In Search of Quantum-Gravity-Induced Decoherence

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Abstract

I review briefly two methods of experimentally bounding/falsifying the assumption that, under certain circumstances, quantum gravity fluctuations at microscopic scales induce decoherence of quantum matter propagating in such non-trivial space-time backgrounds. The first method is a rather old idea employing SQUIDs, which is an area that Prof. Diambrini Palazzi had taken a strong interest in. The second on the other hand, is a novel and rather unique, "smoking-gun" type, experimental method to detect such decoherence, which employs particle interferometry, and in particular entangled neutral Kaons. The latter system, due to its almost complete energy degeneracy, serves as an excellent amplifier of potential quantum-gravity induced decoherence effects, which can be detected through the associated CPT Violating ω-effect, a novel effect associated with the ill-defined nature of the CPT operator in quantum-gravity decoherening backgrounds. The KLOE-2 experiment at (the upgraded) DAΦNE collider (ϕ factory), is an ideal place to search for such effects, exhibiting high sensitivity, compared to the other neutral meson systems, due to its CP violation effects.

1 Introduction

I met Prof. Giordano Diambrini Palazzi for the first time in Rome in 1994, when he organized the first international conference on "Phenomenology of Unification from Present to Future", although I was already aware of his fundamental contributions to particle physics. One of his main scientific interest in those years was on possible experimental tests of quantum gravity, and in particular on searches of violation of the macroscopic (superconducting) quantum coherence of states in a system of SQUIDs. In that period John Ellis and I were (and still are) very active in the field, and therefore Prof. Diambrini Palazzi invited us to give a talk at the conference as theory experts [1].

Although Gravity is very well understood classically, not only at local scales but also at global (Cosmological) ones, through the Einstein theory of General Relativity (GR) and its Cosmological version, nevertheless, a complete microscopic quantum version of it, termed *Quantum Gravity* (QG), is still lacking. In fact, some people even expressed doubts as to whether Gravity can be viewed as a quantum force (for instance, the entropic point of view [2], according to which gravity is a resultant force of the curved geometry of space-time rather than a fundamental interaction of Nature, is one such approach). One of the most important factors responsible for this large uncertainty clouding QG is the distinct lack, so far, of any experimental evidence for it. This is partly due to the fact that the coupling of gravitational interactions is much weaker (some forty orders of magnitude, when properly normalised, being dimensionful) than the strengths of the rest of the fundamental interactions in Nature. However, it is also partly due to the fact that currently we do not have a very clear idea as to how a theory, describing the dynamical structure of space-time at microscopic scales, say of Planck length size (10^{-35} m), would look like, and what symmetries would be characterised by. The Newton constant, G, which serves as the universal (observer independent) coupling of gravity, is a dimensionful coupling with mass dimensions -2, being inversely proportional to the square of the Planck mass M_P:

$$16\pi\,\mathrm{G} = \frac{\hbar\, c}{M_P^2}\ , \quad M_P = 1.2. \times 10^{19}\ \mathrm{GeV}\ . \tag{1}$$

As such, the naive quantum version of Einstein's GR is a non-renormalisable local field theory, which cannot therefore be the ultimate theory describing the dynamical structure, and even the emergence of space-time itself, at Planck scales. At best, GR could be viewed as an effective low-energy local field theory that describes well the world at energy scales much lower than M_P. From this point of view, one might hope of at least constructing some low-energy observables that could describe somehow a (limited, in the best case scenario) number of features of the quantum gravity world. However, it is not even clear what perturbation theory in the coupling G one would face in such an approach. The naive guess, of having terms in the effective lagrangian being proportional to integer powers of G, leads to very gloomy experimental prospects, due to the smallness of Newton constant. However, a real quantum gravity situation need not be described by such perturbative models. The structure of space-time at Planck scales may be a highly non-trivial one, even of "*foamy*" nature, as first envisaged by J.A. Wheeler (For a review see: [3]). The propagation of quantum matter in QG space-time backgrounds may be characterised by non-perturbative effects of QG that may be responsible for novel effects outside a local effective field theory framework.

One type of such effects is the induced decoherence of quantum matter propagating in a QG background, suggested by Stephen Hawking [4], which is attributed to information carried away by microscopic black-hole type singularity structures one encounters in a path-integral formulation of QG, that are inaccessible to a low-energy observer. Although later on, Hawking retracted from his original ideas about the induced loss of quantum coherence in a QG background [5], basing his conclusions on holographic Euclidean Anti-de Sitter regularisation of a quantum Black-hole space time, unfortunately such recent claims cannot constitute a rigorous proof for several reasons. First, the Euclidean anti de Sitter regulator might not cover all aspects of a proper Minkowskian signature QG space-time path integral. Second, there are conformal models of GR, with implications for a pre-Big-Bang Cosmology, suggested by R. Penrose [6, 7], that are claimed to provide rigorous ways of understanding the quantum aspects of the last stages of a black hole evaporation, in which it is demonstrated explicitly that there exist degrees of freedom carrying away information that is not accessible by a low-energy observer, leading to decoherence. Third, QG fluctuations that may cause decoherence may go well beyond the original black hole type singularities envisaged by Hawking. For instance, there may be topologically non-trivial space-time defects in string/brane models of QG (D-particles) [8, 9], whose interactions with quantum string matter may cause low-energy decoherence due to the existence of information-carrying degrees of freedom [10], associated with the back reaction of the recoiling D-particle on the quantum space-time, that cannot be accessible by a low-energy observer.

If one accepts this idea that quantum gravity plays the rôle of an environment that induces decoherence of matter propagating in it, then immediately (s)he is faced with a potential evolution of pure to mixed states, where effective unitarity is lost from the low-energy system (this does not mean, though, that the complete system of QG loses unitarity; such a conclusion is incorrect; the effective loss of unitarity simply parametrises our "ignorance" of what the complete system of QG is). Theoretically, such an evolution from pure to mixed states may be described by the same methods used to treat open quantum mechanical systems interacting with an environment (mostly of Lindblad type [11], but there are exceptions, see below). The "phenomenology" of such decoherence has been a topic that has been studied extensively by several authors, almost immediately after Hawking put forward his original idea [4]. Pioneering works in this subject, with a proposed parametrization of the QG decoherence effects that lead to a formulation of observables for searches of such QG-induced decoherence in particle "interferometers", such as cold neutrons and neutral Kaons, have already appeared in the mid 80s [12, 13, 14] and lead to searches for such effects in a variety of modern facilities, such as SQUIDS [15], or particle physics facilities: CPLEAR experiment at CERN [16, 17] and the DAΦNE ϕ factory [18] and its upgrades [19]. The main effects of decoherence in systems entailing oscillations between particles and antiparticles, like the neutral Kaon system, or between particle species (such as flavour oscillations in neutrinos [20, 21, 22, 23]), is the exponential damping with time of the coefficients of the oscillatory (in time) interference terms of the respective (time-dependent) probabilities. By the non-observation of such damping factors the experiment places bounds on the order of the QG induced decoherence. Care should be taken to remove any other fake decoherence effects that might have been caused by ordinary low-energy environmental decoherence due to background noise.

Induced decoherence of a material particle in a non-trivial QG background, and its potential experimental verification or falsification, especially in SQUIDS, has been one of the topics that fascinated Prof. Diambrini-Palazzi ([24, 25, 26], and references therein), and this is what I will discuss first in the article. Before doing so, I would like to take the opportunity and clarify an issue here which is often confused in the literature. The induced decoherence of a material particle in an open quantum mechanical system interacting with an environment does not necessarily implies a collapse of a wave function. Although decoherence is identified as a process in which the off-diagonal elements of the density matrix of the material subsystem go to zero asymptotically in time, nothing can be said on the effect of the environment in selecting one and only one of the diagonal entries, which would correspond to a "collapse" of the wave function. Thus, in several works in the literature people were talking about a collapse of a wave function induced by QG but they actually meant decoherence. In what follows I will restrict myself to such a loss of coherence, and not discuss the important but yet unsolved problem of the wave function collapse and the associated resolution of the so-called "measurement" problem in quantum theory.

The structure of this contribution is the following: in the next section 2, I will describe tests and models of QG that entail falsifiable (in principle) effects of quantum decoherence at a SQUID apparatus, which is a topic pursued actively by Prof. Diambrini-Palazzi in the 90s. In section 3, I will discuss another aspect of QG-induced decoherence, stemming from the fact that the CPT operator is not well defined in a low energy subsystem undergoing vacuum decoherence due to QG effects. As we shall discuss, this leads to "smoking-gun" type experimental evidence in entangled neutral kaon systems in a ϕ factory. Finally, section 4 will contain our conclusions.

2 Quantum Gravity and SQUIDS

As already mentioned, decoherence of a material particle in a non-trivial QG background, and its potential experimental verification or falsification, has been one of the topics that fascinated Prof. Diambrini-Palazzi in the 90s ([24, 25], and references therein). More generally, he and his collaborators were interested in building arrays of SQUIDS towards detecting macroscopic quantum coherence phenomena (and measuring their environmental decoherence times) as part of their studies towards the use of such devices in *Quantum Computation* [26]. I will restrict myself here only to the use of the SQUID as a test of QG-induced decoherence effects, leaving its other potential uses envisaged by Prof. Diambrini-Palazzi to be described by other expert contributors.

A **S**(uperconducting) **QU**(antum) **I**(nterference) **D**(evice) is a high-sensitivity magnetometer used to measure extremely subtle magnetic fields, based on superconducting loops containing Josephson junctions. There are two main types of SQUID: direct current (DC) and radio frequency (RF). RF SQUIDs can work with only one Josephson junction, which might make them cheaper to produce, but are less sensitive. Nevertheless, it is this type that had been considered in the initial papers suggesting the use of SQUID for searches of QG-induced decoherence phenomena [15], and therefore I will review this category here.

In Ref. [14] it was suggested that among the various topologically non-trivial configurations that one can encounter in a QG path-integral, wormholes play an important rôle in inducing quantum decoherence on matter wavefunctions in interaction with them. Although coherence loss by wormholes is still a controversial open issue, and there are many reasons for it, among which the fact that wormholes exist only in a Euclidean formalism of QG, nevertheless looking for such effects experimentally is probably a good way forward to settle such issues. The problem of course is the order of magnitude of the predicted effects, which can be very small and thus outside of experimental reach in the foreseeable future. In [14, 15], though, a rather optimistic estimate on such effects has been given, under some assumptions, which cannot be rigorously justified nor rejected though due to a lack of a rigorous theory of QG. In particular, it was argued that the wormhole/matter interaction can be modelled by a lagrangian term:

$$\mathcal{L}_I = e^{-S_{wh}}\Big(\frac{m_e}{M_P}\Big)\overline{\psi}\,\gamma^\mu\Big(\partial_\mu - eA_\mu\Big)\,\psi\ , \tag{2}$$

where we restrict ourselves only to the coupling of electrons (ψ) to photons (A_μ) in this discussion, since these are the Standard Model excitations that play a rôle in SQUIDS. We have followed the Euclidean formalism, in which wormholes exist, and we have treated the wormhole terms as corrections to the Minkowski metric, which justifies the suppressing coefficient in front of the matter parts of the Lagrangian term (2). In (2), $S_{wh} = \ell_{wh}^2 M_P^2$ is the wormhole action, and only microscopic wormholes with size $\ell_{wh} = M_P^{-1}$ (*i.e.* with action $S_{wh} = \mathcal{O}(1)$) and a density of one per Planck volume have been assumed in [14, 15] as the dominant QG configurations resulting in loss of quantum coherence of the electrons. With these assumptions the rate of coherence loss (in an appropriate density matrix functional form $\rho(\Phi, \Phi', t)$ for the electrons of a superconducting SQUID in the above wormhole background, in the magnetic-flux (Φ-) state representation, $|\Phi\rangle$) has been estimated to be [15]:

$$\rho(\Phi, \Phi', t) = \rho_0(\Phi, \Phi', t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2\,(\Phi-\Phi')^2}, \tag{3}$$

where

$$\beta^2 = e^{-2\,S_{wh}}\,\Big(\frac{m_e}{M_P}\Big)^2\,\Big(\frac{e^2}{2\,m_e}\Big)^2\,\epsilon_\gamma^2\;, \quad S_{wh} = \mathcal{O}(1)\;, \tag{4}$$

with $\epsilon_\gamma^2 \sim \omega_0^4$ the density of the electromagnetic field (photons) in the RF SQUID with characteristic frequency ω_0 and $\mathcal{N}$ the number of (electron) Cooper pairs in the SQUID, such that the Cooper-pair density is $\mathcal{N}/V$ with V the volume. The term ρ_0 in (3) denotes the standard density-matrix element in the absence of wormhole (or any other gravitational) interactions.

It is important to notice in Eq. (3) the exponential damping of the off-diagonal electron density-matrix elements with the square of the time rather than the time itself. This distinguishes the wormhole decoherence from other standard physics dissipation effects in SQUIDs which fade away as $e^{-(\text{const})^2\,t}$ [15]. Incidentally, the same type of time-squared decoherence also characterises more generally *stochastically fluctuating* quantum space-time environments [27], such as D-particle foam situations, which also induce decoherence of matter propagating in them, as mentioned earlier. However, for reasons of charge conservation that I cannot explain here, such D-particle foam environments interact predominantly only with neutral matter, and thus SQUIDS is not the appropriate place to look for them. On the other hand, other types of stochastic space-time foam, such as space times characterised by coherent graviton states, such as those considered in [28], which are known to induce light-cone fluctuations as well, may be testable in such devices in the future. In fact linear-in-time damping seems to characterise the standard Linbblad decoherence terms [11], which have also been used to model QG-induced decoherence [12, 13, 16, 18]. Thus. it seems that in general it is possible to disentangle experimentally various models of QG decoherence, if and when sufficient evidence presents itself.

The parameters in a SQUID can be arranged in such a way [29] that it can be viewed as a two-quantum state system, with its quantum-mechanical state $|\Psi\rangle$ being a superposition of the two quantum states of the flux, $|\Phi_\pm\rangle$, $|\Psi\rangle = a|\Phi_+\rangle + b|\Phi_-\rangle$, corresponding to the two classical minima of the double-well effective potential in the SQUID Hamiltonian. Here, Φ_{ex} is the external flux threading the SQUID superconducting ring and $\Phi_\pm = \Phi_{ex} \pm |\widehat{\Phi}|$, $|\widehat{\Phi}| < \Phi_0/2$, where $\Phi_0 = h/(2e)$ is the (Cooper pair) flux quantum. These states are associated with the two directions of the current (clockwise or anticlockwise) as it traverses the superconducting ring, $I = \pm|\widehat{\Phi}|/L$, where L is the inductance [29]. The SQUID is a unique device in that, at its operating very low (mK-range) temperature, the system parameters can be chosen in such a way that the two macroscopic quantum coherent states are not mixed by thermal fluctuations. There is a finite probability for tunnelling between these two states. The respective transition probabilities are given by the off-diagonal elements of the SQUID density matrix.

In the presence of quantum gravity wormholes one has the damping of these off-diagonal terms as shown in (3). In fact for the two-state system the SQUID density matrix, ignoring for the moment ordinary dissipation effects, is given by [15]:

$$\rho(t) = \begin{pmatrix} \cos^2(\delta_0\, t) & \frac{1}{2}\sin(2\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2} \\ \frac{1}{2}\sin(2\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2} & \sin^2\delta_0 t \end{pmatrix} , \tag{5}$$

with $\delta_0 = \omega_0\left(\frac{I_0\,\Phi_0}{\omega_0}\right)^{1/2} e^{-\frac{I_0\,\Phi_0}{\omega_0}}$, $\omega_0 \sim 2\pi/(L\,C)$ (with C the capacitance) the frequency of the small oscillations around each minimum of the double-well potential of the SQUID, I_0 the critical current, and $I_0\,\Phi_0$ indicates the height of the barrier separating the two classical vacua in the double-well potential. The physical meaning of the frequency δ_0 is that, in conventional quantum mechanics, if the system is prepared at time $t = 0$, say, in the state $|\Phi_+\rangle$, then at a later time $t > 0$, it will find itself in a superposition of the two flux states, $|\Psi(t)\rangle = \cos(\delta_0\, t)|\Phi_+\rangle + \sin(\delta_0\, t)|\Phi_-\rangle$. We observe from (5) that, in the absence of ordinary dissipation, the total probability is conserved by the wormhole calculus, since $\mathrm{Tr}\rho(t)=1$, but one has an evolution of pure to mixed states, since $\mathrm{Tr}\rho^2(t)\widetilde{\chi}^0\mathrm{Tr}\rho(t)$ [15].

Although a direct measurement of the flux state of a SQUID can only take place through the diagonal density matrix elements, nevertheless one can probe indirectly the QG-induced decoherence of the off-diagonal elements, at least in principle, by shooting a beam of polarized neutrons through the ring of a SQUID which has an averaged magnetic field B [29]. The outgoing flux of neutrons is then correlated to the states of the SQUID. The interference pattern of the neutrons which can be measured will have a time dependence given by (here we introduce ordinary dissipative effects with damping $e^{-a^2\,t}$):

$$P(t) = \sin\theta\, e^{-\beta^2\,\mathcal{N}^2\,t^2}\, e^{-a^2\,t} , \tag{6}$$

where θ is the angle between the successive minima, $\theta = (g_n e/m_n)B\,\Delta t$, with m_n the neutron mass, g_n its magnetic moment, and Δt the time that neutrons spend in the magnetic field of the SQUID.

From Eq. (5), (6) we observe that the main problem in a SQUID, when used for searches of QG-induced decoherence, is the separation of the standard dissipation terms, inducing a decoherence time $t_d \sim 1/a^2$, which is typically of order 10^{-4} s, from the QG-induced decoherence, which in the case of wormholes is estimated to be

$$t_{wh} \sim 1/(\beta\,\mathcal{N}) \tag{7}$$

The wormhole-induced decoherence time cannot be calculated exactly, due to the lack of a consistent formulation of QG. Nevertheless, some estimates can be given [15] from (4), based on the above simplifying assumptions for the wormhole model of [15]. Taking into account that the number of Cooper pairs encountered in a SQUID of volume 1 mm^3 used in [15], is $N > 10^{19}$, and that $\beta \sim 10^{-23}\,\mathrm{s}^{-1}$ in that case, one can estimate the wormhole decoherence time as of order $t_{wh} \sim 10^3\,\mathrm{s}$. In this case the ordinary dissipation implies faster decoherence. However, by increasing the resistance of the SQUID, and a larger number of Cooper pairs, one may arrive at a situation in which fast enough wormhole decoherence may be detectable or falsifiable.

Prof. Diambrini Palazzi and his colleagues designed more sophisticated SQUID apparatus in order to achieve this [25, 24], but also SQUID networks in a coherent superposition to be used in quantum computations [26]. In their design [25], they included a system of three SQUIDs: an RF SQUID, which serves as the source of two quantum states of the flux and is in connection with a SWITCH SQUID, which in turn connects to an amplifier SQUID. The SWITCH SQUID which is weakly connected to the RF one, is arranged in order to have the following behavior. First, it can be activated for a time $\Delta t \ll t_i$, by an impulsive current given to it at a prefixed time t_i; t_i is also the time at which we detect the flux of the RF SQUID, prepared at a given initial state. When we do so, the following two situations may be encountered: either the SWITCH SQUID has a transition to the normal state (termed "Left" (L) state, for concreteness, invasive measurement), or nothing happens and the SWITCH SQUID remain essentially undisturbed ("Right" (R) state, noninvasive measurement in the classical sense); it is the amplifier SQUID which reads the state of the SWITCH SQUID. In both cases the experimenter can infer the sign of the flux of the RF SQUID [25]. In their design, Prof. Diambrini Palazzi and collaborators envisaged the use of a massive RF SQUID with number of Cooper pairs of order $\mathcal{N} \sim 1.3. \times 10^{22}$ (*i.e.*, of order $\mathcal{N} \sim M_P/m_e$), a volume nearly 1 cm^3 and a relative density of pairs 23 % of the atomic density. Such types of SQUIDs are currently available in the market. In such a case, the decoherence time of potential wormhole effects is reduced significantly compared to the case of [15], $t_{wh} \sim 5$ s, and hence problems due to ordinary environmental dissipation effects may be avoided.

As already mentioned, however, to measure the effects of QG-induced decoherence one needs to measure the off-diagonal terms of the RF SQUID density matrix (4). This cannot be done by a simple measurement of the flux of the RF SQUID as the above-described apparatus is designed to do. To evade this, Diambrini Palazzi and collaborators suggested [25] to measure the conjugate variable of the flux, that is the electric charge Q. However they also envisaged another theoretical scenario, according to which the QG-induced damping affects not only the off-diagonal terms of the SQUID density matrix, but also parts of its diagonal elements; in particular they suggested a hypothetical situation in which the RF SQUID density matrix in the presence of QG-decoherening effects and ordinary dissipation reads [25]:

$$\begin{aligned}\rho(t) &= \begin{pmatrix} \frac{1}{2}\Big(1+\cos(\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2}\Big) & \cos(2\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2} e^{-a^2\,t} \\ \cos(2\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2} e^{-a^2\,t} & \frac{1}{2}\Big(1-\cos(\delta_0\, t)\, e^{-2\,\beta^2\,\mathcal{N}^2\,t^2}\Big) \end{pmatrix} \\ &\to \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}\,, \end{aligned} \tag{8}$$

which asymptotically in time transforms itself into a mixed matrix. Unfortunately, the wormhole example of [15] does not lead to a density matrix of the form (8), but one cannot exclude the possibility that such more general situations may be encountered in other stochastically fluctuating space-times with non-trivial metric fluctuations [23, 27].

In this case, by measuring the flux states of the RF SQUID as explained above, one can evaluate the shaping of the decoherence time function, which should be the product of two exponentials, with exponents proportional to t^2 and t for the quantum-gravity and ordinary dissipation damping, respectively. As far as I am aware, no further progress or realisation of the above-suggested QG-decoherence measurements took place, unfortunately, but I believe that the great scientific insights of Prof. Diambrini Palazzi should be pursued in the future. Searching for quantum coherence loss due to gravitational effects is an interesting avenue of research in our quest for QG.

3 Quantum-Gravity Decoherence and CPT Breakdown: the ω-Effect in Entangled Neutral-Meson States

QG-induced decoherence has another effect, which is not associated with time damping of interference term in particle oscillations. This brings me to the second part of my contribution, to which the name of Prof. Diambrini Palazzi is indirectly associated with. Apart from his interest in QG-induced decoherence, as described above, his name is associated with this second part of my contribution implicitly through his ex-student, Prof. Antonio Di Domenico, who (surely inspired by him on these studies) leads the working group of the KLOE-2 experimental collaboration at DAΦNE that is currently searching for such an effect [19], among many other issues of course in meson physics.

The starting point of my discussion is a theorem due to R. Wald [30] according to which, if there is QG decoherence in the low-energy physics, due to inaccessible

QG degrees of freedom, then the CPT quantum mechanical operator that would otherwise generate the symmetry in a relativistic local field theory [31] is *ill-defined*. This effect is exclusive to meson factories and is associated with appropriate modifications to the Einstein-Podolsky-Rosen (EPR) correlators of entangled neutral meson states, to be discussed below. Such modifications are termed in Ref. [32] as the "ω-effect". These effects are qualitatively similar for Kaon [32] and B-meson factories [33, 34], but in Kaon factories there is a particularly good decay channel, that in which both correlated Kaons decay to $\pi^+\pi^-$, in which the sensitivity of the ω-effect increases because of CP Violation effects. Indeed, in such a case, the complex parameter ω, parametrizing the relevant EPR modifications [32], appears in the relevant observables in the particular combination $|\omega|/|\eta_{+-}|$, with $|\eta_{+-}| \sim 10^{-3}$ the CP Violation amplitude. In the case of B-meson factories, on the other hand, one should focus instead on the "same-sign" di-lepton channel [33, 34], where high statistics occurs, but still this cannot rival the high sensitivity of the neutral Kaon system.

To understand in simple terms what the ω-effect is about we should first mention that, prior to the work of [32], in the case of ϕ factories, it was *claimed* that, due to EPR correlations, *irrespective* of CP, and CPT violation, the *final state* in ϕ decays: $e^+e^- \Rightarrow \phi \Rightarrow K_S K_L$ always contains $K_L K_S$ products (where $K_{L(S)}$ are the physical Long-(Short-) lived Kaon mass eigenstates (in the Weisskopf-Wigner approximation), which are different from the CP eigenstates). This is a direct consequence of imposing the requirement of *Bose statistics* on the state $K^0\overline{K}^0$ (to which the ϕ decays). This, in turn, implies that the physical neutral meson-antimeson state must be *symmetric* under C$\mathcal{P}$, with C the charge conjugation and $\mathcal{P}$ the operator that permutes the spatial coordinates. Hence, the initial entangled state (after the decay of a ϕ meson in a ϕ factory that we concentrate our attention here for concreteness) is:

$$
\begin{aligned}
|i> &= \frac{1}{\sqrt{2}}\Big(|K^0(\vec{k}), \overline{K}^0(-\vec{k})> - |\overline{K}^0(\vec{k}), K^0(-\vec{k})>\Big) \\
&= \mathcal{N}\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) \ ,
\end{aligned}
$$

with the normalization factor $\mathcal{N} = \frac{\sqrt{(1+|\epsilon_1|^2)(1+|\epsilon_2|^2)}}{\sqrt{2}(1-\epsilon_1\epsilon_2)} \simeq \frac{1+|\epsilon^2|}{\sqrt{2}(1-\epsilon^2)}$, and

$$
K_S = \frac{1}{\sqrt{1+|\epsilon_1^2|}}\left(|K_+> + \epsilon_1|K_->\right) \ ,
$$

$$
K_L = \frac{1}{\sqrt{1+|\epsilon_2^2|}}\left(|K_-> + \epsilon_2|K_+>\right) \ ,
$$

where ϵ_1, ϵ_2 are complex parameters, such that $\epsilon \equiv \epsilon_1 + \epsilon_2$ denotes the CP- & T-violating parameter, whilst $\delta \equiv \epsilon_1 - \epsilon_2$ parametrizes the CPT & CP violation within quantum mechanics. The $K^0 \leftrightarrow \overline{K}^0$ or $K_S \leftrightarrow K_L$ correlations are apparent after evolution, at any time $t > 0$ (with $t = 0$ taken as the moment of the ϕ decay).

In the above considerations there is an implicit assumption, which was noted in [32]. The above arguments are valid independently of CPTV but only under the provision that such violation occurs within quantum mechanics, *e.g.*, due to spontaneous Lorentz violation, where the CPT operator is well defined but is not commuting with the Hamiltonian of the particle system.

If, however, CPT is *intrinsically* violated, in the sense of being ill-defined as a result of decoherence in space-time foam models [30], the concept of the "antiparticle" may be *modified* perturbatively! The perturbative modification of the properties of the antiparticle is important, since the antiparticle state is a physical state which exists, despite the ill-definition of the CPT operator. However, the antiparticle Hilbert space will have components that are *independent* of the particle Hilbert space. In such a case, the neutral mesons K^0 and $\overline{K}^0$ should *no longer* be treated as *indistinguishable particles*. As a consequence [32], the initial entangled state in ϕ factories $|i>$, after the ϕ-meson decay, will acquire a component with opposite permutation ($\mathcal{P}$) symmetry:

$$\begin{aligned} |i> &= \Big[\frac{1}{\sqrt{2}}\Big(|K_0(\vec{k}), \overline{K}_0(-\vec{k})> - |\overline{K}_0(\vec{k}), K_0(-\vec{k})>\Big) \\ &\quad + \frac{\omega}{2}\Big(|K_0(\vec{k}), \overline{K}_0(-\vec{k})> + |\overline{K}_0(\vec{k}), K_0(-\vec{k})>\Big)\Big] \\ &= \Big[\mathcal{N}\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) \\ &\quad + \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big], \end{aligned} \tag{9}$$

where $\mathcal{N}$ is an appropriate normalization factor, and $\omega = |\omega|e^{i\Omega}$ is a complex parameter, parametrizing the intrinsic CPTV modifications of the EPR correlations. Notice that, as a result of the ω-terms, there exist, in the two-kaon state, K_SK_S or K_LK_L combinations, which entail important effects to the various decay channels. Due to the ω-effect there is *contamination* of $\mathcal{P}$(odd) state with $\mathcal{P}$(even) terms. The ω-parameter controls the amount of contamination of the final $\mathcal{P}$(odd) state by the "wrong" ($\mathcal{P}$(even)) symmetry state. A time evolution of the ω-terms, even in a purely unitary Hamiltonian evolution, will lead [32, 33] to observable differences in the final states, as compared with the CPT conserving case, that can be tested experimentally in principle, as we shall describe briefly below, and in fact constitute, if observed, rather "smoking-gun" evidence of this type of decoherence-induced CPT Violation.

Estimates of the ω-effect can be given in the context of specific models for QG-induced decoherence, as, for instance, is the so-called D-particle foam model [35], where the space-time foamy structures are provided by fluctuating brane defects on brane worlds. Interactions of neutral mesons with such defects may induced appropriate particle/antiparticle oscillations, leading in the appearance of ω-like contamination effects in the initial state after the decay of the ϕ meson. In the analysis of [35] the order of magnitude of such effects has been found by averaging the matter-probe density matrix over the random variables r_i, which express the fraction of the local incident momentum along the $i = 1, 2, 3$ direction that is transferred during the scattering of the neutral meson with a *single* D-particle defect in the foam, *i.e.* $\Delta\vec{k}_i = r_i\, k_i$ (no sum over i). We assume that the variables r_i have a variance $\ll r_i\, r_j \gg = \xi^2\, \delta_{ij}$, where $\ll \cdots \gg$ denotes average over statistical populations of stochastically fluctuating D-particle foam defects, with $\ll r_i \gg = 0$. These variables are treated as independent variables between the two meson particles of the initial state.

We then observe [35] that only terms of order $|\omega|^2$ will survive in the analysis, with the order of $|\omega|^2$ in the initial state of the entangled Kaons being [35]:

$$|\omega|^2 \sim \xi^2 g_s^2 \frac{(m_1^2 + m_2^2)}{M_s^2} \frac{k^2}{(m_1 - m_2)^2} \ , \tag{10}$$

where m_i, $i = 1, 2$ are the masses of the two physical Kaon states, M_s/g_s is the mass of the D-particle, playing the rôle of the QG scale $M_{\rm QG}$ in this specific problem, and the (variance) factor ξ^2 takes proper account of statistical (over populations of D-particles) effects, that might be present during the initial decay of the ϕ-meson, such as density of foam *etc.* For the case of a single D-particle present during the ϕ-meson decay, this factor is of order $\xi = \mathcal{O}(1)$, if substructure of the mesons is ignored when quantum gravitational interactions are considered. In realistic situations, however, where the strong interaction substructure of the Kaons is taken into account, such effects are also absorbed (in a sort of mean-field way) into this parameter, which thus may no longer be of order one, even for a single fluctuating D-particle. In fact, there might be a strong-interaction suppression of the effects due to the D-particle interactions with the (electrically neutral) gluon constituents of the mesons, in which case $\xi \ll 1$. At present, such detailed calculations have not been performed.

The result (10), implies that, for neutral Kaons in a ϕ factory (with $m_1 - m_2 = m_L - m_S \sim 3.48 \times 10^{-15}$ GeV), interacting with D-particles of Planckian-size mass $M_s/g_s \sim 10^{19}$ GeV, one has the following estimate:

$$|\omega| = \xi \mathcal{O}\left(10^{-5}\right) \ , \tag{11}$$

Thus, we see that the near degeneracy of the two mass-eigenstates of the neutral mesons, $(m_1 - m_2)/m_1 \ll 1$, provides the appropriate *magnifying* effects of an otherwise tiny quantum-gravity effect, suppressed by the square of the quantum-gravity mass scale, here the mass M_s/g_s of the D-particle defect in the foam.

Experimentally, the situation concerning the most recent bounds on $|\omega|$ parameters can be summarised as follows: the KLOE experiment at DAΦNE has released the latest measurement of the ω parameter [19]:

$$\begin{aligned} \mathrm{Re}(\omega) &= \left(-1.6^{+3.0}_{-2.1} \pm 0.4\right) \times 10^{-4} \;, \\ \mathrm{Im}(\omega) &= \left(-1.7^{+3.3}_{-3.0} \pm 1.2\right) \times 10^{-4} \;, \\ |\omega| &< \; 1.0 \times 10^{-3} \;\; \text{at 95 \% C.L.} \end{aligned} \tag{12}$$

One can constrain the ω parameter significantly in upgraded facilities. For instance, there are the following perspectives for KLOE-2 at (the upgraded) DAΦNE-2 [19]: $\mathrm{Re}(\omega),\ \mathrm{Im}(\omega) \longrightarrow 2 \times 10^{-5}$. Thus we see that such searches in the next generation facilities can indeed falsify some models of D-particle foam where ω-effects in the initial state arise as a result of foam effects on the decay of the ϕ-meson, provided ξ is of order $\mathcal{O}(1) - \mathcal{O}(10^{-1})$.

A detailed analysis of various physically interesting observables in a ϕ-factory, including identical final states, has been performed in [36], where we refer the reader for details on the form and the magnitude of the ω-like effects, and how the latter can be disentangled from ordinary physics dissipative background effects or other types of decoherent QG Lindblad-type [11] evolution.

4 Conclusions

In this contribution to the volume that commemorates the scientific insights of Professor Diambrini Palazzi I have discussed potential ways of experimentally testing decoherence of quantum matter induced by Quantum Gravity. I have discussed two rather diverse ways of potentially detecting QG-induced decoherence: one, through measurements in (a network of) SQUIDs, which was one of the research areas which Professor Diambrini Palazzi had a direct research interest on, and the other a rather indirect way, exploiting the fact that QG decoherence may cause the generator of the CPT symmetry of the effective low-energy theory to be ill-defined. The latter leads, as a consequence, to the modification of the EPR correlations of entangled particle physics states in meson factories, which in the case of neutral Kaons provides a “smoking-gun” type evidence for this kind of CPT Violation and the associated decoherence. Prof. Diambrini Palazzi surely had an inspiring influence on his ex-student, Prof. A. Di Domenico, who is currently leading the studies inside the KLOE-2 experimental collaboration looking for signatures associated with this and other QG-decoherence effects.

At present there is no experimental evidence for decoherence or any other signature of QG. Nevertheless, the last decade has seen a considerable theoretical effort of models of QG that could potentially be realised in Nature, some of which violate Lorentz symmetry, while others violate just quantum coherence and/or CPT symmetry, without necessarily violating Lorentz symmetry (see, for instance, Ref. [37]). It is surprising that several of such models are already falsified by either terrestrial or astrophysical/cosmological experiments/observations. Nevertheless, the road towards an understanding of QG still looks difficult and long but surprises may be around the corner. It is my firm belief that QG-induced decoherence, independent of whether Lorentz symmetry is violated or not, is probably the most promising way of detecting signals of this elusive theory. Professor Diambrini Palazzi's scientific insights on this field, as a result of his work with SQUIDs, may not take long to be realised. Time will show....

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