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Title: **THEORETICAL MOTIVATION FOR GRAVITATION EXPERIMENTS ON ULTRA-LOW ENERGY ANTIPROTONS AND ANTIHYDROGEN**

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THEORETICAL MOTIVATION FOR GRAVITATION EXPERIMENTS ON ULTRA-LOW ENERGY ANTIPROTONS AND ANTIHYDROGEN

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ABSTRACT

We know that the generally accepted theories of gravity and quantum mechanics are fundamentally incompatible. Thus, when we try to combine these theories, we must beware of physical pitfalls. Modern theories of quantum gravity are trying to overcome these problems. Any ideas must confront the present agreement with general relativity, but yet be free to wonder about not understood phenomena, such as the dark matter problem. This all has led some "intrepid" theorists to consider a new gravitational regime, that of antimatter. Even more "daring" experimentalists are attempting, or considering attempting, the measurement of the gravitational force on antimatter, including low-energy antiprotons and, perhaps most enticing, antihydrogen.

1. Introduction

Classical, worldline, general relativity, and many-path quantum mechanics, are, by the descriptive words, worldline vs. many-path, fundamentally in conflict with each other. It makes no difference if this distinction would manifest itself only at the Placck scale. it is still there.

Indeed, much of the effort of modern theoretical physics is devoted to overcoming this conflict, at least in principle. On the one hand, theories of quantum gravity try to incorporate a gravitational interaction, albeit in some higher symmetry or space-time, and then have general relativity fall out as a classical approximation. On the other hand, cosmologists of the "wave function of the universe" school, are trying to modify quantum mechanics to allow a unified picture of physics.

Independent of whether either of these schools is on the right track, it is logically clear that either 1) general relativity, or 2) quantum mechanics, or 3) both theories have to be modified to obtain a better theory of physics. Ironically, our guide may be in looking at the great body of experimental data which defines the successes of these theories: from the successes of QED [1] to the successes of general relativity.[2]

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It is as a devil's advocate that I discuss the situation. I will argue that in many regimes we know much less than we generally assume we know. This opens up the possibility that there may be something totally unexpected waiting for us when we ultimately reach the essential confrontation of these two fields, in the gravity of antimatter[3].

2. What Do we Not Know?

Given the many successes of general relativity, then, why would one even question that gravity on antimatter might be different that that of matter? To begin, one can give a two-fold rationale. The first is exemplified in Aspect's experimental test[4] of Bell's inequalities.[5] The answer (that quantum mechanics is correct) was "known" before the experiment. but yet, it was important to do the experiment. Even in areas where one already has an answer to a known accuracy, it is important to significantly improve the experimental agreement. That was emphasized by Dicke,[6] who argued, "It is clear ... that if one believes that general relativity is established beyond question by its elegance, beauty, and the three famous experimental checks, then the Eötvös experiment has no point! ... However, if gravitational theory is to be based on experiment, ... " And so, Dicke did his experiment.

2.1. Gravity and CPT

Furthermore, and as indicated in the introduction, modern attempts to unify gravity with the other forces lead to the generic conclusion that $g(p) \neq g(\bar{p})$, at *some* level. Now this statement does not contradict CPT, even though one might have thought so.

CPT tells us that an antiapple falls to an antiEarth in the same way that an apple falls to the Earth. It says nothing about how an antiapple falls to the Earth.

But I already have cheated on you. No CPT Theorem has been given for curved space-time general relativity. In fact, in some string theories, CPT is violated. CPT is OK for intuitive arguments, but not for precise, general arguments. That is to say, one can expect that the statements about apples and antiapples given above are approximately correct, but one has to be careful if statements are given about orbiting black holes vs orbiting antiblack holes.

What else do we really not understand?

2.2. CP violation

We really don't understand CP-violation as manifested in the $K_0 - \bar{K}_0$ system. Remember, a parametrization, the MKW-matrix, is *not* an explanation. Furthermore, upon this parametrization depends our supposed understanding of the dominance of matter over antimatter in the universe.

Recall that, since the early days, some have suggested that there is a connection between the neutral-K system and gravity.[7,8]. More recently some string theories have found CPT and CP violation,[9,10] although the amount predicted by the first of these theories[9] is small.[11]

Even more interesting is the unusual suggestion of Chardin,[12] that CP violation is a reflection of a microscopic violation of the arrow of time, that is, antigravity. What is lost is the permanence of matter. There is a Hawking-like radiation with a connection to entropy.

What else don't we understand about gravity?

3. Actually, We Don't Understand Gravity and Matter (let alone antimatter) for Almost All of the Universe!!

This is the dark matter problem, whose presentation and possible resolutions can be traced to the beginnings of the last century. What does one think if one sees an object that is behaving "incorrectly" from a gravitational point of view. Either 1) there is unseen matter causing the odd motion, or 2) there is a breakdown in Newton's Law. When the orbit of Uranus was found to be behaving badly 150 years ago, both John Couch Adams and Urbain Jean Joseph Leverrier both decided that there had to be a new, unseen planet causing the perturbations ... and so there was, Neptune.[13] But just ten years later, a new planet, "Vulcan," was not the cause of the anomalous advance of Mercury's perihelion. It took another 50 years for this explanation to come, the breakdown of Newton's Law in general relativity.

3.1. Dark matter and large-distance scales

Such is the problem today, on the grandest scales of the universe. One can observe beautiful gravitational lensing of distant galaxies by foreground clusters of galaxies.[14] But the amount of visible matter in the clusters is only a small fraction of what would be needed to have lensed the distant galaxy. Either there is dark matter in the clusters or else the interaction that is causing the lensing (it does not have to be general relativity) is stronger than believed. No one knows. A lot of people think, but no one knows.

On smaller, but still long-distance scales, there are the puzzling rotation curves of galaxies. By Doppler measurements one can find the velocity of stars in spiral galaxies as a function of their distance form the galactic centers. Over a large variation of distance, this velocity is often approximately constant. But when one tries to account for such a velocity distribution from the visible matter in these galaxies, there is not enough visible matter to account for the motions. Therefore, one normally presumes that there is dark matter in the galaxies.

However, it has been observed by a number of people that certain potentials other than Newtonian could account for the motions from the visible matter alone.[15,16,17] Of course, these calculations are not precise since visible mass determination is also not precise. but the results are intriguing. For purposes of discussion, I will go over one of them, the Modified Newtonian Dynamics (MOND) of Milgrom and Beckenstein.[17]

Basically, this dynamics can be viewed as coming from a model equation of the form

$$\mu(g/a_0)\mathbf{g} = \mathbf{g_N} \ , \tag{1}$$

where g_N is the Newtonian acceleration, g is the true acceleration, μ is a monotonic function that satisfies

$$\mu(x) \to \begin{cases} x \ , & x \to 0 \\ 1 \ , & x \to \infty \end{cases} \ . \tag{2}$$

a_0 is a new, critical acceleration constant, that I will return to quickly. The idea is that you have Newtonian acceleration at short distances and a $1/r$ acceleration at long distances. Specifically, one has

$$g = \begin{cases} GM/r^2 \ , & g \gg a_0 \\ [GMa_0]^{1/2}/r \ , & g \ll a_0 \end{cases} \ . \tag{3}$$

a_0 is proportional to the Hubble-Constant- squared. But for this constant equal to 100 (in the usual units), the value of a_0 is

$$a_0 = (2-8) \times 10^{-8} \ (cm/sec^2) \ . \tag{4}$$

This new force allows many galactic-rotation curves to be explained.[18]

3.2. Astronomical-Unit scales

The distance scale at which the Sun's Newtonian force would equal its $1/r$ MOND force is a few thousand Astronomical Units. One might hope to find corrections at smaller distances than this, and this fact suggests one look for such deviations from Newton's Law, at the many AU scale, no matter what the origin might be. (Note that this is in a differeent regime than the much shorter laboratory and geophysical scales which have recently been the object of much study.[19,20])

The first place might be double stars. These objects have been know for about 200 years. The problem is to track their orbits. "Long-period binaries" are not even known for certain to be bound. They travel together is that we know about them. Even the orbits of shorter-period binaries have not been studied extensively enough to look for deviations from Newtonian dynamics. This may be a problem for further investigation.

When it comes to comets, the longest-period repeating comet is the comet discovered by Caroline Herschell in 1788 and rediscovered by Rigollet in 1939.[21] It goes out to a distance of 57 AU from the Sun. However, because of perturbations from the major planets and loss of mass in its orbit, all this comet can tell us is that Newton's Law is approximately correct, say to a few percent, out to such distances. (For example, its calculated orbital period is 155 years vs. the observed 151.)

But better limits o Newtonian gravity can be obtained from the data of the Pioneer missions. Pioneers 10 and 11 were launched in 1972, and were the first close encounters with the major planets, most specifically Jupiter. After encounter, they eventually went into orbits in opposite directions from each other, in the ecliptic. They are in a gyro mode (rotating every 13 seconds), so their motions are not disturbed by attitude-control boosters. Their velocities and distances have been monitored by transponded, Doppler-shifted signals. Past 10 AU, the effect of the solar radiation pressure was low enough so that the data could be very precisely analyzed. This data exists out to 30 AU for Pioneer 11, and is still being obtained at 57 AU for Pioneer 10.

Preliminary analysis indicates a systematic deviation from Newtonian dynamics.[22] At the time of this writing, no artifact of the experimental system or of the analysis has explained the systematic. If this continues to be true, it is hoped that one may soon be able to make a precise announcement. (A smaller, similar effect may also have been observed in the Galileo mission, which now is in gyro mode.)

Whatever is going on here, this whole discussion should emphasize to you that our understanding of gravity within the universe is incomplete.

4. Gravity and Antimatter

This brings us full circle. Given that our theoretical and experimental knowledge of the physics of gravity and antimatter are woefully inadequate, to perform an experiment on the gravity of antimatter would be a monumental milestone in our understanding of physics. This would be true even if we found exactly what we expect, that gravity on antimatter is the same as that on matter. Until we actually do such an experiment, we do not know the answer, we only believe we do.

The proposal to measure the gravitational acceleration of the antiproton[23] has progressed to the PS200 experiment.[24] The first part of this experiment isalready on the floor, the "catching trap. "[25]

There are also two main ideas to form antihydrogen, via positronium-antiproton[26] collisions or directly from positron-antiproton collisions.[27] Then it might be possible to control this antihydrogen by laser cooling, magnetic traps, or fountains. If so, a long-term goal would be to measure gravity on antihydrogen. (See the discussion in Ref. [25,28] for a comparison of these ideas.)

But in any event, it is in the hands of our generation to perform an experiment to measure the gravitational acceleration of antimatter. Some day it will be done, whether we do it or not. It will be done. If we do not do it, and the answer eventually turns out to be what we expect, then future generations will look back upon us a say it was a shame. But if the answer turns out to be a surprise, then, if we do not do it, future generations will look back upon us and say we were fools.

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