Electrostatic Time Dilation and Redshift

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Abstract

We first present the salient features of gravitational time dilation and redshift effects in two ways; by considering the oscillation frequencies/rates of clocks at different heights/potentials and by considering the photons emitted by these clocks such as atoms/nuclei. We then point out to the extension of these gravitational effects to static electricity along with two experiments performed in the 30s with null results of electrostatic redshift. We show that the absence of this redshift is a consequence of the conservation of electric charge. We discuss the electrical time dilation and redshift effects in detail and argue that electrostatic time dilation in an electric field must be a fact of Nature. We emphasize the importance of ionic atomic clocks to measure this effect whose confirmation would shed light on the currently nonexisting general relativistic theory of electromagnetism. We finally go over an attempt in the literature to explain the impossibility of the experimental observation of electrostatic redshift due to its smallness by employing the Reissner - Nordström metric in general relativity. We argue that the $Q^2$- term in this metric is due to the minuscule contribution of the energy of the electric field of the central body to its gravitational field. Thus being gravitational, this metric cannot be used to calculate the amount of the alleged electrostatic redshift.

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That time passes differently at different heights or potentials in a gravitational field is called gravitational time dilation. The time intervals between two events measured by observers located at different altitudes from a gravitational source, a large mass, happen to be different. Time passes faster, in other words, the rate of a clock, namely its oscillation frequency, increases as it gets located farther from a gravitating source. The effect was first predicted by Einstein [1, 2] and was experimentally verified indirectly by means of the Mösbauer effect in [3, 4] and directly in [5, 6] by readings of the airborne and earthbound atomic clocks, and in [7, 8] by comparing the frequencies of microwave signals from hydrogen maser clocks in a rocket at a high altitude and at an Earth station. The precision of these experiments were improved recently by measuring the frequencies of the onboard hydrogen maser clocks in Galileo Satellites of the European Space Agency [9, 10]. It was reported in [11] that time dilation due to a change in height less than a meter could be detected by comparing two optical clocks based on $^{27}\text{Al}^+$ ions.

A directly related concept is the redshift of light in a gravitational field [22]. Usually, it is defined as the lengthening (shortening) of the wavelength (frequency) of light as it moves away from a massive body such as the Earth. Light is thought to lose energy as it reaches higher altitudes in a gravitational field due to its interaction with the field [12, 13, 14]. However, as it has been pointed out in [15] and emphasized in [16], light does not actually interact with the gravitational field and lose energy as it moves up to higher potentials. This is because light, strictly speaking, does not have a gravitational mass and thereby cannot be assigned a potential energy. What happens in reality is that the frequency of light emitted by an atom (or a nucleus) at a lower gravitational potential is smaller than the frequency of light emitted by an identical atom/nucleus at a higher potential [16].

Certain similarities between classical gravitational and electric fields lead one naturally to question if a similar effect might take place in a static electric field. Long before the experimental confirmation of the gravitational effect, this possibility was exercised and found that light does not undergo an actual frequency change as it moves in a static electric field from a low potential to a higher one or vice versa [17]. An interferometer was used to compare the frequencies of light before and after traveling in a static electric field. A second experiment ended up with the same null conclusion [18]. There was no attempt in these works to define and discuss the electrostatic redshift of light.

An endeavor to explain the null results of these experiments theoretically
was presented in [21] by employing the Reissner-Nordström metric in general relativity.

The purpose of the present work is to discuss, to our knowledge for the first time in the literature, the effects that occur in a static electric field similar to those of the gravitational ones. To this end, we first expound the gravitational effects and then extend them to their electrical analogues. We next explain the results of the electrical redshift experiments [17, 18]. Finally, we argue that the Reissner - Norström - treatment of the electrostatic redshift in [21] involves a conceptual error and is irrelevant to electrical redshift.

Let us consider an atom of mass \( M \) at a height \( H_0 \) in a static gravitational field like that of the Earth. Taking this height as the reference level for the gravitational potential, the energy of the atom is

\[
E(0) = Mc^2, \tag{1}
\]

in its ground state, and

\[
E^*(0) = Mc^2 + \mathcal{E} = M^*c^2, \tag{2}
\]

in an excited state, denoted by a superscript *, whose energy exceeds that of the ground state by \( \mathcal{E} \). Here \( M^* \) is the excited mass of the atom and is given by

\[
M^* = M + \frac{\mathcal{E}}{c^2}. \tag{3}
\]

Raising the atom by a height \( H \) changes the energy levels to

\[
E(H) = Mc^2 + MgH, \tag{4}
\]

in the ground state, and to

\[
E^*(H) = M^*c^2 + M^*gH, \tag{5}
\]

in the excited state, where \( g = 9.8m/s^2 \) is the value of gravitational acceleration on the surface of the Earth. As a result of this raising, the oscillation frequency \( f = E/h \) of the atom changes from \( f(0) \) to \( f(H) \) in the ground state, and from \( f^*(0) \) to \( f^*(H) \) in the excited state, where \( h \) is the Planck constant. These frequencies at different altitudes are related to each other in the ground and excited states, respectively as

\[
f(H) = f(0) \left(1 + \frac{gH}{c^2}\right),
\]

\[
f^*(H) = f^*(0) \left(1 + \frac{gH}{c^2}\right). \tag{6}
\]
Therefore, the fractional changes in the oscillation frequencies due to this raising are given by

\[
\frac{\delta f}{f(0)} = \frac{f(H) - f(0)}{f(0)} = \frac{gH}{c^2},
\]

\[
\frac{\delta f^*}{f^*(0)} = \frac{f^*(H) - f^*(0)}{f^*(0)} = \frac{gH}{c^2},
\]

(7)

which are the same both in the ground and excited states. Notice that \( gH \) in these equations and what follows is equal to \( \Delta \phi_g = \phi_g(H) - \phi_g(0) \), where \( \phi_g \) is the gravitational potential. We note that these fractional changes are equal to the ratio of the work done against gravity by the external agent in raising the masses \( M \) and \( M^* \) by \( H \), to their rest energies. Taken as a frequency reference, such an atom can be considered as a clock whose rate, its oscillation frequency, is faster the higher the height \( H \) is. Thus, the time intervals measured by such a clock are proportional to its oscillation frequencies and are given by [23]

\[
\Delta T(H) = \Delta T(0) \left(1 + \frac{gH}{c^2}\right),
\]

\[
\Delta T^*(H) = \Delta T^*(0) \left(1 + \frac{gH}{c^2}\right),
\]

(8)

which indicate how such atoms/clocks age. Thus we find out that atoms at higher altitudes, or higher potentials, age faster than those at lower altitudes from the gravitating source by a fractional change

\[
\frac{\delta \Delta T}{\Delta T(0)} = \frac{\delta \Delta T^*}{\Delta T^*(0)} = \frac{gH}{c^2} = \frac{\Delta \phi_g}{c^2}.
\]

(9)

As we will now show, the same results can be obtained by considering the photon emissions in the excited states. An excited atom at height 0 whose energy is as in Eq.(2) may make a transition to the ground state by emitting a photon of frequency

\[
\nu(0) = \frac{E^*(0) - E(0)}{h} = \frac{E}{h}.
\]

(10)

When this photon is directed up, it cannot be absorbed by an atom at height \( H \) in its ground state whose energy is as in Eq.(1) due to the energy deficiency. An energy of \( E + EgH/c^2 \) is required of the photon to excite the atom so that its energy has the value in Eq.(5). As has been emphasized in [16], the photon with energy \( E \) does not loose energy as it moves up in the gravitational field.
In the experiment [3, 4], the extra energy $E gH/c^2$ the photon needs to have so as to be absorbed is supplied to it through the Doppler effect. The source, the iron - 57 nucleus at height 0, is moved up toward the absorber to increase the energy of the photon to

$$E_\gamma = E \left( \frac{1 + \frac{v}{c}}{1 - \frac{v}{c}} \right)^{1/2} \approx E + E \frac{v}{c}.$$  \hspace{1cm} (11)

This is achieved by adjusting the upward speed of the source, as in [3, 4], to

$$v = \frac{gH}{c}.$$  \hspace{1cm} (12)

As is pointed out in [16], had the photon lost energy as it moved up, as is assumed in the wrong interpretation of the gravitational redshift, the required Doppler speed would have been twice as that in Eq.(12) [24]. The excited nucleus at $H$ with energy $E^*(H)$ may then make a transition to its ground state. The frequency of the photon emitted in this transition is

$$\nu(H) = \frac{E^*(H) - E(H)}{h} = \frac{E_0 + E gH/c^2}{h} \approx \nu(0) \left( 1 + \frac{gH}{c^2} \right),$$ \hspace{1cm} (13)

which is naturally equal to the frequency of the photon absorbed. The fractional change $\delta\nu/\nu(0)$ in the frequencies of the photons emitted and the predicted aging of the nuclei at different altitudes are, respectively, the same as those in Eq.(7) and Eq.(8).

One may wonder why the photon is still said to undergo a redshift even though its energy/frequency does not change as it moves up or down in a gravitational field. As is emphasized in [16], this is because the energy levels of atoms/nuclei at higher altitudes undergo a blueshift, namely their energies increase, relative to atoms/nuclei at lower altitudes. The photon emitted by a nucleus/atom at a lower altitude and absorbed by an identical atom/nucleus at a higher altitude is seen by this atom/nucleus to be redshifted. This can be understood as follows: The higher-up-atom/nucleus, the clock, measures the frequency $\nu(0)$ of the photon when it reaches it as $\tilde{\nu}(H)$, given by

$$\tilde{\nu}(H) = \tilde{\nu}(0) \left( \frac{\nu(0)}{\nu(H)} \right) = \nu(0) \left( 1 - \frac{gH}{c^2} \right),$$ \hspace{1cm} (14)
with a fractional change of \(-gH/c^2\), and \(\tilde{\nu}(0) = \nu(0)\).

To sum up what we have reviewed so far, our analysis shows clearly that
(i) the gravitational time dilation effect is due to the difference in the total
energies of objects when they are at different altitudes in a gravitational field,
(ii) the frequency of photons do not change as they move in a gravitational
field, and (iii) atoms/nuclei higher up in a gravitational field whose energies
are bluishifted see the photons emitted by atoms/nuclei lower down in the
field as redshifted.

Next, we undertake the electrical analogues, if they exist, of the gravita-
tional effects. To this end, let us consider an electric field \(E\) in a region of the
\(xy\) plane directed from right to left in the \(-x\) axis. Assume there are four
identical positively charged atoms (cations) in their ground states at a level
on the \(x\) axis where the electrical potential will be taken to be zero. The
atoms are prevented from interacting with each other through some mecha-
nism. The energies of the atoms at this zero level of potential are given by
Eq. (11), as in the gravitational case. Then we move one of the atoms to the
right to a level \(d\) on the \(x\) axis. The energy of this atom is

\[
E(d) = Mc^2 + Q |E| d, \tag{15}
\]

where \(Q\) is the positive charge of the nucleus. Then, we excite two of the
atoms by letting them absorb a photon of energy \(\mathcal{E}\) increasing their energy
to

\[
E^*(0) = Mc^2 + \mathcal{E}. \tag{16}
\]

Afterwards, we move one of these excited atoms to the right to the same
level \(d\) as before. The energy of this atom will be

\[
E^*(d) = Mc^2 + \mathcal{E} + Q |E| d. \tag{17}
\]

The fractional changes in the energies and vibrational frequencies are

\[
\frac{\delta E}{E(0)} = \frac{\delta f}{f(0)} = \frac{Q |E| d}{Mc^2} = \frac{Q \Delta \phi_e}{M c^2}, \tag{18}
\]

in the ground state, and

\[
\frac{\delta E^*}{E^*(0)} = \frac{\delta f^*}{f(0)} = \frac{Q |E| d}{Mc^2(1 + \frac{\mathcal{E}}{Mc^2})} \approx \frac{Q |E| d}{Mc^2} = \frac{Q \Delta \phi_e}{M c^2}, \tag{19}
\]

in the excited state where \(\mathcal{E}/Mc^2 \ll 1\) has been implemented. Here \(\Delta \phi_e = |E| d > 0\)
is the electrical potential difference between the positions of the two atoms.
The lessons learned in our discussion of the gravitational case lead us to conclude that the aging of these atoms takes place according to

\[ \Delta T(d) = \Delta T(0) \left( 1 + \frac{Q}{M} \frac{|E|}{c^2} d \right), \]

\[ \Delta T^*(d) = \Delta T^*(0) \left( 1 + \frac{Q}{M} \frac{|E|}{c^2} d \right), \] (20)

which are similar to the gravitational ones in Eq.(8). It should be noted that these electrical time dilation effects become contraction effects for anions, atoms with a total negative electric charge, for \( \Delta \phi_e > 0 \). This is an effect with no counterpart in the gravitational case due to the absence of negative inertial mass. The excited atoms at \( x = 0 \) and at \( x = d \) can make a transition to their ground states by emitting a photon of frequency

\[ \nu(0) = \frac{E^*(0) - E(0)}{\hbar} = \frac{E}{\hbar}; \]
\[ \nu(d) = \frac{E^*(d) - E(d)}{\hbar} = \frac{E}{\hbar}. \] (21)

It is no surprise that these frequencies are equal. This is a consequence of the conservation of electric charge. Moving an electric charge from one point to another in an electric field by a distance \( d \) does not change the amount of the electric charge whereas moving it vertically by a height \( H \) in a gravitational field would change the gravitational mass by \( gH/c^2 \).

Let us contemplate a Pound - Rebka - Snider experiment performed in an electric field. The photon of energy \( E \) emitted by the source/emitter at \( x = 0 \), whose energy is as given in Eq.(10), will reach the absorber/receiver nucleus, which is in its ground state at \( x = d \) whose energy is as given in Eq.(15). The photon can be absorbed by this nucleus without the need to increase its energy by a Doppler shift because the mass of the cation plays no role in the energy shift in an electric field in contrast with the gravitational case. Having absorbed the photon, this excited nucleus can in turn emit the photon with the same energy \( E \) by making a transition to its ground state. The overall result is null. There is no change in the frequencies of the absorbed and emitted photons. Thus no electrical redshift! This is also predicted by the electrical analogue of Eq.(14), which would yield \( \tilde{\nu}(d) = \nu(0) \). We can now understand the null results of the electrical redshift experiments. In [17], light of a certain frequency from an electrodeless discharge in mercury vapor was let to travel through a potential difference of 50kV above or below ground. A quartz interferometer kept at zero potential was used to measure the frequency of the received light. No change in the frequency of the light
was detected. This experiment was repeated in [18] by employing a potential difference of \( \pm 300 \text{kV} \) and the findings in [17] were improved by a factor of ten. Theoretically, these results are expected because the energy/frequency of light does not undergo a shift as it travels between different electrostatic potentials in an electric field, just as what happens in a gravitational field as we have discussed.

Before we pass to the next item, we point out to the experimental possibility of measuring the electrostatic time dilation effect by high precision clocks similar to the atomic ones. What is required for such a measurement is ionic clocks [19, 20] whose oscillators are positively (or negatively, in principle) charged ionic atoms whose energy levels will split in an electric field depending on their positions in the field [25]. For example, the fractional change in the oscillation frequencies of two \(^{27}\text{Al}^+\) optical ion clocks in a static electric field for a potential difference of \( \Delta \phi_e (\text{in} \text{V}) \) between them would be

\[
\frac{\delta f}{f(0)} = \frac{Q \Delta \phi_e}{M c^2} = 3.979 \times 10^{-11} \Delta \phi_e / \text{V},
\]  

where \( Q = e = 1.602 \times 10^{-19} \text{C} \) is the charge of \(^{27}\text{Al}^+\) and \( M = 4.480 \times 10^{-26} \text{kg} \) its mass. This would be much larger than the special relativistic and gravitational time dilation effects reported in [11] depending on the value of \( \Delta \phi_e \).

Finally, we comment on the work in [21], where an attempt to explain the null results of [17, 18] was made, by reproducing the derivation of the general relativistic prediction of the electrical redshift in [21]. They start off by giving the fractional change in the frequency of light in general relativity, which is

\[
\frac{\Delta \nu}{\nu} = 1 - \left( g_{00} / g'_{00} \right)^{1/2},
\]  

where \( \Delta \nu = \nu_{\text{observed}} - \nu \) with \( \nu \) being the frequency of the light emitted by the source. \( g_{00} \) is the coefficient of the timelike coordinate in the square of the differential line element

\[
ds^2 = g_{\mu\nu} dx^\mu dx^\nu
\]  

at the position of the absorber/receiver, and \( g'_{00} \) being the one at the position of the source/emitter. The absorber is assumed to be located on the dome of an electrostatic accelerator (like a von de Graaf generator) whose electrostatic potential is given by (in SI units)

\[
\varphi = k_e Q / R,
\]  

where \( k_e \) is the Coulomb constant, \( R \) the radius of the dome, \( Q \) the charge of the dome. The \( g_{00} \) on the dome is assumed to be that of the Reissner -
Nordström line element given by

\[ g_{00} = 1 - 2GM/Re^2 + k_e GQ^2/R^2 e^4, \]  

(26)

where \( M \) is the mass of the dome, and \( G \) the gravitational constant. The authors say they are only interested in the electrostatic effect and thereby drop the second term in the equation above as a result of which Eq.(23) becomes

\[ \Delta \nu/\nu = 1 - \left(1 + G\varphi^2/k_e c^4\right)^{1/2}, \]  

(27)

where \( g'_{00} = 1 \) because the source is assumed to be in a region of zero electrostatic potential inside the dome. Since the potential term is much smaller than one, this reduces to

\[ \Delta \nu/\nu = -G\varphi^2/2k_e c^4. \]  

(28)

For an electrostatic accelerator of several \( MeV \), \( \Delta \nu/\nu \sim 10^{-40} \), and the null results in [17][18] are expected, as proclaimed by the authors. The conceptual error in this treatment is that the Reissner - Nordström metric is a solution to the Einstein - Maxwell field equations for an electrically charged spherical body of mass \( M \) and charge \( Q \). The third term on the right of Eq.(26) is not an electrostatic term, rather it is a gravitational one just like the second term. The meaning of the third term is as follows: The electric field outside the central body due to its charge \( Q \) has an energy \( U_{\text{field}} \sim r^3 \epsilon_0 |\vec{E}|^2/2 \) which is equivalent to a mass \( M_{\text{field}} = U_{\text{field}}/c^2 \sim k_e Q^2/c^2 r \). This mass gives rise to a gravitational potential \( \Phi_g = G M_{\text{field}}/r \) whose contribution to \( g_{00} \) must be proportional to \( \Phi_g/c^2 \) which is approximately equal to \( Gk_e Q^2/c^4 R^2 \) for \( r = R \). This is the third term in \( g_{00} \) in Eq.(26). Thus on the surface of the dome \( g_{00} \) can be written as

\[ g_{00} = 1 - 2GM_{\text{eff}}(R)/Re^2. \]  

(29)

with \( M_{\text{eff}}(r) \) being the effective mass of the dome, the central body, given by

\[ M_{\text{eff}}(r) = M - \frac{1}{2} \frac{k_e Q^2}{r^2 e^2}, \]  

(30)

where \( r \geq R \) is the radial coordinate. Therefore, according to the meaning of the Reissner - Nordström metric, light moving in this spacetime is moving in a gravitational field created by the mass \( M_{\text{eff}} \), and the redshift it may undergo is a gravitational one. Certainly, it is incorrect to call the contribution of the \( Q^2 \)-term an electrostatic redshift.

In conclusion, we have shown that positively charged objects age faster at high potential points than those at low potential points in an electric field.
This effect is similar to its gravitational analogue. The aging of the negatively charged objects, however, takes place in the opposite way. A Pound-Rebka-Snider experiment subjecting the source to a horizontal electric field would show no electrical redshift because electric charge is conserved and is independent of any forms of energy (which is not the case for mass). This is a result confirmed by two experiments that employed interferometers to observe the questioned electrostatic redshift. If, on the other hand, it were possible to measure the frequency change of photons in the gravitational field of the Earth with interferometers, one would observe no gravitational redshift either. This is because the energy/frequency of photons do not change as they move in a gravitational field, as discussed in [16]. An attempt in the literature to explain the null results of the two electrostatic redshift experiments by making use of the Reissner-Nordström metric has been shown to be invalid. We cannot overemphasize the performance of an experiment to confirm the electrostatic time dilation effect presented in this work. Such a confirmation would also cast light on the nature of a currently nonexisting general relativistic theory of electromagnetism by the requirement of producing Eqs. (18) and (20).

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References

[1] Einstein, A., Jahrb. Radioakt. Elektronik 4 (1907) 411.
[2] For an English translation of [1] see, H. M. Schwartz, Am. Jour. Phys. 45 (1977) 899.
[3] R. V. Pound, G. A. Rebka, Phys. Rev. Lett. 4 (1960) 337.
[4] R. V. Pound, J. L. Snider, Phys. Rev. 140 (1965) B788-B804.
[5] J. Hafele, R. Keating, Science 177 (1972) 166.
[6] C. Alley et al., in Experimental Gravitation, Proceedings of the Conference at Pavia (Sept. 1976), ed. B. Bertotti (Academic
Press, New York, NY, 1977).

[7] R. F. C. Vessot, M. W. Levine, Gen. Rel. Grav., 10 (1979) 181.
[8] R. F. C. Vessot, et al., Phys. Rev. Lett 45 (1980) 2081.
[9] P. Delva, et al., Phys. Rev. Lett 121 (2018) 231101.
[10] S. Herrmann, et al., Phys. Rev. Lett. 121 (2018) 231102.
[11] C. W. Chou, D. B. Hume, T. Rosenband, D. J. Wineland, Science 329 (2010) 1630.
[12] Gravitation, C. W. Misner, K. S. Thorne, and J. A. Wheeler, W. H. Freeman and Company, 1973.
[13] Feynman Lectures on Gravitation, R. P. Feynman, F. B. Morino, W. G. Wagner, Ed. by B. Hatfield, Addison - Wesley Publishing Company, 1995.
[14] A First Course in General Relativity, B. F. Schulz, Cambridge University Press, 1999.
[15] Relativity: The General Theory, J. L. Synge, North - Holland Publishing Company, Amsterdam, 1960.
[16] L. B. Okun, K. G. Selivanov, and V. I. Telegdi, Am. J. Phys. 68 (2000) 115.
[17] R. J. Kennedy, E. M. Thorndike, Proc. N. A. S. 17 (1931) 620.
[18] H. T. Drill, Phys. Rev. 56 (1939) 184.
[19] T. Rosenband et al., Science 319 (2008) 1808.
[20] C. W. Chou, D. B. Hume, J. C. J. Koelemeij, D. J. Wineland, T. Rosenband, Phys. Rev. Lett., 104 (2010) 070802.
[21] J. F. Woodward, R. J. Crowley, Nature 246 (1973) 41.
[22] It should be noted that, usually time dilation, frequency change of a clock, and redshift are all referred to as redshift in the literature. We will use a precise language and distinguish among them.
[23] It should be noted that $\Delta T(H)$ or $\Delta T^*(H)$ are related to the oscillation frequencies as $\Delta T(H)/\Delta T(0) = f(H)/f(0)$, but not as $\Delta T(H)/\Delta T(0) = f(0)/f(H)$ as one may expect. This is because the ticks of clocks at height 0 may be normalized so that the time interval between two ticks is one second. Then clocks at height $H$ register a time interval of $N(H)$ seconds for $N(H) + 1$ ticks while those at height 0 register $N(0)$ seconds for $N(0) + 1$ ticks. Obviously $(N(H) + 1)/(N(0) + 1) = f(H)/f(0)$.

[24] This is because, had it lost energy in moving up in the gravitational field, the photon of energy $E$ at level 0 would have reached height $H$ with an energy $E - E_gH/c^2$. Hence the required Doppler speed would have been twice as that in Eq. (12) so that the energy of the photon is $E + E_gH/c^2$, neglecting the $c^{-4}$ and smaller terms.

[25] This should not be confused with the Stark Effect which takes place in an electric field as a result of the interaction of the field with the electric dipole moment of the atom. The effect considered here takes place for electrically charged systems with zero electric dipole moment too, such as a proton, for example. Furthermore, two charged atoms with the same electric dipole moment in a uniform electric field but at different potentials would have the same Stark effect energy level splittings whereas their aging would be different due to the different electric potentials they are exposed to.