

**On the relation between a zero-point-field-induced inertial effect
and the Einstein-de Broglie formula**

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Abstract

It has been proposed that the scattering of electromagnetic zero-point radiation by accelerating objects results in a reaction force that may account, at least in part, for inertia [1,2,3]. This arises because of asymmetries in the electromagnetic zero-point field (ZPF) or electromagnetic quantum vacuum as perceived from an accelerating reference frame. In such a frame, the Poynting vector and momentum flux of the ZPF become non-zero. If one assumes that scattering of the ZPF radiation takes place at the level of quarks and electrons constituting matter, then it is possible for both Newton's equation of motion, $\mathbf{f} = m\mathbf{a}$, and its relativistic covariant generalization, $\mathcal{F} = d\mathcal{P}/d\tau$, to be obtained as a consequence of the non-zero ZPF momentum flux. We now conjecture that this scattering must take place at the Compton frequency of a particle, and that this interpretation of mass leads directly to the de Broglie relation characterizing the wave nature of that particle in motion, $\lambda_B = h/p$. This suggests a perspective on a connection between electrodynamics and the quantum wave nature of matter. Attempts to extend this perspective to other aspects of the vacuum are left for future consideration.

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Using the techniques of stochastic electrodynamics we examined the Poynting vector of the electromagnetic ZPF of the quantum vacuum in accelerating reference frames [1,2]. This led to a surprisingly simple and intuitive relation between what should be the inertial mass, m_i , of an object of proper volume V_0 and the energy density of the ZPF instantaneously contained in V_0 . Besides simplicity, this new approach [1,2] improved over a previous one [3] in that it yielded a covariant generalization. As derived from the force associated with the ZPF momentum flux in transit through the object, m_i and ρ_{ZP} were found to be related as follows:

$$m_i = \frac{V_0}{c^2} \int \eta(\omega) \rho_{ZP}(\omega) d\omega, \quad (1)$$

where ρ_{ZP} is the well known spectral energy density of the ZPF

$$\rho_{ZP}(\omega) = \frac{\hbar\omega^3}{2\pi^2c^3}. \quad (2)$$

Viewed this way, inertial mass, m_i , appeared to be a peculiar form of coupling parameter between the electromagnetic ZPF and the electromagnetically interacting fundamental particles (quarks and electrons) constituting matter. The key to deriving an equation of motion ($\mathcal{F} = d\mathcal{P}/d\tau$ in the relativistic case) from electrodynamics is to assume that some form of scattering of the non-zero (in accelerating frames) ZPF momentum flux takes place. The reaction force resulting from such scattering would appear to be the physical origin of inertia. The parameter $\eta(\omega)$ in eqn. (1) parametrizes such a scattering efficiency whose strength and frequency dependence have been unknown.

It was proposed by de Broglie that an elementary particle is associated with a localized wave whose frequency is the Compton frequency, yielding the Einstein-de Broglie equation:

$$\hbar\omega_C = m_0c^2. \quad (3)$$

As summarized by Hunter [4]: "...what we regard as the (inertial) mass of the particle is, according to de Broglie's proposal, simply the vibrational energy (divided by c^2) of a localized oscillating field (most likely the electromagnetic field). From this standpoint inertial mass is not an elementary property of a particle, but rather a property derived

from the localized oscillation of the (electromagnetic) field. De Broglie described this equivalence between mass and the energy of oscillational motion. . . as ‘*une grande loi de la Nature*’ (a great law of nature).” The rest mass m_0 is simply m_i in its rest frame. What de Broglie was proposing is that the left-hand side of eqn. (3) corresponds to physical reality; the right-hand side is in a sense bookkeeping, defining the concept of rest mass.

This perspective is consistent with the proposition that inertial mass, m_i , is also not a fundamental entity, but rather a coupling parameter between electromagnetically interacting particles and the ZPF. De Broglie assumed that his wave at the Compton frequency originates in the particle itself. An alternative interpretation is that a particle “is tuned to a wave originating in the high-frequency modes of the zero-point background field.” [5, 6] The de Broglie oscillation would thus be due to a resonant interaction with the ZPF, presumably the same resonance that is responsible for creating a contribution to inertial mass as in eqn. (1). In other words, the ZPF would be driving this ω_C oscillation.

We therefore suggest that an elementary charge driven to oscillate at the Compton frequency, ω_C , by the ZPF may be the physical basis of the $\eta(\omega)$ scattering parameter in eqn. (1). For the case of the electron, this would imply that $\eta(\omega)$ is a sharply-peaked resonance at the frequency, expressed in terms of energy, $\hbar\omega = 512$ keV. The inertial mass of the electron would physically be the reaction force due to resonance scattering of the ZPF at that frequency.

This leads to a surprising corollary. It can be shown that as viewed from a laboratory frame, the standing wave at the Compton frequency in the electron frame transforms into a traveling wave having the de Broglie wavelength, $\lambda_B = h/p$, for a moving electron. The wave nature of the moving electron appears to be basically due to Doppler shifts associated with its Einstein-de Broglie resonance frequency. This has been shown in detail in the monograph of de la Peña and Cetto [5] (see also Kracklauer [6]).

Assume an electron is moving with velocity v in the $+x$ -direction. For simplicity consider only the components of the ZPF in the $\pm x$ directions. The ZPF-wave responsible for driving the resonant oscillation impinging on the electron from the front will be the ZPF-wave seen in the laboratory frame to have frequency $\omega_- = \gamma\omega_C(1 - v/c)$, i.e. it is the wave below the Compton frequency in the laboratory that for the electron is Doppler

shifted up to the ω_C resonance. Similarly the ZPF-wave responsible for driving the electron resonant oscillation impinging on the electron from the rear will have a laboratory frequency $\omega_+ = \gamma\omega_C(1 + v/c)$ which is Doppler shifted down to ω_C for the electron. The same transformations apply to the wave numbers, k_+ and k_- . The Lorentz invariance of the ZPF spectrum ensures that regardless of the electron's (unaccelerated) motion the up- and down-shifting of the laboratory-frame ZPF will always yield a standing wave in the electron's frame.

It has been proposed by de la Peña and Cetto [5] and by Kracklauer [6] that in the laboratory frame the superposition of these two waves results in an apparent traveling wave whose wavelength is

$$\lambda = \frac{c\lambda_C}{\gamma v}, \quad (4)$$

which is simply the de Broglie wavelength, $\lambda_B = h/p$, for a particle of momentum $p = m_0\gamma v$. This is evident from looking at the summation of two oppositely moving wave trains of equal amplitude, ϕ_+ and ϕ_- , in the particle and laboratory frames [5]. In the rest frame of the particle the two wave trains combine to yield a single standing wave.

In the laboratory frame we have for the sum,

$$\phi = \phi_+ + \phi_- = \cos(\omega_+t - k_+x + \theta_+) + \cos(\omega_-t + k_-x + \theta_-) \quad (5)$$

where

$$\omega_{\pm} = \omega_z \pm \omega_B \quad (6a)$$

$$k_{\pm} = k_z \pm k_B \quad (6b)$$

and

$$\omega_z = \gamma\omega_C, \quad \omega_B = \gamma\beta\omega_C \quad (7a)$$

$$k_z = \gamma k_C, \quad k_B = \gamma\beta k_C. \quad (7b)$$

The respective random phases associated with each one of these independent ZPF wave-trains are $\theta_{+,-}$. After some algebra one obtains that the oppositely moving wavetrains appear in the form

$$\phi = 2 \cos(\omega_z t - k_B x + \theta_1) \cos(\omega_B t - k_z x + \theta_2) \quad (8)$$

where $\theta_{1,2}$ are again two independent random phases $\theta_{1,2} = \frac{1}{2}(\theta_+ \pm \theta_-)$. Observe that for fixed x , the rapidly oscillating “carrier” of frequency ω_z is modulated by the slowly varying envelope function in frequency ω_B . And *vice versa* observe that at a given t the “carrier” in space appears to have a relatively large wave number k_z which is modulated by the envelope of much smaller wave number k_B . Hence both timewise at a fixed point in space and spacewise at a given time, there appears a carrier that is modulated by a much broader wave of dimension corresponding to the de Broglie time $t_B = 2\pi/\omega_B$, or equivalently, the de Broglie wavelength $\lambda_B = 2\pi/k_B$.

This result may be generalized to include ZPF radiation from all other directions, as may be found in the monograph of de la Peña and Cetto [5]. They conclude by stating: “The foregoing discussion assigns a physical meaning to de Broglie’s wave: it is the *modulation* of the wave formed by the Lorentz-transformed, Doppler-shifted superposition of the whole set of random stationary electromagnetic waves of frequency ω_C with which the electron interacts selectively.”

Another way of looking at the spatial modulation is in terms of the wave function. Since

$$\frac{\omega_C \gamma v}{c^2} = \frac{m_0 \gamma v}{\hbar} = \frac{p}{\hbar} \quad (9)$$

this spatial modulation is exactly the $e^{ipx/\hbar}$ wave function of a freely moving particle satisfying the Schrödinger equation. The same argument has been made by Hunter [4]. In such a view the quantum wave function of a moving free particle becomes a “beat frequency” produced by the relative motion of the observer with respect to the particle and its oscillating charge.

It thus appears that a simple model of a particle as a ZPF-driven oscillating charge with a resonance at its Compton frequency may simultaneously offer insight into the nature of inertial mass, i.e. into rest inertial mass and its relativistic extension, the Einstein-de Broglie formula and into its associated wave function involving the de Broglie wavelength

of a moving particle. If the de Broglie oscillation is indeed driven by the ZPF, then it is a form of Schrödinger's *Zitterbewegung*. Moreover there is a substantial literature attempting to associate spin with *Zitterbewegung* tracing back to the work of Schrödinger [7]; see for example Huang [8] and Barut and Zanghi [9]. In the context of ascribing the *Zitterbewegung* to the fluctuations produced by the ZPF, it has been proposed that spin may be traced back to the (circular) polarization of the electromagnetic field, i.e. particle spin may derive from the spin of photons in the electromagnetic quantum vacuum [5]. It is well known, in ordinary quantum theory, that the introduction of \hbar into the ZPF energy density spectrum $\rho_{ZP}(\omega)$ of eqn. (2) is made via the harmonic-oscillators-quantization of the electromagnetic modes and that this introduction of \hbar is totally independent from the simultaneous introduction of \hbar into the particle spin. The idea expounded herein points however towards a connection between the \hbar in $\rho_{ZP}(\omega)$ and the \hbar in the spin of the electron. In spite of a suggestive preliminary proposal, an exact detailed model of this connection remains to be developed [10]. Finally, although we amply acknowledge [1,2] that other vacuum fields besides the electromagnetic do contribute to inertia, e.g. see [11], no attempt has been made within the context of the present work to explore that extension.

A standard procedure of conventional quantum physics is to limit the describable elements of reality to be directly measurable, i.e. the so-called physical *observables*. We apply this philosophy here by pointing out that inertial mass itself does not qualify as an observable. Notions such as acceleration, force, energy and electromagnetic fields constitute proper observables; inertial mass does not. We propose that the inertial mass parameter can be accounted for in terms of the forces and energies associated with the electrostatics of the ZPF.

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