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Quantum Decoherence in Neutrino Oscillations

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Quantum decoherence in neutrino oscillations was theorized almost 50 years ago, however there is still no clear theoretical understanding of this phenomenon, not even agreement on whether or not it could be observed at all. Treating all particles, including the source and detector, consistently in QFT, we are working on a model where the decoherence emerges from the time evolution of the initial state. We started by studying some simplified cases, obtaining nonetheless interesting results: we have shown that environmental interactions play crucial role in the emergence of decoherence, and if the neutrino creation happens in vacuum there is no maximal coherence length. We have also shown that some of the assumptions commonly used in literature (such as the covariance of the wavepackets) are inconsistent, since the time evolution would break the Lorentz invariance; moreover we have seen that, contrary to the usual intuition, the uncertainty on the detector momentum does not always play a relevant role in decoherence, at least as long as the detector particle is non-relativistic, since its contribution is suppressed by a factor proportional to p/M. Finally, we also notice the emergence of a new quantum effect: when the first neutrinos arrive, the oscillations do not starts immediately but only a very short amount of time; however, since the time window when this effect would be observable is extremely small, the precision required to measure such an effect is most likely well beyond the current technical capabilities

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1. The Model

In any realistic scenarios, neutrinos must be described by wavepackets, which are localized in space. However different mass eigenstates will propagate at different velocities and, while traveling, they will separate: if this separation is larger than the dimension of the wavepacket itself we will have quantum decoherence and the oscillations will be dampened. Even if this effect was first theorized almost 50 years ago, there is still not a clear theoretical understanding of such a phenomenon.

In literature we can find many different approaches, with sometimes contradicting predictions, that can be divided into two categories (see for example [1] for a more detailed overview): those working within a Quantum Mechanic (QM) framework, where the neutrinos are described by rigid wavepackets, which are not created nor evolved dynamically, or those which use a Quantum Field Theory (QFT) approach. The main problem is that crucial parameters, such as the shape and dimension of the wavepacket, must be introduced by hands in most of these approaches and are usually evaluated using order-of-magnitude arguments, which can lead to very different predictions.

Why it is important to understand decoherence? We are entering in a new precision era of neutrino physics; for example, JUNO will measure most of the mixing parameters up to the sub-percentage range [2]. In such a scenario, an excellent understating of the oscillation mechanism is required: indeed, decoherence does not have to completely cancel the oscillations; with such a precision, even a small modification of the oscillation probability could affect the final result [3].

In order to get a better understanding of the mechanisms beyond decoherence, we have been developing a model, using a QFT approach: all the particles are described by fields, the initial conditions are fixed by defining an initial state, that will be evolved in time using the time-evolution operator U. We started by considering some very simplified cases, for example taking into account only the neutrino production and not its detection [4, 5], which were included later on [6, 7], obtaining nonetheless very interesting results that will be presented in the next section. Even if we have inevitability to rely on some assumptions and approximations, that will be discussed more in detail here, our approach allow us treat the fields dynamically and consistently with QFT.

In our model we work in 1+1 dimensions, and we consider only scalar fields. These could seem very strong approximations, since they clearly do not describe any realistic scenario, however they are unlikely to change qualitatively the mechanism beyond decoherence, which is what we want to understand here, so they do not constitute a problem. We have also not taken into account environmental interactions so far, which is equivalent to assume that the creation and detection of the neutrino happens in vacuum; as we will see in the next section, this instead does affect significantly the decoherence, and a good understanding of what is the role of the environmental interactions in the emergence of such a phenomenon is one of the ultimate goals of this project.

In our model, neutrinos are produced and detected via three-body-decays, namely

$$S_H \to S_L + \nu_i \qquad n_j + D_L \to D_H \tag{1}$$

In this presentation, we will consider only the survival probability, so $i = j$. The initial state of our system only contains the heavy source and light detector particles:

$$|0\rangle = \int \mathrm{d}p\mathrm{d}q f(p) g(q) |S_H, p; D_L, q\rangle \tag{2}$$

where $f(p)$ and $g(q)$ are the wavepackets describing the initial states of the source and detector particle, respectively. This state is evolved using the time-evolution operator

$$|t\rangle = U(t)|0\rangle \qquad U(t) = e^{-iHt} \qquad H + H_0 + \lambda H_I \tag{3}$$

where H_0 is the free Hamiltonian and H_I contains the interactions (see [7] for more details). All the information about the neutrino creation and detection are contained in the operator U, and no additional input is required. The transition amplitude is computed by projecting the time-evolved initial state into a final state; since we are in vacuum, there is nothing that can measure the final momenta of the source and the detector particle, so they will be described by plane waves of momentum l and k, respectively

$$A(k,l) = \langle S_L, l; D_H, k|t\rangle = \int \mathrm{d}p\mathrm{d}q f(p)g(q)\langle S_L, l; D_H, k|e^{-iHt}|S_H, p; D_L, q\rangle \tag{4}$$

The transition probability $P(l,k)$ is calculated, as usual, by taking the modulus squared of the amplitude; if, for example, we are not interested in some of the parameters (such as the final momentum of the source particle), the integral of $P(l,k)$ should be considered

$$P(k,l) = |A(k,l)|^2 \qquad P(k) = \int \mathrm{d}l P(k,l) \qquad P = \int \mathrm{d}k P(k) \tag{5}$$

It should be noticed that, while the integrals over p and q are coherent, the one over l (for example) is not, since each l corresponds to a separate final state, and their phases do not contribute to the transition amplitude.

2. Results

Now we will explain more in details how, using our model, it is possible to see that the environmental interactions are crucial for decoherence; later we will briefly present some of the other results as well.

2.1 No maximal coherence length in vacuum

The time evolution operator $U(t)$ can be written as

$$U(t) = e^{-iHt} = \sum_{k=0}^{\infty} \frac{(-i(H_0 + \lambda H_I)t)^k}{k!} \tag{6}$$

We will use an additional approximation, considering only the terms with exactly two entries of λH_I, which is equivalent to consider only the tree-level diagrams: such an approximation is fully justified when the lifetime of the source particle is considerably longer than t, *i.e.* the duration of the experiment.

$$U(t) \to \sum_{k=0}^{\infty}\sum_{n=0}^{k-2}\sum_{m=0}^{k-n-2} \frac{(-it)^k}{k!} H_0^n H_I H_0^m H_I H_0^{k-n-m-2} \tag{7}$$

Using this approximation, the matrix elements that appears in Eq. (4) reads (see [6] and [7] for more details)

$$A(k,l) = \int \mathrm{d}p\mathrm{d}q f(p)g(q) \int_0^t \mathrm{d}t_1 \int_0^{t-t_1} \mathrm{d}T e^{-i(\mathcal{E}_0 t_1 + \mathcal{E}_1 T + \mathcal{E}_2(t-t_1-T))} \tag{8}$$

where t_1 and T are the emission and detection time, respectively; $\mathcal{E}_0$, $\mathcal{E}_1$ and $\mathcal{E}_2$, are the total energy of the system before the neutrino emission, while it's propagating and after it is detected, and $\Delta\mathcal{E}_{ij} = \mathcal{E}_i - \mathcal{E}_j$. We remind the reader that all the $\mathcal{E}_i$'s depend on the momenta as well, even if such a dependence is left implicit.

One of the consequence of this expression is that in such a scenario, *i.e.* where the environmental interactions are not present (for example, if the neutrino creation happens in vacuum), there is no decoherence due to the separation of the wavepackets at all, regardless of the baseline and the dimension of the neutrino wavepacket [7].

Why this is happening? The localization of the neutrino wavepacket is related to the localization in space and time of the neutrino production [8]; such an event is usually not observed directly in an experiment, but that is not required: the environmental interactions can act as "observer" as well [9]. In the scenario we are considering, since these interactions are not present, the neutrino creation and detection are not observed and therefore there cannot be decoherence; indeed, as we can see from Eq. (8), the transition amplitude is the **coherent** integral over all the creation and detection times; this means that, even if the wavepackets created at time t_p are completely separated after traveling a distance L, they can still interfere with the wavepackets created at time $t_p \pm \epsilon$ and the oscillations are still present.

Does this means that the environmental interactions are a crucial ingredient for decoherence, *i.e.* we cannot have the latter without the former? Not necessarily. For example, if the both the initial and the final states would be localized, kinematic would constrain the location of the neutrino production and detection as well. Moreover, in our calculation we assumed that the lifetime of the source particle is considerably shorter than the duration of the experiment; if the opposite is true, however, the neutrino production would be (partially) localized by the decay probability itself. In order to take into account for this effect we need to go beyond the tree-level order approximation we have used; luckily, these kind of calculations are not new in physics, and they would be very similar to the ones used in the computation of the Quantum Zeno Effect (see, for example [10]); using similar techniques we are currently trying to compute the non-perturbative transition amplitude to see if and how the decoherence could emerge in such a scenario.

2.2 Other Results

Among the other results we obtained it is worth mentioning the following:

- One of the assumptions commonly used in literature is that neutrinos must be described by covariant wavepacket [11, 12]. However we showed that such an assumption is inconsntent: even if, at a time t_0, the system is described by covariant wavepackets, the time-evolution would break the Lorentz invariance [5].

- We have found evidence of a new quantum effect: for a very short time windows after the first neutrinos arrive, the oscillations have not started yet. If the detector is placed at the oscillation minimum and has a sufficiently high time resolution, it should be possible to see the detection probability decrease with time, due to the destructive interference [7]. The sensitivity required to see such an effect is, most likely, well beyond our present technical capabilities, however we plan to investigate such an effect more in details, to see precisely what are the requirements for its observation .

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