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Newton force from wave function collapse: speculation and test

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Abstract. The Diosi-Penrose model of quantum-classical boundary postulates gravity-related spontaneous wave function collapse of massive degrees of freedom. The decoherence effects of the collapses are in principle detectable if not masked by the overwhelming environmental decoherence. But the DP (or any other, like GRW, CSL) spontaneous collapses are not detectable themselves, they are merely the redundant formalism of spontaneous decoherence. To let DP collapses become testable physics, recently we extended the DP model and proposed that DP collapses are responsible for the emergence of the Newton gravitational force between massive objects. We identified the collapse rate, possibly of the order of $1/\text{ms}$, with the rate of emergence of the Newton force. A simple heuristic emergence (delay) time was added to the Newton law of gravity. This non-relativistic delay is in peaceful coexistence with Einstein's relativistic theory of gravitation, at least no experimental evidence has so far surfaced against it. We derive new predictions of such a 'lazy' Newton law that will enable decisive laboratory tests with available technologies. The simple equation of 'lazy' Newton law deserves theoretical and experimental studies in itself, independently of the underlying quantum foundational considerations.

1. Quantum mechanics of massive degrees of freedom

Apart from the troublesome relativistic quantum gravity, we have no reason to doubt quantum mechanics' validity in the macro-world. If quantum mechanics is universally valid, massive d.o.f. of a bulk system must be quantized together with the light and atomic d.o.f. For massive d.o.f., we should consider hydrodynamic modes in general. Unfortunately, the existence of large quantum uncertainties of massive d.o.f. in the so-called Schrödinger Cat states seems controversial. In a cautious modification of quantum mechanics [1, 2, 3, 4, 5, 6, 7], parametrized by the Newton constant G , spontaneous wave function collapses of massive d.o.f. will forbid the existence of Schrödinger Cats. A lasting problem has been accompanying this (and other) spontaneous collapse models. Spontaneous collapse is not testable, being the redundant formalism of spontaneous decoherence. What extension of the spontaneous collapse theory makes it testable? — we'll see below.

1.1. Schrödinger Cats

We don't discuss the quantum mechanics of hydrodynamical d.o.f. in general, we consider the c.o.m. motion of a single spherical macroscopic object. In free space, the wave function $\Psi(\text{c.o.m.})$ satisfies the free Schrödinger equation. Accordingly, a well-localized initial $\Psi_0(\text{c.o.m.})$ is unlimitedly expanding. Nothing prevents it to develop a macroscopic wave packet, called



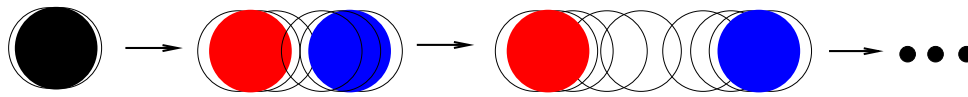


Figure 1. Unlimited macroscopic quantum expansion of the c.o.m. of an isolated massive object.

the Schrödinger Cat (Fig. 1). The interactions with light d.o.f., e.g. with the surrounding thermal gas, will no way block the unlimited expansion of the c.o.m. quantum uncertainty. On the contrary, the composite wave function $\Psi(\text{c.o.m.}, \text{gas})$ will approximately follow the free Schrödinger equation in the c.o.m. [8] while the c.o.m. is getting entangled with the gas (Fig. 2).

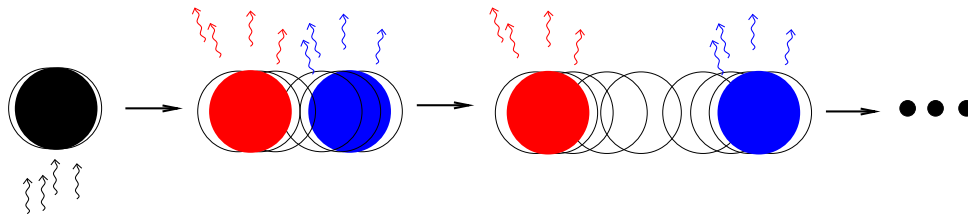


Figure 2. Unlimited macroscopic quantum expansion of the c.o.m. of a massive object entangled with light environment.

Schrödinger Cats are problematic. Some consider the problems are merely metaphysical, not influencing the perfect consistency of quantum mechanics as a physical theory. For others, including the author, the problem becomes physical because the von Neumann collapse of Schrödinger Cats provoke macroscopic violation of all basic conservation laws [9].

Schrödinger Cats can be suppressed by spontaneous collapse models.

1.2. *G*-related DP spontaneous collapse

Many advocates and critics of different spontaneous collapse models including GRW [10] and CSL [11] as well as DP, would overinterpret their subject constructing complicated notions. We rather propose a shortest definition in standard terms saving the reader's time and patience.

In every spontaneous collapse model, the spontaneous collapses are caused by standard von Neumann measurements with three specific features.

- The devices are weakly measuring certain universal observables.
- The devices are present everywhere and every time.
- The devices are hidden, they decohere all accessible systems yet the measurement outcomes remain inaccessible.

Specifically, in DP theory the hidden devices are universally measuring the local mass density operator of our physical system, the strength parameter of the measurement is scaled by the Newton constant G . Accordingly, the local mass density is universally enduring random collapses (disentanglement) by the hidden devices that forbid macroscopic quantum uncertainties of massive d.o.f. and, in particular, prevent Schrödinger Cats of being created.

Under natural circumstances, unitary evolution by the Schrödinger equation and the random DP spontaneous collapses compete with each other. The unitary evolution makes the c.o.m. uncertainty grow whereas the collapses make it shrink. The two can reach balance at a certain

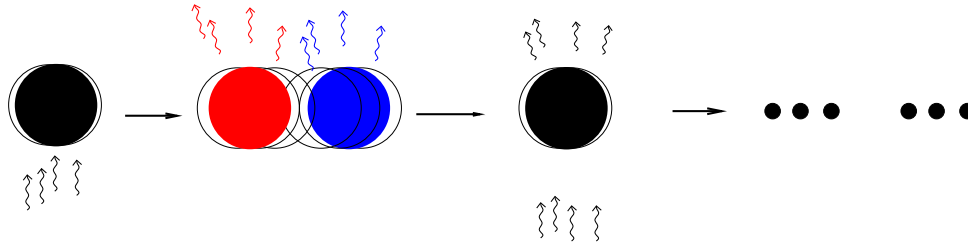


Figure 3. Spontaneous collapse (disentanglement) of the massive d.o.f., leading to random expansion-collapse cycles of characteristic time τ_G .

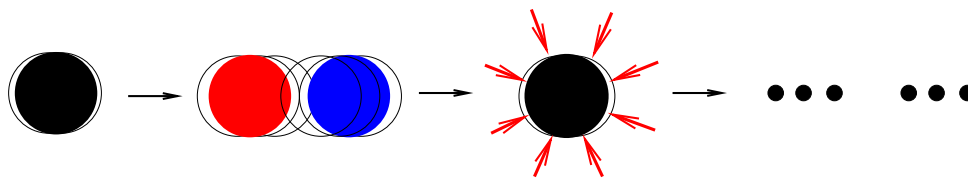


Figure 4. Random spontaneous collapse of massive d.o.f. triggers the Newton gravitational field at a characteristic emergence time τ_G .

equilibrium collapse rate $1/\tau_G$ (where τ_G stands for the equilibrium collapse time scale). The following estimation can be derived:

$$\frac{1}{\tau_G} \sim \sqrt{G\rho^{\text{nucl}}} \sim \frac{1}{\text{millisecond}} \quad (1)$$

where ρ^{nucl} is the nuclear mass density. Details of the estimation, and the particular reasons of the appearance of the nuclear mass density in a literally non-relativistic model, are given in Refs. [9, 12]. We can conclude that in DP theory the massive (hydrodynamic) d.o.f. are, under natural conditions, enduring spontaneous collapses at time scales $\tau_G \sim 1\text{ms}$ (Fig. 3).

1.3. Decoherence vs collapse

According to spontaneous collapse theories, the spontaneous decoherence effects are detectable in principle. Experiments are under way [13, 14, 15, 16, 17] to suppress environmental decoherence that always masks spontaneous decoherence unless we get our massive d.o.f. extremely isolated. Most theoreticians, therefore some experimentalists as well, don't emphasize (or even fail to recognize) that the spontaneous collapse theories are redundant realizations of the corresponding spontaneous decoherence theories. Spontaneous collapse (disentanglement) is never detectable, only the resulting spontaneous decoherence is, see [3]. This becomes obvious from our previous definition of spontaneous collapse theories. Since the hypothetic universal measuring devices are hidden, the measurement outcomes are hidden, one can never detect the collapse of the wave function. What one could detect is the damping of certain well-defined interference terms, i.e.: the phenomenon of spontaneous decoherence.

To let collapse become testable physics, one has to associate it with something physical! Recently we have extended the DP theory, supposed that the Newton force is generated by DP collapses. How should the Newton field emerge from DP collapses? Diverse and highly heuristic arguments have appeared in earlier works [18, 19]. But a detailed model is missing. In fact, we talk about an assumption beyond the DP theory, in minimal formulation.

Suppose the G-related DP collapses induce Newton gravity. Then, independently of the detailed mechanism, the emergence rate/time of Newton gravity is related (proportional) to the wave function collapse rate/time of the sources. Actually, the emergence time scale of Newton gravity must be of the order of the collapse time scale $\tau_G \sim 1\text{ms}$ (Fig. 4). We outline how this hypothesis would lead to a particular modification of the standard Newton theory, offering robust effects compared to an environmentally masked spontaneous decoherence.

2. Lazy Newton force with a delay

Unlike quantum foundational considerations in the previous Section, our resulting task is purely classical, i.e., non-quantum. We have to modify the purely non-relativistic Newton's law to account for a purely non-relativistic delay time τ_G which we think to be of the order of a millisecond. A minimum naive extension of Newton's classical equation would be

$$\phi(r, t) = \int_0^\infty \frac{-GM}{|r - x_{t-\tau}|} e^{-\tau/\tau_G} \frac{d\tau}{\tau_G} \quad (2)$$

where $\phi(r, t)$ is the Newton potential at location r and time t , of a source of mass M moving along the trajectory x_t . The field at time t depends on the position of the source then and before, including a period of the order of τ_G . For zero delay $\tau_G = 0$, our Eq. (2) restores Newton's.

Unfortunately, for $\tau_G > 0$ the predicted modification would violate the equivalence of inertial frames and the equivalence of accelerated frames with gravity. Consider a source at rest at $x_t \equiv 0$, yielding $\phi(r, t) \equiv -GM/r$. Let's boost our inertial frame by a constant velocity v so that $x_t = -vt$ in the new inertial frame where (2) yields

$$\phi(r, 0) = \int_0^\infty \frac{-GM}{|r - v\tau|} e^{-\tau/\tau_G} \frac{d\tau}{\tau_G}. \quad (3)$$

The gravitational field $\phi(r, 0)$ has changed from one inertial frame to the other. This shows that our naive equation (2) is not consistent in itself. Without illustrating how the naive equation (2) violates also the equivalence of accelerated frames and gravity, we show the resolution below.

In Ref. [20], we proposed that the naive equation (2) is valid and should be applied in the co-moving-free-falling reference frame. In other words, before we calculate the Newton potential of the moving source at time t , we install an instantaneous reference frame where $\dot{x}_t = 0$ and $M\ddot{x}_t$ is equal to the non-gravitational force if there is any. Having calculated $\phi(r, t)$ in the co-moving-free-falling frame, we can transform the result back to any other frame.

Hence we guarantee that the proposed modification of the Newton law is the same in all inertial frames. One can also show that the equivalence between gravity and an accelerated reference frame is respected. We should emphasize a major consequence of our chosen frame for Eq. (2): Newton law is completely restored in absence of non-gravitational forces. Accordingly, the effect of the delay time τ_G can only be expected with a massive source which is under the influence of a non-gravitational force. The point is not that the source is moving or isn't, the point is the presence of a non-gravitational force. We show three different experimental situations.

2.1. Testable predictions of gravity's laziness I.

Interestingly, there is a universal effect in Earth gravitational acceleration $g = 9.81\text{cm/s}^2$. Let us start from free falling objects first and apply Eq. (2) in the co-moving-free-falling frame as we have to. The result is that the free-falling object creates the standard instantaneous Newton potential. Now we consider an object at rest in the laboratory frame. Again, we use the co-moving-free-falling frame where the object is accelerated by the non-gravitational force through the support or the thread. We can calculate the effect of the delay in (2) in the lowest order

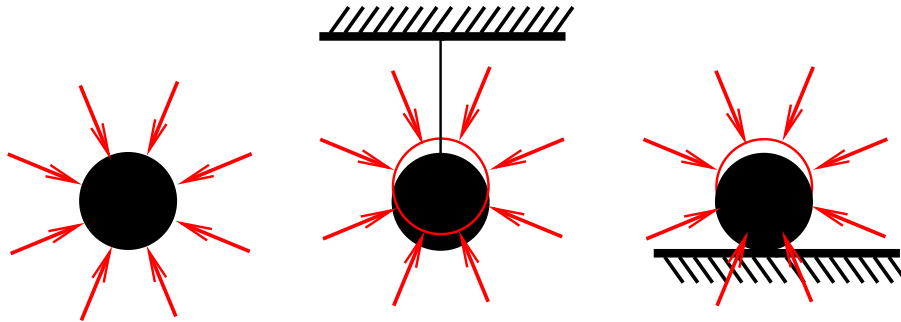


Figure 5. Free-falling object (left) in Earth gravity creates standard Newton field. Static sources, suspended (middle) or supported (right) create standard Newton field shifted slightly upward by a universal height $\delta_G = g\tau_G^2$.

of the delay time τ_G , leading to a surprising result. All static (supported or suspended) objects create Newton forces as if these objects were higher than their geometric position (Fig. 5), by a universal height

$$\delta_G = g\tau_G^2. \quad (4)$$

For $\tau_G \sim 1\text{ms}$ this universal height is of the order of 10^{-3}cm (or nearly 10^{-2}cm), a surprisingly big value. In a recent Cavendish experiment the positioning uncertainty of the source and test masses is ca. $0.5 \times \mu\text{m}$ [21]. This would enable detecting a 10^{-3}cm vertical (there lateral) shift of the source's field.

2.2. Testable predictions of gravity's laziness II.

Alternative to static laboratory objects in Earth gravitational field, also ones accelerated by non-gravitational forces can test the delay τ_G . As a typical example, consider a source revolving at small angular frequency $\Omega \ll 1/\tau_G$ on a rope of length R . For simplicity, we disregard the Earth gravity and calculate the effect of mechanical acceleration $R\Omega^2$ only. Applying Eq. (2) in the instantaneous co-moving frame we find that the source creates Newton field as if it were closer than R to the center by δ_G . A lowest order expansion yields a similar result to (4), with $R\Omega^2$ in place of g :

$$\delta_G = R\Omega^2\tau_G^2, \quad (5)$$

valid if $\Omega \ll 1/\tau_G$. Suppose we are interested in the Newton field in the center of the source's orbit. Since the source generates the field from a shorter distance $R - \delta_G$, we get stronger Newton field by the factor $1 + \Omega^2\tau_G^2$ [22], a small effect for slow revolution and small acceleration (Fig. 6). Experiments with revolving sources, like [23], might make decisive tests or put an upper limit on τ_G at least.

2.3. Testable predictions of gravity's laziness III.

Direct test of the delay τ_G is possible if we impose extreme non-gravitational acceleration on our source. Let us prepare a massive laboratory source at static location $x_t \equiv 0$ for $t < 0$. It develops the standard static Newton field $-GM/r$ for $t < 0$, apart from the tiny universal shift δ_G (4) discussed previously. Here, again, we disregard this small effect, rather we look for a robust explicit delay of the Newton field. To this end, at $t = 0$ we suddenly displace the object to a new static position $x_t \equiv a$ for $t > 0$. Due to the static sources, and because we ignore the

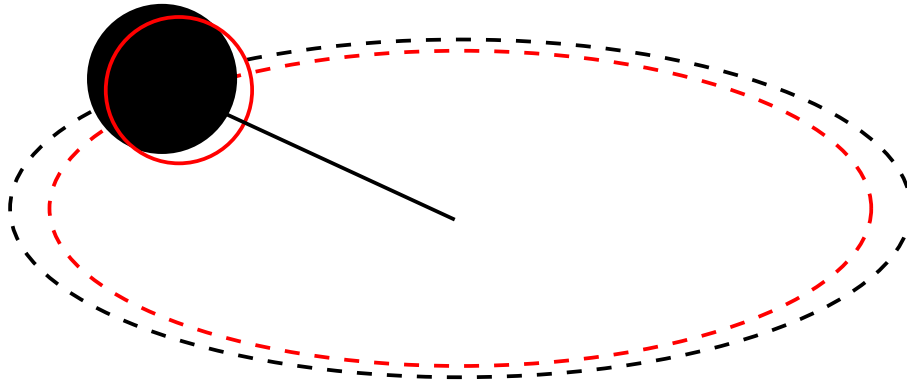


Figure 6. Revolving sources at angular frequency $\Omega \ll 1/\tau_G$ on a circle of radius R create standard Newton field as if the radius were smaller by a factor $1 - \Omega^2\tau_G^2$.

effect of the Earth gravity, we can apply Eq. (2) in the laboratory system, yielding

$$\phi(r, t) = e^{-t/\tau_G} \frac{-GM}{r} + \left(1 - e^{-t/\tau_G}\right) \frac{-GM}{|r - a|} \quad (6)$$

for $t > 0$. From the old to the new Newton fields around respectively the old and new locations 0 and a , the change is gradually taking place with a characteristic delay time τ_G . This is exactly what we expect of the modified Newton law (2): the lazy Newton field follows the sudden displacement of the source with the delay τ_G (Fig. 7). In a real well-controlled test, only

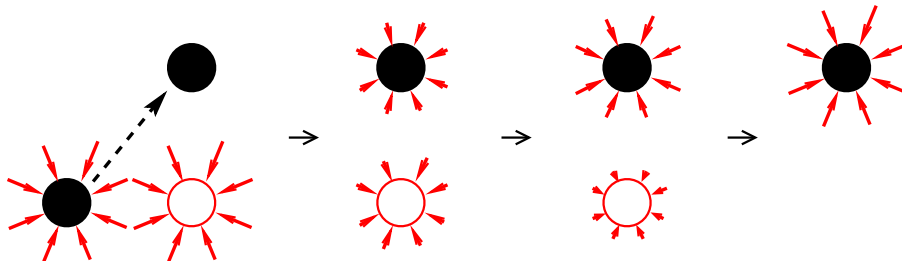


Figure 7. Sudden displacement of the source followed by the delayed redistribution of the Newton field from the old to the new configuration.

small macroscopic objects can be displaced or removed faster than a millisecond. Short-distance gravimetry at fine time-resolution is requesting but not impossible.

3. Summary, outlook

In the first part, we outlined the DP theory of spontaneous collapse of massive d.o.f., yielding an equilibrium time scale $\tau_G \sim 1\text{ms}$ of the collapse (disentanglement). We emphasized that in spontaneous collapse theories, like DP and all the others, the spontaneous decoherence is the testable effect, the spontaneous collapse (disentanglement) is not. We invoked the recent extension of DP theory [20] that makes collapse testable by associating it with the emergence of the Newton potential. The second part discussed the heuristic modification of Newton law to incorporate the ‘lazy’ emergence of the Newton potential just with the delay time of the order of τ_G . We showed three different laboratory tests of the delay. The first test is based on the

indirect effect of the delay, that static Newton fields of static sources in Earth gravitational field will get shifted upward by a universal height. A second test may exploit the slight modification of the standard Newton field of a source in periodic orbital motion. A direct test of the delay is possible with the sudden (i.e.: faster than τ_G) displacement of a small macroscopic source where the old/new configurations should die/emerge exponentially with the characteristic time τ_G . The realization of these tests seems possible with recent technologies.

We have emphasized that the concept of a lazy emergence of the Newton field is extremely speculative, the model is heuristic and minimal. As a non-relativistic theory, it is in peaceful coexistence with the general relativistic theory of gravitation. On one hand experimental evidences have not yet surfaced against it, and on the other hand it has various detectable predictions.

The modified Newton law—given by Eq. (2) in co-moving-free-falling frame—is a naive classical non-relativistic model, it can be considered both by theorists and experimentalists independently of the quantum mechanical DP theory, so that the value of the delay parameter τ_G could be tested in ranges different from the quantum theoretically predicted milliseconds.

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