Elementary Differences between Energy and Mass

The present paper is concerned with the elementary differences between energy and mass. When we consider the famous Einstein's equation: $E = m c^2$ *, these two concepts might look the same with the only difference of a constant of proportionality,* c^2 *. However when we explore these two concepts more carefully we discover that they differ in several fundamental aspects. The paper also explains the meaning of negative energy or time-travel energy.*

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September 2014 (v1) - October 2015 (v10)

Keywords: *Rest mass, relativistic mass, photon, gluon, graviton, positron, Heisenberg uncertainty principle, universal uncertainty principle, particle-antiparticle annihilation, Pauli exclusion principle, boson, fermion, generations of matter, backward-time-travel energy, time-travel energy, backward energy, reverse energy, parallel energy, complement energy, mirror energy, Feynman energy.*

1. Introduction

The celebrated Einstein's equation of equivalence of mass and energy:

$$E = m c^2 \tag{1}$$

means that energy can be converted into matter, and matter into energy. However this does not mean than energy and matter are identical. To make things even more confusing some people go further saying that energy is matter and matter is energy. This is a simplistic statement aiming to explain Einstein's mass-energy relationship in simple terms. A more complete description would be to say that mass can be considered to be another form of energy. However when people talk about equation (1) they, generally, don't explain the differences between energy and mass. Therefore the subject of this article is to pinpoint and explain these differences.

2. Differences

i-Velocity in Vacuum

According to Einstein the speed of light in vacuum is both the maximum speed a massive body can travel through space and also the maximum speed information can propagate through space. He found that massive particles obey the relativistic mass law:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{2}$$

This formula tells us that the velocity, v, of a massive body must be smaller than the speed of light in vacuum, c. Mathematically

$$v < c \tag{3}$$

If gluons, photons, gravitons and neutrinos (*) were massive, as the author has proposed [1, 2], they could still travel at the speed of light without violating special relativity because one or more of the following reasons:

1. The first possible reason is that, as a consequence of *luminar creation*, these particles, do not experience any acceleration. The definition of luminar creation is:

Luminar Creation

Luminar creation is the process by which some particles such as gluons, photons, gravitons, and neutrinos are created directly at the speed of light without undergoing any acceleration. Therefore these particles would not violate Einstein's special relativity because they would begin their existence, already, at the speed of light.

2- The second possible reason is that, for unknown reasons, the mass of these particles do not obey the relativistic mass law given by the relativistic mass equation (2).

3- The third possible reason is that the principle of equivalence between inertial and gravitational mass does not hold. Thus the rest mass of these particles would not be inertial but gravitational. This means, for example, that the rest mass of the photon, $m_{\gamma o}$, would be a gravitational mass and not an inertial one. If this were the case, general relativity would be based on a false assumption. This in turn would mean that quantum mechanics and gravity could be reconciled into a quantum gravitational formulation comprising the four known forces of nature (see Appendix 1).

(*) Because of neutrino mass oscillations, we know that, at least, one of the three known neutrinos must have mass [3, 4]. We also know that they travel at the speed of light. This indicates that, at least, one of the above possibilities must be true. This is bad news for the Standard Model of particle physics which assumes neutrinos are massless particles. This clearly indicates that the Standard Model needs a deep revision.

ii-Time

According to American physicist R. Feynman [5], particles, such as electrons, can travel backward in time. We see an electron travelling backward in time as a positron travelling forward in time. Thus the positron is the antiparticle of the electron. We also know from experiments, that when a particle and its antiparticle, such as an electron and a positron, get in contact with each other, they annihilate. Depending on the kinetic energy of these two particles, two or three gamma rays (photons) are produced. Thus, two material particles are converted into pure energy in accordance to Einstein's equation of equivalence of mass and energy. The electron and the positron annihilate because of two reasons: a) these particles travel in time in opposite directions. One electron travels forward in time while the other one travels backward in time (which is equivalent to a positron travelling forward in time), and b) these two particles have different types energies. The particle travelling forward in time has positive energy while the particle travelling backward in time has negative energy.

When a particle and its antiparticle are in physical contact, they either occupy the same volume of space (or at least they are as close as they are allowed to be by the laws of physics). But the same volume of space cannot have two different times and two different types of energies and therefore time must stop lapsing. The result of this time cancellation is the total conversion of the mass of the two particles into energy (annihilation). Time cancellation means that energy does not travel neither forward nor backward in time. This means that for electromagnetic radiation (photons) time does not lapse. Thus radiation is timeless. This is one of the most profound differences between energy (radiation or photons) and mass.

iii-Fundamental Relationships

The German physicist W. Heisenberg showed that there is a fundamental relationship between the uncertainty of the momentum of a particle and the uncertainty in its position. Heisenberg expressed this relationship with an inequation known as the Heisenberg uncertainty principle (I shall called it *the spatial uncertainty principle* or *the momentum-position uncertainty principle* to distinguish it from *the temporal uncertainty principle*). Thus the Heisenberg spatial uncertainty principle is

Heisenberg momentum-position uncertainty relations

$$\Delta p_x \Delta x \geq \frac{\hbar}{2} \tag{4a}$$

$$\Delta p_y \Delta y \geq \frac{\hbar}{2} \tag{4b}$$

$$\Delta p_z \Delta z \geq \frac{\hbar}{2} \tag{4c}$$

Because the momentum of the particle depends on its mass

$$\vec{p} = m \vec{v} \tag{5}$$

According to equation (2) we can write

$$\vec{p} = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}} \vec{v} \tag{6}$$

Thus equations (4a), (4b) and (4c) tell us that there is a fundamental relationship between the mass of a particle, its velocity and space (momentum and space are conjugate variables).

It was also shown that there is a fundamental relationship between the uncertainty of the energy of a particle and the uncertainty in the duration of this energy. Heisenberg expressed this relationship with an inequation known as the *temporal uncertainty principle or energy-time uncertainty principle:*

Heisenberg energy-time uncertainty relation

$$\Delta E \Delta t \geq \frac{\hbar}{2} \tag{7a}$$

Which Heisenberg principle is more fundamental: the momentum-position uncertainty relations or the energy-time uncertainty relation?

The **energy-time** uncertainty relation is more fundamental than the **momentum-position** relations simply because relations (4b), (4b) nad (4c) are a material "replica" of the temporal relation (7a). In other words the **energy-time** relation comes from the pre-universe or Meta-Universe which does not contain any mass but energy only; while the **momentum-position** relations came to existence only after all material particles were created during and after the Big Bang (or Meta-transformation). I have shown, in another article entitled: *The Quantum Gravitational Cosmological Model without Singularity* [15], that the Universe started with a mass equal to the Planck mass divided by 2. (99 % of the mass of the Universe was created in the first 442 million years after the Big Bang).

In 2012 I generalised the Heisenberg relations by introducing the *universal uncertainty principle* (UUP) which I described in another paper [6]. The special energy-time universal uncertainty principle (SUUP), which is a special case of the general universal uncertainty principle (GUUP), is:

The special energy-time universal uncertainty relation

$$\Delta E \Delta t \geq \sqrt{\frac{\hbar^2}{4} - \frac{\hbar}{4} T_P \Delta t} \tag{7b}$$

These relations mean that there is a fundamental relationship between the uncertainty in the energy of a given physical process and the uncertainty in the interval of time during which the process exists. Thus, there is a fundamental relationship between energy and time. This is also because of the fact that energy (or Meta-energy) and time (or Meta-time) are primordial (*). Thus relation (7b) reflects the relationship between these two primordial physical magnitudes (energy and time are conjugate variables).

(*) The word primordial in this context means that both energy (or Meta-energy) and time (or Meta-time) existed before the Big-Bang and that they are not made by anything more fundamental (they do not have "ingredients" or components). This is the reason why we are unable to know what energy and time are.

iv-Origin

According to my theory on the Universe [7], energy (or Meta-energy) has no origin - it always existed (*). On the other hand, matter (and therefore mass) had a beginning and this beginning is known as the Big Bang. Thus energy is infinitely old while matter is only 13.823 billion years old [8, 9, 10].

(*) Something that has always existed has no origin so the question: Where do the Meta-laws of physics come from? does not make any sense since this question is equivalent to asking: What is the origin of the Meta-laws of physics? However the question: Where do the laws of physics come from? makes sense and the answer is from Meta-laws.

v- “Ingredients”

We do not know the exact difference between Meta-energy and energy. Perhaps anti-particles are made of “frozen” Meta-energy in contrast to particles which are made of “frozen” energy. We also assume that both Meta-energy and energy have no “parts”, “components” or “ingredients”. This means that energy is primordial, meaning it cannot be explained in simpler terms.

On the other hand, mass has “ingredients”. Although these ingredients are more subtle than “parts”. To find the ingredients of mass we have to look at the most celebrated equation of all time: the Einstein's law of equivalence of mass and energy:

$$E = m c^2 \tag{8a}$$

We observe that the proportionality constant, c^2, depends on the velocity of propagation of radiation (photons), and not on the group velocity of matter. This means that energy occupies a higher hierarchy than matter, suggesting that energy was either created before matter or existed before matter. This supports my assumption that Meta-energy (or energy) is primordial (*). To clarify this point I shall write equation (8a) as once Einstein did:

$$m = \frac{E}{c^2} \tag{8b}$$

According to our assumption that Meta-energy is primordial, and considering that time and space were created during the Meta-transformation known as the Big-Bang, we deduce that neither space nor time are primordial but they are by-products of this Meta-transformation (I have postulated that Meta-time is primordial). We also know that, in order to propagate, photons need space and time. Therefore we draw the conclusion that space and time are the rest of the ingredients “used” by Nature to make the mass of all known particles. It could be said that photons are part of space-time by saying that photons are ripples of space-time. However this would not change anything since if this were the case then energy and space-time would still be the ingredients of mass. Thus we can affirm that mass has three “ingredients”: energy, space and time – as shown on the second side of Einstein's equation (8b).

(*) The word primordial in this context means that energy (or Meta-energy) existed before the Big-Bang in its own Meta-time. Normal time, on the other hand, was created during the Big Bang and therefore might not be as primordial as energy (or Meta-energy) or as Meta-time. Thus Meta-time is infinite while time is finite (13.823 billion years). However if Meta-energy, Meta-time and Meta-space were identical to energy, time and space respectively, my conclusion would still hold since mass would be the result of three primordial “components”: energy, space and time.

vi-Universal Lifetime

I shall define the universal lifetime as the time in which all the mass in the Universe ceases to exist. Thus I postulate protons, electrons and neutrinos (and any other kind of “stable” matter may there exist) will transform into energy (or Meta-energy) “at the end of time”. Thus we arrive to the following conclusion: Energy (or Meta-energy) is eternal and matter (and therefore mass) is ephemeral. Here the term ephemeral is used as the opposite to eternal. Protons, electrons and neutrinos are all unstable. In other words there are no stable particles.

vii-Does it Obey the Pauli Exclusion Principle?

Bosons are the force carriers responsible for carrying energy from one particle to another with the “purpose” of transmitting force (e.g. photons are the force carriers between two electrons). These carriers do not obey the Pauli exclusion principle. We can say that they are really social particles. On the other hand, fermions, which are the building blocks of normal matter, obey this principle. They don't group together like bosons do. Fermions are not “social” particles. Thus, because matter is made of mass we can say that material particles such as electrons, protons and neutrons do not “enjoy” a “social” life. In summary, bosons (energy) are “social” in a Pauli exclusion principle sense, while fermions (mass) are “anti-social” in that sense. I have to clarify that if photons are indeed found to be massive, then they should still be considered as a form of energy: radiation. Therefore the rest of the bosons should also be regarded as energy.

viii-Is it One of the Properties of Something Else?

Mass is one of the properties of matter. Other properties of matter include: electric charge, colour charge, spin, etc. However, energy is not the property of anything we know about. Here we can say that energy is a property of the Meta-universe. However, the Meta-universe is something huge that cannot be compared to matter in any way. Thus, we are probably right when we say that energy is not related to any other “structure” in the way that mass and mater are related to each other. The only other possibility I can think of is that energy to be a property of Meta-energy - the energy of our eternal Meta-universe.

ix-Organization

We know that matter is organized into three known generations, however energy does not have such organization. In order to organize matter, and therefore mass, Nature needed energy, time and space. Thus these three “ingredients” are not only necessary to make up the mass of all known particles but also to organize them into generations. This shows a fundamental difference between the Meta-universe and the Universe created during the Big Bang. While the Meta-universe is a relatively featureless "place" (a World of high entropy state), our Universe, is highly organized (a place of low entropy state). This explains the reason we live in a Universe governed by the second law of thermodynamics: it is highly likely that, in a closed system, entropy will increase, but is not 100% certain (this means that the probability of this happening is not 1 but very close to it). This Meta-transformation from a high entropy state to a low entropy state is what we called the Big Bang, and is exactly what it was needed for life to emerge. Thus intelligent life is the maximum known organization state the normal laws of physics can achieve. However, because we cannot prove that life is common to all Universes, we have to assume that there could be other Universes in which life will never emerge. Or perhaps life (of any kind) is the "ultimate cosmological product" in all parallel Universes regardless of the laws of physics they inherited.

x-Can it be Negative?

Two of the most fundamental questions in physics are: a) can mass be negative? and b) can energy be negative? Since negative mass has never been observed, the answer to the first question seems to be, no. However, antiparticles in particle-antiparticle annihilation can be interpreted as particles with negative energy travelling backward in time. Because of Einstein's equation (8b), it seems that negative energy, at least in this case, implies negative mass. Thus we should not discard the existence of negative mass even if we are unable to observe it directly in annihilation experiments. The Casimir effect also indicates that energy density, and thence energy, can be negative. But what is the meaning of negative energy? It depends on the definition we adopt. I shall define negative energy as follows:

Definitions of Negative Energy

Definition 1- The energy of a physical entity (particle, atom, molecule, body, etc.) is negative if when that entity gets into physical contact with another entity of positive energy of the same or similar type (e.g. positron-electron annihilation, antihydrogen atom- hydrogen atom annihilation, etc.), both entities annihilate. Note that time cancellation, as described above (difference ii) is simultaneous to matter-antimatter annihilation. The American physicist R. Feynman proposed the following interpretation of negative energy [5]:

"The fundamental idea is that the "negative energy" states represent the states of electrons moving backward in time...reversing the direction of proper time s amounts to the same as reversing the sign of the charge so that the electron moving backward in time would look like a positron moving forward in time."

I have to clarify one important point. According to this definition the normal addition rule cannot be applied to positive and negative energies. In other words they cannot be added together to give zero energy. When we add the positive energy of a normal particle (e.g. electron) with the negative energy of a particle that travels backward in time (which we observe, for example, as a positron) we get the sum of the normal particle's energy plus the absolute value of the energy of the particle with negative energy, not zero energy. Because we move forward in time, not backward, we see a particle with negative energy travelling backward in time as a positive energy antiparticle travelling forward in time. Because particles with negative energy travel backward in time and because we are unable to travel in that direction (backward), we see these time travellers as entities with positive energy travelling forward in time and thus we call them: *antiparticles*. In other words the view adopted in this paper is that the universe contains:

a) particles with positive energy travelling forward in time, and
b) particles with negative energy travelling backward in time.

When a charged particle changes the direction of time travel at least the following two changes take place:

a) the energy of the time travelling particle becomes negative, and
b) the electrical charge of the time travelling particle is reversed (either from negative to positive or from positive to negative).

I shall not consider electrically neutral particles in this paper (particles that can be their own antiparticles).

In order to get the final energy during an electron-positron annihilation process we must add two energies together: the positive energy of the electron, $E_{electron}$, and the absolute value of the energy of the time traveller particle, $|E_{time\_traveller\_electron}|$. Thus the total energy after annihilation (assuming both particles are at rest before the encounter) is:

$$E_{electron} + |E_{time\_traveller\_electron}| = 2\,E_{electron} = 2\,hf \tag{9}$$

Alternatively we can add the positive energy of the electron plus the positive energy of the positron:

$$E_{electron} + E_{positron} = 2\,E_{electron} = 2\,hf \tag{10}$$

At this point in time I shall emphasize that the “more correct” way of adding energies of particles and antiparticles is as shown by equation (9). Although equation (10) is equivalent it should be avoided because we have adopted the view that the world contains only particles (or ordinary matter) travelling either forward or backward in time. Thus, in certain way we can say that antiparticles with positive energy travelling forward in time are just an illusion produced by our inability to travel backward in time *. Thus, strictly speaking, the term *antimatter* is redundant and misleading.

To avoid confusion you can think of “negative energy” as *backward-time-travel energy, time-travel energy, backward energy, reverse energy*, *parallel energy*, *complement energy*, *mirror energy*, *Feynman energy,* etc., or think of “negative energy states” as “anti-energy states”.

Definition 2- According to the Casimir effect [11, 12], the energy density, ρ_{plates}, in the intervening space between two uncharged conducting plates can be negative:

$$\rho_{plates} < 0$$

To complete the definition of negative energy please refer to the article: “*The Special Quantum Gravitational Theory of Black Holes (Wormholes and Cosmic Time*

Machines)" [13].

* You could use the opposite point of view: that the world contains only antiparticles travelling either forward or backward in time. However because it seems there is more matter than antimatter in the observable universe, and because we are made of matter, it seems more reasonable the point of view we have adopted in this paper.

The total relativistic energy for a particle is given by the Einstein's equation

$$E = \pm\sqrt{(pc)^2 + (m_0 c^2)^2} \tag{9}$$

The equation has two solutions, a positive solution and a negative one:

$$E = +\sqrt{(pc)^2 + (m_0 c^2)^2} \quad \text{Positive solution} \tag{10a}$$

$$E = -\sqrt{(pc)^2 + (m_0 c^2)^2} \quad \text{Negative solution} \tag{10b}$$

We only select the solution or solutions that explain the observations. In general we have to assume that, solutions with negative energy, have physical meaning. The Casimir effect is probably the best example of the existence of negative energy. The attraction force between two relatively large plates was discovered by H. Casimir and experimentally observed. The Casimir force is the result of the different energy densities outside and inside the two conducting plates. Since the plates attract one another, the energy density in the outside of the plates must be grater than the energy density in the inside. Because the energy density in the outside is almost zero, we conclude that the energy density in the outside could be negative.

The Casimir effect is not the only place where negative energy plays an essential role. A black hole is another place where negative energy is present. According to general relativity, the laws of physics do not allow a black hole to lose mass by radiating positive energy to empty space (photons generated inside the black hole cannot escape to empty space). Thus the only way for a black hole to reduce its mass is to absorb negative energy from the surroundings. Steven Hawking proposed a mechanism, known as Hawking radiation, that allows a black hole to lose mass and eventually to evaporate. Thus when a pair of virtual photons (a matter-antimatter pair) are created near a black hole's event horizon, one of the photons is absorbed by the black hole while the other one escapes to space and becomes real. The photon that is absorbed must have negative energy so that the black hole can reduce its mass. The Hawking mechanism involves negative energy. In his book: *"The Universe in a Nutshell"* [14] Stephen Hawking quotes:

"A member of the virtual pair of particles will have positive energy and the other one negative energy. In the presence of a black hole, the member with negative energy can fall into the black hole and the member with positive energy can escape to infinity, where appears as radiation that carries positive energy from the black hole." (See Fig. 1)

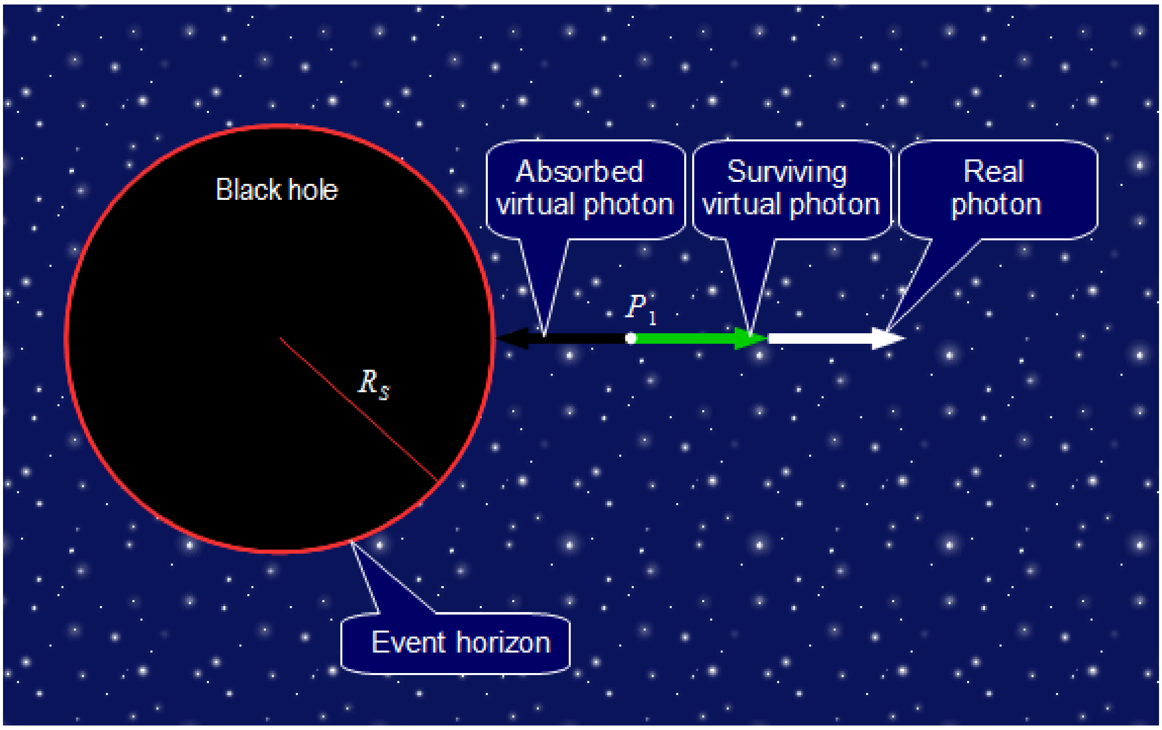

Fig 1: *The black sphere represents a black hole of radius* R_S *. A pair of virtual photons is created near a black hole's event horizon due to the quantum fluctuations of the vacuum. The point of creation is labelled as* P_1*. One of the photons (black arrow) of the pair is absorbed by the black hole while the other one, the surviving photon (green arrow), escapes to space and becomes real (white arrow). This evaporation mechanism was proposed by Hawking and is known as Hawking radiation.*

3. Table of Differences between Energy and Mass

The following table shows the main differences between energy and mass (see next page).

(See next page)

		Energy	Mass
i	Velocity in vacuum (v_{max})	c	$< c$
ii	Time	Does not lapse (photons are timeless)	Lapses
iii	There is a fundamental relationship with	Time $\Delta E \Delta t \geq \frac{\hbar}{2}$ (Temporal Heisenberg uncertainty principle)	Space $\Delta p_x \Delta x \geq \frac{\hbar}{2}$ (Spatial Heisenberg uncertainty principle)
iv	Origin	The Meta-universe or Pre-universe (Energy always existed)	The Big Bang (Matter had a beginning)
v	"Ingredients"	None (Energy or Meta-energy are primordial) $E = m c^2$ (Causes are on both sides of the equation)	Energy, space and time $m = \frac{E}{c^2}$ (Causes are on the second side of the equation only)
vi	Universal Lifetime: in the end there will be	Either energy or Meta-energy only	No matter (and therefore no mass)
vii	Does it obey the Pauli exclusion principle?	No (Bosons, which are force carriers, do not obey this principle)	Yes (Fermions, which are called matter, obey this principle)
viii	Is it one of the properties of something else?	No (unless we accept that energy is a property of Meta-energy)	Yes (Mass is one of the properties of matter. Other properties of matter are: electric charge, color charge, spin, etc.).
ix	Organization	No (generally speaking there are no known generations of energy)	Yes (Matter/mass is organized into three known generations)
x	Can it be negative?	Yes (The Casimir effect, black holes and particles with negative energy travelling backward in time indicate that energy can indeed be negative)	Not Known (Negative mass has not been observed however the existence of this type of mass shouldn't be discarded)

Table 1: *Table of Differences between Energy and Mass*

4. Conclusions

I have presented ten elementary differences between mass/matter and energy (you cannot separate mass from the other properties of matter such as: electric charge, colour charge or spin). We can go even further by observing that, for example, when an electron and a positron annihilate, the result of this annihilation does not contain any information about the charge of the particles that originated the process (only polarization states). Someone observing one of the resulting photons would not be able to decide whether it comes from an electron-positron annihilation or from another process (not necessarily an annihilation). Thus, although charge and another physical properties are conserved, the photons generated in an annihilation process do not carry any information about the electric charge of the particles involved in the annihilation. The information about the electrical charge of the particle-antiparticle pair is lost. This is fundamental difference between matter and energy. I shall call this property of matter *distinctness*. It is necessary to clarify something here. The laws of physics (in this case the uncertainty Heisenberg relations) allows any photon to become an electron-positron pair for a brief period of time, and then to annihilate and become a photon again. So we might be tempted to say that *distinctness* is also a property of energy. However there are two important differences to observe: 1- the transformation of a photon into an electron-positron pair only last an extremely short period of time, and therefore these two particles are ephemeral ones, and 2- any photon (not necessarily one originated from matter-antimatter annihilation), can become an electron-positron pair which will recombine to form a photon again.

In summary, equation (1) implies that *mass is a form of energy*. However, since mass is one of the “built-in” properties of matter, a more complete description is: that *matter is a form of energy in a distinguishable state.* This simply implies that when mass is converted into energy during an annihilation process, all the other properties of matter also disappear. In other words when an annihilation process takes place, mass and only mass is converted into energy but all the other properties of matter are gone in the process and nothing material seems to remain (except for the mass of the photons if they are found to be truly massive). We have also found that there are, at least, two types of energies in the Universe: positive energy, which is the energy associated to particles, and negative energy (or time-travel energy) which is the energy associated to particles travelling backward in time. Thus negative energy, as defined in difference x, definition 1, is definitively inseparable from backward time travel.

Appendix 1
The Forces of Nature and their Carriers

Conventionally, the rest mass of photons, gluons and gravitons is considered to be zero. According to the author photons, gluons and gravitons have non-zero rest mass [1, 2]. Gravitons have been predicted but so far have not been observed. Bosons are particles of integer spin while fermions are particles of odd half-integer spin. Fermions comprise leptons and quarks. Fermions are conventionally called matter. The following table summarizes the four forces of Nature and their exchange particles.

Force (Interaction)	Force Carrier (exchange particle)	Symbol	Mass (GeV/c^2)	Mass proposed by the author (GeV/c^2)	Electric charge	Coupling constant (Measures the strength of the force)
Nuclear	Gluon (observed)	g	0	>0	0	$\alpha_s \approx 0.118$ (Note 1)
Electromagnetic (Electroweak)	Photon (observed)	γ	0	>0	0	$\alpha \approx 0.007$ (Note2)
Weak (Electroweak)	Intermediate bosons (observed)	W^- W^+ Z^0	80.403 80.403 91.1876	80.403 80.403 91.1876	-1 +1 0	$\alpha_w \approx 0.03$ (Note 3)
Gravitational	Graviton (not observed)	g_v	0	>0	0	$\alpha_G \approx 5.9 \times 10^{-39}$ (Note 4)

Table 2: *This table shows the four forces of Nature and the corresponding force carriers or exchange particles. The table also shows the symbols, the conventional mass, the author proposed mass for photons, gluons and gravitons (as greater than zero, in cyan colour), the electric charge, and the coupling constant of the force which is a measure of the strength of the force.*

Note 1 [16, 17]

$\alpha_S(M_Z) = 0.1184 \pm 0.0007$

$\alpha_S(M_Z)$ means that this value of the strong force's coupling constant is measured at an energy equal to the energy of the rest energy of the Z^0 boson.

Note 2

$$\alpha = 0.007\ 297\ 352\ 569\ 8 = \frac{1}{137.035\ 999\ 074}$$

where

α = electromagnetic coupling constant, fine-structure constant or atomic structure constant

Note 3 [18, 19]

According to reference [18] the value of the weak coupling constant is

$$\alpha_w = \frac{g_w^2}{4\pi} = \frac{1}{29} \approx 0.0345$$

According to reference [19] the value of the weak coupling constant is

$$\alpha_w = \frac{g_w^2}{4\pi} = \frac{1}{30} \approx 0.0333$$

As we can see, at low energies, the weak force is not weak compared to the electromagnetic force. In fact, the weak force is about 4.8 times stronger than the electromagnetic force. However, at very high energies, close to the mass of the W bosons ($q^2 \approx M_W^2$), the strength of the weak force is similar to the strength of the electromagnetic force.

Note 4

$$\alpha_G = \left(\frac{m_p}{M_P}\right)^2 \approx 5.9 \times 10^{-39}$$

where

α_G = gravitational coupling constant for the proton
m_p = proton rest mass
M_P = Planck mass

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