

THE MAGNITUDE OF ELECTROMAGNETIC TIME DILATION.

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ABSTRACT. Since there is a time dilation associated with the gravitational potential, theories unifying gravity and electromagnetism naturally give rise to the question of whether there might be a time dilation associated with the electromagnetic 4-potential. While this notion has been widely rejected, a handful of theories explicitly predict such an effect. At least to first order, all of them agree on its magnitude, but it has not been clear why. Here we show that the magnitudes of both gravitational and EM time dilations can be computed from elementary considerations ($E = h\nu$ and $E = mc^2$) that are independent of specific unified theories. This demonstrates that EM time dilation must be a feature of any unified theory that is compatible with both Special Relativity and Quantum Mechanics; and more generally, that there must be a time dilation associated with all potentials, including the weak and strong nuclear ones. This constitutes physics beyond the Standard Model, since the SM excludes all such effects. The ubiquity of time dilation may allow it to be used as a central guiding principle of future unified theories, and provide a fresh approach to the problem of quantum gravity.

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1. INTRODUCTION

From the first publication of General Relativity in 1915 to about 1930, hundreds of classical theories were proposed attempting to unify gravity and electromagnetism[1]. While none of these was completely successful, some of them were very influential.

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For example, Weyl's Space-Time-Matter theory[2] introduced the notion of gauge invariance, while Kaluza-Klein theory[4, 5] used a compact 5th dimension and was an important precursor to string theory.

Given that there is a time dilation associated with the gravitational potential in GR, it seems reasonable to wonder whether there might be a similar time dilation associated with the EM potential in such unified theories. Sadly, this question has rarely been asked, let alone answered. Even after nearly a century, we don't know whether Kaluza-Klein theory has this feature or not. David Apsel in 1978-1981 gave probably the first unified theory to explicitly predict such a time dilation[6, 7, 8], and only a handful of subsequent papers[9, 10, 11, 12, 13, 14, 15, 16] mention anything similar. At least to first order, all of these theories agree on the magnitude of EM time dilation.

In this paper we show why they must. We derive the magnitudes of both gravitational and electromagnetic time dilations from elementary considerations that do not depend on the machinery of GR or any specific unified theory, and thereby demonstrate that they must be features of any unified theory that is compatible with both Special Relativity and Quantum Mechanics.

2. HISTORY

Einstein first derived gravitational time dilation in his 1907 paper on the Relativity Principle[17]. He began in §18 by using Special Relativity to show that clocks at different X-positions in a reference frame accelerated in the X-direction cannot run at the same rate; then in §19 used the Equivalence Principle to infer that the same thing must be true for clocks at different values of a gravitational potential Φ . He carried out all the arguments to first order to give the linear form $T_d = 1 + \Phi/c^2$, which has since become called the weak-field approximation, although he did note in passing that the actual formula must be $T_d = e^{\Phi/c^2}$. The linear approximation cannot be exactly correct because it has two problems: it is logically inconsistent since $(1 + \Phi/c^2)(1 - \Phi/c^2) \neq 1$, and there is an event horizon at $\Phi = -c^2$. The exponential form solves both of those problems.

The conclusion of the 1907 argument is that acceleration causes the rate of time flow to be a function of position in the direction of the acceleration. It did not matter to Einstein whether the acceleration was caused by a rocket, or by standing on the ground in a gravitational field. Although he didn't mention it, it is worth noting that the acceleration of a charged particle by an electric field is not immune to this argument. Neither are accelerations due to the weak and strong forces; *all* accelerations of a given magnitude *must* cause exactly the same time dilation.

The philosophical question here is whether EM acceleration is "gravity-like", i.e. whether the Equivalence Principle applies to EM. This is a yes/no question with only two possible answers. If it does, then application of the Einstein 1907 argument forces EM time dilation, and gives a magnitude identical to that computed below. If it doesn't, then there can be no EM time dilation. Weyl explicitly

assumed that it doesn't[3]; most other researchers have implicitly assumed the same without even discussing it.

After General Relativity in 1915 and the Schwarzschild solution in 1916, another view became possible, although it is still not widely appreciated. Taking the weak field ($r_s \ll r$) and low speed ($\frac{dr}{dt} \ll c$) limit of the Schwarzschild metric leaves us with the Newtonian metric

$$ds^2 = (dx^2 + dy^2 + dz^2 - c^2 dt^2) + \left(-\frac{2GM}{rc^2}\right)c^2 dt^2$$

which is just flat Minkowski spacetime plus the time dilation field. In this metric, space is completely flat and only time is curved, and the curved time gives geodesics that match Newtonian gravity. This pure time dilation field appears as a $1/r^2$ "force". So in the Newtonian limit of GR, matter causes a time dilation field and the time dilation gradient causes gravitational acceleration. The direction of cause and effect is completely reversed from the 1907 argument. This line of thought was anticipated by several early unified theories, although they tended to describe it as a speed-of-light field rather than a time dilation field. For example, Ishiwara stated that "if the speed of light varies in space and in time, then these variations lead to the appearance precisely there of a gravitational field." [18]

If we accept both of these arguments, then we cannot have any acceleration without an associated time dilation gradient, and we cannot have any time dilation gradient without an associated acceleration. The two are inextricably linked.

3. GRAVITATIONAL TIME DILATION FROM $E = h\nu$ AND $E = mc^2$

In this section we use a new method to derive gravitational time dilation without directly invoking relativity theory. We assume only that particles have a rest energy associated with their mass, given by $E = mc^2$, and a frequency associated with their energy, given by $E = h\nu$.

In a uniform gravitational field of strength g , raising a particle by a height z requires work mgz . Thus, to an observer at height 0, the total energy of the particle at height z is given by $E(z) = mc^2 + mgz$ and its frequency by $\nu(z) = E(z)/h$.

However, an observer already at height z would perceive the particle to have merely frequency $\nu(0) = mc^2/h$. This can only be true if the two observers have clocks running at different rates, in the ratio

$$T_d = \frac{\nu(z)}{\nu(0)} = \frac{E(z)}{E(0)} = \frac{mc^2 + mgz}{mc^2} = 1 + \frac{gz}{c^2}$$

which is the weak-field approximation to GR's gravitational time dilation (with $\Phi = gz$). As above, the linear form can't be exactly correct but the exponential form $T_d = e^{gz/c^2}$ is.

This derivation appears in some sense to be quantum, since it utilizes $E = h\nu$. But because time dilation is a ratio, h cancels out and its precise value doesn't

93 matter. This means that the classical ($\hbar \rightarrow 0$) limit is exactly the same as the
 94 “quantum” result.

95 Both this derivation and Einstein’s 1907 one avoid almost all the assumptions
 96 of GR, so each of them implies that any other theory that predicts a gravitational
 97 time dilation must have the same relation of dilation to potential as GR. From
 98 this viewpoint, the existence and magnitude of gravitational time dilation cannot
 99 be viewed as a confirmation of GR specifically, but only of a class of theories of
 100 which GR is the best known example.

101 4. ELECTROMAGNETIC TIME DILATION BY THE SAME METHOD

102 We now consider the case of a particle with mass m and charge q in an electro-
 103 static potential V . The potential energy is qV , so the corresponding time dilation
 104 (to first order) must be

$$T_d = \frac{mc^2 + qV}{mc^2} = 1 + \frac{qV}{mc^2}$$

105 As in the gravitational case, the linear form cannot be completely right, and the
 106 exponential form $T_d = e^{qV/mc^2}$ is the most obvious candidate to replace it. But
 107 unlike in the gravitational case, here both charge and mass matter, or more pre-
 108 cisely the dilation is a function of the charge/mass ration q/m . This means that a
 109 simple Riemannian manifold is inadequate, and the geometry of any unified theory
 110 would have to be something more complicated, like a Finsler space. Uncharged
 111 particles should be completely unaffected. For a given non-zero q , lighter particles
 112 will be dilated more strongly than heavier particles. The electron, being the light-
 113 est charged particle and having the highest charge/mass ratio, should be affected
 114 the most. But since electrons have infinite lifetime, the only observable effect on
 115 them is the shift in phase frequency. Although this is universally observed, most
 116 physicists would not consider it proof of or even evidence for time dilation.

117 Thus, for experimental testing, we are lead to the muon. With a mass-energy
 118 of $m_\mu c^2 = 105.7$ MeV, it is still light enough to have its mean lifetime of $2.2 \mu\text{s}$
 119 affected by a modest potential. For example, a potential of 1.057 MV should alter
 120 its lifetime by about 1%; such a potential could be achieved by a Van de Graaff
 121 generator with a sphere of about 76 cm diameter in air, which is well within reach
 122 of a serious hobbyist. Apsel first proposed this kind of experiment in 1979[7]; 40
 123 years later it still has never been performed.

124 Negative muons (μ^-) bound to low- Z nuclei are also known to have lengthened
 125 lifetimes. The normal explanation for this is that the muon has a kinetic energy
 126 given by the quantum virial theorem, and an average velocity corresponding to
 127 that kinetic energy, and a special-relativistic time dilation corresponding to that
 128 velocity. However, Apsel has argued that this calculation does not match the
 129 experimental data very well, and that adding a (smaller) electromagnetic time
 130 dilation term gives a better fit[8]. If so, we may have already been seeing evidence

for decades. The effect should be more obvious for higher Z . Unfortunately, as Z increases, nuclear capture by a proton begins to dominate, and we don't have good data on non-capture decay rates for most elements.

For magnetic interactions, the muon's measured magnetic moment is -4.49×10^{-26} J/T. To get the same 1% level of time dilation, say between spin-up and spin-down muons, we would need to place them in a field of

$$1.057 \text{ MeV} \times \frac{1 \text{ J}}{6.24 \times 10^{12} \text{ MeV}} \times \frac{1 \text{ T}}{2 \times (4.49 \times 10^{-26} \text{ J})} \approx 1.89 \times 10^{12} \text{ T}$$

Given that the world record magnetic fields are in the range of 45–330 T, this seems far beyond the reach of current experiment. Van Holten thought that 5×10^9 T might suffice and could be found in the vicinity of a magnetar[12, 13].

One characteristic of a pure time dilation is that, all other things being equal, it must necessarily slow down (or speed up) all decay modes equally. Since muons have 3 known decay modes[26], this can be used as a test for whether lifetime alterations can reasonably be viewed as solely due to time dilation, or whether other factors must be invoked.

5. COUNTERARGUMENTS

There are many counterarguments to EM time dilation theories. In this section we point out flaws in two of the main ones.

5.1. Naive Electromagnetic Gauge Invariance. Many physical theories, such as classical EM and Van Holten's theory mentioned in the previous section, have a property that I will call Naive Electromagnetic Gauge Invariance. In NEGI theories, everything can be expressed in terms of fields acting locally, and potentials can be viewed as having no physical reality but being merely aids to computation. NEGI would of course rule out any time dilation effects from an EM potential in a field free region, such as inside the sphere of a Van De Graaff generator. Many physicists seem to think that this is sufficient to disprove the theory.

The problem with this viewpoint is that it is flat-out wrong. The universe does *not* have the NEGI property; the Aharonov-Bohm effect[19, 20] suffices as a counterexample. The importance of this is often glossed over. For example, Jackson and Okun[21, p.24] write:

... gauge invariance is a manifestation of non-observability of A_μ . However integrals ... are observable when they are taken over a closed path, as in the Aharonov-Bohm effect ... The loop integral of the vector potential there can be converted by Stokes's theorem into the magnetic flux through the loop, showing that the result is expressible in terms of the magnetic field, albeit in a nonlocal manner. It is a matter of choice whether one wishes to stress the field or the potential, but the local vector potential is not an observable.

168 Contrast this with the discussion in Feynman Vol. II[22] lecture 15-5, where the
 169 central importance of the potential is emphasized:

170 The fact that the vector potential appears in the wave equation of
 171 quantum mechanics (called the Schrödinger equation) was obvious
 172 from the day it was written. That it cannot be replaced by the
 173 magnetic field in any easy way was observed by one man after the
 174 other who tried to do so. This is also clear from our example of
 175 electrons moving in a region where there is no field and being af-
 176 fected nevertheless. But because in classical mechanics \mathbf{A} did not
 177 appear to have any direct importance and, furthermore, because
 178 it could be changed by adding a gradient, people repeatedly said
 179 that the vector potential had no direct physical significance — that
 180 only the magnetic and electric fields are “right” even in quantum
 181 mechanics. It seems strange in retrospect that no one thought of
 182 discussing this experiment until 1956 . . . The implication was there
 183 all the time, but no one paid attention to it. . . . It is interesting
 184 that something like this can be around for thirty years but, because
 185 of certain prejudices of what is and is not significant, continues to
 186 be ignored.

187 In either case, the NEGI idea (that fields acting locally can explain everything) is
 188 admitted to be false.

189 **5.2. CPT Invariance.** It is often stated (e.g. in [23, 24, 25]) that the CPT the-
 190 orem guarantees that particle and antiparticle masses and lifetimes are identical.
 191 However, this conclusion is only justified at zero potential, or with the further
 192 assumption of NEGI (which renders potential irrelevant). A true CPT reflection
 193 must invert all charges and magnetic moments in the universe, which necessarily
 194 inverts all EM potentials as well. Therefore, the CPT theorem only *really* proves
 195 that a particle’s mass and lifetime at 4-potential \mathbf{A} must equal its antiparticle’s
 196 mass and lifetime at 4-potential $-\mathbf{A}$. This holds true under EM time dilation, since
 197 the dilations for those two cases are identical. Thus, the CPT theorem does not
 198 contradict the claim that particles and antiparticles will be time-dilated oppositely
 199 at a non-zero potential and that their lifetimes will differ there. EM time dilation
 200 is completely compatible with the notion of CPT invariance.

201 6. SUMMARY

202 We reviewed two early derivations of gravitational time dilation and gave a new
 203 elementary derivation of it. Both the 1907 Einstein derivation and this new method
 204 can be trivially modified to give derivations of electromagnetic time dilation as
 205 well, which agree in magnitude with the handful of prior theories predicting such
 206 an effect. That EM time dilation seems so inescapably implied, and is yet so
 207 widely rejected, points perhaps to a deep paradox in current physical thought.

Since testing for the first-order electrostatic effect would be quite easy and cheap,
it seems worthwhile to actually perform that experiment.

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