On whether or not non-gravitational interaction can occur in the absence of gravity

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November 30, 2015

Abstract

The Standard Model of particle physics is built upon the implied assumption that non-gravitational interaction can occur in the absence of gravity. This essay takes this implied assumption at face value and then considers the alternative assumption – non-gravitational interaction *cannot* occur in the absence of gravity. This alternative assumption is then discussed in terms of the dark sector of the Universe.

1 Introduction

As of today, there are two experimentally verified theories that are used to explain the four fundamental interactions.

The first theory is general relativity, which is a classical field theory that accounts for the gravitational interaction in terms of a curved spacetime metric. In essence, "the Sun tells spacetime how to curve; curved spacetime tells the Earth how to orbit".

The second theory is the Standard Model of particle physics, which is a quantum field theory that accounts for the three non-gravitational (electromagnetic, weak, and strong) interactions in terms of particle exchange that occurs in the assumed presence of a flat (gravity-free) spacetime metric. In essence, a pair of electrons (the massive quanta of the electron field) exchange some photons (the massless quanta of the electromagnetic field), which causes the electrons to recoil and move apart.

One of the main goals for many of today's theoretical physicists is to combine general relativity and the Standard Model into a *unified* theory that can account for all four fundamental interactions at the same time. Because the Standard Model already includes the majority of the fundamental interactions in an extremely successful way, most theoretical physicists agree that the final solution to this unification puzzle will require the conversion of general relativity from a classical field theory into a quantum field theory. Ultimately, such a conversion would relegate curved spacetime to being merely an illusion that emerges from some kind of particle exchange that occurs in flat spacetime.

The purpose of this essay is to present a simple, testable assumption about how non-gravitational interaction could be affected by gravity in a way that is not currently accounted

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for by either general relativity or the Standard Model. This is done in four steps. The first step is to consider an implied assumption that is built into the foundation of the Standard Model – non-gravitational interaction can occur in the absence of gravity. The second step is to consider the alternative assumption – non-gravitational interaction *cannot* occur in the absence of gravity. The third step is to generalize this alternative assumption by taking into account the variable strength of the gravitational field. The final step is to discuss this alternative assumption in terms of the dark sector of the Universe – the 'ghostly' portion of the Universe's mass and energy that interacts via gravitation as usual, but for some mysterious reason does not interact via electromagnetism to any significant degree (hence, dark). Because this alternative assumption is presented in terms of curved spacetime (and without the benefit of much mathematical rigour), it's fair to say that this essay isn't so much about presenting a new piece of the unification puzzle, but more so about pointing out where and how we may wish to look for such pieces in the first place.

Before we begin our consideration of the assumptions, let's first define a few physical constants. The speed of light in vacuum is $c = 2.99 \times 10^8$ m s^{-1}; the universal gravitational constant is $G = 6.67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}; the Planck action is $h = 6.62 \times 10^{-34}$ J s; the Planck energy is $E_p = \sqrt{hc^5/(2\pi G)} = 1.95 \times 10^9$ J; Coulomb's constant is $k_e = 8.99 \times 10^9$ N m^2 C^{-2}.

2 Assumptions

Let's begin our consideration of the assumptions by focusing on the Standard Model of particle physics. Given that the Standard Model does not account for gravity (neither in terms of particle exchange nor in terms of a curved spacetime metric), there is an implied assumption built into the foundation of the model:

> Assumption $\boldsymbol{\alpha}$: Non-gravitational interaction can occur in the absence of gravity.

Although assumption $\boldsymbol{\alpha}$ is mostly fair (the Standard Model is only meant to allow for an approximate description of physical reality), it may be useful to explicitly forbid this assumption and then consider the alternative assumption:

> Assumption $\boldsymbol{\beta}$: Non-gravitational interaction *cannot* occur in the absence of gravity.

Since the strength of the gravitational field – or more specifically, the deviation of the metric from that of flat spacetime – is actually a measure that may also take on a wide range of values in-between 'fully strong-present' and 'fully weak-absent' (depending on how distant the gravitational source is), let's replace assumption $\boldsymbol{\beta}$ with a more general assumption:

> Assumption $\boldsymbol{\gamma}$: The maximum allowed energy scale of non-gravitational interaction is dependent on how much the metric deviates from the metric of flat spacetime.

Let's proceed by making some minor assumptions about the bounds of this maximum allowed energy scale in terms of a spherically symmetric gravitational source and its accompanying Schwarzschild metric. First, let's assume that the upper bound of this maximum allowed energy scale is the Planck scale E_p at the Schwarzschild radius $R_s = 2GM/c^2$, where the metric deviates the most from the metric of flat spacetime. Secondly, let's assume that the lower bound of this maximum allowed energy scale is zero at the radius of infinity, where the metric deviates the least from the metric of flat spacetime (in which case the special assumption $\boldsymbol{\beta}$ would apply).

Given these bounds, let's calculate this maximum allowed energy scale $E_{\max}$ in terms of the Schwarzschild metric's 'space' component g_{rr} by the equation $g_{rr} = 1/(1 - R_s/r) = 1/(1 - E_{\max}/E_p)$, which simplifies to $E_{\max} = E_p R_s/r$.

For example, the mass of the Earth is roughly $M = 5.97 \times 10^{24}$ kg ($R_s = 8.86 \times 10^{-3}$ m), and its mean radius is roughly $r = 6.37 \times 10^6$ m. Given these parameters, it is assumed that the maximum allowed energy scale of non-gravitational interaction at the surface of the Earth is roughly 'only' $E_{\max} = 2.7$ J (10^{19} eV).

So far, we have assumed that gravity allows for non-gravitational interaction – the stronger the gravitational field is at some location, the stronger non-gravitational interaction can be at that location. Let's proceed by making some assumptions about how this would affect the propagation, creation, and annihilation of photons. First, let's make a minor assumption that $E_{\max}$ does not *directly* affect the propagation of photons (regardless of the photon energy E). Secondly, let's make a minor assumption that a photon of energy E cannot be created or annihilated at a location where $E > E_{\max}$.

For example, it is assumed that an electron cannot create a photon of energy E at a location where $E > E_{\max}$. In a situation where an electron has a 90% chance of interacting by creating a photon of energy $E > E_{\max}$, the electron would thus have a 90% chance of simply just propagating instead of interacting – there would be a 90% chance that the electron is hidden (dark).

Also for example, it is assumed that a photon of energy E would be hidden (dark) at a location where $E > E_{\max}$, because the photon cannot be annihilated. With regard to our previous calculation of $E_{\max} = 2.7$ J at the surface of the Earth, a photon of energy $E > 2.7$ (which would necessarily have been created at a location where $E_{\max} > 2.7$) would simply just propagate through the Earth undetected. In effect, the Earth's weak gravity would protect us from the most energetic of gamma rays.

As for a broader example, it is assumed that an expanding Universe that starts out in a state in which the gravitational field is extremely strong everywhere and then evolves into a state in which the gravitational field is extremely weak everywhere would undergo a kind of heat death. Since the maximum allowed energy scale of photon creation and annihilation would generally become increasingly limited as time goes on ($E_{\max} \to 0$ as $t \to \infty$), the Universe would become increasingly dark on the whole.

Let's finish by restating assumption $\boldsymbol{\gamma}$ in terms of photon creation and annihilation:

> Assumption $\boldsymbol{\delta}$: The maximum allowed energy scale of photon creation and annihilation is dependent on how much the metric deviates from the metric of flat spacetime.

3 Conclusion

Altogether, by simply assuming that the maximum allowed energy scale of photon creation and annihilation is not infinite everywhere – but rather is finite, and variable in a location-dependent way – we have arrived at a point of view from which it appears that the dark sector of the Universe is not mysterious, but only natural. In essence, all that we would need to do in order to produce a dark photon is to create a standard photon and then just simply let it propagate into a region where it cannot be annihilated. It is important to note that this point of view would remain valid as long as the maximum allowed energy scale of photon creation and annihilation is made finite and variable through *any* mechanism – we wouldn't necessarily be facing a total loss even if assumptions $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$, $\boldsymbol{\delta}$ do not hold.

To be sure, this point of view is not currently built into either general relativity or the Standard Model of particle physics, and so perhaps this point of view could be helpful in the search for pieces of the unification puzzle.

This essay is dedicated to Callie.

4 Technical endnotes

If the maximum allowed energy scale of particle creation and annihilation in general is not infinite everywhere – but rather is finite, and variable in a location-dependent way – then we would no longer have to strictly rely on the technique of renormalization in order to remove the ultraviolet divergences that arise in our calculation of the Hamiltonian.

Consider the Kerr-Newman rotating, electrically charged black hole's outer event horizon at $r_+ = GM/c^2 + \sqrt{(GM/c^2)^2 - a^2 - e^2}$, where $a = J/(Mc)$, $e = q\sqrt{k_e G}/c^2$. Here J is angular momentum, q is electric charge. The maximum energy scale equation may simply be $E_{\max} = E_p r_+/r$; this equation turns into $E_{\max} = E_p R_s/r$ as angular momentum and electric charge drop to zero.

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