Quantum Gravity
Testing time for theories

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Theories of quantum gravity attempt to combine quantum mechanics – which reigns supreme at the atomic scale – and the classical theory of general relativity, which governs planets and galaxies. The era of quantum gravity began about 50 years ago with the pioneering work of Chandrasekhar, when it was realized that quantum mechanics and gravitation combine in a fundamental manner to form white dwarfs – the Earth-sized stars of roughly a solar mass. That singular discovery had to wait another 25 years for the excitement to begin afresh with the ideas put forward by Bekenstein, Hawking, Unruh, and Wheeler, among others. Yet, the present activity runs the danger of evolving into a mathematical science fiction in the absence of an experimental counterpart. For the last quarter of a century an important, though limited, experimental quantum-gravity programme has existed. Giovanni Amelino-Camelia’s paper on page 216 of this issue adds to this in a fundamental and significant manner by suggesting that the fuzziness of space-time is experimentally accessible. Using existing data from a certain type of gravity wave detector he is able to set significant bounds on proposed quantum properties of space-time. Instruments under construction promise to take us far beyond.

If the universe is structured the way theorists believe, the quantum mechanical unification of the non-gravitational and gravitational interactions must occur at a particular energy scale, called the Planck scale – just as the electromagnetic, strong, and weak nuclear forces are predicted to unify at a particular energy scale. But the actual scale at which theories of quantum gravity can be explored has been poorly constrained. The extreme smallness of both the Planck length ($\sim 10^{-35}$ m), on the one side, and the ratio of the gravitational to the electrical forces acting between, say, two electrons, on the other side ($2.4 \times 10^{-43}$) has led to the wide spread belief that the realm
of quantum gravity is beyond terrestrial experiments. But, the following elementary facts can help dispel this view. For terrestrial experiments, a highly relevant dimensionless quantity is derived from the Newtonian gravitational potential $\phi_{grav}$ and the speed of light $c$. The constructed dimensionless object is:

$$\Phi_{grav} \equiv \left[ \frac{\phi_{grav}}{c^2} \right]_{Earth} = -6.95 \times 10^{-10}$$

This is about 33 orders of magnitude larger than the ratio of the gravitational to the electrical force. Moreover, for quantum-gravity experiments it is not only the force that is of relevance, but also the phases of the wave functions of quantum mechanical states. Although in the non-relativistic weak-field limit, the force depends on the gradient of $\phi_{grav}$, the phase depends directly on $\phi_{grav}$. In many situations, phase measurements give an enormous advantage and are also capable of highlighting the differences between the quantum and classical realms of gravity. Therefore, for a physical state appearing as a linear superposition of different mass (or, energy) eigenstates, non-trivial, gravitationally-induced phases can come into play, and in principle are measurable.

Gravity waves are an important prediction of Einstein’s theory of general relativity and though not yet detected directly, may provide information about the very early universe. Although the Planck length is indeed extremely small, modern gravity-wave interferometers are designed to detect minute displacements in the positions of some test masses (relative to a beam-splitter). There are additional consideration that may counterbalance the smallness of the Planck length. In certain quantum-gravity theories the quantity $c^2 f^{-2} \lambda_{Planck}$ ($f =$ frequency) characterizes the fuzziness in the distance between the test masses used in the experiment, whereas the quantity $c S(f)^2$ (where $S(f)$ is the amplitude spectral density of the gravity-wave interferometer) characterizes the level of sensitivity to such fuzziness that modern gravity-wave detectors can achieve. For frequencies of a few hundred hertz the two indicated quantities are comparable.

An experiment that exploited some of these observations, and which still remains relatively unknown in the quantum gravity community, is the 1975 classic experiment of Colella, Overhauser, and Werner (COW). It simultaneously explored the quantum and gravitational realms using neutron interferometry. To the accuracy in phase shifts of about 1% available at that time, the COW experiment established the non-relativistic weak-field limit
of any viable theory of quantum gravity. For a single mass eigenstate, the amplitudes associated with each of the paths in a COW interferometer (to be distinguished from interferometers designed to detect gravity waves) picks up a different gravitationally induced phase, and so result in an observable change in the interference pattern as one path is rotated with respect to the other. In this table-top experiment the rotation is carried out in such a manner that each path experiences a different gravitational potential.

However, as the experimental accuracy has improved, the latest (1997) experiments show that a statistically significant discrepancy has begun to appear between the theoretical prediction of the gravity-induced phase shift and that which is experimentally observed [3]. On the other hand, when one studies effects of gravity in certain atomic systems, where the experimental measurements are about five orders of magnitude superior, no statistically significant discrepancies are observed [4]. In the latest such experiments gravitationally induced quantum effects of local tides at Stanford have been observed.

Is there a slight difference in the manner in which neutrons and electrons interact with gravity, and can this point a way towards an appropriate expression of quantum gravity? In recent years, while the new generation of COW experiments was reaching these higher levels of insight, three more quantum-gravity experiments have been proposed. These experiments are based on the possibility that quantum gravity might affect the nature of fundamental symmetries, or that the theory of general relativity itself may not provide a complete description of gravitation. One experiment is based on tests of CPT (the combined symmetries of particle-antiparticle, parity, and time reversal) invariance using the very sensitive neutral-kaon system [5]. The second concerns the possibility that quantum gravity might deform Lorentz symmetries in a way that would alter the propagation of the γ-rays we collect from astrophysical sources [6]. The third test explores the incompleteness of the theory of general relativity itself, and proposes to measure quantum mechanically any constant gravitational potential in which we may be embedded [7].

Here we come to the Amelino-Camelia paper [1], which opens up yet another realm of quantum gravity to experiments. The experiments he proposes would probe what is perhaps the central element of quantum gravity, namely, the concept of space-time. He notes that almost all existing approaches to quantum gravity expect a modification of the classical picture
of space-time by introducing some sort of fuzziness. With that we all agree, but there are various proposals as to what concrete form this fuzziness takes. Amelino-Camelia convincingly argues that gravity-wave interferometers have precisely the right ability to probe the space-time fuzziness. He sets highly significant limits (in one case ultra-Planckian) on the length scales characterizing two fuzziness situations. Amelino-Camelia’s paper exploits the differences in the fuzziness of the distance between two test masses used in the experiment, as predicted by different theories of quantum gravity. It turns out that these differences are large enough to be detected in the experiments being proposed. So, whereas the smallness of the Planck length and the ratio of gravitational to electrical forces, does play its own essential role in nature, it does not make quantum gravity a science where humans cannot venture to probe her secrets.

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