



On the Essence of Gravitation and Inertia Part 1

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► To cite this version:

Shlomo Barak. On the Essence of Gravitation and Inertia Part 1: Inertia and Free Fall of an Elementary Particle. 2017. hal-01404143v7

HAL Id: hal-01404143

<https://hal.science/hal-01404143v7>

Preprint submitted on 24 Jul 2017

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On the Essence of Gravitation and Inertia

Part 1: Inertia and Free Fall of an Elementary Particle

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Abstract

Masses (elementary particles) curve space positively. They sense (are affected by) curvature, created by other masses, and move accordingly. How, specifically, this occurs, is an open issue, as is the issue of inertia. Our elementary particle model, presented here, enables us to resolve these issues, show mass to be merely a practicality, and prove Newton's First and Second Laws.

We show that contraction (curving) of space by a mass (GR's gravitation) creates a gradient in light velocity. A particle senses this gradient and is forced into free fall. This free fall is attributed to the currently unexplained attraction between masses. We also prove Newton's Law of Gravitation and the equivalence of gravitational and inertial masses.

Part 2 of this paper shows that the spin of a particle induces space torsion that results in space contraction (positive curving) which is GR's gravitation.

Key Words: Gravitation; Free fall; Elementary particle; Inertia

1 Introduction

Although there have been many attempts to explain gravitation or to present alternatives to General Relativity with its Newtonian weak field approximation, none are based on a model of an elementary particle. An example is “On the Origin of Gravity and the Laws of Newton” (2011), [1]. This theory considers gravity to emerge from the thermodynamic concept of entropy; hence it is “independent of the specific details of the underlying microscopic theory”. It also generates a self-contained, logical derivation of the equivalence principle based on the assumption of a holographic universe.

In contrast, our theory is based on a simple “underlying microscopic” model of an elementary particle.

Essential elements of our model of an elementary particle are presented in our papers; “On the Essence of Electric Charge” Part 1 [2], and Part 2, [3]. Reading these papers contributes to the understanding of this paper. It also raises confidence in our model, since in these papers we are able, for the first time, to derive theoretically and calculate accurately the radii and masses of the electron/positron, muon/anti-muon and quark/anti-quark.

In this paper we:

- Construct a simple model of an elementary particle.
- Show that inertia is an intrinsic feature of this model, depending on energy and structure alone.
- Derive Newton’s first and second laws, based on this model.
- Show that mass is not a fundamental attribute of an elementary particle, but just a practicality.
- Show how an elementary particle senses curvature and moves accordingly.

- Derive the universal Newtonian gravitational force, and prove the equivalence principle.

2 On Our GeometroDynamic Model (GDM) of Reality

The following introduction to the GDM enables a better understanding of our arguments and derivations.

The current paradigm, despite the successes of the excellent theories that construct it, quantum mechanics included, is facing many obstacles. Many principles remain unproven, attributes of elementary particles cannot be derived and calculated, and mysteries are unresolved. This situation results from the lack of a deeper theoretical layer.

In order to provide this missing underlying layer, we have constructed a realistic and tangible theory - the GDM. This layer, the GDM, provides an answer as to what is charge, what is an elementary particle, and relates to additional fundamental subjects.

The need for a “deeper theoretical layer” is exemplified by Hartle [4] in his book “Gravity” p 482: “The Einstein equation relating curvature to density of mass-energy is a fundamental equation of classical physics. **It cannot be derived**, for there is no more fundamental classical theory to derive it from.” The GDM is exactly the required theory; a New Foundation that in Part 2, of this paper, enables us to extend Einstein’s equation to incorporate the curving of space by charge.

The GDM Idea

The Elastic and Vibrating three-dimensional Space Lattice is all there is.

Elementary Particles are Transversal or Longitudinal Wavepackets of the vibrating space.

The Units of the GDM

In the GDM all units are expressed by the unit of length L (**cm**) and the unit of time T (**sec**)

only. (A conversion from the **egs system** to the GDM system and vice versa is possible).

The Constants of Nature According to the GDM

$c_T = c$	Velocity of transversal Space vibrations (EM waves)	$[c_T] = LT^{-1}$
$[c_L]$	Velocity of longitudinal Space vibrations ($c_L > c_T$)	$[c_L] = LT^{-1}$
\hbar	Planck Constant	$[\hbar] = L^5T^{-1}$
G	Gravitational Constant	$[G] = T^{-2}$
α	Fine Structure Constant	$[\alpha] = 1$

Note that $c_L/c = \pi/2 \cdot (1 + \pi \alpha)$, see (25) in [3], and we can exclude c_L from the list.

According to [3]: $[v] = LT^{-1}$, $[a] = LT^{-2}$, $[H] = [G] = T^{-2}$, $[Q] = [M] = L^3$, $[E_E] = [E_G] = LT^{-2}$,

$[\varphi_E] = [\varphi_G] = L^2T^{-2}$, $[F] = L^4T^{-2}$, $[U] = L^5T^{-2}$.

“Rest” and Motion in the GDM

Every disturbance in space must move at the velocity of its elastic waves, c_L or c_T . As a consequence there is no state of rest. “Rest” is defined, therefore, as a situation in which a disturbance, although moving at velocity c_L or c_T , is on a closed track. This orbital movement, Dirac’s Zitterbewegung [5], is the spin of elementary particles. A “translational” motion at a constant velocity v , relative to space, is the moving of a wavepacket, of **constant length**, on a spiral. The “translational” motion is thus the motion of the virtual center of circulation of the wavepacket. An accelerated motion is that of a spiral, with an ongoing contraction of its radius.

Space in the GDM is a Special Frame

Space is a special frame, and velocity and acceleration relative to it are measured by the Cosmic Microwave Background (CMB) Doppler shift. The Special Theory of Relativity in the Lorentzian interpretation is encompassed within this idea.

The GDM is based on the Theories of Elasticity and Riemannian Geometry

The geometry of a deformed elastic space lattice is Riemannian [6]. We thus conclude that General Relativity (GR) is not only a theory of bent manifolds of a continuous space, but also a theory of deformed elastic three-dimensional space lattices and four-dimensional space-time lattices [2], [3],[6].

Since this paper has a specific purpose we do not elaborate on the GDM, but simply point out, whenever necessary, its relation to the present work. This work, however, exposes the reader to the ideas and way of reasoning of the GDM.

3 Inertia

3.1 “Rest” and Motion

According to the GDM every space disturbance, a transversal or longitudinal wavepacket, must move at the velocity c_T or c_L , respectively. We distinguish between c_T and c_L when necessary and according to the case. In most cases we use the symbol c instead of c_T .

“Rest”

In the GDM we relate to “rest” as the case in which a wavepacket moves in a closed loop. In this case we consider the geometrical center of the circulating wavepacket as its location at rest in space.

The electron (positron) at rest is a circulating longitudinal dilational (contractional) wavepacket with a tangential velocity of propagation c and radius of circulation R_0 . In [3] we elaborate on this circulation which is actually more complex. Thus, from a distance, the electron (positron) is observed as if at rest, and from close, as a volumetric dilation (contraction), which is its negative (positive) charge that moves in a circle [2] [3].

Fig. (1) is a simplistic description of the electron (positron). The gray sphere (circle) represents the zone of dilated (contracted) space, which is the electric charge. In this discussion we omit, for simplicity, the circulation of the charge, with radius r_e around its surface, as shown in the detailed model in [3]. We also do not show in Fig. (1) that the circulation plane is **not** perpendicular to the velocity vector \mathbf{v} . The projection of the angular momentum \mathbf{L} , of this circulation, on \mathbf{v} is $L_z = 1/2 \hbar$ whereas $L = \hbar\sqrt{j(j+1)} = \hbar\sqrt{1/2(1/2+1)} = 0.866 \hbar$, hence the inclination of the circulation plane.

“Rest” is described on the left of Fig. (1). The zone of dilated space (charge) of our electron revolves, in the xy plane, around the origin with a radius R_0 . In this case: $c = \omega R_0$. From now on, when we relate to the electron we also relate to the positron, unless otherwise is mentioned.

The electron model, presented here, is a simplified version of a much more detailed model that appears in [3] and yields accurately the leptons’ masses and some other features.

Note, however, that in [3] we present the elementary particle at “rest”, whereas here we elaborate on its motion.

Motion

Fig. (1), on the right, describes motion. Motion is the situation in which the circle of revolution of the wavepacket becomes a spiral. The GDM considers the **length of the wavepacket** to be retained. From this conjecture alone we derive the results of the Special Theory of Relativity. Hence the spiral radius R is smaller than R_0 . This is in analogy to a stretched spring. According to Fig. (1):

$$R = 1/\gamma R_0 \tag{1}$$

The resultant electron motion, however, is always at the wave velocity c . Thus a translatory motion at constant velocity, v , does not involve any exertion of force. It is also obvious that necessarily $v \leq c$.

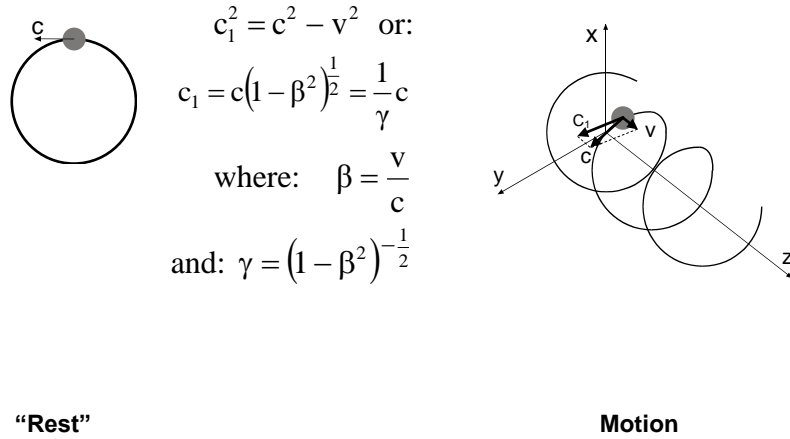


Fig. (1) Rest and Motion

Newton’s first law, and the **first postulate of the theory of relativity**, which implies that no particle or signal can move at a speed that exceeds the light/wave velocity c , are thus a natural result. The helical motion, which is an electric current formally in the direction $-z$, is related to the magnetic field \mathbf{B} and the vector potential \mathbf{A} . The Circular Track is stable since the centrifugal force is balanced by an equal but opposite centripetal force. The Lorentz force, created by the magnetic field of the circulating charge acting on itself, is the required centripetal force, see [3].

3.2 The Elementary Particle Inertia

At rest, the energy of the electron is U_0 , linear momentum is $P_0 = U_0/c$ and the angular momentum is $L_0 = P_0 R_0$.

In motion, energy, linear momentum and angular momentum are U , $P = U/c$ and $L = PR$ respectively.

The conservation of angular momentum $L = L_0$ (which is $1/2 \hbar$ for the electron) implies that:

$PR = P_0 R_0$ hence $UR = U_0 R_0$ but:

$$R = 1/\gamma \cdot R_0 \quad (1)$$

Thus:

$$U = \gamma U_0 \quad (2)$$

Considering the energy as purely electromagnetic, where the elementary charge Q is a sphere of radius r_0 [1] [2], the relations $U_0 = Q^2/2r_0$, $U = Q^2/2r$ and (2) give:

$$r = 1/\gamma \cdot r_0 \quad (3)$$

For $v \ll c$ (3) is:

$$r = (1 - v^2/2c^2) r_0 \quad (4)$$

Acceleration is accompanied by an increase of energy U , and a reduction in the radii R and r . The applied force, needed to accelerate the particle, is doing work to curve space more strongly [2], [3] and thus to reduce r . This force is needed to increase stress and cause more strain in order to enlarge the curvature. Thus we arrive at **Newton's Second Law** and understand **Inertia**.

Note that we have replaced Newton's axiomatic laws by our postulated model of an elementary particle. Some of the merits in this replacement, as we show, are:

- It leads to the proof of the equivalence of gravitational mass and inertial mass.
- It enables us, Part 2, to show that gravitational mass is inertial mass.
- It proves that mass is not a fundamental attribute of matter.
- It proves that inertia is an intrinsic attribute of matter, with no need for an additional field to induce it (Higgs Field).

Note that $L = 1/2 \hbar$, $R = 1/2 \hbar c / U$, $U_0 = Q^2 / 2r_0$ and $r = Q^2 / 2U$ give:

$$\alpha = r/R = Q^2 / \hbar c \quad \textbf{Fine Structure Constant.} \quad (5)$$

Note also that at “rest” the angular momentum can point in any direction, whereas in motion it can point, generally (see Section 3.1), in the direction of motion or opposite to it. This attribute is related to Space Quantization.

3.2 Mass

Our “relativistic” relation (2) gives:

$$U = \gamma U_0 = U_0 \left(1 - \frac{v^2}{c^2} \right)^{-\frac{1}{2}} \simeq U_0 + \frac{\frac{1}{2} U_0 v^2}{c^2} \quad \text{The second term:} \quad \frac{\frac{1}{2} U_0 v^2}{c^2} = \frac{1}{2} (U_0 / c^2) v^2 ,$$

is identified as the **kinetic energy** where:

$$M_0 = U_0 / c^2 \quad (6)$$

Thus **inertial mass** becomes merely a **practical term**. We also get:

$$M = \gamma M_0 \quad (7)$$

The literature distinguishes between the **kinetic energy** $\frac{1}{2} M_0 v^2$, which a particle possesses by virtue of its motion, and its **internal energy** $M_0 c^2$. But here, the kinetic energy is also an internal energy of deformation (the reduction in size of r and R) that cannot be distinguished from the rest energy.

Note again that the electron model, presented here, is a simplified version of a much more detailed model that appears in [3] and yields the masses of the leptons and quarks.

More on our electron is presented in:

Appendix A - The Moving Electron - Supposedly a “Point-Like” Particle

4 How an Elementary Particle Senses Curvature and Moves Accordingly

We contend that the curving (deforming) of space creates gradients in light velocity [7]. Light velocity is a variable, which depends on space density; as is the length of a yardstick and necessarily so too is the rate of a clock. In other words, light velocity is a variable depending on the reference frame of the observer. However, GR shows that this dependence is such that **every observer** in a deformed or non-deformed space will get, by taking measurements, the same local result for light velocity. This invariance is the essence of the concept of a “constant of nature”, a fact that is often overlooked, but is discussed in detail in the following sections.

We further contend that an elementary particle, being a longitudinal circulating wavepacket, with a given radius, can “detect” these gradients and move accordingly - to fall free. In this regard we do not have to relate to gravitation as a force field.

4.1 The Metric and Light Velocity

Schwarzschild, in 1916, was the first to find a solution to Einstein’s field equation - a general spacetime metric - for the exterior of a spherically-symmetric star of radius R , i.e., for $r > R$:

$$ds^2 = -g_{00}c^2dt^2 + 2g_{0r}drdt + g_{rr}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2) \quad (8)$$

where the metric elements g_{00} , g_{0r} and g_{rr} are functions of r and t .

According to [8], Chapter 10, the line element ds^2 is:

$$ds^2 = -e^{-\frac{2GM}{c^2r}}c^2dt^2 + e^{\frac{2GM}{c^2r}}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2) \quad (9)$$

We denote a gravitational scale factor, a :

$$a = e^{-\frac{2GM}{c^2 r}}$$

For the surface of the sun or the edge of our galaxy: $GM/rc^2 \sim 10^{-6}$ and thus $GM/rc^2 \ll 1$. For $GM/rc^2 \ll 1$ a is approximated as:

$$a \sim (1 - GM/rc^2) \quad a < 1 \quad r \rightarrow \infty \quad a \rightarrow 1 \quad (10)$$

Using (10) we rewrite (9) as:

$$ds^2 = -a^2 c^2 dt^2 + a^{-2} dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \quad (11)$$

The metric in (11) is derived by a faraway observer OB1– far away from the center of a mass, M , that serves as the origin of his co-ordinates.

We consider the elastic space to be a lattice [9]. Space density ρ is defined as the number of space cells per unit volume. Space density in a zone of space without deformations (far away from masses and charges) is denoted ρ_0 . Note that we relate to space as a 3D elastic, deformable media, rather than a bent manifold [6]. Note also that this understanding means that **a standard yardstick has the same number** of space cells along its length, anywhere in space.

For OB1, a radial distance interval, dl , close to a mass, contains a smaller number of his yardstick units, dr , than dr_0 , the number of the local observer OB2 yardstick units that dl contains. This is the result of the OB2 yardstick contraction, which is also the contraction of his local space. Hence:

$$dr_0 = a^{-1} dr \quad a < 1 \quad (12)$$

For OB1, a time interval, $d\tau$, contains a larger number of time units, dt , than the number of time units, dt_0 , for OB2. And indeed, from the synchronization of clocks, Rindler [10] p.184 arrives at the conclusion, that:

$$dt_0 = adt \quad a < 1 \quad (13)$$

The 4D spacetime interval between two events; the “emission” of a short pulse of light at point A and its “arrival” at point B is $ds^2 = 0$ [10] p.236. Hence using (11):

$$-a^2 c^2 dt^2 + a^{-2} dr^2 = 0$$

$$acdt = a^{-1} dr$$

$$dr/dt = a^2 c \quad (14)$$

This, $dr/dt = c'$, for OB1, is the light velocity close to the mass M. Light velocity, for OB1, far away from the mass M, is c and $dr/dt = c' < c$. This, $dr/dt = c'$, is a local real and slower light velocity since, according to (10) $a < 1$.

Note that in the literature dr/dt in (14) is called **coordinate speed of light**. This is a misleading name, since dr/dt should be considered a **real speed**.

Substituting (12) and (13) in (14) gives:

$$dr/dt = adr_0/a^{-1}dt_0 = a^2 dr_0/dt_0 \quad \text{Comparing this equation to equation (14), gives:}$$

$$dr_0/dt_0 = c \quad (15)$$

We thus conclude that OB1 and OB2 measuring light velocity in their own zones of space arrive at the same result. On the other hand, again:

$$c' = a^2 c \quad (16)$$

This invariance attributes the title “**a constant of nature**” to light velocity, despite the fact that in different zones of space it can behave differently.

4.2 The Gravitational Field as a Gradient in Light Velocity

According to (14) and (10), for $GM/rc^2 < 1$:

$$dr/dt = a^2 c = (1 - GM/rc^2)^2 c \sim (1 - 2GM/rc^2) c = (1 + 2\phi/c^2) c \quad (17)$$

For the surface of the sun or the edge of our galaxy: $GM/rc^2 \sim 10^{-6}$.

According to (17), **and notating** $dr/dt = c'$, the gravitational potential is:

$$\phi = \frac{1}{2} c (c' - c)$$

Note that $c' < c$, and that $\phi < 0$. The field strength (central acceleration g) is thus:

$$E_g = g = - d\phi/dr = - \frac{1}{2} c dc'/dr \quad (18)$$

$$\mathbf{E}_g = \mathbf{g} = - \frac{1}{2} c \nabla c' \quad (19)$$

Note that $\mathbf{E}_g = \mathbf{g}$ is the free fall acceleration (central acceleration).

Thus the gravitational field can be considered a gradient in light velocity $\mathbf{E}_g = - \frac{1}{2} c \nabla c'$.

Note that c' is not a scalar, it is a vector \mathbf{c}' , and $\nabla \mathbf{c}'$ is a gradient of a vector. This gradient involves Christoffel symbols which are involved in the GR alternative to the classical field.

A check of our derivation:

From (17), and $c' = dr/dt$ we get: $c' = (1 - 2GM/rc^2)c$ and $dc'/dr = 2GM/r^2c$. Hence, according to (18) $g = - \frac{1}{2} c dc'/dr = - GM/r^2$ or :

$$\mathbf{g} = - GM/r^3 \cdot \mathbf{r} \quad (20)$$

Note that M is a **gravitational mass**, since it comes from Einstein's field equation.

Note also that equations (18) and (19) are **general equations**, not necessarily limited to the Newtonian gravitational field. This observation is relevant to the Dark Matter issue, see Section 5.

4.3 Free fall

Free fall is the result of elementary particles being longitudinal circulating wavepackets. As such they sense (are affected by) the gradient in light velocity. At large, if in part of the circular trajectory the particle moves with a slower light velocity than in another part, the linear momentum U/c of the slower part increases. For the particle to retain angular

momentum, $L = (U/c)R$, R should become smaller; a result of an increase in its translational motion, see Section 3. This is an ongoing process and hence the free fall acceleration. Note that the circulation plane, as explained in Section 3.1, is not perpendicular to the direction of the free fall. This enables the particle to continuously sense the gradient in light velocity while falling down and being accelerated.

Taking (20) and $\mathbf{F} = \mathbf{g}M'$, where M' is an inertial mass, gives: $F = - GMM'/r^2$ or

$$\mathbf{F} = - GMM'/r^3 \cdot \mathbf{r} \quad (21)$$

In (21), M' is the inertial mass of the falling particle whereas M is the gravitational mass of the curving mass that creates the gradient in light velocity. Each and every mass falls free in the gradient of light velocity created by the presence of all other gravitational masses.

Let M_1 and M_2 be the gravitational masses of two particles and M_1' , M_2' their respective inertial masses. According to (21):

$F_{12} = - GM_1M_2'/r^2$ and $F_{21} = - GM_2M_1'/r^2$. If $F_{12} = F_{21}$, which is Newton's third law (applicable only for the weak field case in which space translational symmetry holds) then:

$$M_1M_2' = M_2M_1' \quad \text{or:}$$

$$M_1'/M_1 = M_2'/M_2 = \text{constant}. \quad (22)$$

This is a proof of the **equivalence of gravitational mass and inertial mass**.

In Part 2 of this paper we arrive at a proof of their **equality** and not only their **equivalence**.

5 The Repulsive Force between Masses

Positive electric charges repel each other. The GDM assigns positive curvature to a positive charge. GR assigns positive curvature to mass. Thus GDM complies with GR if, and only if, masses repel each other. And, indeed, the Cosmological Constant represents a repulsive force

[11], which can be derived from the GR equation using its weak field approximation - Poisson equation. The relevant general field strength or acceleration is:

$$\mathbf{g} = -\nabla \varphi = -GM/r^3 \cdot \mathbf{r} + 1/3 \cdot \Lambda c^2 \mathbf{r} \quad (23)$$

Hence at large distances, hundreds of kiloparsecs (kpc) from the center of our Milky Way galaxy for example, the repulsive acceleration becomes larger than the “gravitational” central acceleration.

If galaxies repel each other, and space within galaxies does not expand, could this be the reason why space outside galaxies expands? We wonder.

6 Summary

We have explored the nature of Inertia by constructing a simple model of an elementary particle. This model enabled us to realize that mass is only a practicality and not a fundamental attribute of matter. Based on this we have shown how a mass senses curvature of space and moves accordingly. This sensing and moving is “free fall”, to which we refer as the “gravitational attraction”.

Acknowledgements

We would like to thank Professor Y. Silberberg of the Weizmann Institute of Science and Professor A. Zigler of the Hebrew University of Jerusalem for their careful reading and helpful comments, and Mr. Roger M. Kaye for his linguistic contribution and technical assistance.

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Appendix A Size of the Moving Electron

Scattering experiments with energies of 10 TeV (at the LEP storage ring), “sets” an “upper limit” of $\sim 2 \times 10^{-18}$ cm for the electron size [12]. In these experiments, the higher the scattering energy, the shorter the distance between the colliding particles (by overcoming the repulsion). According to the GDM the imparted energy, in the experiment, reduces the radius of the electron, and there is almost no lower limit to its size, see Fig. (2).

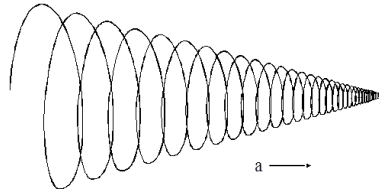


Fig. (2) The track of the Accelerated Particle

Appendix B Disintegration and Radiation of and by the Electron Stability

Considering the electron as a classical particle that can stay at rest, raises the question regarding the electrostatic repulsion that can tear it apart.

In the GDM, however, the electron is a wavepacket that always moves at the speed of light, whether as a closed loop (“rest”) or as an open spiral. Therefore, we should consider the Lorentz force between the “parts of an electron”, each with charge δQ , that happen to run in parallel and at the speed of light.

The Lorentz force: $\mathbf{F} = \delta Q \left(\mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right)$ is the force that “one part of the electron”, with charge δQ , applies on “another part”, also with charge δQ , by creating the fields \mathbf{E} and \mathbf{B} . Using the expression $\mathbf{B} = (1/c) \mathbf{v} \times \mathbf{E}$, that defines \mathbf{B} and taking $v = c$, we get $\mathbf{F} = 0$. This result explains stability.

Radiation

In the “rest” mode, the electron charge moves at a tangential speed c on a closed circle. This might be expected to yield synchrotron radiation, and a loss of energy. But this radiation moves at the speed of light, which is the speed of the emitter and hence can never leave it.

Appendix C A Note on Special Relativity (SR)

We retain the SR formalism, since space is just another frame of reference, although it is universal and special.

Appendix D A Note on Time

We do not know what time is. All we know is that the rate of a clock can be used to define a unit of time. A local clock can be a box with two opposite ideal mirrors that reflect a beam of light back and forth. The time of flight back and forth is our unit of time. This unit of time, according to Lorentz transformation, becomes longer if the box moves parallel to the beam, and/or if it is placed in a gravitational field where light velocity is slower [7]. Measuring time is merely the comparison of the rates of clocks. Time by itself has no meaning for us.

Our time coordinate, in units of distance, is $x = ct$. Relating to our 4D reality as a 3D Space and 1D Time, the following notations are common in the literature; $x_4 = ct$, $x_4 = ict$ or

$x_4 = -ict$. It is now clear that we can relate to space density in a broader sense that includes the rates of clocks (time) at each and every point.

For more on time see [13].

Appendix E Screening

A Faraday cage shields its inside from external electric fields. This is possible since free electrons in the metallic cage create an equipotential surface on the cage and hence the field

inside the cage becomes zero. A Faraday cage, however, does not shield an inside mass from the gravitational field because it cannot cancel the gradient in the velocity of light.

Appendix F Free Fall of an Electron

The consensus is that particles should fall freely in a gravitational field regardless of their charges. For neutrons, this is the case [14]. Electrons, however, fall with an acceleration of 0.1g rather than g. This result was predicted [15] and demonstrated experimentally [16]. This result is explained by the presence of an electric field, created by the gravitational field and opposing it. This electric field is the gravitational “polarization” of the metallic tube used in the experiment. To date, this is the only free-fall experiment that has been performed on an elementary particle.