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On the exhaust of electromagnetic drive

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Recent reports about propulsion without reaction mass have been met on one hand with enthusiasm and on the other hand with some doubts. Namely, closed metal cavities, when fueled with microwaves, have delivered thrust that could eventually maintain satellites on orbits using solar power. However, the measured thrust appears to be without any apparent exhaust. Thus the Law of Action-Reaction seems to have been violated. We consider the possibility that the exhaust is in a form that has so far escaped both experimental detection and theoretical attention. In the thruster's cavity microwaves interfere with each other and invariably some photons will also end up co-propagating with opposite phases. At the destructive interference electromagnetic fields cancel. However, the photons themselves do not vanish for nothing but continue in propagation. These photon pairs without net electromagnetic field do not reflect back from the metal walls but escape from the resonator. By this action momentum is lost from the cavity which, according to the conservation of momentum, gives rise to an equal and opposite reaction. We examine theoretical corollaries and practical concerns that follow from the paired-photon conclusion. [http://dx.doi.org/10.1063/1.4953807]

I. INTRODUCTION

Thrust without exhaust is of course impossible. Namely, for every action there has to be an equal and opposite reaction. This conservation of momentum entails that a rocket can accelerate forwards only by directing backwards a force of equal magnitude. Yet, certain resonant cavities, when fueled with microwaves, deliver thrust without apparent exhaust.[1,2] The thrust has been detected independently[3–9] but there is no consensus about its origin. Possible side-effects have been pointed out, and hence certain experiments have been inconclusive about the thrust.[10] Also credibility of some earlier experimental results has been recently reconsidered in relation to instrumental precision.[11]

Since explanations[12,13] and their refutations[14–17] have not been conclusive, we bring up a new line of thought to the profound discourse that targets to important applications, most notably to keep satellites on orbits. We maintain that the EM drive, like any other propulsion engine, does convert its propellant to expellant, but its exhaust has escaped both experimental detection and theoretical attention.

II. THE CONJECTURE

We begin by asking: Is there any other phenomenon, besides that demonstrated with the EM drive, where photons, as carriers of the electromagnetic force, are 'fed in' but nothing seems to be

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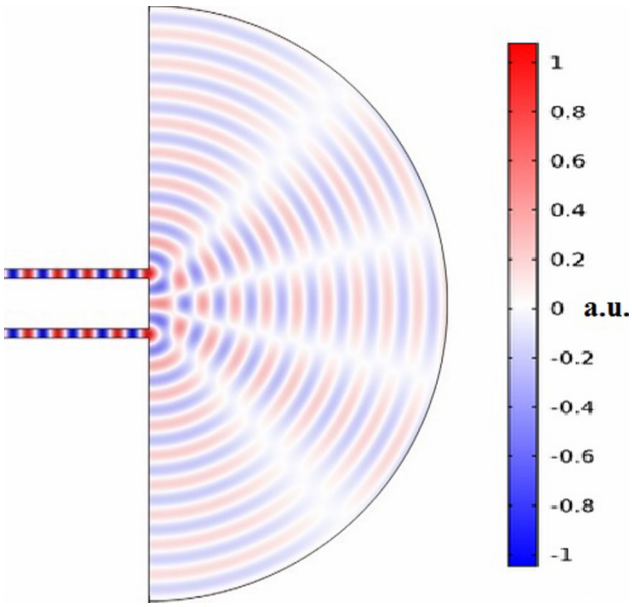

FIG. 1. Two parallel waves, shown with crests (red) and troughs (blue), propagate coherently from left to right through two slits and interfere with each other. Along those directions where the crest of one wave is exactly at the trough of the other wave, the interference is completely destructive (blank). Our reasoning is that when light waves combined with opposite phases, the photons do not vanish for nothing but continue propagating and carrying momentum. (www.comsol.fi/model/diffraction-patterns-117).

'coming out'? Yes, when coherent rays of light interfere, a diffraction pattern emerges with bright and dark bands – and at a dark band we see nothing (Fig. 1). We see no light when two photons combine with opposite phases. Their electromagnetic fields cancel perfectly, but that does not mean that the photons themselves would have vanished for nothing.[18]

Also when photons attain thermodynamic balance with matter in the cavity, their number is changing, but the photons themselves do not vanish for nothing at absorption to the walls and they do not emerge from nothing at emission from atoms constituting the walls. Put differently, quantum field theory, when manipulating photons as virtual particles, has been subject to reservations, because its follows from perturbation theory.[19,20] Instead, the old atomistic tenet makes sense to us by regarding the quanta of light as indivisible and indestructible basic building blocks of nature.[21–24]

We infer that the EM drive expels photons in pairs where the two co-propagate with 180 degree phase difference. These composite bosons have no net electromagnetic field, and hence they do not reflect back from the resonator's metal walls, but escape to surroundings. The paired-photon efflux carries momentum, and hence the cavity experiences an equal but opposite reaction. Thus, we claim that the thrust of an EM drive is the action due to the paired-photon efflux.

Our simple assertion prompts theoretical questions and practical concerns. In the following we will address some of the most burning ones.

III. WHAT IS THE PHOTON?

Our conjecture means that the EM drive converts the microwave-band photon propellant to the paired-photon expellant. Thus, one might wonder: How does the transformation from photons to photons consume free energy which is invariably needed to do work? To answer we will first address: What is the photon?

The quantum of light is a quantum of action whose unit Js tells us that the photon is physical, not virtual. The light quantum measures up to Planck's constant

$$h = Et = \mathbf{p} \cdot \mathbf{x} \tag{1}$$

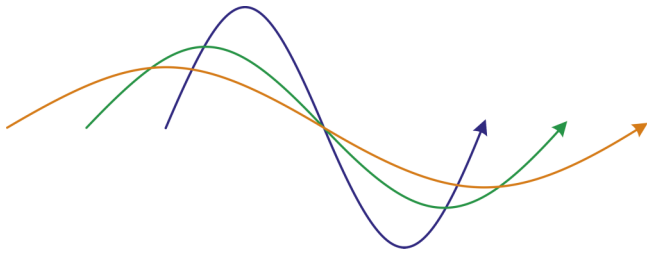

FIG. 2. Three waves with increasing lengths portray three photons (blue, green and orange) with decreasing curvature that relates to decreasing energy and momentum. It is worth noticing the total signed curvature over the wave vanishes because the two lobes are of opposite sign, and hence the photon is massless.

so that the product of photon's energy E and period t attribute remains invariant.[21,25] The same relation for the momentum $\mathbf{p}$ on its wavelength $\mathbf{x}$ underlines that the quantum of action is a geometric notion. The photon is the elementary action in the form of an open wave that carries momentum on its wavelength (Fig. 2).

Geometry at any point along an action can be recapped by signed curvature. The quantity relates to a force. This is familiar, e.g., from the theorem of Gauss and Bonnet. For example, a highly curved photon, i.e., having a short wavelength is able to force electrons free from a metal surface.[26] Conversely, the photon will adapt its curvature, i.e., frequency to match the surrounding energy density embodied in other quantized actions. This change in the photon's interdependent attributes of energy and time manifests itself, for instance, so that an increasing gravitational potential gradient introduces blue shifts and conversely a decreasing gradient causes red shifts.

By the same token for two photons that co-propagate in 180 degrees out of phase the sum of signed curvatures at any point along the wave vanishes, and hence the pair does not exert electromagnetic effects. Since the photon pair without net polarization does not couple to charges, it will easily escape detection, but still carries energy E over its period t as well as momentum p on its wavelength x that relate to each other as $E = pc$ via the speed of light $c = x/t$. Therefore, we claim that the EM drive consumes free energy in the form of propellant electromagnetic fields by pairing photons with opposite phases to non-polarized expellant.

At this point it is of interest to recall that Euler characterized any kind of action by a scalar that integrates projection of the signed curvature along the whole curve with a normal vector that characterizes the surrounding curvature, explicitly, that of the free space. The scalar, known as the geodesic curvature, is proportional to the mass. It is obviously zero for the symmetrical wave of light quantum.[24]

IV. WHAT IS THE VACUUM?

Our claim that the EM drive expels paired photons in the same way as a heat engine exhausts thermal photons entails that the vacuum, as the ultimate dump, comprises of photons. Thus, one might ask: How could the paired photons embody the vacuum, because luminiferous ether[27,28] has been abandoned since the negative outcome of Michelson–Morley experiment?

We agree the vacuum is not a transfer medium for photons, instead we maintain that it is made of photons. When the photons with out-of-phase polarizations co-propagate in pairs, the space is dark as observed. This out-of-phase photon relation, as the free energy minimum configuration, is the natural form of the background energy density. It is no quirk of cosmos the vacuum's energy density, on the order of nJ/m^3, closely matches the average energy density of matter within radius $R = cT$ of the Universe, where c is the speed of light and the age T is 13.8 billion years.[29–31] The equality signifies that the photon-embodied vacuum and all matter coevolve by maintaining thermodynamic balance. Therefore we expect that the paired-photon energy density spectrum parallels that of the black-body spectrum of cosmic background radiation.

We reason that when the paired photons are understood to embody the vacuum, its dielectric characteristics permittivity ε_o, permeability μ_o and impedance $Z = \sqrt{\mu_o/\varepsilon_o}$ naturally relate to light

via $c^2 = 1/(\varepsilon_o \mu_o)$. Already earlier it has been understood that both electromagnetic and gravitational potentials decay inversely with distance r, i.e., as $1/r$, when both are communicated by the photons that embody space.[32–34] By the same token, it has been realized earlier that c, ε_o and μ_o are not fundamental constants, but observable parameters of the quantum vacuum which has been portrayed in the form of continuously appearing and disappearing fermion pairs.[35,36] The ephemeral fermion pair is assumed to result from fusion of two virtual photons to ensure most notably the total neutrality of the vacuum. Our conjecture of the vacuum as a physical substance embodied by the paired photons resembles these models, but we see no compelling reason to account for the vacuum's electromagnetic properties by the transient appearance of paired charges. Instead we reason that when a charge is introduced in the vacuum, a force will appear and move the two photons apart from the out-of-phase relation. This phase shift will manifest itself as an electromagnetic field around the charge. Thus, it is no mystery, for instance, from where the photons of the electromagnetic field will emerge all of a sudden when an atom ionizes. They have been around all the time, but in the out-of-phase configuration that exhibits itself only as energy density.

Moreover, we recognize that our proposal of the physical vacuum parallels the theory of de Broglie[37] where the vibrating particle associates with a spatially extended, particle centered pilot wave.[38] This view of the vacuum, just as ours, rationalizes numerous quantum mechanical phenomena without conceptual conundrums.[18,39]

Considering the vacuum as physical as we maintain, one might question: Where have all the photons that embody the space come from? We argue that the space emerges from matter[23,24] by reminding that when particles annihilate with their antiparticles, only photons will emerge. For example, when an electron of mass m_e annihilates with a positron, it is easy to detect two photons that emerge in propagation in opposite directions each with energy $E = m_e c^2$ according to the mass-energy equivalence, but it is easy to miss additional photons that emerge in vacuum pairwise without net polarization and without net momentum. Also in other changes of state, these photon pairs easily escape detection when absorbed or emitted. Conversely, particles and their antiparticles will materialize pairwise from mere photons.

Newton thought that matter and light are not fundamentally different from each other.[27] This holistic view has been recently reconciled by presenting particles in terms of quantized actions in agreement with measurements.[23,24] Thus, our explanation for the thrust is not in an obvious conflict with observations, and hence it is worth further questioning.

V. WHAT IS GRAVITY?

Acceleration due to the proposed paired-photon efflux from the EM drive implies by the equivalence principle that the paired photons are also dissipated when a body is falling down. However, gravity is not described as a dissipative phenomenon either in elementary textbooks or in expanded editions that model curved spacetime with Riemann metric. Since the contemporary comprehension about gravity accounts remarkably well for numerous, if not for all observations, one might ask: What for is a 'new' dissipative theory of gravity needed?

We agree, nothing new is needed, but Newton's second law ought to be held for its full value. The law states that the force $\mathbf{F}$ equals the change in momentum $\mathbf{p}$, i.e.,

$$\mathbf{F} = d_t \mathbf{p} = d_t (m\mathbf{v}) = m\mathbf{a} + \mathbf{v} d_t m \tag{2}$$

where the second term, albeit often omitted from the textbooks and also from advanced writings, represents the thrust, i.e., the change in mass $d_t m$ multiplied with velocity $\mathbf{v}$. When $d_t \mathbf{p} = 0$, the reaction is equal and opposite to the action, i.e., $-\mathbf{v} d_t m = m\mathbf{a}$. In other words, no new theory is either proposed or required, but we emphasize the full import of Newton's statement.

When multiplying Eq. (2) with $\mathbf{v}$, change in kinetic energy K follows from the change in momentum[40–43]

$$\begin{aligned} \mathbf{v} \cdot \mathbf{F} = \mathbf{v} \cdot d_t (m\mathbf{v}) &= \mathbf{v} \cdot m\mathbf{a} + v^2 d_t m \\ d_t 2K &\equiv -\mathbf{v} \cdot \nabla U + d_t Q \end{aligned} \tag{3}$$

where the familiar term $m\mathbf{a}$ of acceleration corresponds to energy gradient of the [gravitational] scalar potential U, since $d_t = \mathbf{v}\cdot\nabla$, and the change in mass $d_t m$ equals via $m = E/c^2$ dissipation $d_t Q = d_t E/n^2$ to a medium indexed with $n = c/v$ relative to the vacuum whose norm is c^2. It is worth emphasizing that the change in mass (Eq. (3)) does not only count for the difference between the initial and final mass of a rocket with and without propellant but also for dissipation resulting from free energy consumption.

The dissipative change in mass is apparent in nuclear reactions and also noticeable in chemical reactions, but even the tiny change in mass in gravitational changes of state ought to be acknowledged to maintain conceptual consistency. The change can be inferred from the difference between the sum of gravitational potentials of individual bodies and the gravitational potential of the merged bodies. The body is not a mere sum of its material constituents because also the photons are contained in interactions.[44]

Dissipation in the gravitational changes of state is also required by reversibility.[43] When the body falls down on the ground, photons must emit from the gravitational potential to the surrounding vacuum, because when the body is lifted back up on its initial height, some fuel is needed, ultimately in the form of absorbed photons, for example, from insolation. Thus, according Eq. (3) when the body falls down, the gravitational potential changes via emission and when the body accelerates up, via absorption of quanta.

According to Eqs. (2) and (3) gravity is a force, like any other, whose direction and magnitude express the sign and magnitude of the gravitational energy gradient. When the surrounding vacuum is sparse in energy, it will readily accept the paired quanta when bodies fall toward each other. Conversely, when the surrounding is rich with insolation or with some other energetic flux of photons, it will grant these quanta to the systemic potentials. This influx of paired quanta will force the bodies to move apart from each other. In particular, the vast Universe generates huge fluxes of paired photons by transforming bound quanta of matter to freely co-propagating photons by stars, black holes and other mechanisms. Remarkably, these propagating density perturbations, known as gravitational waves, were recently captured from a black hole binary merger.[45] The total flux of pair quanta from numerous sources drives distant galaxies away from us. At a distance about 1.5 Mpc from the Milky Way, the energy influx and efflux balance each other, and hence there is no attraction or repulsion.[46–49]

In the same way as the vacuum's potential is in dynamic balance with the total energy density of matter in the whole Universe, so is the gravitational potential in dynamic balance with a local energy density of matter bound in the body. The paired-photon embodied gravitational potential can be decomposed to the familiar irrotational scalar potential and to the divergence-free vector potential to account also for rotational effects.[23,24,43] Accordingly, the vacuum as the tangible substance couples to a rotating body and hence manifests itself, for example, as the frame-dragging effect[50,51] and flyby anomaly.[52] When the system has attained thermodynamic balance with its surroundings, then the net flux of force carriers vanishes between the system and its surroundings. At the stationary state, where time variable is redundant, Eq. (3) can be integrated to the familiar virial theorem $2K + U = 0$.

The integral form $\int 2K\,dt = \int \mathbf{p}\cdot\mathbf{v}\,dt = \int \mathbf{p}\cdot d\mathbf{x}$ corresponding to the differential equation (3) is the principle of least action in its original form by Maupertuis. The least-time imperative says that bodies, just as light according to Fermat's principle, move along geodesics in agreement with observations.[31,51,53]

In short, we acknowledge general relativity as an excellent mathematical model of gravity for many celestial systems that are stationary or quasi-stationary, but we are not aware of any data that would disprove the dissipative equations (2) and (3) as accurate accounts of gravity including evolving systems. In fact, many observations have been recently interpreted according to the old tangible tenet, and notably without elusive notions of dark energy and dark matter.[49,53]

VI. WHAT IS INERTIA?

No rocket will accelerate instantaneously to a full speed but experiences inertia. It is no new idea that inertial effects are immediate, because the vacuum resists changes by embracing everything.[33,54] The old reasoning becomes tangible by the proposed photon-embodied vacuum [23,24,43] and

also by other forms of vacuum embodiment.[35,36,38] Since the vacuum maintains balance, i.e., free energy minimum state in relation to all bodies, any action taken by a body, will be balanced by the vacuum's reaction. The local action induces an energy density perturbation which will propagate, e.g., in the form of paired photons throughout the Universe so that eventually all other bodies in the Universe will move too. In other words, all other bodies will react to the act of a body. Mach's principle that mass out there influences inertia here follows from the fact that inertia builds up proportional to distance r because the increasing number of bodies proportional to r^2 out weights their decreasing gravitational potential proportional to $1/r$.

When inertial effects are ascribed to the physical vacuum, one might wonder: Why does motion through the proposed photon-embodied vacuum not accompany dissipation similar to motion through some ordinary medium, like water? In fact it does. A change in momentum is a dissipative event according to Eq. (3) also in the vacuum. This is familiar from Unruh effect.[55] Curiously, this character of vacuum was recently linked to an explanation of the EM drive thrust.[56] Actually no piece of a trajectory in the Universe is truly non-dissipative. Along any trajectory the body will invariably change its state relative to some other bodies because bodies distribute asymmetrically, albeit uniformly on the largest scale. Motion along a closed trajectory, i.e., an orbit, is non-dissipative only over its period because when returning back to the initial state, total absorption and emission will sum up to zero. There is no sink lower in energy density than the vacuum that could possibly accept emitted quanta. Conversely, motion through an ordinary medium, say water, is dissipative, because the vacuum will readily accept the quanta of actions that are released from interactions during a work cycle.

Moreover, rotational inertia can also be understood as the reaction taken by the universal vacuum to balance the action taken by the rotating body. Its characteristic quadratic dependence r^2 on the distance from the rotation axis follows from the same reasoning as above. The larger the radius of rotation, the larger realm of surroundings will be perturbed over the period, and hence the larger realm of the photon-embodied vacuum will react to restore the balance. Specifically, the moment of inertia $I = \int r^2 dm$ complies with the stationary-state balance via $I\alpha = \int \alpha r^2 dm = I\omega^2 = mv^2 = 2K = -U$ where the angular acceleration $\alpha = \omega^2 = v^2/r^2$. Furthermore, the renowned equivalence between the so called inertial mass and gravitational mass is only an inescapable identity because both the universal potential of vacuum's energy density and the local gravitational potential are embodied by the paired photons.

Undoubtedly our short examination of fundamental questions is not exhaustive, but shows that energy and momentum carried in the proposed form of paired photons is not in an immediate contradiction with observations, and hence worth examining further.

VII. HOW TO GUIDE IMPERCEPTIBLE EXHAUST?

When designing the EM thruster, one is in for a practical question: How to guide and focus the seemingly imperceptible efflux of paired photons? Namely, if the exhaust were to escape from the cavity uniformly in all directions, no net force, i.e., no thrust would build up.

According to elementary electromagnetism the photons will bounce back and forth between the cavity's metal walls as well as interfere with each other. And we add, no cavity is devoid of the vacuum, and hence even a single photon will interfere with photons embodying the vacuum.[18] Only those photons, whose wavelengths are multiples of a wall-to-wall distance, will interfere constructively, and hence only they will reside in the cavity. Momenta of trapped photons, as has been pointed out,[14,16,17] sum up to zero, that is, standing waves do not produce thrust irrespective of the cavity's shape.

Conversely, all other photons, whose multiple wavelengths do not match any of cavity dimension, will eventually interfere destructively. We reason that when pairing perfectly for destructive interference, the photons will escape from the resonator. In this way momentum will be lost along the exit directions.

When the cavity's geometry guides more photons to pair along a direction than along others, the momentum loss will be biased, which will manifest itself as thrust. Dissimilar electromagnetic modes at the wide and narrow end of a tapered cavity imply to us anisotropic efflux of paired

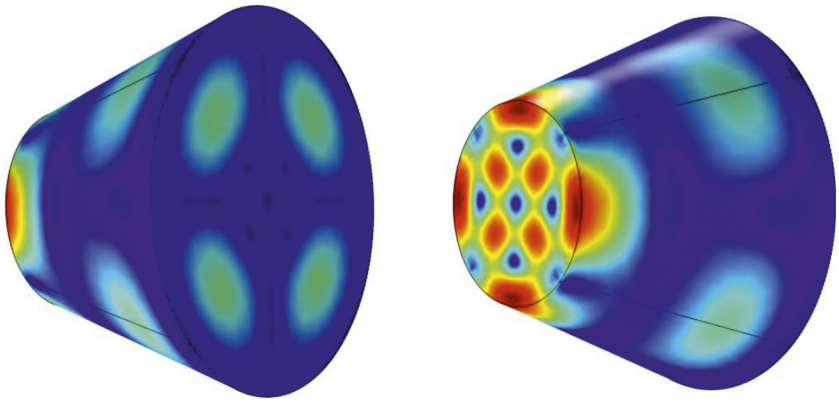

FIG. 3. Simulated transverse magnetic modes TM_{20}, (red high, blue low) at the wide and narrow ends of a metallic tapered cavity differ from each other. This implies anisotropic interference of microwaves, and hence also anisotropic efflux of paired photons. The anisotropic loss of momentum results in an equal and opposite reaction, i.e., thrust.

photons (Fig. 3). In fact, we expect any cavity of an asymmetric composition to deliver some thrust. Conversely, we reason, for example, that a cylindrical resonator will not generate a net force.

In the light of our proposal the thrust will be at most as large as the energy density difference between the microwaves in the cavity and the surrounding vacuum energy density, on the order of nJ/m^3. The thrust $\mathbf{T}$ is according to Eqs. (2) and (3) proportional by an efficiency factor $0 \leq \eta \leq 1$ to the power

$$P = d_t Q = \frac{1}{n^2} d_t E = \eta \frac{v^2}{c^2} \mathbf{v} \cdot \mathbf{T} \tag{4}$$

that has been pumped into the cavity whose index $n = c/v$ relates the photon velocity v to the speed of light c in the vacuum. In other words, at the microwave frequency f the power in the cavity is $d_t Q = v^2 d_t E/c^2 = d_t E/n^2 = hf^2/n^2$.

We expect η to depend on the power, cavity's shape and composition in a non-linear manner. When the cavity guides photons for parallel propagation and interference, energy density along the optical path length will increase. The increased energy density will, in turn, affect the index, and hence interference, and *vice versa*. Due to this interdependency it might be tricky to optimize the non-linear power-to-thrust relation. Indeed it has been reported that RF tuning and optimization constraints are very challenging.[8,9] We think that this characteristic sensitivity of interference phenomena manifested in the test runs where the mean thrust of 91.2 μN with 16.9 W was recorded at 1932.6 MHz corresponding to the first TM_{211} mode in the tapered cavity having a quality factor of about 7320 and the mean thrust of 50.1 μN with 16.7 W was recorded at 1936.7 MHz corresponding to the second TM_{211} mode and the quality factor of about 18000.[8,9] Apparently the high quality factor as such is no end in itself but it will increase the photons density, so that the probability for the photons to end up in the out-of-phase pairing and exit will increase. We believe that the proposed comprehension about the paired-photon exhaust will be helpful in optimizing power to thrust by engineering the cavity so that the photons will pair with opposite phases and exit from a preferred surface.

Finite element methods ought to provide probability densities also for co-propagating photons similarly as for laser modes in a powered cavity where not only electromagnetic fields but also energy densities vary and deviate from that of the free space. Expressly, the continuum condition of vacuum, known as Lorenz gauge $\partial_t \varphi = -c^2 \nabla \cdot \mathbf{A}$, says that the decreasing scalar potential φ in the cavity equals divergence of vector potential $\mathbf{A}$ out of the cavity via destructive interference to the surrounding free space.

VIII. DISCUSSION

We reason that the thrust of EM drive results from the efflux of photons that have paired with opposite phases. The paired photons are without net electromagnetic field, and hence they will

escape from the metal cavity. This loss of momentum, when anisotropic, produces the thrust. Thus, our explanation complies with conservation of momentum but departs from the current consent about photons by regarding photons as indivisible and indestructible basic building blocks of nature.

We acknowledge that our proposal for the paired-photon exhaust is by no means an exclusive explanation. At the same time we recognize no observation and no measurement that would disprove it. Expressly, we recall that Lewis' view of the photon[57] as the elementary constituent was seen to be in conflict with an atom decay from a given initial state either directly due to the loss of a single photon or via two intermediate states due to the successive losses of three photons nevertheless ending up to its ground state with the specified number of quanta. However, this early rejection of conservation of quanta seems to us unwarranted because it does not keep track of quanta in the form of paired photons between the system and its surrounding vacuum.

Our understanding about the EM drive's thrust follows from comprehending the physical character of vacuum, and thereby also gravity and inertia. This insight could be useful in improving electromagnetic drives and help to examine other ideas of propellantless propulsion.[58–60]

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