Decoherence in Neutrino Oscillations

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Decoherence

If neutrinos are in an eigenstate of the momentum, they cannot oscillate, because plane waves are completely delocalized. However, in all realistic scenarios, they can be described by wavepackets, with a certain distribution both in the position and momentum space. Each mass eigenstate will propagate with a different velocity, so the wavepackets will separate: if this separation is larger than the dimension of the wavepackets, the interference cannot take place anymore and the oscillations will be damped.

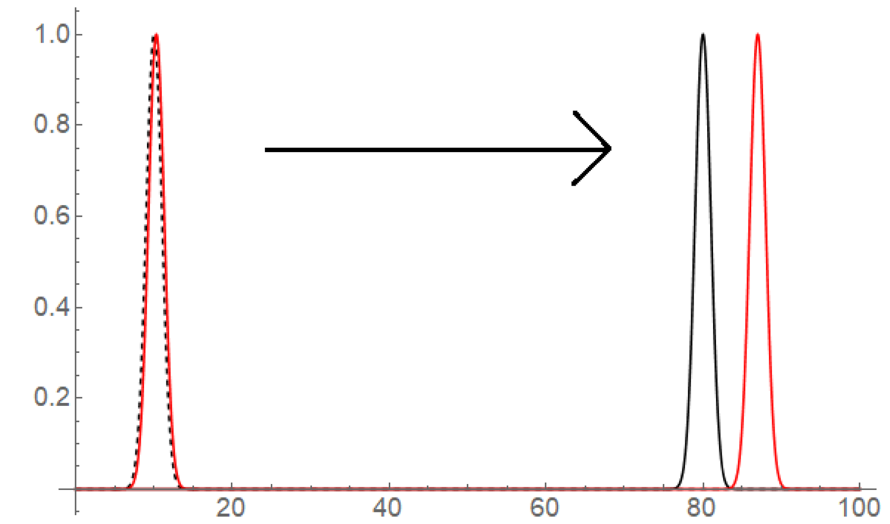

Figure 1: Wavepackets separate after propagating

So far there is no rigorous theoretical description for this phenomenon, even if it was first theorized in the 70's; there is not even consensus on whether quantum decoherence could be observed at all (because there are many other effects that can damped the oscillations, and it is not clear if it is possible to disentangle them).

We developed a model to study in a more consistent way decoherence in neutrino oscillations [1, 2]. We consider both the production and detection of the neutrino, via the processes

$$\phi_{S,H} \to \phi_{S,L} + \nu_i \qquad \phi_{D,L} + \nu_i \to \phi_{D,H}$$

Calling x the distance between the source and the detector, the initial state is defined as

$$|\Omega\rangle = \int \mathrm{d}p\mathrm{d}q f(p) g(q) e^{ixq} |S_H, p; D_L, q\rangle$$

where $f(p)$ and $g(q)$ describe the initial states for the source and detector particle, respectively. The transition amplitude at the time t is given by

$$A(k,l) = \langle S_L, l; D_H, k| e^{iHt} |\Omega\rangle$$

Detector Spread

The dimension of the detector wavepacket could be relevant for the decoherence, because in that range the integration must be coherent. Since the spatial uncertainty is inversely proportional to the uncertainty on the momentum, it was argued that quantum decoherence cannot be observed, because if the momentum precision is sufficiently high to observe the oscillation, the spread of the detector wavepacket would ensure that there is no decoherence [5]. However, while studying our model, we realized that this argument does not imply that quantum decoherence is unobservable [3]. Indeed, the main problem is that, due the Heisenberg principle, the uncertainty on the spatial is related to the one on the momentum, however in order to detect neutrino oscillations we need a good energy resolution, not momentum. We have

$$\delta E = \delta p v \qquad v = \frac{p}{E}$$

where v is the velocity, and $c = 1$. In all the realistic scenarios, the neutrino is ultrarelativitstic, hence $v_\nu \simeq 1$, however usually the detector particle is non-relativistic, so even if the detector wavepacket is very peaked (*i.e.* there is a large uncertainty on the momentum) δE will be suppressed.

References

[1] J. Evslin, H. Mohammed, E. Ciuffoli, Y. Zhou, "Entangled Neutrino States in a Toy Model QFT", Eur.Phys.J.C 79 (2019) 6, 491

[2] H. Mohammed, E. Ciuffoli, J. Evslin, "Neutrino Oscillations in the Vacuum", arXiv: 1909.13529 [hep-ph]

[3] E. Ciuffoli, J. Evslin, H. Mohammed, "Approximate Neutrino Oscillations in the Vacuum", arXiv: 2001.03287 [hep-ph]

[4] H. Mohammed, E. Ciuffoli, J. Evslin, "Wave Packets Losing Their Covariance", Nucl.Phys.B 953 (2020) 114972

[5] Kirk McDonald, "Oscillations and decoherence", talk at NuFact2013, Beijing

Delayed Oscillations

In order to compute the transition amplitude, we need to integrate over several quantities, such as the momenta of the source and detector particles, the time of creation and propagation of the neutrino, etc... The latter is the integration over a Gaussian that can be approximated with excellent precision with a delta function. It would require an incredible precision to probe the shape of the Gaussian.

However, if this could be done, it would be possible to observe a new quantum effect [3]: the oscillations measured would not obey the usual formula, instead one would observe that in a very short time window after the neutrinos arrive, they have not yet oscillated. If the detector is placed at the oscillation minimum, the neutrino detection probability actually then decreases with time at the oscillation minimum, as the oscillations turn on, due to destructive interference in the time integrals in our amplitude. This effect, albeit very interesting, is most likely undetectable given the resolution that is currently achievable, however it will be investigated in a future project, where we will study the requirements for its observation.

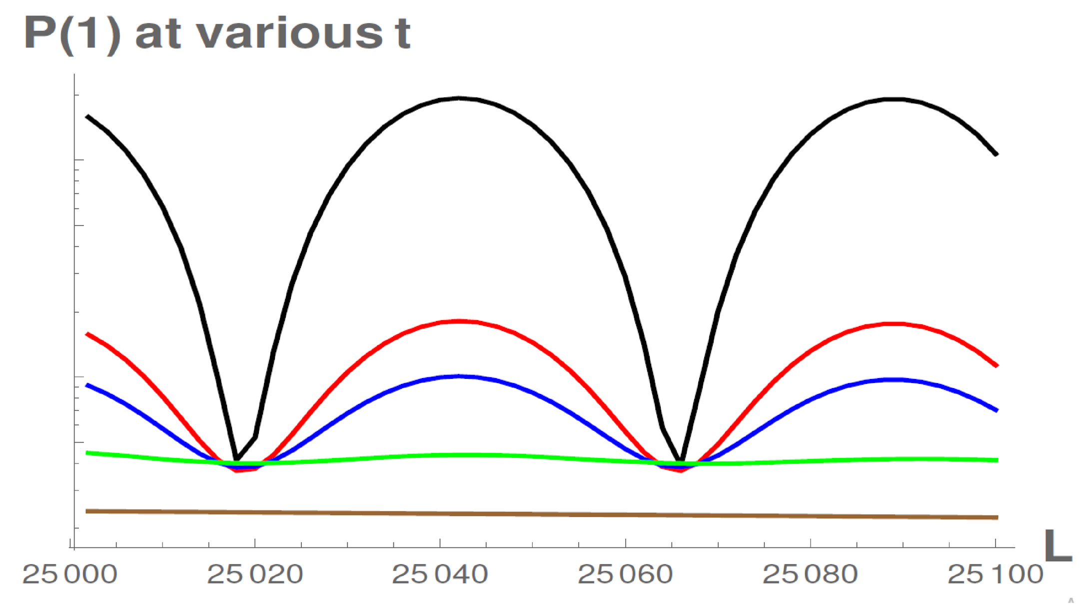

Figure 2: P(k) at different times t: t = 28,000 (brown) 29,000 (green) 30,000 (blue) 31,000 (red) and 40,000 (black). Given the neutrino mass and momentum assumed here, they arrive at $t \simeq 29000$, however the oscillations begin shortly after.

Environment

The environmental interactions are crucial for the quantum decoherence [3]: they measure the position in time and space of the creation of the neutrinos, which is crucial for the spatial localization of the wavepackets. We have showed that, if they are not taken into account, the quantum decoherence does not happen, and there are oscillations long after the maximum distance (assuming that the times considered are smaller than the lifetime of the particle, otherwise that would localize the neutrino creation).

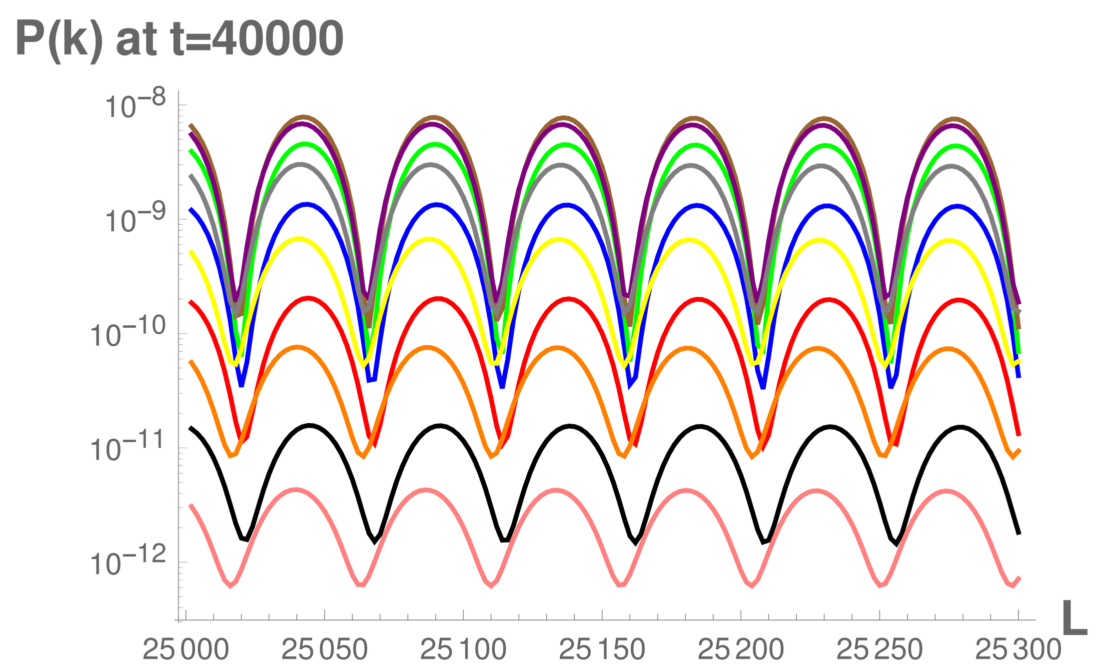

Figure 4: Given the masses and energy spread of the source particle, we would not expect any oscillation for $L > 400$, however they are still present at $L \simeq 25000$.

Covariance

In some works in the literature it is assumed that the neutrino wavefunction is covariant. We have proven that it is not the case [4]. Using our model, we considered the creation of a neutrino, assuming that at the moment $t = 0$ the source particle is described by a covariant wavefunction: we showed that, even if we start with such conditions, the neutrino wavefunction at time $t > 0$ is no longer covariant.

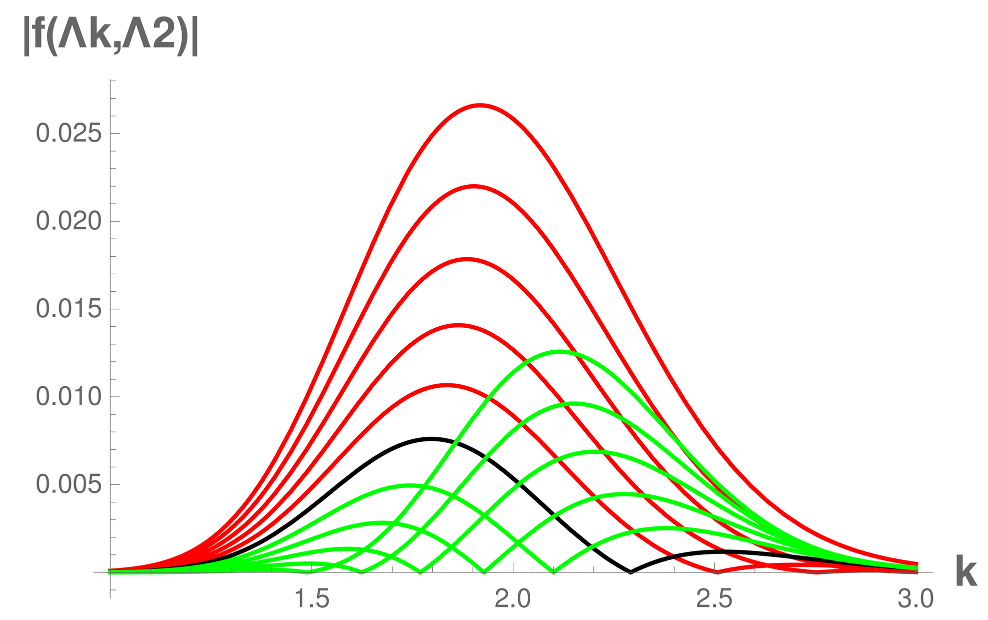

Figure 3: The neutrino wavefunction $f(\mathbf{k}, \tilde{\mathbf{p}})$ as a function of k ($\tilde{\mathbf{p}}$ indicates the average momentum of the neutrino) together with boosted wave functions $f(\Lambda\mathbf{k}; \Lambda\tilde{\mathbf{p}})$ at boost velocities from β=0.5 to 0.5 with steps of 0.1, with red, black and green corresponding to $\beta < 0$, $\beta = 0$ and $\beta > 0$, respectively.