Indirect Evidence for Quantum Gravity

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An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.

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Quantum mechanics appears to govern all nongravitational fields (here called matter), and most people believe it also applies to the gravitational field. However, there has been no explicit experimental test of this. Gravity is so weak that Feynman[1] has questioned whether it must be quantized. As an alternative, Møller[2] and Rosenfeld[3] have proposed a theory in which gravity is described by a classical field which obeys the semiclassical Einstein equations

$$G_{\mu\nu} = 8\pi\langle\psi|\, T_{\mu\nu}\,|\psi\rangle . \qquad (1)$$

Here $G_{\mu\nu}$ is the Einstein tensor of the unquantized metric $g_{\alpha\beta}$, $T_{\mu\nu}$ is the stress-energy quantum operator, and ψ is the wave function or quantum state of the matter. (One could replace ψ by a density matrix or a C^*-algebra state with no essential changes.) In the Heisenberg picture, which we adopt, (1) is to be supplemented by the appropriate covariant field equations and commutation relations for the quantized matter field operators in the presence of the classical metric.

The functional dependence of $g_{\alpha\beta}$ upon ψ by (1) introduces a nonlinearity into the metric-dependent quantum evolution of the matter.[4,5] This makes it crucial to specify what happens during a measurement. In the conventional view, the wave function collapses into an eigenstate of the measured variable.[6] This would change the right-hand side of (1) and produce objectionable consequences.[5,7,8] For example, assuming that one can make a measurement which collapses the wave function outside one's future light cone, Eppley and Hannah show[8] that one could use semiclassical gravity to transmit observable signals faster than light. Such consequences might well lead one to reject the conventional view in the context of the semiclassical theory of gravity, though one could argue that such unexpected effects have not been ruled out experimentally and thus should not yet be dismissed as unphysical.

A more conclusive argument against the collapse of the wave function in the semiclassical theory is that if ψ collapses, in general the right-hand side of (1) will not be conserved, whereas the left-hand side is automatically conserved. That is, if $\psi = \sum_i c_i(x^\alpha)\psi_i$ with constant ψ_i's in the Heisenberg picture but with $c_i(x^\alpha)$'s which change during a measurement, then for almost all conceivable reductions of the wave packet,

$$8\pi\langle\psi|\, T^{\mu\nu}\,|\psi\rangle_{;\nu} = 8\pi\textstyle\sum_{i,j}(c_i{}^*c_j)_{;\nu}\langle\psi_i\,|\,T^{\mu\nu}\,|\,\psi_j\rangle \neq 0 \equiv G^{\mu\nu}{}_{;\nu} . \qquad (2)$$

One might seek to avoid the inconsistency by simply abandoning (1) during a measurement. However, one would need a replacement of (1) in order to determine the evolution of the gravitational field for any particular collapse of the wave function, and this would differ from the semiclassical Einstein equations.

Therefore, in order to retain (1) as the simplest semiclassical theory of gravity, we must assume that the universal matter wave function ψ never collapses, as in the Everett formulation of quantum mechanics.[9] One might think that the conventional collapse view is equivalent to this, as it is in practice for linear quantum theories in which one may ignore components of the wave function which have negligible interference with the ones of interest. But in semiclassical gravity the metric depends upon all components of ψ, none of which can be ignored. Nevertheless, once the evolution of the gravitational field is determined by using the full wave function in (1), ψ may be decomposed into linear components on that four-dimensional metric and any standard interpretation may be applied to the components. One must simply remember that the individual components do not give the full source of the gravitational field.

Having chosen a formulation of quantum mechanics that may be meshed with (1) without creating an immediate inconsistency, we ask whether the resulting semiclassical theory may be distinguished from a theory of quantum gravity in which the gravitational field is included in the full wave function of the universe. The key is to look for the nonlinear gravitational coupling between different components of the matter wave function that exists in the semiclassical theory, but which would be absent in a linear quantum theory of gravity. This coupling would occur through the classical metric even if the components of ψ were eigenstates of $T_{\mu\nu}$, and so it is not a gravitational quantum interference effect that would be nearly impossible to detect. In order for the coupling to be observable in the semiclassical theory, the gravitational field must simply be measurably different from what would be if each component alone (suitably normalized) were the full source of the field. This requires that ψ be a superposition of components with macroscopically different stress-energy configurations, since current experimental techniques can only detect the gravitational fields of macroscopic sources.

Because of the enormous complexity of the full wave function of the universe, it does seem highly likely that it may have significant components in which the earth, moon, sun, and other astronomical bodies are in positions greatly different from those in our component, the relative state[9] corresponding to our nongravitational observations. This would lead to a semiclassical gravitational field quite in conflict with gravitational observations.[10] However, it is plausible (though perhaps intrinsically unlikely) that ψ has all astronomical bodies at macroscopically well-defined positions. A quick calculation then shows that the quantum-mechanical uncertainty of their positions could remain observationally negligible during their lifetimes. Hence to make a more definite test of semiclassical gravity, one needs to make certain that the wave function does have components that would give measurably different gravitational fields.

We performed an experiment to make such a test of semiclassical gravity. A quantum-mechanical decision and amplification process was used to set the positions of certain macroscopic masses. As amplitudes for different decisions occurred, ψ developed simultaneous components in which the masses were in macroscopically different configurations. The gravitational field induced by the masses was measured in our component and was found to be highly correlated with the mass distribution in our component alone. There was no indication of any gravitational coupling with other components of ψ. This was consistent with quantum gravity but inconsistent with the semiclassical Einstein equations.

The experiment included ten runs of a procedure which had two parts that were done at different times but were coupled by the action of the experimenter. The first part was a simultaneous 30-sec measurement of γ rays from a small cobalt-60 source by two nearby Geiger counters. The application of quantum mechanics to the radioactive decay and detection events leads to various amplitudes for all possible results of this decision and amplification process. Those in which the ratio of counts in the two counters was greater than an overall average were classified as decision α, and those in which the ratio of counts was less than average were classified as β. This classification was selected so that for each run the Born-Dirac square-amplitude measure on the components of ψ in which α was registered should be roughly equal to that on the components in which β was registered. We assume that there was no precise correlation of nuclei and incoming γ rays in the initial state to upset this approximate equality predicted.

The second part of the experiment used a Cavendish torsion balance to measure the gravitational field induced by two macroscopic masses whose configurations were determined by the quantum decision process. The balance consisted of two small lead balls mounted 10 cm apart (center to center) on a light horizontal rod hung in its center by a thin metallic fiber. A mirror attached to the balance reflected a light beam to a scale 1283 cm away to determine the angle of twisting which would result from a gravitational torque. The macroscopic masses were two larger lead balls, 1497 g each, which could be placed in stationary positions 4.63 cm in front or behind the mean equilibrium positions of the smaller balls. In position A the large balls were each on the clockwise side of the respective small ball (as seen from above); in position B they were on the counterclockwise side. The gravitational field corresponding to the large balls in each definite position should thus exert either a clockwise or a counterclockwise torque on the torsion balance.

The procedure for each run was to generate a quantum decision with the Geiger tubes, position the macroscopic masses accordingly, and measure the gravitational field by the torsion balance. If the quantum decision was α, we set the masses in configuration AB, meaning the four-dimensional configuration in which the large balls were placed in position A for 30 min of Cavendish balance measurements and then in position B for 30 min. If the Geiger counters gave β, we set configuration BA, meaning position B first and then A. (Using a sequence of two positions rather than one increased the sensitivity and reduced the effects of slowly varying nongravitational influences on the torsion balance, but it is in principle unnecessary.) In each experimental run, the appropriate configuration was started at a predetermined time, independent of the quantum decision.

Since the quantum process caused the wave function to have amplitudes of comparable weight for both decisions α and β, the corresponding positioning of the masses led to simultaneously occurring amplitudes for both mass configurations AB and BA. We of course assume that the full wave function never collapses and that it includes all aspects of the positioning (including the experimenter who recorded the Geiger tube counts, calculated the ratio to classify the decision, and then placed the masses in the corresponding positions), as is necessary even to discuss the semiclassical Einstein equations consistently. We also assume that the positioning was generally faithful to the quantum decision rather than being determined by some systematic effect. A refinement of the experiment might employ a completely inanimate positioning process, but this is not necessary so long as it is assumed that the experimenter did not put the masses in nearly the same configuration in nearly all components of the wave function, disregarding the quantum measurements. With these assumptions we conclude that the wave function really did have a comparable measure of amplitudes for components with both mass configurations. We had no information about the complicated phase relations between these amplitudes, but that was not necessary since we were not doing an interference experiment.

Now in a quantum theory of gravity, we would predict that the quantized gravitational field would differ from component to component of the wave function and be highly correlated with the mass configuration. Thus we would expect the torsion balance to respond in each component according to the mass configuration in that component. But in the semiclassical theory of gravity, we would predict a definite classical four-dimensional (i.e., not necessarily static) gravitational field that would correspond to the expectation value of the stress-energy operator. Since the amplitudes for different components have rapidly varying relative phases, there would be negligible contributions from cross terms in the right-hand side of (1). For our nonrelativistic configurations it would essentially be a square-amplitude-weighted average over the mass distributions of the different components of the wave function. Because the configurations AB and BA have nearly equal weights, we would expect only a small response by the torsion balance in the semiclassical theory, and no correlations with the particular mass configuration in our component of the wave function.

The series of ten experimental runs gave 30-sec γ-ray counts with means and standard deviations 1509.1 ± 31.0 and 887.6 ± 23.0 for the two respective Geiger counters. The fluctuations are consistent with Poisson statistics and thus were attributed to the quantum mechanics of the radioactive decays and detections. There was a negligible background count rate when the cobalt-60 source was removed. The ratios of counts in the two counters in our present component of the wave function gave the sequence of decisions α, α, α, β, β, α, β, α, β, β, and the masses were set in the appropriate configurations. During each run the torsion balance responded to each repositioning of the masses and then underwent damped oscillations with a mean period of 710 sec. By fitting the extrema of the oscillations to exponentially decaying sine waves during each half-hour, the change in the equilibrium position (of the reflected light beam on the distant scale) as the large balls were moved from A to B or B to A was determined. The changes in equilibria (in cm) we measured were -61.3, -63.9, -36.0, $+69.2$, $+36.1$, -48.8, $+46.4$, -45.2, $+51.3$, and $+59.6$.

Although the sensitive torsion balance was affected by temperature changes, vibrations, and other factors not under our control, so that the data have a large scatter, they give a correlation coefficient with the quantum decisions of $r = 0.9788$. If our data came randomly from an uncorrelated population, as would be predicted by the semiclassical Einstein equations, the correlation coefficient for $N-2=8$ degrees of freedom would have a probability distribution[11] $P(r)\,dr = (35/32)(1-r^2)^3\,dr$, giving a chance of only 4×10^{-7} of being as large as ours was. Thus the correlation we observed is highly significant, as would be expected if gravity is quantized. Under that assumption the data give a gravitational constant $G=(6.1\pm0.4)\times10^{-8}$ $cm^3\ g^{-1}\ sec^{-2}$, where the uncertainty represents one standard deviation of the mean. Although the accuracy is poor, this result is within 1.3 standard deviations of the accepted value and thus shows that at least most of the torque on the torsion balance can be attributed to gravity (if quantized), so that there is no evidence that the strong correlation observed is likely to have arisen from nongravitational forces. Of course, the correlation is what one would intuitively expect, but it is in conflict with the predictions of the semiclassical Einstein equations (cf. Ref. 5).

In conclusion, our theoretical arguments show that the semiclassical Einstein equations (1) are mathematically inconsistent if the matter wave function collapses arbitrarily during a measurement, and our experimental results show that these equations are inconsistent with nature (to a high confidence level) if the wave function does not collapse. (An analogous argument and experiment could easily be used to rule out the semiclassical Maxwell equations, but we already know the electromagnetic field is quantized.) Because there are presumably more complicated schemes for coupling a classical gravitational field to matter that we know is quantized, this does not prove that gravity is quantized, but it may be interpreted as indirect evidence supporting the hypothesis of quantum gravity by ruling out what is probably the simplest plausible alternative.

Since performing our experiment, we have been informed privately that many other people (including Davies,[12] D. Deutsch, Kibble,[5] and W. G. Unruh) have suggested such an experiment, perhaps in a modified form, though we are not aware of any actual previous experiments that explicitly tested semiclassical gravity.

Discussions with D. Deutsch, G. N. Fleming, G. W. Gibbons, R. H. Good, S. W. Hawking, E. Kazes, J. Stachel, K. S. Thorne, W. G. Unruh, and R. M. Wald (some of whom independently voiced ideas suggested here and others of whom strongly disagreed) were helpful on the interpretation of the experiment after it was performed, particularly in suggesting references. This work was supported in part by the National Science Foundation under Grant No. PHY79-18430.

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