

Are The Concepts of Mass in Quantum Theory and in General Relativity the Same?

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Abstract

The predominant approaches to understanding how quantum theory and General Relativity are related to each other implicitly assume that both theories use the same concept of mass. Given that despite great efforts such approaches have not yet produced a consistent falsifiable quantum theory of gravity, this paper entertains the possibility that the concepts of mass in the two theories are in fact distinct. It points out that if the concept of mass in quantum mechanics is defined such that it always exists in a superposition and is not a gravitational source, then this sharply segregates the domains of quantum theory and of general relativity. This concept of mass violates the equivalence principle applied to *active* gravitational mass, but may still produce effects consistent with the equivalence principle when applied to *passive* gravitational mass (in agreement with observations) by the correspondence principle applied to a weak field in the appropriate limit. An experiment that successfully measures the gravity field of quantum objects in a superposition, and in particular of photons, would not only falsify this distinction but also constitute the first direct empirical test that gravity must in fact be described fundamentally by a quantum theory.

Keywords: Concept of Mass, Equivalence Principle, Actual Mass, Actualizable Mass

1 Introduction

It is well known that one of the outstanding problems in fundamental physics is understanding how our two most fundamental theories of nature, quantum theory and general relativity (GR) fit together. Attempts to unify the two theories have so far met enormous difficulties and despite great efforts have not yet produced “a consistent and complete quantum theory of gravity” [1] [2].

A major difference between the theories is that according to the former, an object always exists in a superposition of mutually exclusive states unless it is ‘measured’ (at least according to the most widely accepted interpretation), whereas according to the latter an object never exists in a superposition. An implicit assumption in current approaches to solving this problem, which to the knowledge of this author has not received much attention yet, is that the concept of mass in quantum theory is the same as the concept of mass in general relativity. This short paper will point out that if the concepts are in fact different in a specific way, then the conflict between quantum theory and general relativity may dissolve because the difference in conception establishes sharply segregated domains of validity for the two theories.

2 Mass and the Equivalence Principle

The evolution of the concept of mass has a rich history[3]. The conception of mass that is familiar to us in our everyday experience corresponds most closely to that found in classical physics and can be regarded as

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consistent with that found in general relativity¹. In fact, the fundamental assumption of GR, the equivalence principle (EP), is formulated by explicitly using this conception, not the conception of mass that is associated with a superposition of properties. This is plainly clear when one considers the usual examples that are given to explicate the principle: They all involve the classical conception of mass [5, pp.114- 115][6, pp.148-149]. Before going on, let us briefly point out a particular subtlety associated with the EP. It has multiple variants, such as what are often called the strong, the Einstein and the weak equivalence principles, all of which equate² in varying degrees of generality gravitational mass m_g and inertial mass m_i [7, pp.48-50]:

$$m_i = m_g \tag{1}$$

The difference between the various formulations does not concern us so much as the fact that the concept of gravitational mass can be thought of in two distinct ways: In terms of passive gravitational mass, which is affected by a gravitational field in its vicinity, and in terms of active gravitational mass, which acts as a gravitational field source. We will in the following refer to the EP when it involves passive gravitational mass as the *passive* EP, and when it involves active gravitational mass as the *active* EP.

Let us now consider this in light of the conception of mass in quantum theory. That the conception of mass is implicitly taken to be *identical*, as opposed to merely analogous, to that in classical physics can already be seen from the fact that, unlike other dynamic quantities, mass is not described in terms of an operator but a simple scalar. Consequently, attempts to formulate a quantum theory of gravity implicitly assume that the equivalence principle also holds for mass that exhibits a superposition of properties, since such attempts assume the concepts of mass in quantum theory and in general relativity are the same. What empirical evidence do we have to back up this assumption?

It turns out that a relevant experiment was already performed in 1980: Staudenmann *et. al* showed that the passive EP does indeed hold for a beam of neutrons split by Bragg reflection[8]. Also, more recent matter wave interferometry experiments with larger atoms or molecules must increasingly take the downward acceleration of the objects in quantum superposition due to gravity into account [9][10]. It appears therefore that the passive EP as it applies to mass that exists in a superposition has been experimentally verified, although remarkably discussions in this context never distinguish between the active and the passive EP.

What about the active EP? To the knowledge of this author, no such corresponding experimental evidence exists to date. This is hardly surprising, since given the weakness of gravity and the smallness of the mass of objects in the quantum regime such an experiment would be extraordinarily challenging to perform.

On the face of it, it seems safe to assume that if the passive equivalence principle holds for quantum objects, then surely the active version must also hold. This assumption can be substantiated by a conservation of momentum argument: If the active EP did not hold, then one would have a situation in which objects are affected by gravitational fields but do not “act back” gravitationally on the source. This is an eminently reasonable argument, but in science, experiment trumps even the most reasonable of arguments. Although it may be considered unlikely, in the absence of direct empirical evidence to the contrary it is at least in principle possible that the active EP might be violated for mass that exists in a quantum superposition and that the conservation of momentum argument did not take into account some other factor we had not yet imagined.

There is a precedent for this which in fact pertains directly to conservation of momentum: If the special theory of relativity had been proposed prior to the Michelson-Morley experiment, then one of the eminently reasonable arguments to immediately dismiss special relativity as nonsense would have been that it is in complete violation of the conservation of momentum as understood in Newtonian theory. Yet it turns out that, as reasonable as it was, this argument was overruled, essentially by changing the definition of momentum.

The point here is not to argue that our definition of momentum might be subject to modification, but rather that we should still leave a little room for doubt about a reasonable scientific assumption for which we do not yet have direct empirical evidence. Given the so far insurmountable difficulties of formulating a consistent falsifiable theory of quantum gravity, which is implicitly based on this reasonable assumption, let us explore the consequences of making the alternative assumption.

¹for an opposite point of view, however, see [4], where it is argued that fundamental concepts of different theories are “incommensurable”, although mass is not explicitly mentioned as one of those concepts

²Empirically, we only know that the constant of proportionality is the same for all inertial and gravitational masses, but an appropriate choice of units allows us to set this constant to unity, in accordance with the EP

3 Actual Mass vs. Actualizable Mass

In this section, we will entertain a different assumption than above, namely, we will assume that the concept of mass between the two theories is in fact different. More specifically, let us call the conception of mass in classical physics as “actual mass”, and attribute to it the following properties: It is inertial charge that is never associated with a superposition of properties, and it is both a source and a passive charge of gravity in accordance with the EP. This is exactly the familiar conception that is used in GR.

Let us contrast this conception with what we will call *actualizable mass*, meant to be applicable to quantum objects with inertia. The term actualizable means “capable of becoming actual” and describes the fact that immediately after measurement, a quantum object manifests itself no longer in a superposition and must therefore by the above definition be considered actual. Let us attribute to actualizable mass the following properties: It is inertial charge that is always associated with a superposition of properties, and it is not a source of gravity. As indirect support for such a distinction between the concepts of mass in classical and in quantum physics one may count the empirically verified phenomenon of neutrino oscillations[11], as these arise from a phenomenon for which there is no classical physics analog, namely the superposition of mass eigenstates.

Actualizable mass obviously violates the active EP, as it is meant to, since this is how it falls outside the domain of validity of GR. Does it violate the passive EP? It can be argued by an appeal to the correspondence principle that at least in the classical limit of observations it would still be observed to obey it. For example, in the case of light, we already know that the path integral on a curved spacetime produces a phenomenology that in the appropriate limit is quite consistent with a classical trajectory that is “bent” by the force of gravity. It seems safe to assume that the same should hold for other quantum objects, which in turn seems to render the concept of actualizable mass consistent with experiments such as that performed by Staudenmann *et al.*, albeit by a non-classical mechanism. So, because, as discussed above, we do not yet have an experiment that has directly tested the active EP for quantum objects, the claim about a type of mass not producing gravity fields is at this time still defensible, even if it may seem improbable.

If we entertain this distinction, what does it do for us? It immediately implies that the state reduction in quantum mechanics can be understood as a consequence of an underlying transformation from actualizable to actual mass, since the state is just an expression of the configuration of the properties of its massive constituents:

$$|\Psi\rangle \xrightarrow{m_{\text{actualizable}} \rightarrow m_{\text{actual}}} |\psi\rangle \quad (2)$$

Where $|\Psi\rangle$ is the pre-measurement superposition state, and $|\psi\rangle$ is the immediate post-measurement eigenstate³. Because we already know that shortly after a collapse, a quantum object can once again spread into a superposition, this transformation must be reversible. However, according to this conception, the reversibility must necessarily be suppressed for classical objects, since we never associate effects arising from superposition with these.

Most importantly within the context of this discussion, it implies that the domains of quantum theory and general relativity are mutually exclusive: When an object is actualizable, it is not subject to General Relativity in the role of a source of gravity fields, and when it is actual, it is not subject to quantum theory because it is not in a superposition. The transformation from actualizable to actual mass serves as a ‘bridge’ between the theories and ultimately suggests that the collapse is a mechanism for producing a gravity field, i.e. it suggests that gravity is, in this sense, an emergent phenomenon. Indeed, this division of the concept of mass undermines a main argument against the compatibility of general relativity with quantum theory based on the uncertainty principle[12]: Since actual mass is outside the domain of quantum theory an argument based on the uncertainty principle cannot be applied to it; as a concept of mass that is defined to be exclusively “post-measurement”, the applicability of the uncertainty principle to it has already ceased. This highlights how, if this distinction really exists, our present belief that the two theories conflict with each other only reflects our confusion about denoting two very distinct concepts of mass with the same symbol. In fact, it would imply that in order to make them fit each other, the two theories only need to be modified to take this distinction and its implications into account.

³of course, under a change of basis of outcomes, even a non-superposition state can be expressed in terms of a superposition, but that involves, strictly speaking, an additional extrapolation beyond the empirical observation. The empirical fact is that when quantum objects are directly observed, they do not manifest themselves in a superposition.

4 Falsifying the Distinction

The most direct way to falsify the distinction presented here is an experiment showing that actualizable objects, i.e. objects in a quantum superposition, are gravitational field sources while they exist in a superposition (i.e. ‘uncollapsed’) state. Apart from the tremendous difficulties posed by the weakness of gravity, such an experiment must also be careful to ensure that the measurement of the gravity field of a quantum object does not inadvertently ‘collapse’ its superposition while making the measurement. Furthermore, although in this assumption we did not specify which property is in superposition, it is at least conceivable that this also may bear on the results. It would appear that position is the most definitive property that could falsify this assumption: If a gravity field is found for a quantum object in a superposition of positions, then this would in the most straightforward way imply that its gravitational field must also be in a superposition. Such a result would not only falsify this assumption but provide the first kind of direct empirical evidence whatsoever that gravity must in fact be described by a quantum theory, since everything that could be marshalled as empirical evidence up until now can (to the best knowledge of this author) be satisfactorily explained in terms of standard quantum theory against a classically curved spacetime background.

Since the mass-energy equivalence $E = mc^2$ is most directly applicable within the context of quantum field theory (QFT), where particle type and number is not conserved, this implies that the m in this equation must be actualizable and by this distinction cannot be a gravity source. It should be kept in mind that from the perspective presented here, any mechanism that endows particles with mass, such as possibly the Higgs mechanism, only endows them with inertia. The acquisition of gravitational charge would occur separately in a process that in the non-relativistic limit is symbolized by equation (2). As a discussion of a state collapse is almost invariably absent within the context of QFT, this distinction may be easily overlooked.

From these considerations follows the prediction that electromagnetic radiation cannot be a gravity source, either. Since this directly conflicts with the prediction of GR, that makes the measurement of the gravity field of radiation an even more definitive test. The gravity field of radiation according to GR was already calculated in 1931 [13], but also more recently [14][15][16][17][18] and can be compared against the prediction entailed by the distinction given here, which is null.

On astrophysical scales, this prediction implies that photons in the interior of stars do not contribute to the star’s gravitational field while in transit. Since due to ion-scattering they are almost always in transit, it may be possible to extract from this the prediction of an observational consequence that conflicts with that of GR as pertaining to a relevant measurement on the sun. Cosmologically, this prediction may have non-trivial implications when considering gravity in the radiation-dominated era of the universe, and these could point toward observational clues that can be used to falsify it. Theoretically, there is also the question of how macroscopic gravitational sources can be made up of fundamental constituents which-most of the time-do not produce gravitational fields themselves. However, as the absence of a particular property in microscopic constituents tends to be the defining feature of an epiphenomenon, and the state vector reduction may point to an explanation if one considers macroscopic classical objects as essentially permanently “collapsed”.

In short, while the distinction presented here offers the possibility of a very simple resolution of the conflict between General Relativity and Quantum theory, it has implications over an enormous range and may pose new problems on its own. But this yields potential opportunities for falsifying the distinction based on direct empirical (as opposed to merely theoretical) evidence in a variety of ways.

5 Conclusion

This paper pointed out that a certain assumption about mass that underlies current approaches at unifying quantum theory with general relativity, namely that mass in a superposition satisfies the active EP, has not yet in fact appear been subjected to an empirical test. This opens up the possibility for a specific alternative assumption about mass which in turn sharply segregates the domains of the two theories but also has a wide range of important implications.

A question one might ask is what the physical basis of such a distinction might be. This author has produced a framework in which such a distinction naturally appears. A conceptual overview of this framework can be found in reference [19], and a presentation with more mathematical details can be found in reference[20]. As the ideas in that framework are highly unfamiliar, if there is an interest in examining the framework, it is recommended to consult the conceptual overview first.

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