Nonquantum Gravity

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Abstract

One of the great challenges for 21st century physics is to quantize gravity and generate a theory that will unify gravity with the other three fundamental forces of nature. This paper takes the (heretical) point of view that gravity may be an inherently classical, i.e., nonquantum, phenomenon and investigates the experimental consequences of such a conjecture. At present there is no experimental evidence of the quantum nature of gravity and the likelihood of definitive tests in the future is not at all certain. If gravity is, indeed, a nonquantum phenomenon, then it is suggested that evidence will most likely appear at mesoscopic scales.

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1 Introduction

Ever since the earliest attempts by Einstein and others [1, 2, 3] to unify the two fundamental fields of classical physics, gravity and electromagnetism, one of the major goals of physics has been to unify all the fundamental forces of nature. Such a unification was not without precedent; after all, Maxwell had previously unified electricity and magnetism. Since then, the electromagnetic and weak forces have been successfully unified (electroweak theory) and these have been, more or less, unified with the strong force in the Standard Model of particle physics. So far, unifying gravity with the strong, weak, and electromagnetic forces has proved to be much more difficult and only minor progress has been made; although, the proponents of superstring theory have great hopes that they are on the right track. It seems reasonable to expect

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that in order to unify gravity with the other quantum theoretical forces, gravity must also be quantum mechanical in origin. Efforts to quantize gravity began shortly after the advent of quantum mechanics and continue to this day. While there are several intriguing candidates, including superstring theory [4] and loop quantum gravity [5] there is, as of yet, no successful theory of quantum gravity. Quantizing gravity is, to be sure, fraught with technical difficulties but the total lack of any observations of the quantum nature of gravity must certainly be listed as one of the important reasons for lack of progress.

Because there is currently absolutely no experimental evidence of the quantum nature of gravity, it seems reasonable to at least contemplate the hypothesis that gravity is an entirely classical, nonquantum phenomenon. While such a conjecture is, perhaps, viewed as heretical by most physicists, it is not a new conjecture [6, 7, 8]. The study of the possibility of coupling quantum and classical systems is an active area of research motivated primarily by “the measurement problem” in quantum mechanics, i.e., how it is that a quantum mechanical system can interact with a measuring apparatus to yield a classical observation [9, 10]. Most of this research is theoretical in nature and much of it involves the theoretical consistency of a classical-quantum coupling. The present paper, by contrast, is motivated almost entirely by what has and what has not been observed or by what can and what cannot be experimentally verified. In short, it is the analysis of an experimental physicist (which I am). Little attention is paid to theoretical consistency, for example, even whether or not energy and momentum are conserved if there is no observable consequence of such an inconsistency. For this reason, the conjectures of this paper by no means constitute a theory or even a simple model of gravity but are offered simply to entice others to look seriously at the possibility of nonquantum gravity.

In one model of nonquantum gravity, semi-classical gravity, Einstein’s equations

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]  

are replaced with

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} \langle T_{\mu\nu} \rangle \]  

where \( \langle T_{\mu\nu} \rangle \) is the expectation value of the stress-energy operator [8]. There have been both experimental and theoretical objections to this generalization and these will be discussed in [6]. The primary conjecture of this paper is that the classical Einstein’s equations of Eq. [1.1] describe gravity where the stress-energy tensor, \( T_{\mu\nu} \), has its usual classical meaning. Of course, this classical description is possible only when the classical stress-energy of the system is well-defined. A prerequisite for this is, in the language of decoherence theory, that the system is in a decoherent, mixed quantum state for only then do the probability predictions of quantum theory agree with those of classical physics. Even then, in the fully classical case, there is a single stress-energy tensor while in the general decoherent quantum state the expectation
value of the stress-energy operator is a linear combination of possible stress-energy tensors. This distinction is crucial because the gravitational fields implied by Eqs. 1.1 and 1.2 are not the same.

In cases where the source is in a coherent, non-localized quantum state, there is no well-defined, classical stress-energy tensor and Eq. 1.1 is of no use in specifying the gravitational field. (Just what non-localized and coherent mean in this context will be dealt with in §5.) It is tempting to conjecture that such systems are not sources of gravity; however, it is not necessary to be this unequivocal. It is the conjecture of this paper that the gravitational field of a non-localized, coherent quantum system is simply not well-defined. Therefore, Eq. 1.1 need not be invoked and the above quandry does not arise. It will turn out that for microscopic systems, in which quantum coherence is most commonly observed, the effects of gravity are, in principle, unobservable. For larger macroscopic systems, decoherence is assured and the classical stress-energy is well-defined. This leaves open the question of gravitational interactions of mesoscopic, coherent systems. It is these and other issues that are discussed below.

The following section deals with the detectability or rather undetectability of gravitons, which was one motivation for the present paper. §3 investigates the conditions under which coherent quantum systems can have measureable gravitational effects and an implied mass lower limit required to observe these effects. §4 concerns the emission of gravitational radiation and whether or not this process affects quantum coherence. §5 deals with the effects of gravity in mesoscopic systems and the relation to quantum decoherence. Inherent inconsistencies in a nonquantum theory of gravity and previous claims that gravity must be quantized are discussed in §6. §7 includes a brief discussion of the importance of classicality in quantum measurements as well as further speculation on the consequences of nonquantum gravity.

I note in passing that another approach to unifying gravity with the other fundamental forces of nature is to consider gravity as an emergent mean field approximation of more fundamental underlying microscopic phenomena. Some such theories have already been ruled out [11] while others are still under consideration [12]. However, I will not discuss any relation between emergent theories and the nonquantum conjecture of this paper other than to note that the no-go theorem of Weinberg and Witten [11] is not applicable because an implicit conjecture of this paper is that gravitons do not exist.

## 2 The Detectability of Gravitons

If gravity is, indeed, a quantum phenomenon, it seems quite likely that a prominent feature of the theory will be the graviton, the fundamental quantum of gravitational radiation with energy $\hbar \nu$ where $\nu$ is the frequency of the radiation. Several years ago, Freeman Dyson posed the question of whether or not gravitons can in principle be detected, that is, whether the quantization of the gravitational field can ever be
detected [13]. If not, Dyson continues, then one wonders whether or not gravitons actually exist. Motivated by Dyson’s question, Tony Rothman and I investigated the detectability of gravitons [14, 15]. We concluded that it is possible to concoct an idealized experiment capable of detecting a small fraction of incident gravitons; however, when anything remotely resembling realistic physics is taken into account, detection becomes impossible. (Smolin [16] has used similar arguments to invoke the necessity of an intrinsic entropy associated with the gravitational field.) While one may not conclude that gravitons are in principle undetectable, one can conclude that they never will be directly detected. This leaves Dyson’s conjecture in an ambiguous state. However, we also found that it is physically impossible, i.e., impossible in principle, to detect a given single graviton with reasonable probability. This latter conclusion has implications for the effect that the emission of gravitation radiation might have on quantum coherence as will be discussed in §4. The following back-of-the-envelope argument for the undetectability of a single graviton is typical of these types of analyses.

Consider a resonant-mass gravitational wave (GW) antenna as a prototypical GW detector. The GW cross-section of an undamped harmonic oscillator of mass $m$ and length $l$ is approximately [17]

$$\sigma \sim \frac{Gm\omega^2 l^2 \delta t}{c^3}.$$ (2.1)

where $\omega$ is the resonant frequency (equal to the frequency of the GW), $G$ is the gravitional constant, $c$, the speed of light, and $\delta t$, the duration of the harmonic GW.

Now suppose that a gravitational wave pulse is incident on an ensemble of such detectors distributed in a sphere of radius $R$. Further suppose that the incident GW beam is focused (this is not necessarily even possible for GW’s) such that it has a width of $\sim R$ so as to maximize the flux on the detectors. Because $\delta x \sim R$ and $\delta x \delta k \sim 1$, the spread in wavenumber, $k$, of the pulse is $\delta k \sim 1/R$. Therefore, the spread in frequencies is $\delta \omega \sim c/R$. Then $\delta \omega \delta t \sim 1$ implies a pulse duration of $\delta t \sim R/c$. Finally, suppose that the total energy of the pulse is that of a single graviton, $\hbar \omega$, which implies an incident flux, $f$, of

$$f \sim \frac{\hbar \omega}{R^2 \delta t}.$$ (2.2)

The energy absorbed by a single detector is $f \sigma \delta t$ and the total energy absorbed by all the detectors is

$$E_{abs} \sim \frac{GM\omega^2 l^2}{c^4 R} \hbar \omega.$$ (2.3)

where $M$ is the total mass of the ensemble of detectors. This is a classical argument but one can infer the quantum mechanical interpretation that $E_{abs}/\hbar \omega$ is the probability that a quantum of energy is absorbed by any of the ensemble of detectors. So, in order that this single graviton be detected with high probability, $E_{abs} \sim \hbar \omega$. The
term $\omega l$ is the order of the speed of sound, $v_s$, in the detector. Then

$$(R_S/R)(v_s/c)^2 \sim 1$$

where $R_S = 2GM/c^2$ is the Schwarzschild radius of the ensemble of detectors. For ordinary materials, $v_s/c \sim 10^{-5}$ and, in any case, $v_s < c$; therefore, the condition for absorbing a significant amount of energy from the wave, i.e., detecting a graviton with high probability, is $R < R_S$, a condition that cannot be met in principle. The overall conclusion is that a single graviton cannot be detected with reasonable probability.

Of course, the detector envisioned above, a resonant mass, is not the only conceivable GW detector. However, it is straightforward to convince oneself that the condition $R < R_S$ also holds for a Michelson interferometer detector and the conjecture is that the result is quite general. One might also consider employing more ensembles of detectors at greater distances ($r > c\delta t$); however, due to the dispersion of the focused wave the number of additional detectors required to intercept the beam actually results in $r/R_S' < R/R_S$, where $R_S'$ is the Schwarzschild radius of the larger system, and so more detectors only aggravates the situation.

The above argument was offered to address the detectability of a single graviton. One of the motivations of the present paper is just the result that it is impossible to directly detect a graviton and part of the nonquantum conjecture of this paper is that gravitons, as such, do not exist. The above calculation is completely classical and so can also be interpreted as indicating that a classical GW pulse with energy less than $\hbar\omega$ cannot be detected. In §4 this will be invoked in the context of quantum interference. One might ask whether or not classical gravitational waves of arbitrarily small amplitude are possible; however, because such waves are in principle undetectable, the question is rendered unanswerable and is, therefore, irrelevant.

### 3 Gravity and Quantum Interference

Quantum effects are nowhere more apparent than in the context of quantum interference and we shall use the standard two-slit interference experiment as a prototype quantum system. This system will be analyzed with back-of-the-envelope/order-of-magnitude methods only, which is sufficient for the present purpose. Two important questions to be addressed are: 1) What conditions must be satisfied in order that the gravitational effects of the system can be observed? and 2) If gravity is a nonquantum phenomenon, then how does one treat gravity in the context of a coherent quantum system such as a quantum interference experiment? The first of these questions can be simply addressed by considering the double slit experiment, while the second is open to conjecture.

Suppose that a nonrelativistic, neutral particle of mass $m$ is in a momentum eigenstate with momentum $p$ and is incident on a double slit screen with slit separation $r$. A neutral test particle of the same mass is located near the screen between the two
slits. The position of the test particle is monitored in order to detect the presence of the incident particle via its gravitational attraction. Equal masses for the two particles turns out to be the optimum choice. If the position of the incident particle can be detected with enough precision to determine through which slit it passes, then presumably the subsequent interference pattern (resulting from an ensemble of incident particles detected behind the slits) will be washed out.

The gravitational acceleration of the test mass, \( a_t \), due to the incident particle is \( a_t \sim Gm/r^2 \) when the incident particle is near the screen and is insignificant when it is far away. Then, to order-of-magnitude, the net change in the position of the test particle will be

\[
\delta x_t \sim \frac{Gmt^2}{r^2}
\]  

where \( t \sim r/v_i \) is approximately the time the incident particle is near the test particle and \( v_i \) is the velocity of the incident particle. The uncertainty in the test particle position is given by the Heisenberg uncertainty relation,

\[
\Delta x_t > \hbar/\Delta p_t = \hbar/m\Delta v_t,
\]  

and a criterion for detection is \( \delta x_t > \Delta x_t \). In addition, \( \Delta v_t \) must be small enough so that in the time \( t \), \( \Delta v_t t < \delta x_t \). Combining these relations, \( \delta x_t > \hbar t/m\delta x_t \). Substituting \( \delta x_t \) from Eq. 3.1 yields the following inequality for \( t \),

\[
t > \frac{\hbar^\frac{3}{2}r^\frac{1}{2}}{G^2m^\frac{3}{2}}.
\]  

In order for robust quantum interference to be observed, the deBroglie wavelength of the incident particle, \( \lambda \sim \hbar/p_i \) must be on the order of or smaller than the slit separation. Because the velocity of the incident particle is related to the interaction time by \( v_i \sim r/t \), this leads to another inequality,

\[
t < \frac{mr^2}{\hbar}.
\]  

Combining Eqs. 3.3 and 3.4 yields the following inequalities

\[
\begin{align*}
    r &> \frac{\hbar^2}{Gm^3}, \\
t &> \frac{\hbar^3}{G^2m^5}, \\
a_t &< \frac{G^2m^7}{\hbar^4}, \\
v_i &< \frac{Gm^2}{\hbar}.
\end{align*}
\]
These values should be interpreted as the conditions that must be satisfied for a gravitational measurement to be made that will sufficiently localize the incident particle so as to destroy the quantum interference. If the conditions are not satisfied, the gravitational interaction is insufficient to detect the incident particle and quantum interference remains intact.

There are two other conditions that should be imposed on this system: 1) the gravitationally induced motion of the test particle should be less than the slit separation, \( \delta x_t < r \); otherwise, the test particle will not remain within the vicinity of the system; and 2) the gravitationally induced motion of the incident particle should be less than the slit separation, \( \delta x_i < r \); otherwise, the inequality in Eq. 3.4 can be violated and quantum interference compromised. It can be readily shown that these additional conditions are also consistent with Eqs. 3.5, 3.6, 3.7 and 3.8, and that it is, in fact, these conditions that result in the optimal choice of equal masses. [Note that dimensionless numerical factors have been ignored in the above relations, which is consistent with the order-of-magnitude philosophy of the analysis.]

None of the above constraints can be used to place specific limits on any of the parameters, \( m, r, t, a_t, \) and \( v_i \), because each of the relations involve a different pair of the parameters. However, one can use Eq. 3.6 to limit the mass \( m \) by imposing the additional, modest constraint that \( t \) be less than the age of the universe, \( t_u \). Then

\[
m > \frac{\hbar^2}{G^2 t_u^4} \tag{3.9}
\]

or \( m > 10^7 m_p \) where \( m_p \) is the mass of the proton. We conclude that for quantum coherent systems with masses less than \( \sim 10^7 m_p \), there is no measurable gravitational effect that would compromise their coherence. The corresponding limits on the other parameters of interest are \( r > 3 \times 10^3 \text{ cm}, a_t < 10^{-31} \text{ cm s}^{-2}, \) and \( v_i < 10^{-14} \text{ cm s}^{-1} \). To be sure, \( t \sim t_u \) is an extreme limit but because of the large power of \( m \) in Eq. 3.6, the limit on \( m \) is not overly sensitive to \( t \) in an order-of-magnitude sense. For example if \( t \sim 1 \text{ s} \), the limit on \( m \) is only increased to \( 3 \times 10^{10} m_p \) with \( r > 2 \times 10^{-7} \text{ cm}, a_t < 2 \times 10^{-7} \text{ cm s}^{-2}, \) and \( v_i < 2 \times 10^{-7} \text{ cm s}^{-1} \). Even the latter values of \( a_t \) and \( v_i \) are so extreme that an experiment capable of detecting them is barely conceivable and so \( m > 10^{10} m_p \) can be viewed as a practical lower mass limit.

From the small velocities above, one might guess that allowing the incident and test particles to be relativistic won’t change the results. This is, indeed, the case. It is straightforward to show that for an ultrarelativistic, \( \gamma >> 1 \), incident particle the net change in the position of the test particle in the transverse direction is the same as in Eq. 3.1 with \( t = r/c \), i.e.,

\[
\delta x_t \sim \frac{G m_i}{c^2} \tag{3.10}
\]

while in the direction parallel to the trajectory of the incident particle the displacement is

\[
\delta x_t \sim \frac{\gamma G m_i}{c^2}. \tag{3.11}
\]
In order to detect either of these motions, clearly $\delta x > \ell_{Pl}$ where $\ell_{Pl}$ is the Planck length. Combining this relation with Eq. 3.11 implies $\gamma m_i > m_{Pl}$ where $m_{Pl} \sim 10^{19} \, m_p$ is the Planck mass. So unless $\gamma$ is extraordinarily large, the constraint on $m_i$ is even more severe than in the nonrelativistic case. Eq. 3.10 yields an even stronger constrain, $m_i > m_{Pl}$; however, it’s only necessary to measure the displacement of the test particle in a single direction to detect the gravitational force of the incident particle. Using the weaker constraint $\gamma m_i > m_{Pl}$, the deBroglie wavelength of the incident particle is

$$\lambda_{dB} \sim \frac{\hbar}{\gamma m_i c} < \ell_{Pl}. \tag{3.12}$$

Because the physical size of any particle is much larger than $\ell_{Pl}$, it is clear that coherent interference in this system cannot be observed. Therefore, ultrarelativistic particles, as expected, do not alleviate the nonrelativistic constraints.

To facilitate comparison with another condition, note that $t_u \sim 1/\sqrt{G\rho_{crit}}$, in which case Eq. 3.9 becomes

$$m > \frac{\hbar^2 \rho_{crit}}{G^{3/10}} \tag{3.13}$$

where $\rho_{crit}$ is the nominal critical density of the universe. Because $\rho_{crit}$ appears only to the $\frac{1}{10}$ power in the relation, it can be taken as anything roughly of this magnitude, e.g., the density of dark matter, the density of baryons, or even the density of cosmic microwave background photons.

There are other conditions that might serve to constrain the mass of such systems. Because the durations of the experiments are so long and the accelerations so small, it is likely that environmental noise will place limits on the measurement. This is especially true for gravitational environmental noise, which cannot be shielded. Suppose there is an unbalanced mass $M$ at a distance $R$ from the interference system. Then the differential acceleration between the the incident and test masses will be $\delta a \sim GMr/R^3 \sim GPr$ where $\rho$ is the mean density of the environmental mass spread over a volume of linear dimension $R$. If we require that $a_t > \delta a$ then Eqs. 3.5 and 3.7 imply a mass limit given precisely by Eq. 3.13 with $\rho_{crit}$ replaced by $\rho$. (Of course, it might be possible to orient the interference experiment to minimize the differential acceleration so long as all the sources of gravity can be accurately determined.) As an example, consider the effect of a nearby solar mass star at a distance of 10 light years. The effective, average density of this star alone is $2 \times 10^{-24} \, g \, cm^{-3}$, which implies a mass limit of $m > 2 \times 10^7 \, m_p$. Again, the $\frac{1}{10}$ power of the density results in little difference from the previous limit in Eq. 3.13. Note that the time scale for an experiment with this mass is $t > 10^8$ years, much longer than the star is likely to remain within 10 light years. A more proximal source of gravitational noise might be a 5000 kg truck passing by 100 m from the experiment. In this case, the limit becomes $m > 2 \times 10^9 \, m_p$; although, the duration of the experiment relevant to this mass is $> 3$ weeks so that a single passing truck would not compromise the measurement. Larger scale motions, such as ground water movement, might do so. We note in
passing that if the acceleration is constrained to be above the characteristic value in Milgrom’s MOND theory of gravity, $a_t < 10^{-8} \text{cm s}^{-2}$, then the mass limit becomes $m > 2 \times 10^{10} \text{m}_p$.

A more insidious type of environmental noise is the background of gravitational waves that permeate the universe. (The fact that such a background has yet to be detected is an indication of the level of extreme precision required for the gedanken experiments considered here.) Suppose the gravitational background at frequency $\omega$ is characterized by a dimensionless metric perturbation $h$. The relative acceleration of the incident and test masses is given by $a_{gw} \sim \omega^2 h r$ and the equivalent mass density of this wave is $\rho_{gw} \sim \omega^2 h^2 G$ [17]. Therefore, $a_{gw} \sim \frac{\sqrt{\Omega_{gw}} \omega r}{t_u}$ (3.14)

where $\Omega_{gw} \equiv \rho_{gw}/\rho_{crit}$ and $t_u \sim 1\sqrt{G\rho_{crit}}$. Combining this expression with the inequalities for $r$ and $a$ in Eqs. 3.5 and 3.7, the implied lower limit of $m$ is

$$m > \frac{\hbar^2 \omega \sqrt{\Omega_{gw}}}{G^{5/2} t_u^{1/10}}.$$  

(3.15)

Typical estimates for the equivalent mass densities per octave of the gravitational wave background range from $10^{-7} \rho_{crit}$ to $10^{-18} \rho_{crit}$ depending on the frequency; however, because of the $\frac{1}{20}$ power dependence, it barely matters and for an order-of-magnitude estimate we take $\Omega_{gw} \sim 1$. For the lowest possible frequency, $\omega \sim 1/t_u$, the mass limit is precisely the same as in Eq. 3.13 i.e., $m > 10^7 \text{m}_p$. For the much higher frequency of $\omega \sim 1 \text{ s}^{-1}$, $m > 5 \times 10^8 \text{ m}_p$ about a factor of 60 smaller than the above fundamental limit for $t \sim 1 \text{ s}$.

Clearly the shorter the duration of the measurement, the larger the lower mass limit and it is reasonable to ask if there is a largest value of such a lower limit. Setting $v_i = c$ in Eq. 3.8 yields $m > \sqrt{\hbar c/G} = m_{Pl}$ where $m_{Pl}$ is the Planck mass. In fact all the limits in Eqs. 3.5, 3.6 and 3.7 become their corresponding Planck values.

The conclusions from these sorts of analyses is that there is a mass limit below which particles cannot be detected via a gravitational interaction. Test masses below this mass cannot detect a coherent quantum particle and, therefore, cannot frustrate quantum interference experiments via gravitational measurements/interactions. There is a fundamental lower limit of $m > 10^7 \text{m}_p$ for an experiment of the duration of the age of the universe; however, the lower limit for anything approaching a practical experiment is on the order of $10^{10} \text{ m}_p$ and in no case does the lower mass limit exceed the Planck mass, $m_{Pl} \sim 10^{19} \text{ m}_p$. These limits span the mesoscopic mass scale. Even though the values were obtained with rough, order-of-magnitude estimates, the high power of the mass in the above inequalities renders the estimates fairly robust.

The conclusion of the above argument is that the question of whether or not a coherent quantum system is the source of a well-defined gravitational field is unanswerable for systems with masses $< 10^{10} \text{ m}_p$. This leaves open the question of whether
mesoscopic coherent systems are sources of gravity as well as questions about the theoretical consistency of the nonquantum conjecture. These will be addressed below. Another, anecdotal piece of evidence for the nonobservability of gravitational interactions in certain quantum systems is provided by the 3d to 1s transition rate in hydrogen due to the emission of a graviton. A linear field theoretic calculation of this rate [15] gives a value of $5.7 \times 10^{-40} \text{s}^{-1}$, i.e., the decay time is roughly $10^{22}$ times the age of the universe, which is again absolutely undetectable. Before moving on to coherent quantum systems above the mass limit, we next investigate the question of whether or not the emission of gravitational radiation might frustrate the observation of quantum interference.

4 Coherence and the Emission of GWs

There is another way that quantum interference might be frustrated even in the absence of a particular gravitational measurement and that is if the diffracting particle emits gravitational radiation. In that case, it might be argued that whether or not there is an observer of the experiment, relevant information about it, i.e., knowledge of through which slit the particle passes, is carried to infinity by a gravitational wave. Because in the context of this paper GWs are classical phenomena, one might conclude that a measurement has been performed and, therefore, quantum interference will be destroyed. However, what if the emitted radiation is below the fundamental detection limit discussed in Section 2? Then, perhaps, one should consider this as a case where no information is transmitted, in which case no measurement has been made and quantum interference remains intact. While this may seem somewhat inconsistent and/or arbitrary, I remind the reader that, in this paper, only inconsistencies that are in principle verifiable are considered problematic. Of course, a quantum theory of gravity would also predict that no measurement has been made because no gravitational energy less than $\hbar \omega$ can be emitted from the system.

Returning to the double slit experiment with an incident particle of mass $m$ in a momentum eigenstate, it is straightforward to estimate the radiated gravitational power with the order-of-magnitude relation [17]

$$P_{gw} \sim \frac{G}{c^5} (P_{int})^2 \quad (4.1)$$

where $P_{int}$ is the internal quadrupole power sloshing around in the emitting system. In the present case, $P_{int} \sim mv^2/t$, and the total GW energy radiated is

$$E_{gw} \sim P_{gw}t > \frac{Gm^2v^4}{c^5t}. \quad (4.2)$$

In order that the GW be detectible $E_{gw} > \hbar \omega$. Because $\omega t \sim 1$ then

$$m > \sqrt{\frac{\hbar c^2}{G^2v^2}} > m_{Pl}. \quad (4.3)$$
If one considers the Planck mass as defining the upper mass limit of the mesoscopic scale, then the conclusion is that the emission of gravitational waves cannot frustrate coherence in mesoscopic scale systems. That this constraint is weaker than those of §3 is, perhaps, not surprising since the emission and detection of gravitational waves is more challenging than near field gravitational measurements. For macroscopic systems, however, gravitational wave emission would be a source of decoherence.

5 Gravity and Decoherence

The conjecture that the gravitational field of a coherent quantum system is not well-defined has no observable consequences for systems with masses \( < 10^{10} m_p \), as was shown in §3. However, systems above this mass limit can be probed gravitationally and so it might be possible to devise an experiment that would test the conjecture. Note, however, that quantum coherence, in the sense we are using the term here, has not been demonstrated in anything close to such large systems [19] and it has even been suggested that the random gravitational wave background discussed in §3 might lead to an unavoidable decoherence mechanism for mesoscopic mass scales [20].

Penrose [21], following the ideas of Diosi [22] and Ghirardi et al. [23], suggests that there is a gravitationally induced spontaneous quantum state reduction and that the associated time scale is on the order of 1 second for mesoscopic scales of the order considered here. If either of these is the case, then an experiment to detect gravitational effects in coherent mesoscopic systems becomes even more difficult.

The study of decoherence in quantum systems has been advanced by Zurek [24] and others in order to understand, entirely within the context of quantum theory, the interaction of quantum systems immersed in a surrounding environment. “In short, decoherence brings about a local suppression of interference between preferred states selected by the interaction with the environment” [25]. Because macroscopic systems invariably undergo decoherence on very short time scales, they behave as they would in a classical world, i.e., no quantum interference effects. One of the main successes of the decoherence program is a precise (quantum mechanical) description of how specific quantum mechanical coherent states interact with a (quantum) measuring apparatus to produce precisely the probability distribution for measurements that was the core of the Copenhagen interpretation of quantum mechanics.

One might conclude that decoherence theory has solved the “measurement problem” in quantum mechanics. This is clearly not the case. “What decoherence tells us, is that certain objects appear classical when they are observed. But what is an observation? At some stage, we still have to apply the usual probability rules of quantum theory.” [26] The probability density matrix may be diagonal in the possible outcomes of a particular measurement; however, there is no implication that the quantum system realizes one of those possible outcomes, i.e., there is no implied “collapse of the wave function”. While decoherence theory may not satisfactorily explain the transition of a quantum to a classical system, one might suspect that when
a quantum system becomes decoherent then it also becomes a well-defined classical system, whether or not this transition is or ever will be understood in terms of a physical theory.

The transition of a quantum system to a classical system is critical to the conjecture of this paper because it is supposed that it is the classical mass distribution that generates a well-defined gravitational field. At least in the macroscopic case, I suspect that nearly all physicists would agree with this statement. For example, I’m sure most would agree that it is either one or the other of Schroedinger’s cats that is the source of a gravitational field even before one peers inside the box. An actual experiment of this effect was performed by Page and Geilker [27] and will be discussed in §6. However, in the case of mesoscopic, decoherent systems I doubt that the agreement would be quite so general. The conjecture of this paper implies that the gravitational field of any coherent, mesoscopic system is not well-defined but that a decoherent, mesoscopic state is the source of a gravitational field, which is, in principle, measurable. Such an assertion can lead to inconsistencies, e.g., nonconservation of momentum, as will also be discussed in §6. Of course, the same conjecture is made regarding “microscopic states” (with $m < 10^{10} m_p$); however, there is no measurement that can confirm or refute it (see §3).

According to decoherence theory, interactions of an initially coherent quantum system with its surroundings “superselect” a preferred set of orthogonal basis states that are stable and correspond to classically observed quantities. For macroscopic systems, this superselection process, i.e., decoherence, occurs very rapidly. The interaction Hamiltonians of such systems usually depend on position (and other classical quantities) and the resulting preferred basis consists of position eigenstates, which typify classical descriptions [25]. It is precisely this type of preferred basis that is needed to specify the classical stress-energy tensor, the source of gravity. In microscopic systems, on the other hand, energy eigenstates are often the preferred, stable basis and position remains a property of coherent, non-localized wavefunctions and, therefore, quantum interference remains intact [25].

To be sure, there are macroscopic systems that are, in a certain sense, coherent, for example, superconducting and superfluid systems. It would seem absurd that such macroscopic systems are not sources of a well-defined gravitational field. While a superfluid Bose condensate may be coherent in some respects, it has a classically well specified mass density (stress-energy tensor) to which anyone who has observed superfluid helium in a glass dewar can attest. Therefore, superfluids still qualify as classical sources of gravity. This behavior is undoubtedly due to the many particle nature of a macroscopic superfluid. Electromagnetic radiation provides another such example. A classical, monochromatic electromagnetic wave is a superposition of many coherent photons and this superposition can certainly exhibit interference. However, the stress-energy tensor of the electromagnetic field is well-defined and undoubtedly acts as a source of classical gravity (although, this has never been directly observed). Again, this behavior is undoubtedly due to the many particle nature of the system.
So it seems that the general term “coherence”, as I have been using it, is not precise enough to describe these systems.

Consider the example of a macroscopic crystal that has been cooled to sub-microKelvin temperatures. In such a system the electrons are in a “coherent” ground state as is the ion lattice if it is in a phonon ground state. On the other hand, the macroscopic crystal can be extremely well-localized and certainly not in a (coherent) momentum eigenstate even if it happens to be moving. So I’m forced to refine the use of “decoherent” and “coherent” to refer explicitly to whether or not the the stress-energy, by which we usually mean mass density, of the system is well-defined, i.e., localized. That is, a macroscopic body can consist of microscopic parts, some of which are coherent, and still constitute a decoherent, localized system.

For mesoscopic scale crystals, it is possible to conceive of a coherent superposition of two states, the ground state and first excited phonon state, and then perform some sort of interference measurement on them that reveals their quantum coherence. In fact, Marshall et al. \[28\] and Armour et al. \[29\] have proposed such experiments in which a superposition of two different phonon states in a mesoscopic vibrator is probed with a photon in the former case and a Cooper-pair in the latter. While such systems have yet to be realized, even they would not be in the regime to test the nonquantum conjecture of this paper. The mass densities of the systems of the two superposed states are nearly identical and it not possible to distinguish between the two states via their (classical) gravitational interaction with a test particle without violating the uncertainty relation. In this example of mesoscopic, internally coherent states, the stress-energy tensor is still well defined enough that classical gravity can prevail. So it seems that the nonquantum conjecture has to be revised to include such cases, i.e., “coherent” superpositions whose mass densities are never-the-less well localized should also be considered sources of classical gravity.

According to the present nonquantum hypothesis, macroscopic systems are sources of gravity as described by the classical Einstein’s equations while the gravitational fields of coherent microscopic systems are not well-defined. Whether or not decoherent microscopic systems are sources of gravity is irrelevant because gravitational effects in these systems are, in principle, undetectable. This leaves the case of mesoscopic systems. These systems are normally in decoherent, localized states and, consequently, are sources of gravity. However, it might be possible to create a mesoscopic coherent state which, under the current conjecture, would not be the source of a well-defined gravitational field. (Problems with the consistency of these statements are discussed in \[30\].) There is another possible mesoscopic state and that is a partially decoherent system. Partially decoherent microscopic states with masses up to $\sim 10^3 m_p$ have been generated and observed in interference experiments \[30,31\]. As decoherence increases, fringe contrast decreases in accordance with decoherence theory. How would a nonquantum theory of gravity treat such systems? To answer this question requires an interpretation that goes beyond the usual quantum prescription. In order to determine whether a given mesoscopic particle is the source of a well-defined gravitational
field, we must know whether it is or is not in a coherent state.

Consider, again, the double slit diffraction experiment. Suppose we advance the interpretation of a partially decoherent state as a probability $P_c$ that the mesoscopic particle is in a coherent state and the probability $P_d$ that the particle is in a decoherent state, such that $P_c + P_d = 1$. Those particles in the coherent state will generate the usual diffraction pattern while those in the position eigenstates will pass through one of the slits or be stopped by the screen. The net result will be an interference pattern with decreased fringe contrast. One then can predict that, with probability $P_d$, a particle will exhibit a detectable gravitational field. A decoherence analysis, on the other hand, results in a wavefunction that is partially entangled with the environment, and every particle has the same wavefunction. As far as quantum theory is concerned, no other interpretation is needed; however, neither does the above interpretation imply any difference in the expected interference pattern. Therefore, the interpretation necessary to predict the gravitational interaction is not in conflict with the usual predictions of quantum mechanics. It does, however, give a prediction that might well differ from the prediction of a quantum theory of gravity, i.e., according to this present nonquantum model, some of the particles will generate a well-defined gravitational field, while others will not. If this prediction is valid, then it might be possible to observe the consequences with prepared states of mesoscopic particles. On the other hand, the discussion in §6 indicates that this might not be possible.

After submitting this paper for review, I discovered an intriguing treatment of the interaction of classical and quantum systems, the configuration space model of Hall and Reginatto [10]. In this model the classical and quantum systems are put on equal footing and both described probabilistically in terms of ensembles on configuration space. This description obviates the need for a Copenhagen-type interpretation and may be able to provide a natural path to modeling the interaction of quantum systems with a classical gravitational field. In addition to conserving probability and energy, the model allows for back-reaction on the classical system and provides automatic decoherence of the quantum system. Perhaps such a description can lead to a legitimate model for nonquantum gravity.

6 Consistency and Experimental Tests of Nonquantum Gravity

The incompatibility of the coexistence of quantum and classical fields has been demonstrated by many people in many different ways [27, 32, 33, 34, 35, 36]; however, "the general question of whether one can consistently couple classical and quantum systems is a matter of ongoing research....and is not yet resolved." [8, 10]. Most of these arguments are formal in nature and proceed by demonstrating the inconsistency of the mathematical formalisms of quantum field theory with that of a particular description of classical gravity (or some other classical field). In any case, because the
nonquantum conjecture of this paper is not a formal theory in any sense, it is not surprising that most of these analyses are not particularly relevant to the present case. However, two such demonstrations of the necessity of quantum gravity are less formal and offer experimental (gedanken experimental in one case) evidence to support their claims.

Eppley and Hannah [32] considered two gedanken experiments. In the first a completely classical gravitational wave of arbitrarily small amplitude is used to “detect” the position of a particle (i.e., collapse its wave function) while only imparting to it an arbitrarily small momentum impulse. In this case, both the particle’s momentum and position can be determined to arbitrary accuracy. Therefore, either the uncertainty principle or conservation of momentum must be violated. Considering the discussion in §2 on the detectability of GWs, one should be skeptical of such an experiment, even a gedanken experiment. In fact, Mattingly [37] has used a similar argument to show that such an experiment is, in principle, impossible to conduct. The other possibility supposes that observing with a GW does not collapse the wave function. The relevant gedanken experiment involves the scattering of a classical GW from the wave function of one of two entangled particles in an Einstein, Rosen, Podolsky [38] type experiment. If one of the two particles is observed via some nongravitational method, then the entangled wavefunction collapses and a distant observer, by observing the wave function with a GW, would detect this collapse thereby allowing a signal to be propagated instantaneously over an arbitrarily large distance. Mattingly [37] attacks this gedanken experiment on similar grounds. Albers et al. [39] have criticized the Eppley and Hannah analyses on the grounds that the interaction between the classical gravitational wave and the quantum systems was not adequately specified. They show that a general measurement analysis of the coupled quantum/gravitational wave system leads to no inconsistencies.

Page and Geilker [27] carried out an actual experiment to test a particular nonquantum theory of gravity, namely the gravitational field equations given by Eq. 1.2. The experiment consisted of a Schroedinger’s cat type setup in which the positions of the two masses in a Cavendish experiment were determined by the result of a quantum decay process in a radioactive source. Because the expectation value of the stress-energy operator was 1/2 the sum of the stress-energy tensors of the masses in the two positions, the response of the Cavendish experiment would be 1/2 the sum of the two expected classical responses. Of course, the observations revealed otherwise as, I have no doubt, any physicist would have expected.

In fact, the “semi-classical” theory of gravity, as expressed in Eq. 1.2, is bothersome for several reasons. In atomic physics, the semi-classical treatment of electromagnetic radiation is used to give a plausible account of the interaction of electromagnetic radiation with a quantum system (see, e.g., [40]). That it gives the correct expression for spontaneous emission from quantum transitions in simple atoms is interesting but not convincing and such analyses can only be justified by a proper quantum field theoretic calculation. The same has been shown to be true for the spon-
taneous emission of gravitons from hydrogen [15]. However, the method breaks down for more complicated systems. That is, semi-classical treatments are introduced primarily in order to guess the results of a full quantum mechanical treatment. Although mathematically well-defined, the semi-classical theory expressed in Eq. 1.2 is quite non-physical. The standard interpretation of the expectation value on the right-hand side of this expression is the probability distribution of the outcomes of “classical” experiments performed on similarly prepared systems. That one might consider such a probability distribution to be a source of gravity seems rather strange. A more physical way to interpret Eq. 1.2 might be to postulate that the measured gravitational field would be that due to one of the particular observed stress-energy tensors occurring with a certain probability. Of course, this would be fine for decoherent systems but would result in the usual contradictions for coherent states.

Analogous to the Page-Geilker experiment[27] for Newtonian gravity, Ford [41] introduced a hypothetical experiment involving gravitational waves and concluded, not surprisingly, that semi-classical gravity results in different predictions than would a quantum theory of gravity. Because gravitational waves have not been (and probably never will be) generated and detected in the laboratory, Ford’s analysis is more akin to the gedanken experiments of Eppley and Hannah [32]. In any case, the analysis of Ford and the results of the Page-Geilker experiment are consistent with the nonquantum conjecture of this paper, because the assumption is that the source of gravity is the classical stress-energy tensor and not the expectation value of a quantum mechanical operator.

Even though the present nonquantum gravity conjecture is, as was pointed out in the introduction, by no means a theory, there are still issues of whether it is experimentally consistent with the rest of physics. One of the looming issues is conservation of momentum. Whether or not a particle in a coherent quantum state is the source of well-defined gravitational field, it is certainly true that the gravitational field of a decoherent, macroscopic body interacts with such a particle. The equivalence principle demands it. Pound and Rebka’s [42] detection of the gravitational blue shift of gamma rays provides experimental verification. In that case, a coherent quantum particle (photon) gains momentum (and energy) from the gravitational interaction with the earth. However, if our nonquantum conjecture is valid, there is no well-defined gravitational attraction of the earth by the quantum particle and thus the momentum impulse received by the earth can not be determined. The implication is that the total momentum of the system might not be conserved. Of course, in the Pound-Rebka experiment this has no observational consequence because measuring such a small change in the earth’s momentum is impossible, as would be the case for any macroscopic system. It is necessary to look for the effect in microscopic or possibly mesoscopic experiments.

One can show that precisely the same detection criteria (Eqs. 3.5 - 3.8) apply to this case where again the optimum experiment would employ equal mass particles. Therefore, it is impossible in principle to perform such an experiment with particles.
less massive than $10^7 m_p$. In anything remotely approaching a realistic experiment this mass limit is surely much greater, perhaps $10^{10} m_p$ or even larger. On the other hand, if the particle is too massive it will be virtually impossible to prepare it in a coherent state. Therefore, a mesoscopic scale experiment (e.g., from $10^{10} m_p$ to $10^{15} m_p$) is the most likely arena.

Even if an experiment to test this example of nonconservation of momentum is wholly impractical, i.e., it is relegated to the realm of a gedanken experiment, it should still be taken as a serious problem for the present nonquantum conjecture. On the other hand, if such a measurement were performed on a coherent particle, the process would be expected to promote decoherence, i.e., wavefunction collapse, of the coherent particle, in which case the particle would be a source of a well-defined gravitational field and momentum would then be conserved. Our current nonquantum conjecture has nothing to say about how this process would occur. A standard decoherence analysis would necessarily have to consider one of the particles as a classical source of a classical field, an anathema for an inherently quantum mechanical analysis. On the other hand, the configuration space model of Hall and Reginatto [10] seems to be designed for just this sort of system. An obvious next step would be to introduce a specific configuration space interaction Hamiltonian in order to predict how this transition might occur and determine whether or not there are observable consequences that might test the model. In any case, if gravity is a nonquantum phenomenon, it seems likely that it would make itself known on mesoscopic scales. Salzman and Carlip [43] suggested that that experiments on somewhat smaller mesoscopic mass scales might be able to test the version of nonquantum gravity expressed in Eq.1.2. Also, evidence for a variety of models of gravitationally induced wavefunction collapse would most likely appear on mesoscopic scales [22, 21, 20, 44].

7 Discussion and Further Speculation

It was pointed out in the Introduction that the nonquantum gravity conjecture introduced in this paper is tantamount to heresy. Actually, the real heresy is, perhaps, the characterization of nonquantum, classical states of matter as fundamentally real and legitimate concepts in a fundamental theory of physics. The tremendous success of quantum theory in the last 80 years has been such that it seems inconceivable that any fundamental theory will not be quantum in nature. To be sure, the 1 part in $10^{12}$ agreement of the quantum electrodynamic prediction with observations of the gyromagnetic ratio of the electron is a spectacular confirmation of the theory. However, this is a single example in a specific microscopic system. Classical electrodynamics also has spectacularly confirmed predictions. For example, Maxwell’s equations predict the $1/r^2$ dependence of the electric field of a point charge and this has been confirmed to an accuracy of 1 part in $10^{16}$. Still, I suspect that it is the consensus among physicists that classical physics is simply an approximate limit to a fundamental quantum theory. The irony of this view is that aspects of classical physics
are absolutely necessary in order to give meaning to quantum theory. After all, the predictions that quantum theory makes are of the statistical outcomes of measurements and these measurements are ultimately described in terms of classical physics. The once orthodox and, perhaps, currently disfavored Copenhagen interpretation of quantum mechanics is, in brief, that quantum theory provides a complete account of microscopic phenomena by making probabilistic predictions of the outcomes of experiments that are described operationally (i.e., classically). (Of course, any brief statement of the Copenhagen interpretation is necessarily incomplete. [45]) It is the accumulated empirical knowledge of how to (classically) prepare a quantum system and then how to (classically) conduct a measurement that is essential to give meaning to the theoretical predictions of quantum theory.

I find it rather curious that there is a perceived great need to unify all the fundamental forces into an all encompassing quantum theory of nature while the need to unify classical (experimental) physics with quantum (theoretical) physics seems much less important even though the former is absolutely essential in the interpretation of the latter. It is for this reason that I am willing to consider the classical stress-energy tensor as the fundamental source of gravity. To be sure, a primary goal of the decoherence program is to illuminate the interactions of quantum systems with measuring apparatus. This program, by and in large, has successfully demonstrated how the laws of quantum theory lead to decoherence and consequently demonstrated that the resulting probability distributions of outcomes of experiments conform to those of classical physics. However, as to just why it is that an essentially quantum mechanical world appears classical to us, decoherence theory is silent. In the case of Schroedinger’s cat, quantum decoherence is able to demonstrate, in principle, why it is that the two states of the cat cannot be made to exhibit quantum interference. However, as to which of the two states actually occurs or even that only one of the two states does occur, we have to resort to the usual probabilistic interpretation of quantum theory, which links quantum wavefunctions with classical observations. I suspect no physicist would doubt that it is the real cat, alive or dead, that is the source of a gravitational field, whether or not an outside observer determines the state of the cat.

I suppose that a legitimate criticism of the conjecture put forward in this paper is its lack of predictive power. Except possibly in the case of the coherent to decoherent transitions in mesoscopic systems, and even in this case the conjecture makes no specific prediction, the nonquantum conjecture makes no additional predictions that can not already be made by quantum theory and general relativity. However, even the simple conjecture in this paper does, in a sense, make the prediction that none of the specific predictions made by any quantum theory of gravity will be confirmed experimentally. A specific criticism might be that the nonquantum conjecture has nothing to say about the Planck scale, at which surely some interesting new physics must appear. This may be so; however, the Planck density exceeds nuclear densities by a factor of nearly $10^{80}$ and I personally have no confidence that any current theory
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... of physics is valid at this scale. At a slightly larger scale there are questions associated with cosmological inflation. Here again I must admit that the current nonquantum conjecture has nothing to offer; however, even at this scale, physics in general is not yet well understood.

A related issue is that of the singularities predicted by general relativity. If gravity is fundamentally classical, will these persist? If so, then clearly it would be a crisis for fundamental physics. The current understanding is that such singularities become resolved at the Planck scale by quantum gravity. As I indicated above, I doubt that any of our current physical theories, including general relativity, are valid at this scale. There is currently no experimental evidence regarding such small scales with the possible exception of inflation in the early universe and indirect observations of that epoch are extremely limited. So, at least for now, I’m willing to ignore the singularities implied by general relativity until more is known (observationally) about the extreme conditions in their vicinities.

There are also quantum issues having to do with both particle creation by and the entropy of black holes [46, 47]. While these may, indeed, be important problems for the consistency of theoretical physics, there is, as far as I know, no experimental observations relevant to them nor is there even strong observational evidence that general relativity provides an accurate description at the black hole event horizon. Nevertheless, the “information loss paradox” has garnered a great deal of attention and is considered by some to be key to our understanding of fundamental physics [48, 49, 50]. The paradox arises because the “no hair” theorem of classical gravity implies that information is lost in black holes. If this is so, then Hawking evaporation of black holes implies that pure quantum states evolve into mixed states with the implication that quantum gravity is not unitary. However, if gravity is a classical field then, perhaps, nonunitarity is not so strange. A similar problem occurs in the interaction of a quantum system with a classical measuring apparatus. The outcome of a particular measurement of such a system is also not consistent with unitary evolution.

The accelerated expansion of the universe is a model with some observational support [51] and certainly is in desperate need of explanation. However, it is still possible that these observations are explained within the context of general relativity [52] or some classical variant of it. Finally, there is the “cosmological constant” problem, i.e., the problem that quantum theory seems to quite generally imply the existence of a cosmological constant that is more than \(10^{120}\) times larger than that observed. One might hope that some future quantum theory of gravity will explain this. While the current nonquantum conjecture does not address this problem directly, if the vacuum is, indeed, a non-localized, coherent state, then the nonquantum conjecture would imply the resulting cosmological constant is not a well-defined source of gravity and indicates that a nonquantum theory of gravity might help solve this problem. Although, I wouldn’t call it a prediction, the present nonquantum conjecture does suggest that relevant experimental evidence might appear in coherent and partially
decoherent systems of mesoscopic scale ($> 10^{10} m_p$) as discussed in §6.

How one might go about incorporating the nonquantum conjecture into a more complete model or theory is not clear to me. The transition from coherence to decoherence, especially the configuration space model of Hall and Reginatto [10], might offer some clues. Of course experimental evidence of the gravitational effects of this transition would be invaluable; however, both the preparation of such systems and the measurement of their gravitational interactions may be virtually impossible by practical standards.

There are two great field theories of classical physics, gravitation and electromagnetism. I have argued that the source of gravity, i.e., the right-hand side of Einstein’s equations, is the classical stress energy tensor. Likewise, the source terms of electricity and magnetism, the right-hand side of Maxwell’s equations, are classical charge and current densities. In the case of gravity, I claim that coherent (non-localized) mass-energy distributions do not generate well-defined gravitational fields. Why not make the same claim for quantum sources of electromagnetism? The fact is that when microscopic phenomena are probed, one finds evidence of the quantum nature of electromagnetism. The resulting theory of quantum electrodynamics (QED) appears to describe all electromagnetic phenomena, microscopic and macroscopic; although, the application of QED to complicated macroscopic phenomena is problematic at best. One might argue by analogy that the general relativity is simply the classical limit of a quantum theory of gravity. Arguments by analogy, while often compelling, are also often wrong. It is the contention of this paper that when one probes deeply into microscopic gravitational phenomena, there is simply nothing there.

If the other fundamental forces of nature are described by a unified quantum theory, why should gravity lie outside this framework? Certainly, gravity is distinct in several respects. Gravity is extraordinarily weaker than the other fundamental interactions and couples universally to all forms of energy. It also has an inherently global aspect to it, i.e., locally the effects of gravity vanish in a local inertial (free-falling) frame. It is the other, Lorentz invariant forces of nature that fix the local Minkowskian structure of space-time and it is the theory of gravity, general relativity, that tells us how to stitch these local Minkowskian patches together into a global structure. In this sense, gravity is associated with the global structure of space-time, the stage upon which the other fundamental forces play. Clearly, this picture must break down at the Planck scale. The energy of a Planck frequency photon will, upon detection, be localized within it’s Schwarzschild radius whether or not gravity is a quantum phenomenon.

Still, it may well be that an elegant and useful quantum theory of gravity will be discovered in the future. How far in the future, I don’t know. I’m tempted to borrow a statement from Freeman Dyson who once told me, in a response to my query about string theory, that he thinks string theory is probably correct, it is simply premature. How premature, I asked. About a hundred years, he responded. Perhaps one of the reasons quantum gravity might be premature is the current total lack of any
observational evidence of the quantum nature of gravity. As an experimentalist, I think of theories as models that are created to make sense out of our observations of nature. Successful theories make additional predictions that are then confirmed. It seems to me that the current quest for a quantum theory of gravity is the search for a consistent mathematical model in the absence of experimental evidence with the hope that the model makes predictions that will someday be confirmed.

Striving to comprehend our world is human nature and it is understandable that scientists, physicists in particular, relish elegant and simple universal laws that describe the cosmos. What could be more elegant than a unified theory of all the fundamental forces from which all else follows, especially if that theory were expressed in terms of a single physical quantity, for example, the tension in string theory? However, it may simply be that the world is not so tidy and will ultimately elude our attempts to ever more simplify our description of it. Whatever our fundamental theory of the universe might be, its stature will be due, in large part, to the experimental observations that support it. Let me end with a caution offered by Léon Rosenfeld [7]. “There is no denying that, considering the universality of the quantum of action, it is very tempting to regard any classical theory as a limiting case to some quantal theory. In the absence of empirical evidence, however, this temptation should be resisted.”

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