

Gravitation as a source of decoherence

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It is believed that classical behavior emerges in a quantum system due to decoherence. It has also been proposed that gravity can be a source of this decoherence. We examine this in detail by studying a number of quantum systems, including ultra-relativistic and non-relativistic particles, at low and high temperatures in an expanding Universe, and show that this proposal is valid for a large class of quantum systems.

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I. INTRODUCTION

An outstanding question in theoretical physics is how classical behavior emerges from a quantum mechanical framework. It is believed that interactions between a system and its environment cause the system to lose its ability to form a coherent superposition, in a process known as decoherence [1, 2]. One proposed mechanism for the Universe exhibiting observed classical behavior is decoherence via gravitation [3–6]. In this paper, we study this possibility, focusing on the recent work of Refs. [5] and [6], in which the decoherence effects of gravitons on quantum systems at high and low temperatures were studied. We show that in several cases, gravity can indeed be the source of decoherence in our Universe.

Following [5] and [6], we consider a thermal bath of gravitons in a Minkowski background (with small deviations). The gravitationally induced decoherence time for a non-relativistic macroscopic system in the *high temperature* limit (under the Born-Markov approximation) is given by [5]

$$t_d = \frac{\hbar}{k_B T} \left(\frac{E_P}{\Delta\omega} \right)^2 \quad (1)$$

where k_B is Boltzmann's constant, T is the temperature of the bath, $\Delta\omega$ is the difference between the energy levels of two states in a superposition, and E_P is the Planck energy. At this point, it should be stressed that although Ref.[5] starts off with the non-relativistic energy-momentum dispersion relation, the rest of the derivation is done using relativistic quantum field theoretic methods. Therefore Eq.(1) can rightly be applied to relativistic systems (as well as their non-relativistic limits).

On the other hand, also for gravitationally induced decoherence of non-relativistic systems of arbitrary size, due to Gaussian metric fluctuations around flat spacetime, and at *low temperatures*, the decoherence time was estimated to be [6]

$$t_d = \frac{1}{4} \sqrt{\frac{27}{\pi}} \frac{E_P \hbar}{k_B T \Delta\omega}. \quad (2)$$

Furthermore, if we consider a bath of gravitons of energy density ρ_g , then the decoherence time, again in the low-temperature limit, is given by [6]

$$t_d = \sqrt{\frac{9}{32\pi}} \frac{E_P}{\lambda_g \Delta\omega} \sqrt{\frac{\hbar}{\rho_g c}} \quad (3)$$

where λ_g is the graviton wavelength. We point out that although Eqs.(2) and (3) were initially proven for non-relativistic systems, they can also be applied for relativistic systems. The reason is that (as shown in Refs. [7, 8]) the wavefunctions used for non-relativistic particles are the same (at least for the first energy eigenstates) with those used for relativistic particles and the energy formula for the particle in a box depends only on the boundary conditions $\Psi(0) = \Psi(L) = 0$ with L to be the size of the box. The criterion to decide if a particle in a box is non-relativistic or relativistic is the size L of the box. Thus, the derivations in Ref. [6] goes through for relativistic particles and at the end one has to substitute the corresponding energy formula. We do precisely this in this paper for the relevant cases.

We will consider the above decoherence times for a variety of quantum systems in an expanding Universe, and check if these times are indeed less than the current age of the Universe ($\approx 4 \times 10^{17}$ s). In such cases, one would be able to conclude that gravitation had sufficient time to decohere quantum systems, and in fact may have been the primary source of decoherence. On the other hand, decoherence times exceeding the Universe's age would imply that there was not enough time for gravitational decoherence to occur and subsequent classical behaviour to emerge. Consequently, this would rule out the proposed models.

To determine the age of the Universe t_U in a give epoch characterized by the scale factor a , or equivalently the red-shift z , we employ the following relations, valid for early and late epochs, respectively [9] and [10], (more on this in the Discussion section; we assume $a = 1$ in the current epoch)

$$t_U \approx \frac{28\pi \times 10^{16}}{1 + 1/a^2}, \quad (4)$$

$$t_U = \frac{2H_0^{-1}}{3\Omega_\Lambda^{1/2}} \operatorname{arcsinh} \left[\left(\frac{\Omega_\Lambda}{\Omega_M} \right)^{1/2} a^{3/2} \right] \quad (5)$$

where $H_0 = 2.19 \times 10^{-18} \text{ s}^{-1}$ is the Hubble constant, $\Omega_\Lambda = 0.689$ is the dark energy density, and $\Omega_M = 0.311$ is the

matter density ¹. We also use the following in our calculations: $z = 1/a - 1$, $T = T_0/a$, $L = L_0a$, where $T_0 = 2.73$ K is the current CMBR temperature, and $L_0 \approx 8.8 \times 10^{26}$ m and L are the Hubble radius at the current epoch and at any given epoch, respectively. Note that given the spatial flatness of the Universe, and the existence of a horizon at any epoch of extent $\approx L_0a$, it is reasonable to approximate a quantum system, relativistic or non-relativistic, as a particle in a very large box (of length L_0a). We also take $\Delta\omega$ that appears in Eqs.(1), (2), and (3) to be the energy difference between the ground state and the first excited state.

Now, we consider a number of quantum systems, characterized by the following values of $\Delta\omega$. The examples we consider, namely ultra-relativistic and non-relativistic particles, gravitons and atomic systems, although are not exhaustive, cover most realistic scenarios and the matter content of our Universe :

(i) Ultrarelativistic particles

$$\Delta\omega = \frac{\pi\hbar c}{L_0a} \quad (6)$$

Note that the above being mass independent, holds for any ultra-relativistic particle, including for example electrons and gravitons.

(ii) Non-relativistic electrons ($m = 0.5$ MeV/ c^2)

$$\Delta\omega = \frac{\pi^2\hbar^2}{m(L_0a)^2} \quad (7)$$

(iii) Non-relativistic gravitons ($m_g = 10^{-32}$ eV/ c^2)

$$\Delta\omega = \frac{\pi^2\hbar^2}{m_g(L_0a)^2} \quad (8)$$

As was shown in [12], non-relativistic gravitons can form part of a *macroscopic* Bose-Einstein condensate at very early epochs, due to a very high critical temperature of the condensate. Note that the decoherence time for these gravitons can be estimated by using Eqs.(1) and (2), applicable to non-relativistic systems, as well as by using Eq.(3), also applicable to non-relativistic systems and requiring a background bath of gravitons.

(iv) Atomic systems

We use a characteristic value of $\Delta\omega \approx 1$ eV [5].

The rest of the paper is organized as follows. In Tables I, II and III, we compute the decoherence times t_d by equating (1), (2), and (3), respectively, to the Universe's age estimated by Eq.(4).

In Tables IV, V and VI, we repeat the calculations using Eq.(5) for estimating the age of the Universe. When applying equation (3), we assume ρ_g to be equal to the energy density of dark matter, i.e., $\rho_{DM} = 0.25\rho_{crit}c^2/a^3$, as discussed in Ref. [12]. We also present the corresponding values of L_0a and z in the above Tables.

In particular, when we substitute into the expression for the decoherence time, i.e., Eq. (1), or Eq. (2), or Eq. (3), one of the expressions for the energy difference and then equate it with one of the expressions for the age of the universe, i.e., Eq. (4) or Eq. (5), we obtain the values for the scale factor a (for multiple solutions, we select the smallest non-zero value of a). Then, we estimate the corresponding length, i.e., L_0a , the redshift, i.e., z , and finally the decoherence time, i.e., t_d .

By inspection, we find that for a number of cases, which in fact exhaust the most important quantum systems, the decoherence time is significantly less than the age of our Universe, *but* is not less than the Planck time. Therefore, for these systems, gravitation may indeed have been the dominant source of decoherence ². We also ensure that those systems are valid in the high or low temperature approximations as required by equations (1)-(3). In Section III, we discuss our results and the implications of our calculations.

¹ All values are averaged from the data released by the Planck mission in 2015 [11].

² In those cases for which the decoherence time turns out to be smaller than the Planck time, about 10^{-43} s, the equations used here and the subsequent results cease to remain trustworthy, as it is expected that a full theory of quantum gravity is needed to study the sub-Planckian regime. Away from this regime however, the decoherence time formulas Eqs.(1-3) derived from a minimal set of assumptions are quite robust, and expected to hold for the situations we consider. .

II. CALCULATIONS

A. Using the Cosmic Time Formula from Ref. [9]

Here we utilize Eq.(4) to determine the age of the Universe, for a system undergoing decoherence.

$\Delta\omega$ (J)	L_0a (m)	z	t_d (s)
UR	9×10^{-67}	10^{93}	10^{-168}
NR (g)	4×10^{-28}	2×10^{54}	2×10^{-91}
NR (e)	10^{-30}	8×10^{56}	2×10^{-96}
1.6×10^{-19}	0	∞	0

TABLE I. Determining the redshift, i.e., z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , for various energies by using Eqs. (1) and (4).

$\Delta\omega$ (J)	L_0a (m)	z	t_d (s)
UR	0	∞	0
NR (g)	2×10^{-5}	6×10^{31}	3×10^{-46}
NR (e)	3×10^{-44}	3×10^{70}	10^{-123}
1.6×10^{-19}	3×10^{25}	34	7×10^{14} *

TABLE II. Determining the redshift, i.e., z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , for various energies by using Eqs. (2) and (4).

$\Delta\omega$ (J)	λ_g (m)	L_0a (m)	z	t_d (s)
UR	1	10^{-26}	5×10^{52}	3×10^{-88}
		L_0a	6.2	4.4×10^{15} *
NR (g)	1	3×10^8	2×10^{18}	2×10^{-19} *
		L_0a	6.2	4.3×10^{15} *
NR (e)	1	3×10^{-17}	3×10^{43}	9×10^{-70}
		L_0a	2×10^{-50}	4×10^{76}
1.6×10^{-19}	1	2×10^{13}	4×10^{13}	6×10^{-10} *
		L_0a	3×10^4	3×10^{22}
				9×10^{-28} *

TABLE III. Determining the redshift, i.e. z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , by using Eqs. (3) and (4), for various energies, and assuming that the graviton bath energy density is equal to the energy density of dark matter.

B. Using the Cosmic Time Formula from Ref. [10]

Here we utilize Eq. (5) to determine the age of the Universe, for a system undergoing decoherence.

$\Delta\omega$ (J)	L_0a (m)	z	t_d (s)
UR	7×10^{-36}	10^{62}	5×10^{-107}
NR (g)	0.46	2×10^{27}	6×10^{-24} *
NR (e)	10^{-22}	7×10^{48}	2×10^{-80}
1.6×10^{-19}	0	∞	0

TABLE IV. Determining the redshift, i.e., z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , for various energies by using Eqs. (1) and (5).

$\Delta\omega$ (J)	L_0a (m)	z	t_d (s)
UR	2×10^{-27}	4×10^{63}	2×10^{-78}
NR (g)	9×10^4	9×10^{21}	$6 \times 10^{-16*}$
NR (e)	7×10^{-21}	10^{47}	10^{-53}
1.6×10^{-19}	2×10^{24}	473	$5 \times 10^{13*}$

TABLE V. Determining the redshift, i.e., z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , for various energies using Eqs. (2) and (5).

$\Delta\omega$ (J)	λ_g (m)	L_0a (m)	z	t_d (s)
UR	1	2.3	4×10^{26}	$7 \times 10^{-23*}$
	L_0a	2×10^{27}	-0.59	9×10^{17}
NR (g)	1	10^{13}	7×10^{13}	$9 \times 10^{-4*}$
	L_0a	10^{26}	5.1	$4 \times 10^{16*}$
NR (e)	1	2×10^{-6}	5×10^{32}	$5 \times 10^{-32*}$
	L_0a	3×10^{-12}	3×10^{38}	10^{-40*}
1.6×10^{-19}	1	10^{32}	-1	7×10^{18}
	L_0a	3×10^{-7}	3×10^{33}	$3 \times 10^{-33*}$

TABLE VI. Determining the redshift, i.e., z , the size of the Universe, i.e., L_0a , and the age of the Universe, i.e., t_d , by using Eqs. (3) and (5), for various energies, and assuming that the graviton bath energy density is equal to the energy density of dark matter.

III. DISCUSSION

We note from Tables I-VI that the decoherence times marked by an asterisk (*) are less than the age of the Universe, *but* not smaller than the Planck time (as noted earlier for the latter, a full theory of quantum gravity would be needed, and the equations used here cease to remain trustworthy). These are the ultra-relativistic particles, non-relativistic gravitons, non-relativistic electrons and atomic systems. While these may not form an exhaustive list, they cover much of the spectrum of quantum systems.

Several points are in order. First, we note that Eq. (1) requires the system to be macroscopic, while neither Eq. (2) nor Eq. (3) have constraints regarding the size of the system. Furthermore, while Eq. (1) applies to high temperature systems, Eqs. (2) and (3) are valid for systems at low temperatures. Second, the decoherence time for a macroscopic system composed of non-relativistic gravitons, as calculated using Eqs. (1) and (4), lies between the GUT and Hadron epochs³.

Third, it is also noteworthy that Eqs. (2) and (3) are calculated in the low-temperature limit [6]. Therefore, for the systems that appear in Tables II and V, we have to discard the results for which the Universe appears to be too hot. In the last case, with $\Delta\omega = 1$ eV, the age of the Universe according to Eq. (4) is approximately 22.2 million years, while Eq.(5) suggests an age of about 1.6 million years. This indicates that a system whose difference in energy levels is around 1 eV would decohere during the Dark Ages⁴.

Fourth, in Tables III and VI, it is evident that the decoherence time depends on the characteristic wavelength of the graviton. The characteristic wavelengths of $\lambda_g = 1$ and $\lambda_g = L_0a$ were chosen to demonstrate two possible extremes: a small constant wavelength and a wavelength that grows at the same rate as the Universe.

It is usually assumed that gravitons have the speed of light, i.e., c . For subluminal gravitons, Eq. (3) can still be utilized, though the graviton's speed, v_g , has to be incorporated probably by modifying λ_g , such that it becomes $\lambda_g = \lambda_g(v_g)$. It should also be stressed that the characteristic wavelength of the graviton has to be smaller than the size of the Universe. Thus, we can eliminate one of the cases in which $\lambda_g = 1$. As already mentioned, Eq. (3) is computed in the low-temperature limit [6]. Thus, two of the only remaining cases correspond to $z = 13.1$ and $z = 13.3$, with the age of the Universe to be around 140 million years. Therefore, decoherence would occur near the end of the Dark Ages. We also have $z = 3 \times 10^{38}$ and $z = 3 \times 10^{33}$, with a decoherence time of 3×10^{-33} s and 10^{-40} s, respectively, occurring between the GUT and Hadron epochs. The final remaining case is $z = 5.1$, at an age of 1.27 billion years. In this case, decoherence would occur almost at the start of Galaxy formation and evolution epoch⁵.

³ The GUT epoch starts at time 10^{-43} s while the Hadron epoch starts at time 10^{-6} s [13, 14].

⁴ The Dark Ages of the Universe are considered to be between 3.8×10^5 years and 150×10^6 years after the Big Bang [13, 14].

⁵ Galaxy formation and evolution epoch took place between 10^9 years and 10×10^9 years [13, 14].

Fifth, as already mentioned, the derivations of the formulas for decoherence time involve either the high-temperature approximation or the low-temperature approximation. Thus, it is anticipated that a new formula for decoherence time will be more accurate both at high and low temperatures. This will ensure that decoherence time could be calculated for a particle or a system transitioning from a high-temperature environment (the early Universe) to a low-temperature environment (current time).

Sixth, decoherence due to scattering by various sources was considered in Ref. [15] and the author demonstrated that the decoherence time varied depending on the size of the system. We might expect similar results with decoherence due to gravitons. In addition, for a system whose $\Delta\omega$ is equivalent to that of a non-relativistic particle, the decoherence time depends on the particle's mass as given in Eq. (8). Moreover, we might expect this dependence of decoherence time on particle's mass to hold also for the case of ultra-relativistic time but in this case the dependence will not come through $\Delta\omega$. Thus, a new theoretical model is expected to incorporate not only the superposition of energy levels of a system, but also the system's size and mass [16]. Otherwise, two macroscopic systems whose sizes are radically different (for example, a planet and an asteroid) would have the same decoherence time, as long as $\Delta\omega$ is the same. This result seems to make little physical sense. Furthermore, as the Universe evolves, it initially includes particle-sized objects before eventually forming macroscopic systems. As these particle-sized objects are initially relativistic, it will be necessary in the new formula for the decoherence time in the early Universe to account for transitioning from relativistic speeds to non-relativistic speeds, changing the energy level, and changing the mass of the system.

Equally important, Eqs. (4) and (5) both describe the age of the Universe, however they have different ranges of validity. By utilizing the accepted values for the redshift of each epoch, it can be shown that Eq. (4) yields a closer estimate to the accepted age of the Universe from GUT epoch till the start of Nucleosynthesis Epoch as well as from the start of the Reionization epoch until the present time. Eq. (5) yields a closer estimate to the accepted age of the Universe from the end of Recombination Epoch until the present time.

Finally, further research is needed to determine whether gravitational decoherence is the dominant form of decoherence in the early Universe, or if it is necessary to consider multiple sources of decoherence. Assuming decoherence is induced solely by gravitation, one interpretation of our calculations is that gravitational decoherence may be insufficient in some situations to produce a classical Universe. In each of the cases considered here, the decoherence time was of the order of millions or billions of years. Such a timescale is heavily dependent upon the system and environment under consideration. This may alternatively indicate that different sectors of the Universe decohere before others.

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