American Journal of Zoology
2026; 9(2): 33-40
http://www.sciencepublishinggroup.com/j/ajz
doi: 10.11648/j.ajz.20260902.11

A Proposal for the Reaction Force in the Emission of Electromagnetic Radiation

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To cite this article:

Paolo Tritella. (2026). A Proposal for the Reaction Force in the Emission of Electromagnetic Radiation. *American Journal of Zoology, 9*(2), 33-40. https://doi.org/10.11648/j.ajz.20260902.11

Received: 3 October 2025 ; **Accepted:** 17 January 2026 ; **Published:** 24 April 2026

Abstract: An equation for the radiation reaction force is proposed that does not violate causality and produces fairly intuitive results. The equivalence principle is solved. The radiating charge appears to be in an excited state. This may seem strange, but the Compton effect seems to confirm this assumption. Applications are made to the most relevant cases of electromagnetic radiation emission. The results appear to confirm the correctness of the assumptions made. Motion with a constant electric field yields results that are as one would expect. Motion under the action of a constant magnetic field occurs with the same frequency obtained previously, and the approximation required due to the complexity of the calculations yields the spiral motion already obtained in a previous publication starting from different assumptions. Free motion without external forces is discussed, and in addition to uniform rectilinear motion, there is a motion that brings the charge to rest, as one would expect. A simple numerical application is suggested for experimental verification. The key point is that, compared to classical electromagnetism, used by all previous authors, an axiom has been added that solves the problem. Evidently, the axioms of classical electromagnetism are not sufficient to derive an expression for the reaction force, for which one must rely on experience. The Compton effect seems to confirm the hypotheses assumed. Before emission, the electron is off-shell, in a virtual state in which it has the extra energy required by the formula we used. Therefore, the additional energy required is not pure fantasy, or an assumption to be verified, one of the mysteries and wonders of quantum mechanics.

Keywords: Radiation Reaction Force, Violation of Causality, Euler Spiral, Incompleteness of Theoretical Principles, Axiom's, Clothoid, Compton Effect, Off-shell, Virtual Particle

1. Introduction

A modified expression for the electromagnetic force (fourth component) is introduced. The problem of violating causality is overcome [7][17]. The case of constant four-acceleration is solved, with the necessary approximations. The motion in a constant uniform magnetic field B is addressed. Free motion (without forces) is also considered. The obtained solutions appear plausible. Simple numerical examples are presented to estimate the effects.

2. Method

2.1. Premise

The key idea is that only the acceleration fields [1][2], which are detached from the charge, act on the charge and determine its motion. The velocity fields move with the charge. Their force is an internal force that does not contribute to the trajectory. At the quantum level, only the emitted photon transfers momentum to the charge. The photon moves away, so it belongs to the acceleration field [16].

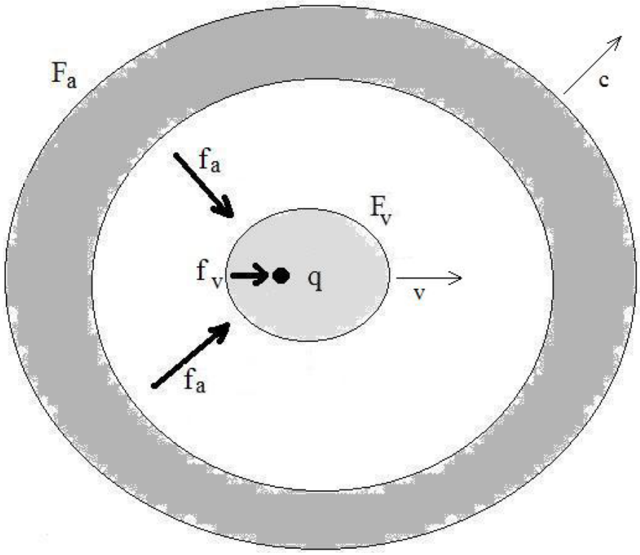

Figure 1. Fields and forces: Fa acceleration electromagnetic field, Fv electromagnetic velocity field, fa force of the acceleration field on the charge, fv force of the velocity field on the charge.

2.2. Theory

Let's consider an electric charge that moves with accelerated motion [4] [5]. Until now the equation of motion, including the reaction force R, is (p the four-impulse, u the four-velocity, w the four-acceleration, F the electromagnetic tensor field, τ the proper time, the speed of light c set to 1, $u^2 = 1$) [3]

$$\frac{dp^{\mu}}{d\tau} = \lambda w^2 u^{\mu} + eF^{\mu\nu}u_{\nu}, \tag{1}$$

plus a term added to satisfy the null scalar product with the four-velocity ($\frac{dp^{\mu}}{d\tau}u_{\nu} = 0$),

$$\lambda = \frac{e^2}{6\pi}, \tag{2}$$

or more generally (R^{μ} the radiation reaction force, K^{μ} the electromagnetic force)

$$\frac{dp^{\mu}}{d\tau} = R^{\mu} + K^{\mu}. \tag{3}$$

We define a new reaction force **R'** equal to

$$(\frac{\lambda w^2 \overrightarrow{u}^2}{u^0}, \lambda w^2 \overrightarrow{u}), \tag{4}$$

(the arrows mean spatial components, γ is the relativistic factor, $\overrightarrow{u} = \gamma\overrightarrow{v}$, $\overrightarrow{v}$ the newtonian velocity, $\overrightarrow{f}$ the newtonian force).

The new four-force is

$$\frac{dp^{\mu}}{d\tau} = R^{'\mu} + K^{\mu} = (\frac{\lambda w^2 \overrightarrow{u}^2}{u^0}, \lambda w^2 \overrightarrow{u}) + K^{\mu}. \tag{5}$$

In **R'** we see again the power component as the dot product of the spatial component of force with the spatial component of the velocity u, $\vec{u}$

$$R'^0 = \gamma \overrightarrow{f}_{reaction} \cdot \overrightarrow{v}. \tag{6}$$

We redefine also the fourth component of the Lorentz force K^0. The work done by external forces on a system of charges is

$$K'^0 = -\frac{\lambda w^2}{u_0} + \overrightarrow{E} \cdot \overrightarrow{j}. \tag{7}$$

The term

$$-\frac{\lambda w^2}{u_0}, \tag{8}$$

comprises the term

$$-\lambda w^2 u_0, \tag{9}$$

the energy stored in the field and

$$\frac{\lambda w^2 \overrightarrow{u}^2}{u^0}, \tag{10}$$

the energy subtracted to the kinetic energy of the particle (restrained) .

The energy in the field is greater than the work done by the external forces for the field. The extra amount comes from the kinetic energy subtracted to the particle. Therefore, the two terms in the work done by the external forces interact through the reaction force.

There is a need from outside to provide extra energy

$$-\frac{\lambda w^2}{u_0}, \tag{11}$$

therefore, it is not transformed into the energy of the particle, but is radiated suddenly, without the particle's mediation. It is like an additional field provided from the outside to cancel out the variation in the field around the particle caused by thee new-born acceleration field. It restores the external field necessary to impart the desired motion to the particle.

It is as a body pushed by a force on a frictional surface. The work is transformed partly into an increase in kinetic energy and partly into heat.

If the heat isn't sufficient, the body can also be heated with a flame.

It may seem strange that we have to supply energy separately, but if we think about the elementary process, we see that the emission of a photon is not spontaneous, but requires the exchange of four-momentum with a heavy nucleus.

The Compton effect can also help us understand the assumption made. In the Compton effect, the acceleration is given by the absorbed photon and the radiation by the emitted photon. We have the situation shown in the figure

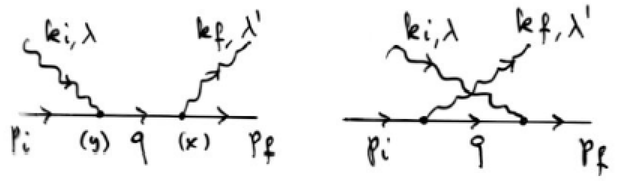

Figure 2. *Feynman diagrams for the two main Compton scattering processes. Taken from: Roberto Casalbuoni, Appunti per il Corso di Elettrodinamica, Firenze A.A. 1993-94.*

The matrix T of the first graph is the following ([64] formula 17.18)

$$\begin{aligned} iT_{fi}^{\text{current}}(1) =&(2\pi)^4\delta^4(p_i+k_i-p_f-k_f)\prod_{\text{ext}}\left(\frac{1}{V2\omega}\right) \\ &\cdot\left[ie(p_f+q)^\mu\right]\epsilon_\mu^{(\lambda')*}(k_f) \\ &\cdot\frac{i}{q^2-m^2+i\epsilon} \\ &\cdot\left[ie(q+p_i)^\nu\right]\epsilon_\nu^{(\lambda')*}(k_i) \end{aligned}$$

where the momentum q is $q=p_f+k_f=p_i+k_i$.

We see that the charged particle q is virtual, off-shell, between the first photon and the second

$$q^2=p_i^2+k_i^2+2p_i^2\cdot k_i=m^2+2\omega m$$

(if the charge is at rest at the beginning). So the electron has a surplus of energy which it then gives to the emitted photon together with the energy lost due to the recoil.

For the microscopic process the theory presented is consistent.

And we know that macroscopic processes are the sum of microscopic processes.

But is there a force that transfers momentum to the accelerating charge? Can I push the charge with a stick? I think not. The force acting on the charge must be of electromagnetic nature. So the *paradox of radiation of charged particles in a gravitational field* is solved .[55]$^{pag.54}$ [16] [63] The gravitational mass acts on a charge, free-falling or steady, only on the mass, not on the charge. In fact, in the quantum Lagrangian, there is not a term coupling charge and mass (a force between them). A proton and a neutron fall together. So a charge in a gravitational field must not emit or absorb electromagnetic energy (with photons) because it accelerates! This happens if there is another charge nearby. *Is not the acceleration that produces the emission, but the acceleration produced by another charge* (interaction with it) [13] [14].

2.3. Constant and Uniform Electric Field E (in the x Direction)

Now let's study the simplest motion, uniformly accelerated (in the rest frame) rectilinear motion, and apply the theory we've developed to see what kind of motion we get. The situation is as follows.

The equations of motion in the x direction, four-velocity $(u^0,u,0,0)$, external four-force $(eEu,eEu^0,0,0)$, are

$$\begin{cases} m\dfrac{du^0}{d\tau}=\lambda w^2v^2u^0+eEu \\ m\dfrac{du}{d\tau}=\lambda w^2u+eEu^0 \end{cases}. \tag{12}$$

Defining

$$\alpha=\frac{\lambda}{m}, \tag{13}$$

and remembering

$$w^2=-g^2, \tag{14}$$

$$\frac{eE}{m}=g, \tag{15}$$

with some approximations, we obtain

$$u\cong\sinh[g(1-\alpha g)\tau]+C, \tag{16}$$

$$\tau=0,\quad u=0\Rightarrow u\cong\sinh[g(1-\alpha g)\tau], \tag{17}$$

$$\frac{dx}{d\tau}=\sinh[g(1-\alpha g)\tau], \tag{18}$$

and

$$x=\frac{1}{g(1-\alpha g)}\cosh[g(1-\alpha g)\tau]+C_1, \tag{19}$$

$$u^0=\sqrt{1+u^2}=\cosh[g(1-\alpha g)\tau], \tag{20}$$

$$t=\frac{1}{g(1-\alpha g)}\sinh[g(1-\alpha g)\tau]+C_2. \tag{21}$$

Then, starting from the origin (vertex of hyperbola)

$$\begin{cases} t=\dfrac{1}{g(1-\alpha g)}\sinh[g(1-\alpha g)\tau] \\ x=\dfrac{1}{g(1-\alpha g)}\{\cosh[g(1-\alpha g)\tau]-1\} \end{cases}. \tag{22}$$

We see that the solution represents, in a first approximation, a motion with the acceleration decreased by a factor αg, as one should expect.

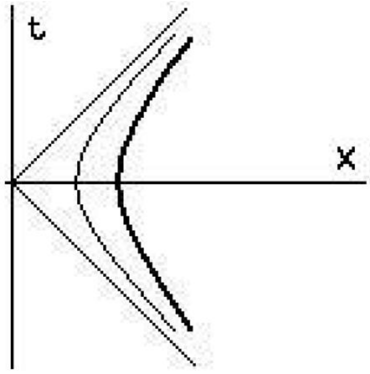

Figure 3. *(origin in the center of hyperbola): the thin hyperbola represents the motion without self-force. the dark hyperbola represents the motion with acceleration decreased by the self-force.*

2.4. Free Particle (Null Force)

From uniformly accelerated (in the rest frame) rectilinear motion it is spontaneous to pass to free motion, the particle left to itself without active forces acting on it. The data are as follows.

Four-velocity $(u^0, u, 0, 0)$, four-acceleration $(w^0, w, 0, 0)$. Follows (**w** quadri-acceleration)

$$\begin{cases} w = \alpha(\mathbf{w})^2\, u \\ w^0 = \alpha(\mathbf{w})^2 \dfrac{(u)^2}{u^0} \end{cases} . \tag{23}$$

Solving, we get

$$w = \alpha w^2 \Big[\frac{(u)^2 - (u^0)^2}{(u^0)^2}\Big] u. \tag{24}$$

The solutions are [6]

$$w = 0, \tag{25}$$

the solution $\vec{v} = cost$, no acceleration, no radiation emitted and

$$u^0 = C' e^{-\frac{\tau}{\alpha}}, \tag{26}$$

$$u = \sqrt{C" e^{-\frac{2\tau}{\alpha}} - 1}, \tag{27}$$

$$v = \frac{u}{u^0} = \sqrt{1 - \frac{e^{\frac{2\tau}{\alpha}}}{C}}. \tag{28}$$

The motion is from 0 and $\tau(\vec{v} = 0)$

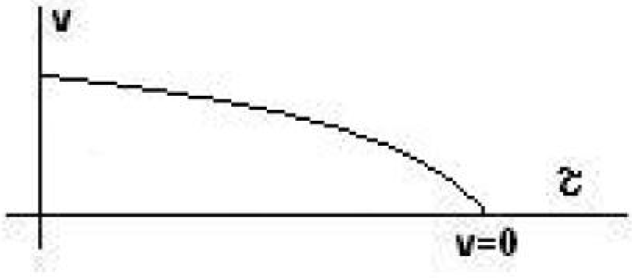

Figure 4. *The velocity of a free particle stopped by the self-force.*

Initial conditions, $\tau = 0, v = v_0$,

$$v = \sqrt{(v_0)^2 e^{\frac{2\tau}{\alpha}} - e^{\frac{2\tau}{\alpha}} + 1}, \tag{29}$$

$$\tau \leq = -\frac{\alpha}{2} ln\big(1 - (v_0)^2\big), \tag{30}$$

the time for a particle to stop.

2.5. Constant and Uniform Magnetic Field B (in the z Direction)

Now we tackle the more complicated motion, motion under the action of a constant magnetic field. It won't be possible to obtain an exact solution. The approximate solution will lead us to the Cornu spiral, already obtained by another method in a previous publication.

We have a field B like in the picture $\vec{B} = (0, 0, B)$

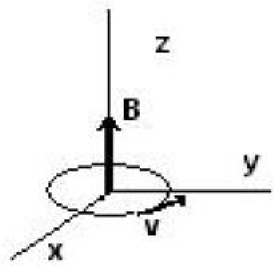

Figure 5. *The motion of a charge inside a uniform constant magnetic field.*

A charged particle is moving in the plane z=0. At a determinate instant, the magnetic field B is on. The equations of motion are

$$\begin{cases} mw^0 = \lambda(w)^2 \dfrac{(\vec{u})^2}{u^0} \\ mw^1 = \lambda(w)^2 u^1 + \dfrac{e}{c} B u^2 \\ mw^2 = \lambda(w)^2 u^2 - \dfrac{e}{c} B u^1 \end{cases} , \tag{31}$$

$$\begin{cases} w^0 = \frac{\lambda}{m}(w)^2\frac{(\vec{u})^2}{u^0} \\ w^1 = \frac{\lambda}{m}(w)^2 u^1 + \frac{eB}{mc}u^2 \\ w^2 = \frac{\lambda}{m}(w)^2 u^2 - \frac{eB}{mc}u^1 \end{cases}, \quad (32)$$

$$\begin{cases} w^0 = \alpha(w)^2\frac{(\vec{u})^2}{u^0} \\ w^1 = \alpha(w)^2 u^1 + \omega u^2 \\ w^2 = \alpha(w)^2 u^2 - \omega u^1 \end{cases}, \quad (33)$$

$$\alpha = \frac{\lambda}{m} = 0.6 \cdot 10^{-23} sec \qquad (electron),$$

$$\omega = \frac{eB}{mc}.$$

In a polar frame we have for the spatial components of four-velocity u

$$\begin{cases} u_1 = \rho\cos\theta \\ u_2 = \rho\sin\theta \end{cases}. \quad (34)$$

After a long calculation we have that the rest frame frequency does not change

$$\dot{\theta} = -\omega, \quad (35)$$

and, at last, after some approximation to first order in α,

$$\rho = \frac{1}{\sqrt{2\alpha\omega^2\tau + \frac{1}{(u_0)^2}}} = \frac{u_0}{\sqrt{2\alpha\omega^2(u_0)^2\tau + 1}} \approxeq u_0[1 - \alpha\omega^2(u_0)^2\tau]. \quad (36)$$

$(\alpha \ll 1)$

We recognize the equation of the Cornu spiral [8–10]. Expanding again to first order in α we get a more simplified expression for the equation of trajectory.

$$x^1 = \int u_1\,\mathrm{d}\tau = \int \rho\cos\theta\,\mathrm{d}\tau = \int \frac{u_0}{\sqrt{2\alpha\omega^2(u_0)^2\tau + 1}}\cos\omega\tau\,\mathrm{d}\tau$$

$$\approxeq \int u_0\big(1 - \alpha\omega^2(u_0)^2\tau\big)\cos\omega\tau\,\mathrm{d}\tau. \quad (37)$$

Then

$$x^1 = \frac{u_0}{\omega}\Big[1 - \alpha\omega^2(u_0)^2\tau\Big]\sin\omega\tau - \alpha(u_0)^3\cos\omega\tau, \quad (38)$$

$$x^2 = -\frac{u_0}{\omega}\Big[1 - \alpha\omega^2(u_0)^2\tau\Big]\cos\omega\tau - \alpha(u_0)^3\sin\omega\tau, \quad (39)$$

$$r^2 = \frac{(u_0)^2}{\omega^2}\Big[1 - \alpha\omega^2(u_0)^2\tau\Big]^2 + \alpha^2(u_0)^6. \quad (40)$$

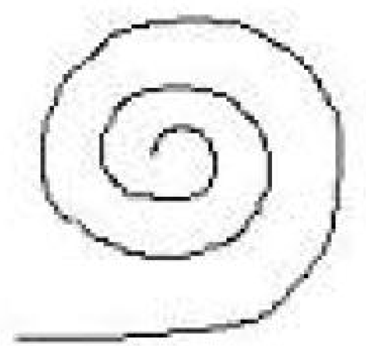

Figure 6. *The spiral of a charged particle moving in a uniform constant magnetic field.*

3. Result

The solutions obtained may be verified by experiments.

Now we describe a simple way to verify the obtained results. Particle uniformly accelerated.

Consider an electron of charge e, moving under the action of an electric field

$$E = 100\frac{MVolt}{m} = 10^8\frac{1}{300}Statvolt\frac{1}{10^2 cm} = \frac{10000}{3} = 3.3 \cdot 10^3\frac{statvolt}{cm},$$

$$g = \frac{eE}{m} = \frac{4.8 \cdot 10^{-10} statcoulomb \cdot 3.3 \cdot 10^3 \frac{statvolt}{cm}}{9.1 \cdot 10^{-28} g} = 1.7 \cdot 10^{21}\Big(\frac{g\,cm^3}{sec^2}\Big)^{\frac{1}{2}}\Big(\frac{g}{cm\,sec^2}\Big)^{\frac{1}{2}}\frac{1}{g} = \quad 1.7 \cdot 10^{21}\frac{cm}{sec^2}.$$

Choosing a length l=1m=100cm , we have for the time of flight

$$t = t_{n.r.}[1 + 2.3 \cdot 10^{-15}],$$

$$t_{n.r.} = 0.3 \cdot 10^{-8} sec$$

($t_{n.r.}$ the time of fly non relativistic.),

$$\triangle t = t - t_{n.r.} = t_{n.r.} \cdot 2.3 \cdot 10^{-15},$$

$$\triangle t = 2.3 \cdot 10^{-15} \quad of \quad t_{n.r.},$$

$$\triangle t = 0.7 \cdot 10^{-23} sec,$$

the variation of time with respect to the non-relativistic case, a very thin effect, difficult to test.

For the magnetic field see:

Paolo Tritella, A simplified trajectory for a radiating charge moving in a uniform magnetic field. [11]

https://www.sciencepublishinggroup.com/article/10.11648/j.ajz.20250802.13

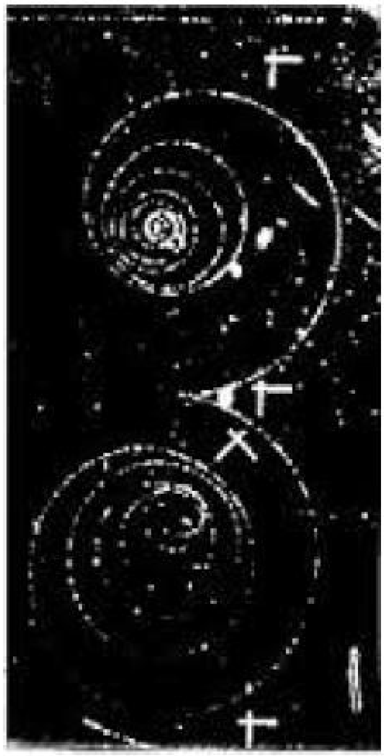

Figure 7. Charges in spiral motion (Taken from Internet).

4. Discussion

For a uniformly accelerated particle, the result is consistent with intuition. The effect of the reaction force is expected to cause a decrease in acceleration. This result is obtained for constant acceleration with an approximation. But the neglected term becomes smaller and less important as time passes. In the case of a constant magnetic field, the result is the classical spiral, well observed in experiments. The frequency is the same as in the absence of radiation. For a free charged particle, moving at constant velocity, we obtain the same constant-velocity motion, but also a motion that, if for some reason it prevails over the former, will bring the particle to a halt.

5. Conclusions

The results obtained are certainly in qualitative agreement with the experiments. Quantitative agreement remains to be verified, but in any case, this approach seems more correct and profitable for the most likely results.

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Abbreviations

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Acknowledgments

Thanks to Cristina, Bruno, Grazia, Natale, Carina, Orazio, Pietro, Mary, all my teachers and everyone who helped me. Thanks to the Internet.

Supplementary Material

The supplementary material can be accessed at https://www.researchgate.net/publication/396912123_A_proposal_for_the_electromagnetic_self-force_detailed

Conflicts of Interest

The author declares no conflicts of interest.

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