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Galileo vs. Aristotle, Principles of Equivalence and the Gravitational Acceleration of Atoms according to General Relativity

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Abstract

We derive the gravitational acceleration of atoms according to general relativity. Our results show that elements differ in the gravitational acceleration they experience, which means that the principles of equivalence are not valid for atoms. Bulk matter consists of atoms. Therefore, bulk matter also violates the principles of equivalence. The primary cause of the violation is the gravitational effect of the electric field energy of the charged particles that constitute atoms. A secondary cause is the gravitational field energy associated with each atom. However, the influence of the electric field energy on gravitational acceleration is very small for uranium atoms, which have one of the largest values among the natural elements found on Earth. It is only $-3.4\times10^{-23} g_N$, where g_N is the Newtonian acceleration of gravity. This value is orders of magnitude smaller than current experimental precision.

Keywords

General Relativity, Principles of Equivalence

1. Introduction

In the last few years, a number of authors have questioned the validity of the "equivalence principle" and experiments have been performed to test it. However, the term is ambiguous because it embodies three different interrelated principles [1]. Galileo's principle of equivalence maintains that bodies fall with the same gravitational acceleration independent of their mass. This principle contrasts with Aristotle, who maintained that the acceleration experienced by falling bodies depends upon the mass of the falling body, specifically, the greater the mass the larger the acceleration. Apart from [2] the discussion of Galileo's and Aristotle's viewpoints has been carried on recently by philosophers [3]-[9]. In contrast, our approach to resolve this issue is via Einstein's theory of general relativity.

Newton's principle of equivalence states that gravitational and inertial masses are equal. Einstein's principle of equivalence maintains that it is not possible to distinguish between an accelerated coordinate system and gravitational acceleration. In a previous work [10], we showed that the gravitational acceleration of charged particles according to general relativity depends on their charge and mass, which means that the principles of equivalence are not valid for charged particles. Here we extend our approach to atoms.

1.1. Experimental Work

Experimental work has tested the validity of the principles of equivalence [11]-[19]. The Principles of Equivalence have been tested in the solar system [15] [20] [21] and their are suggestions on how to test it at cosmological distances [22]-[25].

1.2. Theoretical Work

In 1908 Einstein published his principle of equivalence [26]. It had its critics. For example, Max von Laue, who was a strong supporter of special relativity and wrote the first book on the subject [27], in a letter to the physicist and philosopher Moritz Schlick wrote that he believed that Einstein's principle of equivalence is "not correct" [28]. Recently, interest in exploring the possible violation of the principles of equivalence is motivated by two circumstances. 1) The desire to unify quantum mechanics and general relativity. Most attempts suggest that the principles of equivalence may not be valid. 2) The desire to understand both dark energy and dark matter, neither of which is part of the standard theory of elementary particles [29]. Our views on dark energy and dark matter are at: [30] [31].

None of the above experiments has led to the conclusion that the principles of equivalence are invalid. Nevertheless, many authors have recently questioned the validity of the principles of equivalence. [32] showed that the twin paradox in accelerated systems does not agree with the prediction according to the equivalence principle. [33] investigated limits on Einstein's Equivalence Principle in the Standard Model Extension of particle physics. [34] showed that two other theories of gravity do not require Einstein's principle of equivalence meaning that it may not be a fundamental principle of nature. [35] discuss possible violations of the principles of equivalence. [36] suggest a new scalar particle with generic couplings to the standard-model particles is a possible source for the violation of the Galileo's principle of equivalence and the lepton anomalous magnetic moment. [37] maintains via a direct calculation that Einstein's principle of equivalence is not valid. [38] discuss the violation of the equivalence principle induced by oscillating rest mass and transition frequency. [39] emphasize that the mass-dependent quantum dynamics explicitly breaks Galileo's principle of equivalence even at macroscopic scales. [40] discuss equivalence principle violation in non minimally coupled gravity. [41] has shown that cosmic inflation is inconsistent with Einstein's principle of equivalence.

Our approach to the question of the validity of the principles of equivalence differs from all the above mentioned work. All elements are made of atoms. Our approach is to calculate the gravitational acceleration the atoms of each element experience. We show that each element consists of atoms that experience a different gravitational acceleration than the atoms of any other element. Thus, any bulk body made of atoms of an element will experience a different gravitational acceleration than another bulk body consisting of the atoms of a different element. This circumstance violates the principles of equivalence.

2. Gravitational Acceleration of Charged Particles

[10] derived the gravitational acceleration experienced by charged particles according to general relativity. In this section we briefly review the pertinent equations and results of this work because we will use the equations to derive the gravitational acceleration experienced by atoms, which consist of charged particles. We start with Equation (1) in [10]. In Newtonian physics the acceleration, a, of a falling body is given by:

$$a = \frac{m_G}{m_I} g_N \tag{1}$$

where $g_N = -\frac{GM}{r^2}$ is the Newtonian acceleration of gravity, m_G the gravitational mass and m_I the inertial mass.

Galileo's principle of equivalence maintains that all bodies fall with the same acceleration, which applied to Equation (1) means that $m_I = m_G$. This result is Newton's principle of equivalence.

According to Einstein energy gravitates, so both the electrostatic field energy as well as the gravitational field energy associated with charged particles must gravitate. Their effect on the gravitational acceleration experienced by charged particles, g_E, is given by Equation (7) in [10]:

$$g_E = \frac{\left(1 - \frac{e^2}{c^2 mr} - \frac{Gm}{c^2 r} - \frac{GM}{c^2} - \frac{3\dot{r}^2}{2c^2}\right) g_N}{1 + \frac{3GM}{c^2 r} + \frac{3\dot{r}^2}{2c^2}} \tag{2}$$

G is the gravitational constant, e the charge of the particle, c is the speed of light, m the mass of the particle experiencing gravitational acceleration, $M \gg m$, r is the distance to the center of M and and $\dot{r}$ is the radial velocity of m, which we set equal to zero because we are only interested in the gravitational effect of electrostatic and gravitational field energies.

According to the above equation for an electron of mass, m_e, on the surface of the earth, the effect of their electrostatic field energy on the gravitational acceleration is:

$$g_e = -\frac{e^2}{m_e c^2 r} g_N = -4.4 \times 10^{-22} g_N \tag{3}$$

Which is the classical electron radius divided by the radius of the earth. The mass of the proton is 1836 times that of the electron, so the effect for protons is: $\frac{g_e}{1836} g_N = -2.4 \times 10^{-25} g_N$.

Both of the above values are many orders of magnitude smaller than the most precise experiments mentioned above. However, [42] attempted to measure the gravitational acceleration of electrons. They found that the electrons do not fall at all in their apparatus, a result that they attributed to a gravity induced electric field in their apparatus. Other experimental suggestions on how to determine the gravitational acceleration of charged particles are [43]-[45]. The ALPHA, AEGIS and GBAR experiments at CERN are attempting to measure the gravitational acceleration of anti-hydrogen.

The term for the gravitational effect of the electrostatic field energy in Equation (2), $-\frac{e^2}{mc^2 r} g_N$, is proportional to the square of the charge. This circumstance has two major consequences. First, the term is independent of the sign of the charge. Consequently, the value of this term for positrons is the same as that for electrons and the value for antiprotons is the same as that for protons. Second, if a physical body consists of n charged particles whereby each individual particle possesses the charge, e, then the numerator is: $n^2 e^2$. We will use this circumstance in the next section.

Equation (2) tells us that the gravitational acceleration of charged particles depends upon both their charge and mass, meaning that charged particles do not all fall with the same acceleration; therefore, according to general relativity Galileo's principle of equivalence is not valid for charged particles. Comparing Equation (2) with Equation (1) leads to:

$$m_{GE} = 1 - \frac{e^2}{c^2 mr} - \frac{Gm}{c^2 r} - \frac{GM}{c^2} - \frac{3\dot{r}^2}{2c^2} \tag{4}$$

and

$$m_{IE} = 1 + \frac{3GM}{c^2 r} + \frac{3\dot{r}^2}{2c^2} \tag{5}$$

where m_{IE}, m_{GE} are the inertial and gravitational masses of a charged particle respectively. Thus, $m_{IE} \neq m_{GE}$ meaning that Newton's principle of equivalence is also not valid for charged particles.

In an accelerated coordinate system all particles appear to accelerate at the same rate. We have shown that this circumstance is not correct if the acceleration is caused by gravity because charged particles fall at a different rate, which is a function of both their charge and mass. Thus, Einstein principle of equivalence is also not valid.

Finally, we note that the gravitational field energy of m, $-\frac{Gm}{rc^2}$ and M,

$-\frac{GM}{rc^2}$ as well as the electrostatic field energy of m, $-\frac{e^2}{mc^2 r}$ all gravitate repulsively.

3. Gravitational Acceleration of Atoms

Atoms are electrically neutral. However, they consist of electrically charged particles whose electric field energies must gravitate. Consequently, following the results of the previous section on charged particles, the gravitational acceleration they experience will depend upon the total number of charges the atom contains as well as the mass of the atom. Due to quantum effects and the interactions of multiple electrons, the electric field inside atoms is complicated [46]-[49]. Here we do not consider these complexities because our aim is merely to determine how close this effect is to current achievable experimental precision. We suggest that the generalization of Equation (2) will accomplish this task. This generalization leads to the gravitational acceleration experienced by atoms, g_A:

$$g_A = \frac{\left(1 - \frac{n^2 e^2}{c^2 mr} - \frac{Gm}{c^2 r} - \frac{GM}{c^2} - \frac{3\dot{r}^2}{2c^2}\right) g_N}{1 + \frac{3GM}{c^2 r} + \frac{3\dot{r}^2}{2c^2}} \tag{6}$$

The right side of the above equation and Equation (2) appear to be same except for the factor n^2. However, there is a fundamental difference between these equations. It comes about because in the above equation both n and m are atomic quantities, whereas in Equation (2), m refers to a single ($n = 1$) charged particle. Specifically, in Equation (6), n is the total number of charges an atom contains, that is the sum of the number of protons and electrons and m refers to the mass of the atom.

In calculating m, we neglect the mass of the electrons and set:

$$m = 1836.15 n_p + 1838.68 n_n \tag{7}$$

which is the mass of an atom in terms of the electron mass. n_p and n_n are the number of protons and neutrons in the atom respectively.

From Equation 6 the contribution of the electric field energy, g_{EA}, to the gravitational acceleration of atoms is:

$$g_{EA} = \frac{n^2}{m} g_e \tag{8}$$

where as in Equation (3), g_e is the contribution of the electrostatic field energy of an electron to the gravitational acceleration.

Employing the above equation, we first calculate this effect for the lest massive atoms in nature. For hydrogen ($n_p = 1$, $n_n = 0$, $n = 2$, $m = 1836.15$), the electric field energy term is: $-\frac{4e^2}{mc^2 r} g_N = -9.6 \times 10^{-25} g_N$, which is four times that of the proton. The value of this term for deuterium ($n_p = 1$, $n_n = 1$, $n = 2$, $m = 3674.83$) is: $-4.8 \times 10^{-25} g_N$, which is half of the term for hydrogen. The term for Tritium ($n_p = 1$, $n_n = 2$, $n = 2$, $m = 5513.51$) is: $-3.2\times10^{-25} g_N$, Helium 3 ($n_p = 2$, $n_n = 1$, $n = 4$, $m = 5510.98$): $-1.3\times10^{-24} g_N$ and Helium 4 ($n_p = 2$, $n_n = 2$, $n = 4$, $m = 7349.66$): $-9.6\times10^{-25} g_N$, which is the same as the hydrogen term.

Next we calculate this effect for a few of the more massive atoms. Uranium ($n_p = 92$, $n_n = 146$, $n = 184$, $m = 437373$) $-3.4\times10^{-23} g_N$, Copernicium ($n_p = 112$, $n_n = 165$, $n = 224$, $m = 509031$) $-4.3\times10^{-23} g_N$, Oganesson ($n_p = 118$, $n_n = 176$, $n = 236$, $m = 540273$), the most massive element produced so far, $-4.5\times10^{-23} g_N$. The least radioactive element that undergoes alpha decay is Bismuth-209 ($n_p = 83$, $n_n = 126$, $n = 166$, $m = 384074$). The effect for this isotope is: $-3.1\times10^{-23} g_N$.

Astrobiology and astrophysics appear to be completely disconnected. However, we connected them in a recent publication [50]. So we present the contribution of the electric field energy for the elements most important to living things. In the above, we have already calculated this for hydrogen. For carbon ($n_p = 6$, $n_n = 6$, $n = 12$, $m = 22049$) $-2.3\times10^{-24} g_N$, nitrogen ($n_p = 7$, $n_n = 7$, $n = 14$, $m = 25723.8$) $-3.4\times10^{-24} g_N$, oxygen ($n_p = 8$, $n_n = 8$, $n = 16$, $m = 29398.6$) $-3.8\times10^{-24} g_N$, sulfur ($n_p = 16$, $n_n = 16$, $n = 32$, $m = 58797.3$) $-7.7\times10^{-24} g_N$ and phosphorus ($n_p = 15$, $n_n = 16$, $n = 30$, $m = 56961.1$) $-7.0\times10^{-24} g_N$.

We now turn to comparing the influence of the electric field energy on one of the most precise experiments [12], which determines the difference in the gravitational acceleration between beryllium and titanium. Equation (8) leads to the value of the electrostatic field energy term for beryllium ($n_p = 4$, $n_n = 5$, $n = 8$, $m = 16538$) $-1.7\times10^{-24} g_N$ and Titanium ($n_p = 22$, $n_n = 26$, $n = 44$, $m = 88201$) $-9.7\times10^{-24} g_N$. So the difference between the two accelerations due to the electric field energy is just $7.0\times10^{-24} g_N$. This experiment measures a difference of accelerations down to 8.8×10^{-15} m/s^2. Consequently, the gravitational effect of the electric field energy of beryllium and titanium plays absolutely no role in the experiment.

Finally, we discuss what our equations mean for the Principles of Equivalence. Equation (6) tells us that atoms experience a gravitational acceleration, which depends upon the number of charged particles in an atom and the atomic mass. Consequently, Galileo's principle of equivalence, which maintains that gravitational acceleration is independent of mass of the falling body, is invalid. Einstein's principle of equivalence is also not valid because each type of atom experiences gravitational acceleration different from other atomic types meaning we can distinguish between gravitational acceleration and an accelerated coordinate system in which all atoms experience the same acceleration.

Next we consider Newton's principle of equivalence. Comparing Equation (1) and Equation (6) leads to:

$$m_{GA} = 1 - \frac{Gm}{c^2 r} - \frac{GM}{c^2 r} - \frac{n^2 e^2}{c^2 m r} - \frac{3\dot{r}^2}{2c^2} \tag{9}$$

and

$$m_{IA} = 1 + \frac{3GM}{c^2 r} + \frac{3\dot{r}^2}{2c^2} \tag{10}$$

where m_{IA}, m_{GA} are the inertial and gravitational masses of an atom respectively. We see that $m_{GA} \neq m_{IA}$. That is, Newton's principle of equivalence is also not valid for atoms.

4. Conclusion: Galileo vs. Aristotle and the Principles of Equivalence

Galileo demonstrated through experiments that gravitational acceleration is independent of the mass of falling bodies and consequently is the same for all bodies. What does general relativity teach us? We have employed general relativity to show that the atoms of each element experience a different gravitational acceleration than the atoms of other elements. Bulk matter is made of atoms. By showing that atoms violate the principles of equivalence it follows that bulk matter violates the principles of equivalence too.

For example, two bodies that are made of different elements, for instance one body beryllium and the other body titanium as in [12] will experience different gravitational accelerations. This circumstance violates Galileo's principle of equivalence, which maintains that all bodies fall with the same acceleration.

To understand this mathematically consider Equation (6), which contains the terms $-\frac{Gm}{rc^2} g_N$ and $-\frac{n^2 e^2}{mc^2 r} g_N$, which are the contributions of the gravitational field energy and the electric field energy respectively to the gravitational acceleration of atoms. Thus, according to general relativity Galileo was wrong and Galileo's principle of equivalence is not correct because both of these terms depend on the mass, m. So Aristotle is correct because he maintained that the gravitational acceleration depends upon the mass. However, Aristotle thought that the more massive the body, the more rapidly it would fall. The above terms are preceded by a minus sign, which means they gravitate repulsively. Consequently, the more massive bodies experience a smaller acceleration than less massive bodies. Thus, Aristotle was wrong in this respect.

The influence of the gravitational field energy of the falling body is extremely small. For example, in the [12] experiment 4.84 g test bodies were employed, which yields: $-\frac{Gm}{rc^2} g_N = -5.6 \times 10^{-37} g_N$, whereas this experiment measures a difference of accelerations down to 8.8×10^{-15} m/s^2.

We conclude from the field energy terms in both Equation (2) and Equation (6) that according to general relativity, charged particles, atoms and bulk matter do not obey Galileo's, Newton's, and Einstein's principles of equivalence.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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