we know that this was the position adopted by Einstein around 1920 (and thereafter)? When asked by a reporter what space-time would be like if all of the sources of gravity were removed, Einstein responded that there would be no space-time at all. Why? Because space-time is the gravitational field, and if there are no sources of the field, there is no field, and thus no space-time. Einstein's interpretation of his theory as making space-time the gravitational field, and in so doing making inertia a gravitational interaction, did not catch on a hundred years ago. To this day it hasn't. This incorrect separation of gravity and inertia has made possible speculative conjectures relating inertia to electrodynamics independently of gravity.

1.2 Making a Vector Field Theory Look Like Gravity

Trying to explain gravity as an electrostatic field was never seriously considered for the reasons mentioned above. But in the second half of the 19th century James Clerk Maxwell "unified" electricity and magnetism, creating classical electrodynamics. Maxwell's equations, based on the empirical laws discovered by Coulomb, Ampere, and Faraday, however, merely relate the electric and magnetic fields at some location to their sources. To state the action of these fields on their sources requires a force law. This was supplied toward the end of the century by H,A. Lorentz. It is the sum of the actions of the electric and magnetic fields acting separately on a particle with charge *q*:

$$\mathbf{F} = q\left(\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B}\right) \tag{3}$$

Where **v** is the velocity of the charged particle, *c* the vacuum speed of light, and **E** and **B** are the electric and magnetic field strengths. Gaussian units are used here to make plain that usually the second term on the right is much smaller than the first term. It might seem that nothing much has been gained with this more complicated force law, for the electric charge is a common factor in both terms, and when q reverses sign, so do the directions of the forces of the terms. But to conclude that nothing helpful has been found would be a mistake.

Consider an electrically charged particle at rest in a laboratory between the plates of a capacitor. At some point we turn the capacitor on, creating a uniform electric field between the plates. The electric field accelerates the charged particle which acquires some velocity. We now turn on a magnetic field oriented at right angles to the electric field (using suitable coils) and ask what is the force on the particle produced by the second term in the Lorentz force involving the magnetic field? Evidently,

$$\mathbf{F}_{mag} = \frac{q}{c}\mathbf{v}\times\mathbf{B} \tag{4}$$

But we know that **v** is the result of the action of **E**. Ignoring the (small) second term in the Lorentz force, we have:

$$\mathbf{F} = q\mathbf{E} = m\mathbf{a} \tag{5}$$

where m is the mass of the particle and **a** the acceleration of the particle that results from the action of the electric field. To get the value of **v** we simply integrate this equation of motion, getting:

$$\mathbf{v} = \frac{q^2 t}{m}\mathbf{E}t \tag{6}$$

where **E** has been assumed constant and t is the elapsed time the electric field has acted on the particle. Substituting this expression for **v** into Equation (4) we find:

$$\mathbf{F}_{mag} = \frac{q\ \ t}{}\mathbf{E}\times\mathbf{B} \tag{7}$$

We now note that since the value of the charge in this equation is squared, the direction of the magnetic part of the Lorentz force is unaffected by the sign of the charge it acts upon. Believe it or not, this is the basis of all claims to explain gravity and/or inertia as an electromagnetic effect in deep disguise. To make contact with claims that have already been made, we will need to do one further simple calculation.

Much of the interaction of electromagnetic fields and electric charges in matter is mediated by electromagnetic waves. To understand how that interaction takes place, we want to examine the simplest possible situation: the action of a plane monochromatic electromagnetic wave on a free electric charge. We note that the electric field strength can be written as a simple sinusoidal function of time, as can the magnetic field strength, and that the electric and magnetic parts of the wave are perpendicular to each other (E_x, B_y), transverse to the direction of motion of the wave (z), and in phase. To compute the response of the charge to the action of the passing wave, we invoke the "Einstein-Hopf" approximation where one first calculates the action of the electric part of the wave ignoring the second term in the Lorentz force to obtain the velocity of the charge, and then uses this velocity in the second term. Taking:

$$\mathbf{E}_x = E_o \sin(\omega t) \tag{8}$$

Equation (5) gives an acceleration, in the x-direction:

$$a = \frac{q}{m}E_x = \frac{qE_o}{m}\sin(\omega t) \tag{9}$$

And velocity change:

$$dv = \frac{qE_o}{m}\sin(\omega t)\,dt \tag{10}$$

Integrating,

$$v = \frac{qE_o}{m\omega}\cos(\omega t) \tag{11}$$

This velocity is in the direction of the electric field and conditions have been chosen to make integration constants zero. Noting that B_y has the same time dependence as E_x and substituting this expression for v into Equation (4), we find:

$$F_{mag} = \frac{q^2 E_o B_o}{mc\omega}\sin(\omega t)\cos(\omega t) = \frac{q^2 E_o B_o}{2mc\omega}\sin(2\omega t) \tag{12}$$

in the direction of propagation of the wave (z perpendicular to $\mathbf{E}_x$ and $\mathbf{B}_y$) for the magnetic part of the Lorentz force. If we combine the actions of the forces in Equations (5) and (12), we find that our charged particle executes figure 8 motion as the wave passes, as shown in Fig. 2.

Since the force in Equation (12) acts in the direction of the propagation of the wave, it is of interest to ask if the action of the wave will be to impart net momentum to the charge. Since the force is time dependent, we will have to average the force over some suitable time interval to answer this question. The obvious choice for an integration interval is one (or an integral multiple of one) period of the oscillation. In this case, however, notwithstanding that the wave is monochromatic and thus has only one period and frequency, the response of the charge has two frequencies, the frequency of the wave, and its second harmonic in the magnetic part of the Lorentz force. If we use the frequency of the wave to determine the integration interval, the averages of interesting quantities vanish. If the period of the second harmonic is used, finite results are obtained, but this is only half the true period of the wave, hence the finite result.

2. EARLY SPECULATION ON THE QUANTUM VACUUM AND EM-DRIVE PROPULSION

In 1994, B. Haisch, A. Rueda, and H. Puthoff (HRP) [1], described a classical way to treat the quantum vacuum zero-point fluctuations. They speculated that inertial forces could be accounted for, as the action of electromagnetic zero point fluctuations on accelerating electric charges. This implies that inertia could be described as zero-point-field Lorentz force. Since inertia is encompassed as a "gravity-like" phenomenon in Einstein's general relativity theory, this proposal amounted to the assertion that at least part of the gravitational interaction was actually a quantum mechanical electromagnetic interaction in deep disguise.

Toward the end of the '90s, uncritical tolerance of HRP's electromagnetic inertia conjecture, led one of us [JFW] and

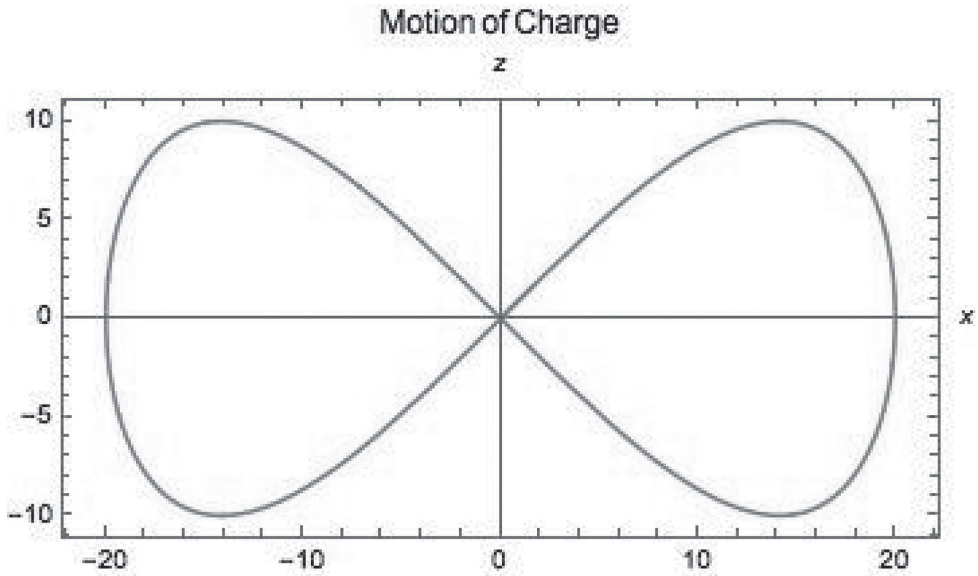

Fig. 2 Motion of a charge under the action of the electric and magnetic forces described in the text. This plot is greatly exaggerated in the z direction and would be very flat, an almost horizontal (in x) oscillation. The y-axis is into the page. (z-axis amplitude smaller by factor qB_o / ω).

Thomas Mahood, to show that this conjecture was wrong [2,3]. We briefly recapitulate the core arguments of that work here.

HRP's *inertia* conjecture drew its inspiration from the Davies-Unruh effect [4]: the appearance of a bath of thermal photons in an accelerating frame of reference. That is, fluctuations in an accelerated vacuum frame appear to be like thermal fluctuations in a stationary frame. They reasoned that if accelerations promoted the virtual photons of the quantum vacuum to "real" existence, those photons could act on accelerating electric charges, producing the inertial reaction forces universally experienced by accelerating objects. Their model of this force did not involve the absorption and re-radiation of the photons. Rather, their analysis proceeded in a semi-classical fashion by considering the action of electro-magnetic waves on electric charges. Employing the "Einstein-Hopf" approximation, they assumed that the (alternating) electric field of the wave(s) would induce a transverse oscillation of the electric charge, making it an oscillatory current. That current, in turn, would be acted upon by the magnetic part of the wave(s) via the magnetic part of the Lorentz force. (Put in its simplest form, the electric part of the Lorentz force gives the charge a velocity, then the magnetic part of the Lorentz force acts on the moving charge to give the force.) Many technical details accompanied this argument when it was first presented, but the basic idea is all that is needed to see that this conjecture is wrong.

HRP's fundamental equation for their putative inertia effect is their Equation (18) in their 1994 paper where their scheme was first presented. That equation, the magnetic part of the Lorentz force, reads:

$$\mathbf{F} = e\frac{\mathbf{v}(\tau)}{c}\times\mathbf{B}_{\tau}^{ZP}(0,\tau) \qquad (13)$$

where τ indicates evaluation in the proper time of the accelerating electric charge e. The electric part of the Lorentz force, $e\mathbf{E}_{\tau}^{ZP}$, is ignored by HRP on the grounds that being oscillatory, it averages to zero. (The superscript ZP in [1] refers to Zero Point vacuum.) The velocity **v** and magnetic field $\mathbf{B}^{ZP}$ are to be averaged over "random phases", because a broad spectrum of *ZP* photons with many frequencies and phases are expected. HRP proceed (at great length) to evaluate **v** and $\mathbf{B}^{ZP}$. Not surprisingly, they got non-zero results for each, and accordingly, a non-zero value for **F**.

Now, if **v** and $\mathbf{B}^{ZP}$ can be evaluated separately and the product of those evaluations computed, there might be something to this argument. This, however, amounts to the assumption that **v** and $\mathbf{B}^{ZP}$ due to a single photon are uncorrelated. And this is plainly incorrect. $\mathbf{E}^{ZP}$ and $\mathbf{B}^{ZP}$ for real photons (promoted from the vacuum due to the acceleration of the charged particle) are transverse and in phase. The velocity **v** induced by $\mathbf{E}^{ZP}$ is 90 degrees out of phase with both $\mathbf{E}^{ZP}$ and $\mathbf{B}^{ZP}$. It follows that $\mathbf{v}\times\mathbf{B}^{ZP}$ will be proportional to $\sin(\omega t)\cos(\omega t) = (1/2)\sin(2\omega t)$. When this is time-averaged for single photons passing the charge, **F** (which oscillates as the photons pass) will be zero. For mathematicians:

$$\langle\mathbf{v}\rangle \times \langle\mathbf{B}^{ZP}\rangle \neq \langle\mathbf{v}\times\mathbf{B}^{ZP}\rangle = 0 \qquad (14)$$

HRP effectively calculated the left hand side of this non-equation and got a non-zero result. As we found in the previous section, if the period of the second harmonic is used, finite results are obtained because this is only half the true period of the wave. The correct calculation is the right hand side of Eq (14), and since electrodynamics is "linear", we are assured that the individual photons actions on our accelerating charged particle do not affect the actions of the other photons. The total force on the particle is just the sum of the forces due to each of the photons present, at any instant. That, since the force exerted by each photon is zero, is a sum of zeros. That is, there is no net time-averaged force exerted by the electromagnetic ZPF.

The foregoing argument is, by itself, sufficient grounds to reject electromagnetic schemes that purport to explain inertial forces. But there is an even simpler argument that achieves the same end. It depends on the fact that a passing electromagnetic wave produces a force on an electric charge in a direction that is *independent of the sign of the charge*. This is a consequence of the fact that the velocity in the magnetic part of the Lorentz force depends on the action of the electric field on the electric charge as $e\mathbf{E}$. So the magnetic part of the Lorentz force depends on the **square** of the electric charge – a quantity that is positive irrespective of the sign of the charge. This is important because were the HRP conjecture true, the masses of the proton and neutron would be very different, whereas in fact they are almost exactly the same. The proton consists of two up quarks and one down quark. Up quarks have electric charge + 2/3 (of the electron charge) and the down quark – 1/3. When these charges are summed, you get +1, the proton charge. Neutrons have one up quark and two down quarks, and their charges sum to zero. As far as the neutron and proton are concerned, any force they experience from the action of an EM wave should be proportional to the sums of the squares of the individual quark charges. That is,

$$\begin{aligned} \mathbf{F}_p &= (2/3)^2 + (2/3)^2 + (-1/3)^2 = 9/9 = 1 \\ \mathbf{F}_n &= (2/3)^2 + (-1/3)^2 + (-1/3)^2 = 6/9 = 0.67 \end{aligned} \qquad (15)$$

And the HRP conjecture predicts a neutron mass (if inertia is indeed electromagnetic) 0.67 times that of the proton. Physics can be very unforgiving. It should be noted that most of the "mass" of the proton and neutron comes from the kinetic and potential energy of their constituent quarks not from the tiny quark rest masses.

3. THE QUANTUM VACUUM PLASMA

The arguments of the previous section pretty much put an end to speculative schemes involving the zero point fluctuations of the electromagnetic field. Did the advocates of the EMZPF (also called the "polarizable vacuum" because the photons of the ZPF can spontaneously produce electron-positron pairs that are polarized by electric fields. This is not the same as quark plasma of QCD.) abandon the conjecture when confronted with a clearly wrong, fundamental prediction? No.

Later, H. White conjectured that electron-positron (e-p) pairs could be induced in the vacuum by the presence of an externally applied "laboratory strength" electromagnetic fields. Once induced, the (e-p) pairs can be pushed against, before they annihilate and disappear back into the vacuum. They become the "fuel" ejected out of the tailpipe of a "quantum vacuum plasma thruster". Since the "vacuum plasma" is present everywhere, fuel tanks of plasma need not be carried along for one's travels. This is not the EMZPF conjecture of 1994. It appeared to White and his collaborator P. March to provide an explanation for the performance of Roger Shawyer's "EM Drives".

Shawyer [5,6] asserts that the thrust seen with his devices has nothing to do with quantum mechanical effects; that it is a strictly "classical" system. It is known with certainty, however, that production of net thrust in any isolated system employing only electromagnetic effects is physically impossible [7,8]. Invariance of the laws of electrodynamics – classical and quantum – under transformations of the Poincaré group guarantees the conservation of energy-momentum. This poses a problem. If Shawyer type devices produce real thrust, how do they do it?

It does appear that these Shawyer type EM drives (with plastic discs) produce real thrusts, and a fairly straight-forward explanation of these EM drives is possible in terms of Mach effects [3]. Conservation law violation ceases to be a critical issue, for Mach effects depend on gravitational coupling, and that is not screened the way EM radiation is confined in a conducting cavity. An important fact to note about H. White's device is that *significant* thrust is *only* produced when a thermoplastic disk is present in one end of the cavity (see Fig. 3). It is possible that a small amount of thrust could come from

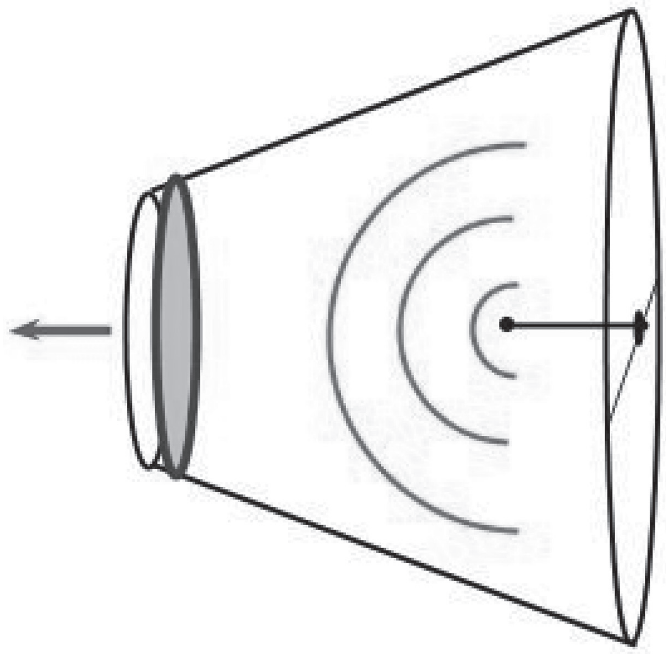

Fig. 3 The EM-drive as a truncated conical cavity with a plastic disc (high density polyethylene) at the smaller end. The disc will have electrostrictive properties.

a skin effect of the copper cavity which has electrostrictive properties. But our purpose here is not to explain EM drives in terms of Mach effects. Here we show that the quantum vacuum has nothing to do with the operation of these devices and there is no such thing as a "quantum vacuum plasma" in which one might find a "*wake of e-p pairs*" in the vicinity of a thruster. To that we now turn.

We start by specifying some particulars of the disposition and operation of, as White calls them, "Q-thrusters". The actual device tested by White and March [9] is made of copper and the microwave energy is delivered to the device via a small antenna disposed as shown in Fig. 3. The plastic disk at the smaller end of the frustrum is about 15 cm in diameter and roughly 5 cm thick. It is attached to the wall of the cavity with a plastic bolt. This disk is especially important, for if it is removed from the cavity, no thrust is produced when the device is activated. The radio frequency signal source and amplifier is mounted, along with the device, on a sensitive horizontal thrust balance. DC power for the system, and all instrumentation leads to components on the thrust balance, are made with liquid metal (Galinstan) contacts to insure that mechanical forces are not communicated to the balance beam by these components.

The bearings that support the balance beam provide a small restoring torque when the beam is displaced from its rest position. Thrust is measured with an optical position sensor that determines the displacement of the balance beam. This apparatus is shown in Fig. 4.

White accepts the observed fact of reality: the vacuum, with an energy density of about 2×10^{-29} gm/cm^3, is almost empty. A plasma of this density is useless for propulsive purposes. There isn't enough material present in the vacuum to push against. To accommodate this unpleasant fact, White assumes that when an electromagnetic field is present in a region of space-time, the e-p pairs expected as vacuum fluctuations are "densified". Why? Because if this is not so, the quantum vacuum cannot explain the behaviour of EM Drives.

Fig. 4 EM drive on balance, inside vacuum chamber [8]. Large diameter of the EM drive (also called RF cavity in vacuum) is 27.94 cm, small diameter is 15.88 cm and the length is 22.86 cm.

"Densification" [4-6] is taken to mean that "virtual" e-p pairs are promoted to "real" pairs that can be acted upon with transfer of energy and momentum *by the action of an external electromagnetic field.* The e-p pairs are then acted upon by the electromagnetic field that promotes them to "real" status, producing a thrusting force on the cavity. However, the QED vacuum's highly nonlinear nature does not respond to lab-strength electric and magnetic fields. Instead, it responds to what Schwinger defined to be the critical QED vacuum breakdown electric field strength, $E_c = 2m_e^2c^3/(\hbar e) \approx 10^{18}$ V/m, where e is the electron charge, m_e is the electron rest-mass, c is the speed of light, and $\hbar$ is Planck's reduced constant. This quantity is defined by assuming the breakdown electric force= e E_c is equal to the total rest-energy of an electron-positron pair created from the vacuum divided by the Compton wavelength, basically force = energy/length. The critical QED vacuum breakdown magnetic field strength is $B_c = E_c/c \approx 10^{10}$ Tesla. Since the Schwinger limit is not exceeded in the interstitial space between elementary particles, the vacuum, spontaneous e-p pair production in the vacuum is **not** expected on the basis of standard QED.

Actually, the behaviour of White and March's Q-thruster makes plain, that more than the presence of an electromagnetic field in space-time is required, to cause the hypothetical "densification" of the e-p pairs of the quantum vacuum. A material substance – the plastic disk – must also be present. The walls of the cavity (skin depth) may also suffice to a lesser extent. The plastic used were either high density polyethylene (HDPE) or polytetrafluoroethylene (PTFE). During the questions of the talk in Ref [10], White mentions the "*wake*" of e-p pairs that he hopes to measure from his Q-thruster device. The "physics" is not really gone through in any detail, and we have not found it written in any peer review paper. Hence we may only refer the interested reader to an AIAA Joint Propulsion Conference proceedings and *youtube* videos [10] and online files [11,12]. Early on in testing Shawyer had used inorganic dielectrics (UK patent Application GB 233461A, date of publication 01.09.1999, application No. 9809035.0 date of filing 29.04.1998) and these did not help the thrust levels. White and March also used inorganic dielectrics and concluded that these inorganics had meager or deleterious effects since they lower the cavity Q without a concomitant increase in thrust. White does have a peer review paper, accepted for publication, due to come out later this year December 2016 in the AIAA Journal of propulsion and power. This should be up to date and show experimental evidence for the RF cavity in a vacuum (EM drive) operation.

It might be expected that the mere presence of normal density material (a few grams per cubic centimeter) is sufficient to bring about the "densification" of the e-p pairs of the "quantum vacuum plasma". Brief reflection, however, should dispel such thoughts. QED does predict the presence of e-p pairs in the vacuum, but they are only significant in the process of electric charge "renormaliztion". The "bare" charges of electrons (and quarks), being point-like, induce gargantuan electric fields in their immediate vicinities – fields in excess of the "Schwinger limit", the minimum electric field strength required by QED to induce e-p pairs. For the time of their fleeting existence, these pairs are polarized by the bare charge of the electron, "dressing" it down to the observed charge. The e-p pairs that make up the dressing polarization charge of the electron are so tightly bound to the bare charge that electrons show no internal structure down to a scale of 10^{-16} cm.

4. MOMENTUM TRANSFER TO THE EM-DRIVE FROM E-P PAIRS?

We set these concerns aside and ask, what would have to be true for the "quantum plasma" conjecture to be viable proposition?

The amount of thrust any particle e-p pair can contribute to the total thrust is limited by the lifetime of the pair, because if the lifetime is short, it cannot acquire much momentum, for it annihilates before much momentum is acquired. That lifetime is dictated by the Heisenberg Uncertainty Principle which specifies the allowable duration of energy conservation violations given some specified energy that is to be promoted to 'real' status from the vacuum. In the case of e-p pairs created at rest, the energy is twice the rest mass-energy of an electron $\left(\varepsilon = 2m_e c^2\right)$. The Heisenberg Uncertainty principle gives,

$$\Delta\varepsilon\Delta t \geq \hbar / 2 \tag{16}$$

So

$$\Delta t \leq \frac{\hbar}{2\Delta\varepsilon} = \frac{\hbar}{4m_e c^2} \tag{17}$$

Substituting in known values, $\hbar = 1.05\times10^{-34}\,\text{Js}$, $m_e = 9.1\times10^{-31}\,\text{Kg}$ and $c = 3\times10^{8}\,\text{ms}^{-1}$ we obtain, a lifetime of $\Delta t \leq 3.2\times10^{-22}\,\text{sec}$. Armed with the e-p lifetime we ask how much thrust can be generated by acting on the pair with an external EM field? From COMSOL results of Paul March [13], we are given that the maximum field strength at the disc is in the order of 3780 V/m, with a cavity Q=7000. This is using 200 V/m for 1.0 Watt input power and a power of 18.9 Watt. If it is even sensible to use Newtonian equations for a quantum particle, you might assume that F=ma and then an approximate velocity for the electron starting from rest,

$$v = \left(\frac{eE}{m}\right)\Delta t = 2.1\times10^{-7}\ \text{m/s} \tag{18}$$

where we have used the lifetime of the electron or positron as the time change. To be generous, in order to get a large thrust, let us assume you can in fact get to 1m/s velocity, a stretch. Given this short a lifetime, vast numbers of e-p pairs can be expected to be required to produce any thrust. But this does not solve the problem of momentum conservation. It holds the prospect, according to White [9,10], of an observable signature of this process- a "wake"- in the putative plasma- that might be detectable. We explain here why this proposal is simply wrong.

"Hydrodynamics is the appropriate "effective theory" for describing any fluid medium at sufficiently long length scales", a quote from the abstract of the paper by Stevenson [14], entitled *Hydrodynamics of the vacuum*. The e-p pair lifetime is only 3×10^{-22} seconds, and that implies they are formed at rest. Assuming some strong external E field is present (and the e-p pairs are not just attracted directly to the nucleus of some large atom) velocities on the order of a meter per second or so might be attained by the electrons and positrons (all in the same direction). For an estimate, we assume that the electrons and positrons travel at a meter per second for their entire lifetimes (rather than accelerating to this velocity from zero). With this assumption, it follows that the longest distance an electron or a positron can travel before annihilation is $\delta \approx 3\times10^{-22}$ m. This can hardly be considered a long length scale, since the size of an average atomic nucleus is 10^{-15}m. Hydrodynamics then does not apply by definition. Results obtained by hydrodynamic arguments are meaningless.

The thrust generated in P. March's conical cavity EM-drive is produced in one (or two) plastic discs located in one end of the cavity. The discs are the only object inside the cavity that could change shape, via electrostriction, when an electromagnetic field is present. We assume there is vacuum between the atoms of the disk that gets compressed, or otherwise distorted, by the change in shape of the disk. The disks are roughly 15 cm diameter and about 2.5 cm thick. The volume of the disks in which the pairs of the plasma are formed then is $\pi R^2 h = 4.4\times10^{-4}\,\text{m}^3$. We now ask; How many electrons and positrons must be present in this volume for a reasonable amount of momentum transfer to take place via scattering when the material is irradiated with an external electromagnetic field? Subject to the particle lifetime constraint of the Heisenberg Uncertainty Principle.

To estimate the density and calculate the weight of the electrons and positrons we imagine each electron and positron to be located (on average) at the center of a small cubical volume with edge length equal to δ so that the inter-particle distance is $\delta \approx 3\times10^{-22}\,\text{m}$. The volume of one of these boxes is $\delta^3 = 2.7\times10^{-65}\,\text{m}^3$. To get the number of electrons and positrons, we divide the volume of the disk by this volume, getting 1.6×10^{61} particles. Multiplying this number by the electron mass, 9.1×10^{-31} kg , we find the mass of the quantum vacuum plasma required to see a wake is approximately 1.5×10^{31} kg. For purposes of comparison, we mention that the mass of the Sun is 2×10^{30} kg. Clearly not very realistic, but then hydrodynamics is not really applicable on microscopic scales such as these.

5. CONCLUSIONS

We have considered the hypothesis of H. White [9-12], namely the possibility that e-p pairs are created inside a material medium when it is subjected to large electromagnetic fields. These e-p pairs could be pushed against and used for propulsion. However, it is unlikely that the electrons and positrons would accelerate sufficiently in the applied electric field to produce much thrust, far too many would be required and they could in fact be "weighed". Previously, we assumed the maximum velocity of the e-p pairs would be ~1m/s and this was shown to be wildly optimistic. In the extreme case where we allow the electrons and positrons to attain a velocity near the speed of light c (v=c, very unlikely) the maximum distance they can travel according to the Heisenberg Uncertainty principle is $\delta \approx 9\times10^{-14}$ m. The volume of a box with this dimension becomes $\delta^3 \approx 7.29\times10^{-40}$ m^3. The number of electrons inside one plastic disc becomes 6.04×10^{35} which leads to a mass of 5.5×10^{5} kg. This is much too large a mass and would clearly have been noticed experimentally. We conclude that no such densification of the vacuum takes place and there is no such thing as a quantum plasma. Gravitation is not an electromagnetic phenomenon.

Finally, if you want to get across space-time quickly, you need to consider gravitation and Mach effects [3, 15-17].

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