A Vacuum – Generated Inertia Reaction Force

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Abstract. A clear and succinct covariant approach shows that, in principle, there must be a contribution to the inertia reaction force on an accelerated object by the surrounding vacuum electromagnetic field in which the object is embedded. No details of the vacuum to object electromagnetic interaction need to be specified other than the fact that the object is made of electromagnetically interacting particles. Some interesting consequences of this feature are discussed. This analysis strongly supports the concept that inertia is indeed an opposition of the vacuum fields to any attempt to change the uniform state of motion of material bodies. This also definitely shows that inertia should be viewed as extrinsic to mass and that causing agents and/or mechanisms responsible for the inertia reaction force are neither intrinsic to the notion of mass nor to the entities responsible for the existence of mass in elementary particles (as, e.g., the Higgs field). In other words the mechanism that produces the inertia-reaction-force requires an explicit explanation. This explicit explanation is that inertia is an opposition of the vacuum fields to the accelerated motion of any material entities, i.e., of entities that possess mass. It is briefly commented why the existence of a Higgs field responsible for the generation of mass in elementary particles does not contradict the view presented here. It is also briefly discussed why a strict version of Mach's Principle does really contradict this view, though a broad sense version of Mach's Principle may be in agreement.

Keywords: Quantum-vacuum, inertia-reaction-force

INTRODUCTION

In his recent book, "Concepts of Mass in Contemporary Physics and Philosophy", Max Jammer [1] examines in detail many aspects of the mass concept including the origin of inertia. In particular, in reference to our recent work [2,3,4] he states [5]: "*However, debatable as their theory still is, it is from the philosophical point of view a thought-provoking attempt to renounce the traditional priority of the notion of mass in the hierarchy of our conceptions of physical reality and to dispense with the concept of mass in favor of the concept of field. In this respect their theory does to the Newtonian concept of mass what modern physics has done to the notion of absolute space: As Einstein [6] once wrote, 'the victory over the concept of absolute space or over that of the inertial systems became possible only because the concept of the material object was gradually replaced as the fundamental concept of physics by that of the field.'* "

Here we outline an attempt to show that the inertia reaction force has a contribution from the vacuum electromagnetic field. It strongly suggests that other vacuum fields (weak, strong interactions) do also contribute. A recent proposal by Vigier [7] that there is also a contribution from the Dirac vacuum very much goes along this line.

Most of the work outlined here appears in Refs. [2] and [3] (Those two papers we will refer to as RH, and specifically in most cases RH will directly refer to Ref. [2]). Another related paper prior to these is Ref. [4] (This one we denote by HRP).

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GENERAL COMMENTS ON THE ARGUMENTS LEADING TO THE ZPF-GENERATED INERTIA REACTION FORCE

We highlight here the main aspects of the RH approach [2]. In general the RH analysis is carried out in two complementary but totally independent and comprehensive ways (in addition to the completely different original HRP approach [4] that we shall not discuss in this paper). In the first way (next section), which is the more intuitive, one calculates the radiation pressure resulting from a non-zero Poynting vector of the electromagnetic zero-point field (ZPF) as viewed by an accelerated object. This radiation pressure is exactly opposite to the direction of the imposed acceleration, and in the subrelativistic case turns out to be directly proportional to the magnitude of the acceleration. The second way (section after next) leads to this same results by showing why and how an accelerating object acquires its four-momentum. This turns out to be directly related to the amount of ZPF energy and momentum contained within the object: it is that fraction of the contained energy that interacts with the fundamental particles comprising the object. From any change in this four-momentum one can straightforwardly calculate the resulting inertia reaction force. Not surprisingly this proves to be exactly the same force as in the first case.

In both representations one obtains an (electromagnetic) expression for the corresponding inertial mass that is essentially the amount of ZPF energy, divided by c^2, instantaneously contained within an object and which actually interacts with the object. This mass is a factor of 4/3 too large in the first two (noncovariant) versions (next two sections) we present below. This requires a correction. The correct form then comes about from a fully covariant derivation that we briefly outline at the end (section entitled: "Covariant approach-....."). There we introduce an important contribution from the ZPF electromagnetic Maxwell stress tensor that had been neglected in the previous two sections.

INERTIA REACTION FORCE FROM THE ZPF RADIATION PRESSURE ON AN ACCELERATED OBJECT

We consider a small material object to be undergoing hyperbolic motion, i.e. uniformly accelerated motion, i.e., motion with constant proper acceleration $|\mathbf{a}| = a =$ constant. Consider the object, that for simplicity we may identify with a particle, at the point $(c^2/a, 0,0)$ of a frame S that is rigid and noninertial because it comoves with the particle. At particle proper time $\tau = 0$ the particle point $(c^2/a, 0,0)$ of S exactly coincides and instantaneously comoves with the corresponding $(c^2/a, 0,0)$ point of an inertial frame that we denote by I_* and call the "inertial laboratory frame." We take the direction of the particle acceleration vector to coincide with the positive x-direction in both S and I_*, and in general in all subsequent frames that we will introduce. We consider also an infinitely continuous family of inertial frames, each denoted by I_τ, and such that each one of them has its $(c^2/a, 0,0)$ point instantaneously coinciding and comoving with the particle at the point $(c^2/a, 0,0)$ of S at the particle proper time τ. Clearly then $I_* = I_\tau(\tau = 0)$. The acceleration of the particle at $(c^2/a, 0,0)$ of S as seen from I_* is $\mathbf{a}_* = \gamma_\tau^{-3}\mathbf{a}_\tau$. The frame S is called the Rindler noninertial frame and as it is rigid, its acceleration is not the same for all its points but we will only be interested in points in the neighborhood of the $(c^2/a, 0,0)$ point.

The particle undergoes well-known hyperbolic motion, in which the velocity of the particle point with respect to I_* is then $u_x(\tau) = \beta_\tau c$, or

$$\beta_\tau = \frac{u_x(\tau)}{c} = \tanh\left(\frac{a\tau}{c}\right) \tag{1}$$

and then

$$\gamma_\tau = (1-\beta_\tau^2)^{-1/2} = \cosh\left(\frac{a\tau}{c}\right) \tag{2}$$

The position of the particle in I_* as function of particle proper time is then given by

$$x_*(\tau) = \frac{c^2}{a}\cosh\left(\frac{a\tau}{c}\right), \quad y_*(\tau) = 0, \quad z_*(\tau) = 0 \tag{3}$$

and the time in I_* when the proper time of the particle is τ is

$$t_* = \frac{c}{a}\sinh\left(\frac{a\tau}{c}\right). \tag{4}$$

Observe that we select $\tau = 0$ at $t_* = 0$.

We refer the reader to RH [2] for a detailed classically exact representation of the stochastic form of the electromagnetic field as well as for the details on the stochastic averaging plus useful references. In what follows we will also omit a number of subtle points, fully discussed in App. C of RH [2], in which the reader may also find some useful intuitive analogies and a more thorough discussion of essential aspects of the arguments sketched here.

According to an observer fixed to I_* (say at the (c^2/a, 0,0) point of I_*), the object moves through the ZPF as viewed in I_* with the hyperbolic motion described above. At proper time τ the object instantaneously comoves with the corresponding (c^2/a, 0,0) point of the inertial frame I_τ and thus at that point in time is found at rest in the inertial frame I_τ. We calculate the I_τ frame Poynting vector, but evaluated at the (c^2/a, 0,0) point of I_*. This allows us to obtain the net ZPF rate of momentum density that is accumulating in the object due to the uniformly accelerated motion. Recall that this is the ZPF of I_*. This Poynting vector we denote by $\mathbf{N}_*^{zp}$, and

$$\begin{aligned} \mathbf{N}_*^{zp} &= \frac{c}{4\pi}\left\langle \mathbf{E}_\tau^{zp}(0,\tau) \times \mathbf{B}_\tau^{zp}(0,\tau)\right\rangle \\ &= \hat{\mathrm{x}}\frac{c}{4\pi}\left\langle \mathrm{E}_{y,\tau}\mathrm{B}_{z,\tau} - \mathrm{E}_{z,\tau}\mathrm{B}_{y,\tau}\right\rangle \end{aligned} \tag{5}$$

where the angular brackets represent stochastic averaging. That only the *x*-direction is relevant in (5) follows from symmetry. There are several subtle points that we must sweep under the rug here, details of which may be found in RH [2], especially App. C. We refer particularly to the so-called *k*-sphere of integration. Each inertial frame has its own *k*-spheres and even though the ZPF is Lorentz-invariant and it has the same form of energy-density spectrum and is homogeneous and isotropic in every inertial frame, the ZPF of I_* does not appear to be that way to an observer of I_τ and vice versa.

In concise form we present calculations subsequent to (5) as follows:

$$\begin{aligned} \left\langle E_{y,\tau} B_{z,\tau} - E_{z,\tau} B_{y,\tau}\right\rangle &= \gamma_\tau^2 \left\langle \left(E_{y,*} - \beta_\tau B_{z,*}\right)\left(B_{z,*} - \beta_\tau E_{y,*}\right) - \left(E_{z,*} + \beta_\tau B_{y,*}\right)\left(B_{y,*} + \beta_\tau E_{z,*}\right)\right\rangle \\ &= -\gamma_\tau^2\beta_\tau\left\langle E_{y,*}^2 + B_{z,*}^2 + E_{z,*}^2 + B_{y,*}^2\right\rangle + \gamma_\tau^2\left(1+\beta_\tau^2\right)\left\langle E_{y,*} B_{z,*} - E_{z,*} B_{y,*}\right\rangle \\ &= -\gamma_\tau^2\beta_\tau\left\langle E_{y,*}^2 + B_{z,*}^2 + E_{z,*}^2 + B_{y,*}^2\right\rangle \end{aligned} \tag{6}$$

Observe that in the last equality of eqn. (6) the term proportional to the *x*- projection of the ordinary ZPF Poynting vector of I_* vanishes as it should. The integrals are taken with respect to the I_* ZPF background (using then the *k*-sphere of I_*, cf. App. C of RH [2]) as that is the background that the I_* observer considers the accelerated object to be sweeping through. The net amount of momentum of the background that the object has swept through after a time t_*, as judged again from the I_* -frame viewpoint is then

$$\mathbf{p}_*^{zp} = \mathbf{g}_*^{zp} V_* = \frac{\mathbf{N}_*^{zp}}{c^2} V_* = -\hat{x} \frac{1}{c^2} \frac{c}{4\pi} \gamma_\tau^2 \beta_\tau \frac{2}{3} \left\langle E_*^2 + B_*^2 \right\rangle V_* \tag{7}$$

where $\mathbf{g}_*^{zp}$, the momentum density, is introduced and V_* represents the volume of the object as seen in I_*. Clearly then, because of Lorentz contraction, $V_* = V_0/\gamma_\tau$, where V_0 is the proper volume. In obtaining eqn. (7) from eqn. (6) and for the following step we use the fact that

$$\left\langle E_{y,*}^2 + B_{z,*}^2 + E_{z,*}^2 + B_{y,*}^2 \right\rangle = \frac{2}{3} \left\langle \mathbf{E}_*^2 + \mathbf{B}_*^2 \right\rangle = \frac{2}{3}\, 8\pi \mathrm{U}_* = 2 \cdot \frac{8\pi}{3} \int \frac{\hbar\omega^3}{2\pi^2 c^3} d\omega \,. \tag{8}$$

With the last two equalities of eqn. (8), eqn. (6) becomes

$$\mathbf{p}_*^{zp}(\tau) = -\hat{x} \frac{4V_0}{3} c\beta_\tau \gamma_\tau \left[\frac{1}{c^2} \int \eta(\omega) \frac{\hbar\omega^3}{2\pi^2 c^3} d\omega \right] \tag{9}$$

where we used the fact that $V_* = V_0/\gamma_\tau$ and we introduced the frequency function $\eta(\omega)$, where $0 \leq \eta(\omega) \leq 1$ for all ω. This represents the fraction of ZPF radiation that actually interacts with the object at a given frequency. Clearly we expect $\eta(\omega) \to 0$ as $\omega \to \infty$ sufficiently rapidly.

The force applied by the ZPF to the uniformly accelerated particle or physical object can now be easily calculated:

$$\mathbf{f}_*^{zp} = \frac{d\mathbf{p}_*^{zp}}{dt_*} = \frac{1}{\gamma_\tau} \frac{d\mathbf{p}_*}{dt_*} \Big|_{\tau=0} = -\frac{4}{3} \left[\frac{V_0}{c^2} \int \eta(\omega) \frac{\hbar\omega^3}{2\pi^2 c^3} d\omega \right] \mathbf{a} \tag{10}$$

where $\mathbf{a} = \hat{x} a$ is the particle proper acceleration and where use was made of eqns. (1) and (2). We have thus obtained what can be called the ZPF inertia reaction force

$$\mathbf{f}_*^{zp} = -m_i \mathbf{a} \tag{11}$$

with an "inertial mass" of the form

$$m_i = \left[\frac{V_0}{c^2} \int \eta(\omega) \frac{\hbar\omega^3}{2\pi^2 c^3} d\omega \right] . \tag{12}$$

This is an invariant scalar with the dimension of mass. It represents the amount of ZPF radiation enclosed within the object (or particle) of proper volume V_0 that actually interacts with it. In eqn. (12) we have omitted a factor of 4/3 that appears in eqn. (A10). One of the revenues of a fully covariant analysis (cf. App. D of RH [2]), that we sketch below in § 5, is to show that the 4/3 factor disappears when proper use is made of the electromagnetic stress tensor which has been omitted so far.

INERTIA REACTION FORCE FROM THE ANALYSIS OF THE ZPF MOMENTUM CONTENT OF THE ACCELERATED OBJECT

This approach is totally independent from the one above. However, it is strongly complementary. It is "the other side of the coin." One approach requires the other.

From Newton's Third Law applied to the accelerated object, when an external agent applies a motive force, f_* and thus uniformly accelerates the object, according to the view proposed herein the vacuum applies an equal and opposite force, $\mathbf{f}_*^{zp}$, in the opposing direction, i.e.

$$\mathbf{f}_* = - \mathbf{f}_*^{zp} \tag{13}$$

where the star subscripts just means that we refer here to the laboratory inertial frame I_*. Eqn. (13) implies that the corresponding impulses, $\Delta\mathbf{p}_*$ and $- \Delta p_*^{zp}$, taken to be zero, say, at time $t_* = 0$ and $\tau = 0$, also obey after a short lapse of time Δt_* and correspondingly a short proper time lapse $\Delta\tau$,

$$\Delta\mathbf{p}_* = - \Delta\,\mathbf{p}_*^{zp} \tag{14}$$

Integrating over longer times in I_*, from zero to some final time t_*, we can write

$$\mathbf{p}_* = - \mathbf{p}_*^{zp} \tag{15}$$

This allows us to introduce an equation between the corresponding momentum densities where $\mathbf{p}_* = V_*\mathbf{g}_*$ and $\mathbf{p}_*^{zp} = V_*\,\mathbf{g}_*^{zp}$, thus

$$\mathbf{g}_* = - \mathbf{g}_*^{zp} \tag{16}$$

where we have already confronted $\mathbf{g}_*^{zp}$ in eqn. (7), and $\mathbf{g}_*$, as carefully argued in App. B of RH [2], corresponds to the fraction of the momentum density of the ZPF radiation within the object that interacts with the object. Expressing this momentum density in terms of the corresponding Poynting vector we write

$$\mathbf{g}_* = \frac{\mathbf{N}_*^{zp}}{c^2} = -\hat{x}\frac{1}{c^2}\frac{c}{4\pi}\left\langle \mathbf{E}_*^{zp}(0,\tau)\times\mathbf{B}_*^{zp}(0,\tau)\right\rangle_* \tag{17}$$

where $\mathbf{N}_* = \hat{x}\,N_*$ is the Poynting vector due to the ZPF as measured *in* I_* at the object's point, at proper time τ of eqns. (3) and (4), in the I_* laboratory frame. Because of symmetry again, only the x-component appears. Recall however that we are calculating the ZPF momentum associated with the object. At proper time τ the object is instantaneously at rest in the inertial frame I_τ. This means (cf. App. C of RH [2]) that we must perform the integrals over the k-sphere of the I_τ frame. This becomes more revealing when we Lorentz-transform the field in eqn. (17) from I_* to I_τ:

$$\begin{aligned}
\left\langle \mathbf{E}_*^{zp}(0,\tau)\times\mathbf{B}_*^{zp}(0,\tau)\right\rangle_x &= \left\langle E_{y,*}\,B_{z,*} - E_{z,*}\,B_{y,*}\right\rangle \\
&= \gamma_\tau^2\left\langle \left(E_{y,\tau}+\beta_\tau B_{z,\tau}\right)\left(B_{z,\tau}+\beta_\tau E_{y,\tau}\right) - \left(E_{z,\tau}-\beta_\tau B_{y,\tau}\right)\left(B_{y,\tau}-\beta_\tau E_{z,\tau}\right)\right\rangle \\
&= \gamma_\tau^2\beta_\tau\left\langle E_{z,\tau}^2 + B_{y,\tau}^2 + E_{z,\tau}^2 + B_{z,\tau}^2\right\rangle + \gamma_\tau^2\left(1+\beta_\tau^2\right)\left\langle E_{y,\tau}B_{z,\tau} - E_{z,\tau}B_{y,\tau}\right\rangle \\
&= \gamma_\tau^2\beta_\tau\left\langle E_{y,\tau}^2 + B_{y,\tau}^2 + E_{y,\tau}^2 + B_{y,\tau}^2\right\rangle \\
&= \gamma_\tau^2\beta_\tau\frac{2}{3}\left\langle \mathbf{E}_\tau^2 + \mathbf{B}_\tau^2\right\rangle
\end{aligned} \tag{18}$$

where again we have a term that vanishes, namely the one proportional to the x-component of the ZPF statistically-averaged Poynting vector in I_τ. Recall that integrals are performed with respect to the k-sphere of I_τ (App. C of RH [2]). We then have

$$\mathbf{p}_*^{zp} = \mathbf{g}_*^{zp} V_* = \hat{x} \frac{1}{c^2} \frac{c}{4\pi} \gamma_\tau^2 \beta_\tau \frac{2}{3} \left\langle \mathbf{E}_\tau^2 + \mathbf{B}_\tau^2 \right\rangle V_* = \hat{\mathrm{x}} \frac{4 \mathrm{V}_0}{3} \mathrm{c} \beta_\tau \gamma_\tau \frac{1}{c^2} \int \eta(\omega') \frac{\hbar \omega'^3}{2\pi^2 \mathrm{c}^3} \mathrm{d}\omega' \tag{19}$$

where as in § A1 we have used the fact that

$$\frac{2}{3} \left\langle \mathbf{E}_\tau^2 + \mathbf{B}_\tau^2 \right\rangle = \frac{2}{3} 8\pi U_\tau = 2 \frac{8\pi}{3} \int \frac{\hbar \omega'^3}{2\pi^2 \mathrm{c}^3} \mathrm{d}\omega' \tag{20}$$

The prime in ω' indicates just that frequencies and fields refer now to those in I_τ. In eqn. (19) we again used the fact that $V_* = V_0/\gamma_\tau$ and we introduced the factor $\eta(\omega')$ again because only the fraction of the ZPF radiation that actually interacts with the particles in the object is relevant.

If we differentiate the impulse $\mathbf{p}_*$ with respect to time we get the corresponding force, $\mathbf{f}_*$ and with eqn. (13) we obtain the inertia reaction force due to the ZPF as

$$\mathbf{f}_*^{zp} = - \mathbf{f}_* = - \frac{d\mathbf{p}_*}{dt_*} = - \frac{1}{\gamma_\tau} \frac{d\mathbf{p}_*}{d\tau} \bigg|_{\tau=0} = - \mathbf{a} \frac{4}{3} \frac{V_0}{c^2} \int \eta(\omega') \frac{\hbar \omega'^3}{2\pi^2 \mathrm{c}^3} \mathrm{d}\omega' \tag{21}$$

which reproduces eqn. (10) as should be expected. Now again, the formulae (11) and (12) follow accordingly.

COVARIANT APPROACH – REMOVING THE SPURIOUS 4/3 FACTOR

Here we briefly sketch the argument and calculation that lead to the fully relativistic form of the inertia reaction force and that as a byproduct eliminates the bothersome 4/3 factor. In the previous sections only the contribution due to the momentum density $\mathbf{g}$ was included (or equivalently the Poynting vector $\mathbf{N} = c^2\mathbf{g}$). There is however an additional contribution to the momentum $\mathbf{p}$ that was neglected. In order to obtain it, one has to perform a covariant generalization of the previous analysis. We cannot perform here a detailed account of it (see App. D of RH [2] for details). The analysis is a bit more easily grasped by the intuition if the momentum-content approach of § 4 is used. For this reason we select in this section the momentum-content approach.

The covariant extension of momentum in the radiation field is the four-vector.

$$\mathcal{P} = P^\mu = (P^0, \mathbf{p}), \tag{22}$$

where

$$P^0 = \gamma \int \left(\frac{U}{c} - \frac{\mathbf{v}.\mathbf{g}}{c} \right) d^3\sigma \tag{23}$$

$$\mathbf{p} = \gamma \int \left(\mathbf{g} + \frac{\mathbf{T}.\mathbf{v}}{c^2} \right) d^3\sigma \tag{24}$$

We see that $\mathbf{p}$ now carries an additional term of the form $\mathbf{T}.\mathbf{v}/c^2$, where $\mathbf{T}$ is the Maxwell stress tensor,

$$T_{ij} = \frac{1}{4\pi} \left\langle E_i E_j + B_i B_j - \frac{1}{2} (E^2 + B^2) \delta_{ij} \right\rangle \tag{25}$$

With $i, j = x, y, z$. the angular brackets, as usual, signify stochastic averaging. In P^0 the zero component of $\mathcal{P}$, we find again the energy density U (as in eqn. (8)) but there is now an additional contribution to the energy in the zero component, namely a term of the form **–v.g.** Since we are now considering a relatively small proper volume, V_0, written in the I_* frame we have

$$\mathbf{p}_* = \gamma \left(\mathbf{g}_* + \frac{\mathbf{T}_* . \mathbf{v}_*}{c^2} \right) V_0. \tag{26}$$

A detailed calculation of $\mathbf{p}_*$ yields

$$\mathbf{g}_* + \frac{\mathbf{T}_* . \mathbf{v}_*}{\mathbf{c}^2} = \hat{x} \frac{1}{c^2} c\beta_\tau \int \frac{\hbar \omega'^3}{2\pi^2 c^3} d\omega' \tag{27}$$

and then

$$\mathbf{p}_* = \hat{x}\, c\gamma_\tau \beta_\tau \frac{V_0}{c^2} \int \frac{\hbar \omega'^3}{2\pi^2 c^3} d\omega' \tag{28}$$

From this we may obtain the inertia reaction force of eqn. (21)

$$\mathbf{f}_*^{zp} = - \frac{d\mathbf{p}_*}{dt_*} = - \frac{1}{\gamma_\tau} \frac{d\mathbf{p}_*}{d\tau} \bigg|_{\tau=0} = - m_i \mathbf{a}. \tag{29}$$

But now m_i is precisely

$$m_i = \frac{V_0}{c^2} \int \eta(\omega') \frac{\hbar \omega'^3}{2\pi^2 c^3} d\omega' \tag{30}$$

and the factor 4/3 does not need to be artificially removed as in eqn. (10) to (12) and (21) where it was de facto removed. Of course in eqn. (30) we again introduced the factor $\eta(\omega)$ for the fraction of the ZPF that actually interacts with the particles in the object.

On the other hand the zero-component of the momentum, P^0, for sufficiently small proper volume V_0, can be written as

$$P^0 = \gamma_\tau \left(\frac{U}{c} - \frac{\mathbf{v.g}}{c} \right) V_0 \tag{31}$$

Detailed calculation (App. D of RH[2]) yields then

$$P^0 = \gamma_\tau \frac{V_0}{c} \int \eta(\omega') \frac{\hbar \omega'^3}{2\pi^2 c^3} d\omega' = m_i\, c\, \gamma_\tau \tag{32}$$

Where m_i is the mass found in eqn. (30).

Putting together eqns. (28), (30) and (32) we recover the conventional form of the four-momentum in relativistic mechanics, namely,

$$\mathcal{P} = P^\mu = m_i V^\mu = m_i\, (c\gamma_\tau, \mathbf{v}\gamma_\tau) \tag{33}$$

With m_i, the "inertial mass" of eqn. (30) that indeed represents the amount of electromagnetic ZPF energy inside the object volume V_0 that actually interacts with the object. From eqn. (33) we can then obtain the relativistic form of Newton's Second Law

$$\mathcal{F} = \frac{d\mathbf{P}}{d\tau} = \frac{\mathrm{d}}{\mathrm{d}\tau}(\gamma_\tau \, m_i \mathrm{c}, \mathbf{p}) \tag{34}$$

where the star indices have been suppressed for generality. And where $\mathbf{p}$ is the relativistic momentum

$$\mathbf{p} = m_i \, \gamma_\tau \mathbf{v}_\tau \tag{35}$$

The origin of inertia in this picture becomes remarkably intuitive. Any material object resists acceleration because the acceleration produces a perceived and instantaneous flux of radiation in the opposite direction that scatters within the object and thereby pushes against the accelerating agent. Inertia in the present model appears as a kind of acceleration-dependent electromagnetic vacuum-fields drag force acting upon electromagnetically-interacting particles.

CONCLUDING COMMENTS

In the Standard Model of particle physics it is postulated that there exists a scalar field pervasive throughout the Universe and whose main function is to assign mass by transferring mass to the elementary particles. This is the so-called Higgs field or more specifically, the Higgs boson, and it originated from a proposal by the British physicist Peter Higgs who introduced that kind of field as an idea for assigning masses in the Landau-Ginzburg theory of superconductivity. Recent predictions of the mass that the Higgs boson itself may have, indicate a rather large mass (more than 60 GeV) and this may be one of the reasons why, up to the present, the Higgs boson has not been observed. There are alternative theories that give mass to elementary particles without the need to postulate a Higgs field, as e.g., dynamical symmetry breaking where the Higgs boson is not elementary but composite. But the fact that the Higgs boson has not been detected is by no means an indication that it does not exist. Recall the 26 years which passed between the proposal by Pauli in 1930 of the existence of the neutrino and its first detection when the Reines experiment was performed.

It should be clearly stated that the existence (or non-existence) of the hypothetical Higgs boson does not affect our proposal for the origin of inertia. In the standard Model attempt to obtain, in John Wheeler's quote, "*mass without mass,*" the issue of inertia itself does not appear. As Wilczek [8] states concerning protons and neutrons: "*Most of the mass of ordinary matter, for sure, is the pure energy of moving quarks and gluons. The remainder, a quantitatively small but qualitatively crucial remainder – it includes the mass of electrons – is all ascribed to the confounding influence of a pervasive medium, the Higgs field condensate.*" An explanation of proton and neutron masses in terms of the energies of quarks motions and gluon fields falls short of offering any insight on inertia itself. One is no closer to an understanding of how this energy somehow acquires the property of resistance to acceleration known as inertia. Put another way, a quantitative equivalence between energy and mass does not address the origin of inertial reaction forces. And the manner in which, say the rest mass of the neutrino, is taken from the Higgs field, does not at all explain the inertia reaction force on accelerated neutrinos.

Many physicists apparently believe that our conjecture of inertia originating in the vacuum fields is at odds with the Higgs hypothesis for the origin of mass. This happens because of the pervasive assumption that inertia can only be intrinsic to mass and thus, if the Higgs mechanism creates mass, one automatically has an explanation for inertia. If inertia is intrinsic to mass as postulated by Newton, then inertia could indeed be considered to be a direct result of the Higgs field because presumably the Higgs field is the entity that generates the corresponding mass, and inertia simply comes along with the rest mass of an elementary particle automatically. However, if one accepts that there is indeed an extrinsic origin for the inertia reaction force, be it the gravity field of the surrounding matter of the universe (Mach's Principle in senso stricto) or be it the electromagnetic quantum vacuum (or more generally the quantum vacua) that we propose, then the question of how mass originates – possibly by a Higgs mechanism – is a separate issue from the property of inertia. This is a point that is often not properly understood. The modern Standard Model explanation of mass is satisfied if it can balance the calculated energies with the measured masses (as in the proton) but obviously this does not explain the origin of the inertia reaction force. It is the inertia reaction force associated with acceleration that is measurable and fundamental, not mass itself. We are proposing a specific mechanism for generation of the inertia reaction force resulting from distortions of the quantum vacua as perceived by accelerating elementary particles.

We do not enter into the problems associated with attempts to explain inertia via Mach's Principle, since we have discussed this at length in a recent paper [9]: A detailed discussion on intrinsic vs. extrinsic inertia and on the inability of the geometrodynamics of general relativity to generate inertia reaction forces may be found therein. It had already been shown by Rindler [10] and others that Mach's Principle is inconsistent with general relativity, and Dobyns et al [9] further elaborate on a crucial point in general relativity that is not widely understood: Geometrodynamics merely defines the geodesic that a freely moving object will follow. But if an object is constrained to follow some different path, Geometrodynamics has no mechanism for creating a reaction force. Geometrodynamics has nothing more to say about inertia than does classical Newtonian physics. Geometrodynamics leaves it to whatever processes generates inertia, to generate such a force upon deviation from a geodesic path, but this becomes an obvious tautology if an explanation of inertia is sought in Geometrodynamics.

We would like to point out that Mach's Principle in senso stricto is, as described above, the hypothesis that inertia here is due to the overall matter there, in the distant Universe, that produces a net gravitational effect so that the inertia reaction force is generated on an accelerated object by the gravitational field of all the Universe. This Mach's Principle in a strict sense is not compatible with our proposal that inertia is generated by the vacuum fields [9]. However, a more broad interpretation of some of Mach's ideas is the view that inertia is not just inherent to mass but due to an external agent that acts on the accelerated massive object. Such agent is different from the accelerated massive object itself and should reside in the external Universe. This view is then perfectly compatible with the view that we propose, namely that the vacuum fields are the entities responsible for producing, on the accelerated massive object, the inertia reaction force.

We finally, acknowledge that Newton's proposal that inertia is intrinsic to mass looks, superficially at least, more economical (Occam's razor) but it is also oversimplistic as one may always continue asking for a deeper reason for the operation of physical processes or for more fundamental bases for physical laws. The question of why the mass associated with either matter or energy should display a resistance to acceleration is a valid question that needs to be addressed even if the Higgs boson is experimentally found and confirmed as the origin of mass.

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