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THE INVERSE-SQUARE LAW AND QUANTUM GRAVITY

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I'm going to describe a program which Terry Goldman, Richard Hughes, and I are involved in at Los Alamos. As a matter of fact, it started 7 years ago when Terry and I proposed measuring the gravitational acceleration of antiprotons. We came to this idea from a particle physics point of view. I'm going to explain what I consider to be that point of view, starting with some history of physics over the last 200 years.

At the beginning of the 1800's, there were understood to be three forces: electricity, magnetism, and gravity. Through the work of Faraday, Orsted, and Maxwell, we realized that electricity and magnetism are two aspects of the same force. So, there were two forces: electromagnetism and gravity. Around 1900, manifestations began to appear of what ultimately became known as the strong and the weak forces.

In the same period, Einstein put relativity into gravity in the form we discuss it today, general relativity. If you apply general relativity to Mercury in a power series expansion you get a $1/r^3$ force. But you do not say that this is a new, nongravitational force. You say that this is a new aspect of gravity which becomes manifest when you put in relativity.

Similarly, when quantum mechanics was applied to electromagnetism, we found that there were new aspects which appeared. This was not because we changed Maxwell's equations but because we put quantum mechanics into them. To me, the prime example is the Lamb Shift. In the 1930's, this was parametrized by something that was called the Uehling potential. Nobody said that the Uehling potential manifested a new force. It was a new aspect of electromagnetism which appeared when you brought quantum mechanics into it.

In this spirit, it is the prime goal of modern particle theory to try to unify all the forces of nature in a relativistic, quantum field theory. The work of Weinberg, Salam, and Glashow, in the 1960's and 1970's, resulted in the unification of the weak and the electromagnetic forces into what we now call the electroweak force. This theory was verified in the discovery of the W and Z particles at CERN. In this unification the Z particle and the photon are two aspects of the same object: one has a mass and one doesn't.

Independently, a model of the strong force was invented. It is called QCD, for Quantum Chromo Dynamics. It is still by itself. The hope was that we could unify QCD and the electroweak theory using the group $SO(5)$. But one of the predictions of the theory was that the proton would decay with a lifetime $<10^{32}$ years. To test this idea, people, instead of taking one proton and waiting for 10^{32} years, decided to take 10^{32} protons and wait for 1 year. Unfortunately, they waited for more than 1 year and the protons still didn't decay. So, as it stands now, even though we wish we had a successful unified theory of the strong and the electroweak forces, we don't.

However, we particle physicists are undaunted. Even though we have not unified the strong and electroweak interactions, we already are trying to unify them

with gravity. Such theories are called theories of quantum gravity. One of the manifestations of these theories is that, as with electromagnetism, new gravitational effects arise simply because quantum mechanics is brought into gravity.

But how could things be different with these new quantum gravity theories? Before I answer that I must emphasize that none of these theories produce anything like the particle spectrum which you see. In fact, every time a new accelerator goes on, people first search for the expected new particles and then say, "Wait till the next accelerator." So, all of these concepts remain theories of theories. I'm pushing them, but I have to be honest. However, they all have tantalizing phenomenological features.

In general, in these theories, the spin-2 graviton has spin-0 and spin-1 partners. The partners may couple to fermions (and therefore violate the weak equivalence principle), and they may have a finite rest mass (and so violate the inverse-square law). There are many people who have put in a lot of work: Joel Scherk, Cosmos Zachos, and I could go on and on. But let me tell you what it all boils down to. One can parametrize the static potential as

$$V = -Gm_1m_2[1 + (-/+) a e^{-v/r} + b e^{-s/r}] / r . \quad (1)$$

The first term is normal gravity. The second term is from the spin-1 graviphoton. It has the (-) sign for matter-matter interactions (overall repulsion) and the (+) sign (overall attraction) for antimatter-matter interactions. The graviscalar term is always attractive. For matter-matter interactions these two new forces could approximately cancel and yield a small effect. For matter-antimatter interactions the two new terms add, and so could produce a relatively large effect.

But, people often wonder, does a different gravitational acceleration for antimatter violate CPT? You might think so, that if you drop antimatter it has to fall the same as if you drop matter. But actually, CPT only tells you that if you drop an apple to the earth it will fall exactly as if you drop an antiapple to an anticarh. CPT doesn't tell you what happens if you drop an antiapple to the earth.

There are two schools of thought on all of the above arguments. The loyal opposition believes that there actually may be a new force of nature. They can argue that this is just like in the days when Einstein was trying to unify electricity and gravity. He couldn't do it because he didn't know about the weak and the strong forces, so he missed the boat. So too, this school would argue, the reason why we're having trouble unifying things is because there is a "fifth force" out there and we just haven't realized it before.

Of course, the school to which I belong says that if there are new forces of approximately gravitational strength, then they are new manifestations of gravity which arise because we're bringing quantum mechanics into it: if it's approximately of gravitational strength it's gravity. That's where I'm coming from. But you know, God didn't talk to me when he built this place. So, it could indeed turn out that there is a "fifth force" of nature. This is something which experiment and theory will have to settle.

So, what are the experimental indications? As to possible Principle of Equivalence violations, Jim Faller will be talking about this tomorrow. Let us just note that the recent tests of the Principle of Equivalence have all found, with one

notable exception, a null or very small signal. Contrariwise, there have been three recent tests of the inverse-square law, on scales of the order of hundreds of meters to perhaps as much as hundreds of kilometers. All of them have found an anomaly. This includes the Australian mine results, the Air Force tower experiment, and geophysical well-logging results. So, could it possibly be that there is a lack of violation of the Principle of Equivalence and not a violation of the inverse-square law? This entire question is very exciting right now.

I want to mention two ongoing Los Alamos experiments. One is the proposal to measure the gravitational acceleration of antiprotons at LEAR, the low energy antiproton ring at CERN. This is a "Galileo" experiment which measures the antiproton's time of flight (at 4° K) up a drift tube. The experiment is approved, is underfunded and undermanned, but is going along. Equipment is being built and hopefully we're on the floor in 1991. (A complementary experiment to measure gravity on positrons is being pushed by Bill Fairbank.) An experiment to test the inverse-square law was performed last summer in the Greenland Ice Sheet. A thin bore-hole gravity meter was lowered down the DYE-3 bore-hole, which is 2 kilometers deep. This experiment is now being analyzed and the results should come out August 1.

There are many related experiments which can be done in space. Most obvious are tests of Newton's Law. For scales on the order of 10's to 100's of kilometers one could do a precise orbit analysis of a lunar positional satellite, or even analyze LAGEOS or Starlette data to higher precision. Smaller-scale tests could be done in earth orbit.

But in any event, these are exciting times for gravity. Certainly I and my collaborators are excited.

REFERENCES

For references by the many people who have contributed to this field, see our articles:
Ander, M. E., Goldman, T., Hughes, R. J., and Nieto, M. M. 1988, *Phys. Rev. Lett.*, **60**, 1225.
Goldman, T., Hughes, R. J., and Nieto, M. M. 1986, *Phys. Lett. B*, **171**, 217.

DISCUSSION

SCHUTZ: In theories where antiparticles couple to gravity differently from particles, what happens to photons, which are their own antiparticles?

NIETO: The genesis of your question was raised by the old "anti-gravity" ideas studied in the 1950's. This one asked if one could have normal tensor gravity for matter, but exactly opposite gravity for "anti-matter", then you would have "likes attract" not "opposites attract".

Such a system would violate conservation of energy. In Morrison's gedanken experiment, you could create an antiproton-proton pair in the earth's field, raise it at no cost in energy, annihilate to photons, which gain energy following, and then create a new pair with added kinetic energy. In fact, this is a variation of Wigner's perpetual motion machine if change is not conserved.

For the quantum-gravity ideas, the tensor forces are normal, and you have no change in photon dynamics. The new vector piece has 'like repel' and no coupling to photons, so this is no problem. The scalar piece could or could not couple to photons and/or not violate the principle of equivalence, depending on the particular model. Therefore, although the models are mathematically consistent on this point, different models will have restrictions imposed upon them on the size of the effects allowed by experiment.

SHAPIRO: Can you particularize the limit on the ability to "maneuver" within grand unified theories as far as the lowest "acceptable" proton decay rate is concerned?

NEITO: The simplest, most obvious, and specifically predictive "Grand Unified Theory" was $SU(5)$, which was to break down into $SU(3)$ -color (the strong interactions) cross the $SU(2) \times SU(1)$, the electroweak theory. This is now ruled out by the lack of proton decay. The decay rate goes as X^{-4} , where X is the massive vector boson that converts quarks into leptons. The existence of a unified coupling constant then determines rather precisely what X must be since it is the scale where all the various interaction coupling constants become the unified coupling constant. The end result is that, even with optimistic theoretical "fudges", the proton lifetime must be less than 10^{32} years. The experimental limits are now significantly greater than this number. See, e.g., T. Goldman, *Ad. Nucl. Phys.* 18, 315 (1987), Sec. 7.