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A New Relativistic Electromagnetic Force Law Alternative to the Lorentz Force Law in Special Relativity

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Abstract

We introduce new relativistic mechanics of a material particle, where the rest mass of the particle is not a constant, but a known function of the Lorentz factor γ, alternative to the relativistic mechanics of Einstein's special relativity, where the rest mass of the particle is a constant. We first introduce a new relativistic linear momentum alternative to the relativistic linear momentum in special relativity, and then we find a new relativistic force law alternative to the relativistic force law in special relativity. After that, we introduce a new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity, and then we use the muon g-2 experiments, done by J. Bailey *et al.* [*Nature* **268**, 301-305 (1977)] and G.W. Bennett *et al.* [*Phys. Rev. D* **73**, 072003 (2006)], to see whether those experiments are supportive evidence for the new law alternative to the Lorentz force law in special relativity.

Keywords: Special relativity, new relativistic linear momentum, relativistic mechanics, new relativistic relationship between total energy and momentum, experimental tests of relativistic equation of motion

1 Introduction

In the present paper, we consider new relativistic mechanics of a material particle, where the rest mass of the particle is not a constant, but a known function of the Lorentz factor γ, alternative to the relativistic mechanics of Einstein's special relativity, where the rest mass of the particle is a constant. We first introduce a new relativistic linear momentum alternative to the relativistic linear momentum in special relativity, and then we find a new relativistic force law alternative to the relativistic force law in special relativity. After that, we introduce a new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity, and then we use the muon g-2 experiments, done by J. Bailey *et al.* [1] and G.W. Bennett *et al.* [2], to see whether those experiments are supportive evidence for the new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity.

2 Relativistic mechanics of a material particle, when the rest mass is a constant.

In the relativistic mechanics of a material particle we look at the acceleration of a particle under the influence of a force $\vec{F}$. From Newtons second law in modern form the force $\vec{F}$ is given by

$$\vec{F} = \frac{d\vec{p}}{dt} = \frac{d(m\vec{v})}{dt} = m\frac{d\vec{v}}{dt} + \vec{v}\frac{dm}{dt}, \tag{1}$$

where $\vec{p}$ is the relativistic linear momentum, m is the moving mass of the particle, and $\vec{v}$ is the velocity.

If we assume that mass-energy equivalence $E = mc^2$ applies to any form of energy (in the absence of gravity), where E is the total energy of the particle, $c = const. > 0$ is the speed of light in vacuum, then

$$\begin{gathered} c^2 dm = dE = d(K + m_0c^2) = dK = \vec{F}\cdot d\vec{r} = \frac{d(m\vec{v})}{dt}\cdot d\vec{r} = d(m\vec{v})\cdot\vec{v} \\ \longrightarrow c^2 dm = v^2 dm + \frac{1}{2}md(v^2) \longrightarrow \int_{m_0}^{m}\frac{dm}{m} = \frac{1}{2}\int_0^v \frac{d(v^2)}{c^2 - v^2} \\ \longrightarrow \ln\left(\frac{m}{m_0}\right) = -\frac{1}{2}\ln\left(1 - \frac{v^2}{c^2}\right), \end{gathered} \tag{2}$$

where K is the kinetic energy of the particle, $m_0 = const. > 0$ is the rest mass of the particle, $\vec{F}\cdot d\vec{r}$ is the work done by the force $\vec{F}$ in displacing the particle through $d\vec{r}$, $|\vec{v}| < c$.

From Equation (2) we have

$$\begin{aligned} m &= \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} = m_0\gamma, \\ \vec{p} &= m_0\gamma\vec{v}, \\ K &= E - m_0c^2 = E - E_0 = m_0c^2(\gamma - 1), \end{aligned} \tag{3}$$

where $\gamma = 1/\sqrt{1-\frac{v^2}{c^2}}$ is the Lorentz factor, E_0 is the rest-mass energy of the particle. From Equation (3) we have

$$\frac{E^2}{c^2} - p^2 = m_0^2\gamma^2c^2\left(1-\frac{v^2}{c^2}\right) = m_0^2c^2, \tag{4}$$

the relativistic relationship between the total energy and the momentum for the moving material particle.

It is known [3], that the formula for the binding energy $E_b = (\Delta m_0)c^2$ is experimentally confirmed with high accuracy, where (Δm_0) is the "mass-defect". This formula follows from expression for the rest-mass energy E_0.

Let's emphasize that the above derivation of Equation (3) and (4) was made when considering the motion of the material particle with acceleration and has no relation to the Lorentz transformations.

From Equation (2) we have

$$c^2\frac{dm}{dt} = \frac{d(m\vec{v})}{dt}\cdot\vec{v} = (\vec{F}\cdot\vec{v})$$

and substitute this into Equation (1) we obtain the relativistic force law

$$\vec{F} = \frac{d(m_0\gamma\vec{v})}{dt} = m_0\gamma\frac{d\vec{v}}{dt} + \frac{\vec{v}(\vec{F}\cdot\vec{v})}{c^2}. \tag{5}$$

The acceleration $\vec{a}$ is defined by $\vec{a} = \frac{d\vec{v}}{dt}$, therefore

$$m_0\gamma\vec{a} = \vec{F} - \frac{1}{c^2}\vec{v}(\vec{v}\cdot\vec{F}) = \vec{F}\left(1-\frac{v^2}{c^2}\right) + \frac{1}{c^2}\vec{v}\times(\vec{F}\times\vec{v}). \tag{6}$$

The acceleration $\vec{a}$, in general, is not parallel to the force $\vec{F}$. The acceleration $\vec{a}$ of the particle in the direction of force $\vec{F}$ occurs in the following cases: (1) $\vec{F}$ is perpendicular to $\vec{v}$; (2) $\vec{F}$ is parallel to $\vec{v}$; (3) $v = 0$. For these cases from Equation (6) we have

$$\begin{aligned} m_0\gamma\vec{a} &= \vec{F}, \quad \text{if} \quad \vec{F}\perp\vec{v}; \\ m_0\gamma^3\vec{a} &= \vec{F}, \quad \text{if} \quad \vec{F}\parallel\vec{v}; \\ m_0\vec{a} &= \vec{F}, \quad \text{if} \quad v = 0. \end{aligned}$$

The relativistic force law in Einstein's special relativity Equation (5) is one of the most fundamental and important laws in modern physics. Even a slight discrepancy between the relativistic force law in special relativity and the actual relativistic force law would cause serious problems for modern physics. Thus, to experimentally verify the relativistic force law in special relativity is essential to build a strong foundation for modern physics.

To my knowledge, as yet, no experimental evidence is reported for directly testing the Equation (5) in the relativistic region, when $v \approx c$ and purely relativistic effects predominate.

There are currently different opinions about accuracy of Equation (6) in the relativistic region. Equation (6) is believed to be confirmed by many experiments in high energy physics, which are based on the Lorentz force law, if we assume that in the relativistic region the expression of the Lorentz force law

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

is valid, where q is the charge (electrical property) of the moving particle, $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, and the magnitude of the charge does not change ($q = const.$).

Among that supportive experimental evidence, the muon g-2 experiments are often thought of as high-precision evidence for Einstein's special relativity. However, the relationship between magnetic field force $\vec{F} = q(\vec{v} \times \vec{B})$ (Lorentz's formula) and Newton's third law of motion can be tricky. Lorentz's formula for magnetic field force leads to the paradox of violation of Newton's third law of motion when moving charges or currents interact. Therefore this formula has a limited scope of application, for example, for a nearly uniform magnetic field in accelerators.

It is possible that the Lorentz force law in special relativity

$$\frac{d(m_0 \gamma \vec{v})}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \tag{7}$$

might be only approximately true. To my knowledge, the Lorentz force law (7) has not been systematically tested for the material particle in the relativistic region. Therefore, any inquiry on the extent of accuracy of Equation (6) is legitimate and warranted.

3 New relativistic mechanics of a material particle, when the rest mass is not a constant.

In our analysis above, we considered that $m_0 = const. > 0$. Now we assume that m_0 is not a constant, but depends on the particle's state of motion. Since we assume that mass-energy equivalence $E = mc^2$ applies to any form of energy (in the absence of gravity), then there must be a mass equivalence for kinetic energy $K = m_k c^2$. Under such assumptions we have

$$dK = \vec{F} \cdot d\vec{r} = d(m\vec{v}) \cdot \vec{v} = \left(\frac{K}{c^2} + m_0\right) \vec{v} \cdot d\vec{v} + v^2 \left(\frac{1}{c^2} dK + dm_0\right). \tag{8}$$

Taking into consideration that

$$vdv = vd\left(\sqrt{v_x^2 + v_y^2 + v_z^2}\right) = v\frac{v_x dv_x + v_y dv_y + v_z dv_z}{v} = \vec{v} \cdot d\vec{v},$$

$$d\gamma = d\left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}\right) = \frac{\gamma^3}{c^2} vdv,$$

Equation (8) can be written as

$$\begin{aligned} dK &= \left(\frac{K}{c^2} + m_0\right)\frac{c^2}{\gamma^3}d\gamma + \frac{v^2}{c^2}dK + v^2 dm_0 \\ \longrightarrow dK &= \frac{K + m_0 c^2}{\gamma}d\gamma + \gamma^2 v^2 dm_0. \end{aligned} \tag{9}$$

Taking into account that

$$\gamma d\left(\frac{K}{\gamma}\right) = dK - \frac{K}{\gamma}d\gamma,$$

then from Equation (9) we have

$$d\left(\frac{K}{\gamma}\right) = \frac{m_0 c^2}{\gamma^2}d\gamma + \gamma c^2\left(1 - \frac{1}{\gamma^2}\right)dm_0. \tag{10}$$

Equation (10) can be integrated if we additionally assume a relationship between m_0 and γ. We consider

$$m_0(\gamma) = M_0(1 + \alpha \ln \gamma), \tag{11}$$

where $M_0 = m_0(1) = const. > 0$ ($\gamma = 1$, when $v = 0$), $\alpha = const. \geq 0$.

In fact, the assumption of variable rest mass (11) involves a free parameter α in addition to those that are necessary in Einstein's special relativity. The new relativistic force law needs to account for this new parameter α. Then we use the muon g-2 experiments to chose this parameter.

From Equations (10) and (11) we have

$$d\left(\frac{K}{\gamma}\right) = c^2 M_0\left(\frac{d\gamma}{\gamma^2} + \alpha\frac{\ln\gamma}{\gamma^2}d\gamma + \alpha d\gamma - \alpha\frac{d\gamma}{\gamma^2}\right). \tag{12}$$

Taking into account that

$$d\left(\frac{ln\gamma}{\gamma}\right) = \frac{d\gamma}{\gamma^2} - \frac{ln\gamma}{\gamma^2}d\gamma,$$

Equation (12) can be written as

$$d\left(\frac{K}{\gamma}\right) = c^2 M_0 \left[\frac{d\gamma}{\gamma^2} - \alpha d\left(\frac{\ln\gamma}{\gamma}\right) + \alpha d\gamma\right]. \tag{13}$$

Therefore integrating Equation (13) with respect to γ and taking into consideration that $K = 0$, when $\gamma = 1$ ($v = 0$), we obtain

$$\begin{aligned} &\frac{K}{\gamma} = c^2 M_0 \left[-\left(\frac{1}{\gamma} - 1\right) - \alpha\left(\frac{\ln\gamma}{\gamma}\right) + \alpha(\gamma - 1)\right], \\ &\longrightarrow K = -c^2 M_0 \left(1 + \alpha\ln\gamma\right) + c^2 M_0 \gamma \left[(1-\alpha) + \alpha\gamma\right]. \end{aligned} \tag{14}$$

It is easy to verify that $K \geq 0$ when $\gamma \geq 1$, and if $\frac{v^2}{c^2} << 1$, then $K \approx \frac{M_0 v^2}{2}$.
From Equations (11) and (14) we obtain

$$m = \frac{K}{c^2} + m_0 = M_0\gamma\left[(1-\alpha) + \alpha\gamma\right]. \tag{15}$$

Note that Equation (15) reflects the increasing inertia (resistance to acceleration) as the particle's speed increases. It is an alternative to the standard equation for mass-velocity variation in special relativity $m = m_0\gamma$ Equation (3).

Now we introduce the new relativistic linear momentum alternative to relativistic momentum Equation (3):

$$\vec{p} = M_0\gamma\left[(1-\alpha) + \alpha\gamma\right]\vec{v}. \tag{16}$$

From Equations (15) and (16) we have

$$\frac{1}{\left[(1-\alpha)+\alpha\gamma\right]^2}\left(\frac{E^2}{c^2} - p^2\right) = \frac{M_0^2\gamma^2\left[(1-\alpha)+\alpha\gamma\right]^2 c^2\left(1 - \frac{v^2}{c^2}\right)}{\left[(1-\alpha)+\alpha\gamma\right]^2} = M_0^2 c^2,$$

the new relativistic relationship between the total energy and the momentum for the moving material particle alternative to Equation (4).

It is not difficult to see that Equation (1) can be written as

$$\begin{aligned} \vec{F} &= \frac{d\vec{p}}{dt} = m\frac{d\vec{v}}{dt} + \vec{v}\frac{d}{dt}\left(\frac{K}{c^2} + m_0\right) = m\frac{d\vec{v}}{dt} + \frac{\vec{v}(\vec{F}\cdot\vec{v})}{c^2} + \vec{v}\frac{dm_0}{dt} \\ &= m\frac{d\vec{v}}{dt} + \frac{\vec{v}(\vec{F}\cdot\vec{v})}{c^2} + \alpha M_0\vec{v}\frac{1}{\gamma}\frac{d\gamma}{dt} = m\frac{d\vec{v}}{dt} + \frac{\vec{v}(\vec{F}\cdot\vec{v})}{c^2} + \alpha M_0\vec{v}\frac{1}{\gamma}\frac{\gamma^3}{c^2}v\frac{dv}{dt}. \end{aligned} \tag{17}$$

Taking into consideration that

$$\frac{dv}{dt} = \frac{d}{dt}\left(\sqrt{v_x^2+v_y^2+v_z^2}\right) = \frac{v_x}{v}\frac{dv_x}{dt} + \frac{v_y}{v}\frac{dv_y}{dt} + \frac{v_z}{v}\frac{dv_z}{dt} = \frac{(\vec{a}\cdot\vec{v})}{v},$$

Equation (17) can be written as

$$\begin{aligned}\vec{F} &= \frac{d\{M_0\gamma\left[(1-\alpha)+\alpha\gamma\right]\vec{v}\}}{dt} \\ &= M_0\gamma\left[(1-\alpha)+\alpha\gamma\right]\vec{a} + \frac{\vec{v}(\vec{F}\cdot\vec{v})}{c^2} + \alpha M_0\frac{\gamma^2}{c^2}\vec{v}(\vec{a}\cdot\vec{v}),\end{aligned} \tag{18}$$

and Equation (18) is the new relativistic force law alternative to the relativistic force law (5).

The acceleration $\vec{a}$, in general, is not parallel to the force $\vec{F}$. Let's calculate the components of force and acceleration in the directions parallel and perpendicular to the velocity. Let's start with the parallel components. For the acceleration and force we have

$$\begin{aligned}\vec{a_\parallel} &= \frac{(\vec{a}\cdot\vec{v})\vec{v}}{v^2}, \\ \vec{F_\parallel} &= \frac{(\vec{F}\cdot\vec{v})\vec{v}}{v^2}.\end{aligned} \tag{19}$$

From equation (18) we have

$$\begin{aligned}&(\vec{F}\cdot\vec{v}) = M_0\gamma\left[(1-\alpha)+\alpha\gamma\right](\vec{a}\cdot\vec{v}) + \frac{v^2}{c^2}(\vec{F}\cdot\vec{v}) + \alpha M_0\gamma^2\frac{v^2}{c^2}(\vec{a}\cdot\vec{v}) \\ \longrightarrow\ &(\vec{F}\cdot\vec{v})\frac{1}{\gamma^2} = M_0\left[(1-\alpha)\gamma + \alpha\gamma^2 + \alpha\gamma^2(1-\frac{1}{\gamma^2})\right](\vec{a}\cdot\vec{v}).\end{aligned} \tag{20}$$

Substituting Equation (19) in Equation (20), we obtain

$$\vec{F_\parallel} = M_0\gamma^2\left[-\alpha + (1-\alpha)\gamma + 2\alpha\gamma^2\right]\vec{a_\parallel}. \tag{21}$$

Now let's calculate the components of force and acceleration perpendicular to the velocity. For the acceleration we have

$$\vec{a_\perp} = \vec{a} - \vec{a_\parallel}.$$

Then, with the help of Equations (19) and (21), we can rewrite Equation (18) in the form

$$\begin{aligned}\vec{F} &= M_0\left[(1-\alpha)\gamma+\alpha\gamma^2\right](\vec{a_\parallel}+\vec{a_\perp}) + \frac{v^2}{c^2}\vec{F_\parallel} - \vec{F_\parallel} + \vec{F_\parallel} + \alpha M_0\gamma^2\frac{v^2}{c^2}\vec{a_\parallel} \\ &= M_0\left[(1-\alpha)\gamma+\alpha\gamma^2+\alpha\gamma^2\frac{v^2}{c^2}\right]\vec{a_\parallel} + M_0\left[(1-\alpha)\gamma+\alpha\gamma^2\right]\vec{a_\perp} \\ &-(1-\frac{v^2}{c^2})\vec{F_\parallel} + \vec{F_\parallel} = \frac{1}{\gamma^2}\vec{F_\parallel} + M_0\left[(1-\alpha)\gamma+\alpha\gamma^2\right]\vec{a_\perp} - \frac{1}{\gamma^2}\vec{F_\parallel} + \vec{F_\parallel},\end{aligned}$$

therefore the component of the force perpendicular to the velocity is

$$\vec{F_{\perp}} = \vec{F} - \vec{F_{\parallel}} = M_0\left[(1-\alpha)\gamma + \alpha\gamma^2\right]\vec{a_{\perp}}. \tag{22}$$

From Equations (21) and (22) follows that if the applied force $\vec{F}$ is either perpendicular or parallel to the velocity $\vec{v}$, then the acceleration will be in the same direction of the force $\vec{F}$:

$$M_0\left[(1-\alpha)\gamma + \alpha\gamma^2\right]\vec{a} = \vec{F}, \quad \text{if} \quad \vec{F} \perp \vec{v};$$
$$M_0\gamma^2\left[-\alpha + (1-\alpha)\gamma + 2\alpha\gamma^2\right]\vec{a} = \vec{F}, \quad \text{if} \quad \vec{F} \parallel \vec{v}.$$

Now we introduce the new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity Equation (7):

$$\frac{d\left[M_0\gamma(1-\alpha+\alpha\gamma)\vec{v}\right]}{dt} = q(\vec{E} + \vec{v}\times\vec{B}). \tag{23}$$

4 The uniform circular motion experiment to test the new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity.

In the muon g-2 experiments [1] the muons are performing uniform circular motion in the uniform magnetic field $\vec{B}$ in the muon storage ring at CERN with radius $R = 7$ m and their velocity vectors are always perpendicular to the direction of the magnetic field force.

According to special relativity, the equation of motion of the particle with the rest mass $m_0 = const.$ and the charge $q = const.$ moving in the uniform magnetic field $\vec{B}$ is

$$\frac{d(m_0\gamma\vec{v})}{dt} = q(\vec{v}\times\vec{B}).$$

For the simple case of uniform circular motion ($|\vec{B}| = const.$) we have

$$R = \frac{m_0 v\gamma}{qB} = \frac{m_0 v}{qB}\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}. \tag{24}$$

According to the new relativistic electromagnetic force law Equation (23), the equation of motion of the particle is

$$\frac{d\{M_0\left[(1-\alpha)\gamma + \alpha\gamma^2\right]\vec{v}\}}{dt} = q(\vec{v}\times\vec{B}).$$

For the simple case of uniform circular motion we have

$$R = \frac{M_0 v}{qB}\left[(1-\alpha)\gamma + \alpha\gamma^2\right]. \tag{25}$$

Here, we use the mass of a muon $m_0 = M_0 = 1.8835326 \times 10^{-28}$ kg, the charge $q = 1.60217738 \times 10^{-19}$ C, the speed of light $c = 2.99792458 \times 10^8$ m/s, and the magnetic field inside the storage ring $B = 1.472$ Tesla.

As predicted by special relativity Equation (24), the period of circulating muon $T = \frac{2\pi R}{v}$ is 146.8 ns (ns= 10^{-9} s).

Examining the muon g-2 experimental results, Fig. 2 Reference [1], we see that the muonic bunch circulates slightly less than 27 turns during the time interval from 6 ms to 10 ms (ms= 10^{-6} s), i.e. the muonic bunch circulates approximately 27 turns in the time interval of 4 ms. Therefore the mean period of the circular motion, obtained directly, is slightly more than $T_{ex} = 148.2$ ns. The quoted bin width in measuring the muonic bunches, as shown in Fig. 2 Reference [1], is 10 ns. Due to at most 1 bin width uncertainty in determining the position of either the first or the last peak, the uncertainty of the mean period is estimated as, at most, $20/27 = 0.74$ ns. Hence, the mean period should be $T_{ex} = 148.2 \pm 0.74$ ns as estimated directly from experimental results.

If the experimental period of circular motion of the muon is estimated at 148.2 ns, then $v = \frac{2\pi R}{T_{ex}} = 0.98994c$. Substituting it in Equation (25), we obtain that $\alpha = 0.524$.

The discrepancy of 1.4 ns in the period of circular motion of the muon between the two theories Equation (7) and Equation (23) is supportive of the new relativistic electromagnetic force law Equation (23).

In the muon g-2 experiments [2] the muons are performing uniform circular motion in the uniform magnetic field $B = 1.4513$ Tesla in the muon storage ring at Brookhaven National Laboratory (BNL) with radius $R = 7.112$ m.

As predicted by special relativity Equation (24), the period of circulating muon $T = \frac{2\pi R}{v}$ is 149.1 ns.

Examining the muon g-2 experimental results, Fig. 21 Reference [2], we see that the muonic bunch circulates 32 turns during the time interval from 4.8 ms to 9.6 ms, i.e. muonic bunch circulates 32 turns in the time interval of 4.8 ms. Therefore the muon period of the circular motion, obtained directly, is $T_{ex} = 150$ ns.

If the experimental period of circular motion of the muon is estimated at 150 ns, then $v = \frac{2\pi R}{T_{ex}} = 0.9937c$. Substituting it in Equation (25), we obtain that $\alpha = 0.291$ at BNL.

5 Conclusion

In the present paper we introduced new relativistic mechanics of a material particle, where the rest mass of the particle is not a constant, but a known function of $\gamma = 1/\sqrt{1 - \frac{v^2}{c^2}}$, alternative to the relativistic mechanics of Einstein's special relativity, where the rest mass of the particle is a constant. We first introduced a new relativistic linear momentum alternative to the relativistic linear momentum in special relativity, and then we found the new relativistic force law alternative to the relativistic force law in special relativity. After that we introduced the new relativistic electromagnetic force law alternative to the Lorentz force law in special relativity.

In this paper, the appropriate conclusion is reached that experimental evidence, such as high-precision muon g-2 experiments, can distinguish between the two relativistic force laws: the Lorentz force law in special relativity Equation (7) and the proposed alternative Equation (23), and provides empirical evidence to potentially refute the Lorentz force law in special relativity Equation (7).

Note that parameter α targeting requires the availability of experimental data in sufficient quantity and quality. Thus, experiments with more massive particles, for example, protons, in circular motion inside the storage ring should be very important. To my knowledge, as yet, those experiments have not been carried out.

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