# Kaon Interferometry and Quantum Gravity Phenomenology

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Uniwersytet Wrocławski

NCBJ

# Are we at the Dawn of Quantum Gravity Phenomenology?

- For most of the last quarter of the century the community has been trying to find traces of QG phenomena in astrophysical observations.
- Advantages: Highly energetic messengers and large distance as an amplifier.
- Disadvantages: Poor statistics and limited understanding of sources.

**Are We at the Dawn of Quantum-Gravity Phenomenology?**

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**Abstract.** A handful of recent papers has been devoted to proposals of experiments capable of testing some candidate quantum-gravity phenomena. These lecture notes emphasize those aspects that are most relevant to the questions that inevitably come to mind when one is exposed for the first time to these research developments: How come theory and experiments are finally meeting in spite of all the gloomy forecasts that pervade traditional quantum-gravity reviews? Is this a case of theorists having put forward more and more speculative ideas until a point was reached at which conventional experiments could rule out the proposed phenomena? Or has there been such a remarkable improvement in experimental techniques and ideas that we are now capable of testing plausible candidate quantum-gravity phenomena? These questions are analysed rather carefully for the recent proposals of tests of space-time fuzziness using modern interferometers and tests of dispersion in the quantum-gravity vacuum using observations of gamma rays from distant astrophysical sources. I also briefly discuss other proposed quantum-gravity experiments, including those exploiting the properties of the neutral-kaon system for tests of quantum-gravity-induced decoherence and those using particle-physics accelerators for tests of models with large extra dimensions.

**1 Introduction**

Traditionally the lack of experimental input [1] has been the most important obstacle in the search for "quantum gravity", the new theory that should provide a unified description of gravitation and quantum mechanics. Recently there has been a small, but nonetheless encouraging, number of proposals [2–9] of experiments probing the nature of the interplay between gravitation and quantum mechanics. At the same time the "COW-type" experiments on quantum mechanics in a strong (classical) gravitational environment, initiated by Colella, Overhauser and Werner [10], have reached levels of sophistication [11] such that even gravitationally induced quantum phases due to local tides can be detected. In light of these developments there is now growing (although still understandably cautious) hope for data-driven insight into the structure of quantum gravity.

The primary objective of these lecture notes is the one of giving the reader an intuitive idea of how far quantum-gravity phenomenology has come. This is somewhat tricky. Traditionally experimental tests of quantum gravity were believed to be not better than a dream. The fact that now (some) theory and (some) experiments finally "meet" could have two very different explanations:

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J. Kowalski-Glikman (Ed.): Proceedings 1999, LNP 541, pp. 1–49, 2000.

# Are we at the Dawn of Quantum Gravity Phenomenology?

- Maybe we should start looking at an observation setup that is better controlled?
  - ➢ QG induced noise in gravitational interferometers (Verlinde-Zurek).
  - ➢ Terrestrial accelerator experiments looking for minute CPT-invariance violation/deformations.
  - ➢ This talk is based on our works with Andrea Bevilacqua and Wojtek Wislicki, ArxiV 2310.05080 [hep-ph] and 2404.03600 [hep-ph]

## Are We at the Dawn of Quantum-Gravity Phenomenology?

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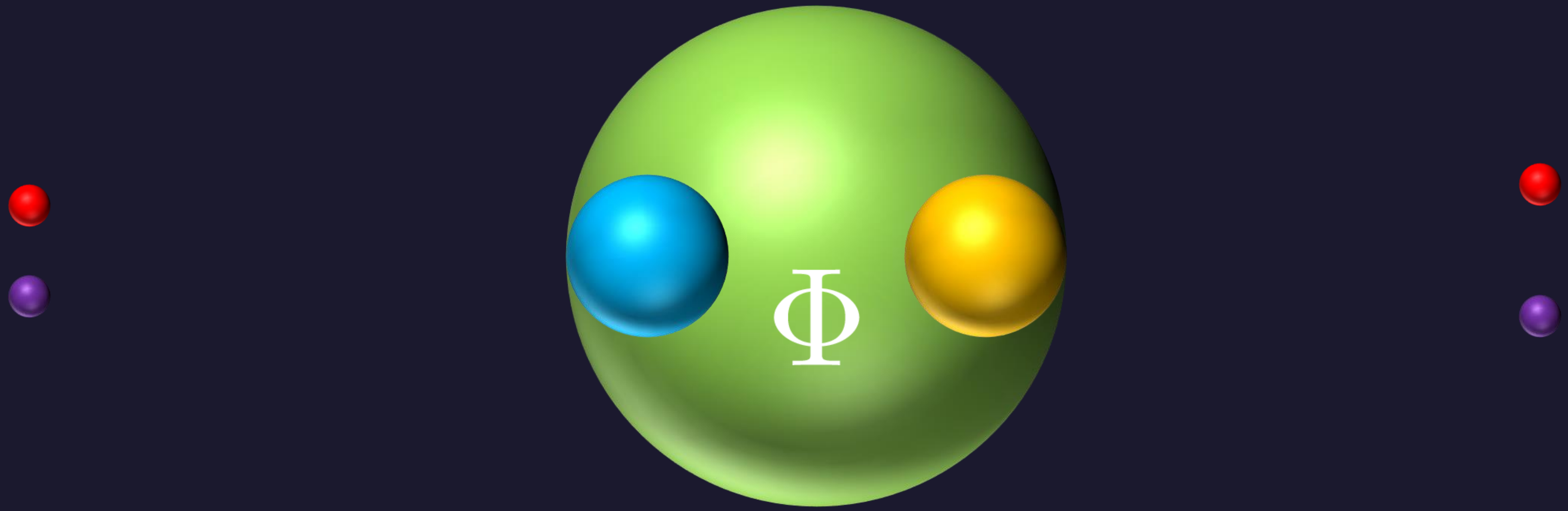
$$\Phi \to K^0 \bar{K}^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$$

- We consider the kaon-anti-kaon pair produced in the decay of the Φ(1020) resonance and the subsequent decay of kaons into a pair of two pions $\pi^+ \pi^-$.



# Kaon interferometry – the standard picture

- The $\Phi(1020)$ resonance decays into an entangled kaon-anti kaon pair (CP is a symmetry of strong interactions and $\Phi$ is a pseudescalar)

$$|\Phi\rangle_0 = \frac{1}{\sqrt{2}}\left(|K^0(\mathbf{p})|\overline{K}^0(-\mathbf{p})\rangle - |\overline{K}^0(\mathbf{p})\rangle|K^0(-\mathbf{p})\rangle\right)$$

- The (anti) kaon states are not eigenstates of the Hamiltonian (because of the weak interactions) and to investigate their time evolution we must express them in terms of energy eigenstates, called short- and long-lived kaons

$$|K_{S,L}\rangle = \frac{1}{\sqrt{2(1+|\varepsilon \pm \delta|^2)}}\left[(1+\varepsilon \pm \delta)\big|K^0\rangle \pm (1-\varepsilon \mp \delta)|\overline{K}^0\rangle\right]$$

- The experimental value of $|\varepsilon|$ is of order $2\times 10^{-3}$ and significantly differs from zero, whereas the value of $|\delta|$ is of order $10^{-4}$ and is consistent with zero within one standard deviation.

$$|\Phi\rangle_0 = N(\varepsilon,\delta)\left(|K_L(\mathbf{p})|\overline{K}_S(-\mathbf{p})\rangle - |\overline{K}_S(\mathbf{p})\rangle|K_L(-\mathbf{p})\rangle\right)$$

# Kaon interferometry – the standard picture

- Now we consider decay of kaons into pions $\pi^+ \pi^-$ (there are some other decay channels, of course.) The decay rate into final states $|f_{1(2)}\rangle$ at times $t_{1(2)}$ is generally

$$I(f_1, t_1; f_2, t_2) = |\langle f_1, t_1; f_2, t_2 | H | \Phi \rangle|^2$$

- It is convenient to introduce variables $T = t_1 + t_2$ and $\Delta t = | t_1 - t_2 |$ and integrate over T from $\Delta t$ to infinity, to find

$$I(\Delta t) = \frac{4|f_L|^2 |f_S|^2}{\overline{\Gamma}} \left[ e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2e^{-\overline{\Gamma} \Delta t} \cos(\Delta E \Delta t) \right]$$

$$f_{S,L} = \langle \pi^+ \pi^- | H | K_{S,L} \rangle \,, \quad \Delta E = E_L - E_S \,, \quad \overline{\Gamma} = \frac{1}{2}(\Gamma_L + \Gamma_S)$$

- The ratio of the amplitudes $\eta_{+-} = f_L/f_S \sim \varepsilon \sim 10^{-3}$ is a small parameter. As we will see its inverse serves as an amplifier. The presence of the cos term is the reason for the name “interferometry”.

# Kaon interferometry – the standard picture

- In DaΦne/CLOE experiment the Φ resonance was created at rest. If instead we boost the Φ resonance with large boost parameter $\gamma \gg 1$, the kaon state will be

$$|\Phi\rangle_0^\gamma = \frac{1}{\sqrt{2}}\Big(|K_\gamma^0(\mathbf{P},\mathbf{p})|\overline{K}_\gamma^0(\mathbf{P},-\mathbf{p})\rangle - |\overline{K}_\gamma^0(\mathbf{P},\mathbf{p})\rangle|K_\gamma^0(\mathbf{P},-\mathbf{p})\rangle\Big)$$

$$|\mathbf{P}| = \gamma M \gg |\mathbf{p}|$$

# Kaon interferometry – BMP model

- In 2003 J. Bernabeu, N. E. Mavromatos and J. Papavassiliou proposed a model to test CPT-violation in the context of kaon interferometry. They assume presence of an additional CPT-violating term (ω-term).

$$|\Phi\rangle_\omega = \frac{1}{\sqrt{2}}\Big(|K^0(\mathbf{p})\rangle|\overline{K}^0(-\mathbf{p})\rangle - |\overline{K}^0(\mathbf{p})\rangle|K^0(-\mathbf{p})\rangle\Big) + \frac{\omega}{\sqrt{2}}\Big(|K^0(\mathbf{p})\rangle|\overline{K}^0(-\mathbf{p})\rangle + |\overline{K}^0(\mathbf{p})\rangle|K^0(-\mathbf{p})\rangle\Big)$$

- Experimentally, $\omega \sim 10^{-4}$, but compatible with $\omega = 0$.

# Discrete symmetries and κ-Poincarè

- The κ-Minkowski defining commutator

$$[x^0, x^i] = \frac{i}{\kappa} x^i$$

- is manifestly invariant under T and P symmetries (for T symmetry $x^0 \rightarrow -x^0$ is accompanied with $i \rightarrow -i$ ), and thus only C (and therefore CPT) can be modified (deformed).

# Discrete symmetries and κ-Poincarè

- Investigations in κ-deformed complex scalar field theory* led to the following properties of κ-deformed CPT:

1. The plane waves of the particles are labeled by momentum p, while the plane waves of the antiparticles are labeled by momentum antipode S(p).

2. C is undeformed for particles at rest; therefore, the masses of particles and anti-particles are equal. The effect of C- (CPT-)deformation is momentum dependent: the larger the momentum, the more sizable the deviation of C (CPT) is.

3. The boost operator does not commute with the C (and CPT); as a result, the decay rates of particles and antiparticles in motion are not the same. This effect might be observable e.g., for muons.

M. Arzano, A. Bevilacqua, JKG, G. Rosati, J. Unger, *Phys.Rev.D* 103 (2021) 10, 106015, 2011.09188 [hep-th] ; A. Bevilacqua, JKG, W. Wislicki, *Phys.Rev.D* 105 (2022) 10, 105004, 2201.10191 [hep-th]

# The κ-deformed model

- In the κ-deformed model, we consider the Φ resonance boosted with respect to its rest frame (contrary to DaΦne/CLOE), and neglecting the small momenta transversal to the boost we obtain

$$
\begin{aligned}
|\psi\rangle_\kappa &= \frac{1}{\sqrt{2}}\Big(|K^0(\mathbf{p})\rangle|\overline{K}^0(\mathbf{S}(p))\rangle - |\overline{K}^0(-\mathbf{S}(p))\rangle|K^0(-\mathbf{p})\rangle\Big) \\
&= 2^{-3/2}\Big(|K_L(-\mathbf{S}(p))\rangle|K_L(-\mathbf{p})\rangle - |K_L(\mathbf{p})\rangle|K_L(\mathbf{S}(p))\rangle \\
&+ |K_L(-\mathbf{S}(p))\rangle|K_S(-\mathbf{p})\rangle - |K_S(\mathbf{p})\rangle|K_L(\mathbf{S}(p))\rangle \\
&- |K_S(-\mathbf{S}(p))\rangle K_L(-\mathbf{p})\rangle + |K_L(\mathbf{p})\rangle|K_S(\mathbf{S}(p))\rangle \\
&- |K_S(-\mathbf{S}(p))\rangle|K_S(-\mathbf{p})\rangle + |K_S(\mathbf{p})\rangle|K_S(\mathbf{S}(p)\Big)
\end{aligned}
$$

$$
\mathbf{S}(p) \simeq -\mathbf{p}\left(1 + \frac{E}{\kappa}\right) + \mathcal{O}\left(\frac{1}{\kappa^2}\right)
$$

- Notice that contrary to the standard result the $K_L K_L$ and $K_S K_S$ terms are present.

# The κ-deformed amplitude

- The κ-deformed decay amplitude contains now 8 terms

$$\langle f_1, t_1; f_2, t_2 | H | \psi \rangle_\kappa = Q_1 - Q_2 + Q_3 - Q_4 - Q_5 + Q_6 - Q_7 + Q_8$$

$$Q_1 = \langle f_1 | K_L \rangle \langle f_2 | K_L \rangle e^{-iE_L t_1 - \Gamma_L t_1 + i\zeta t_1} e^{-iE_L t_2 - \Gamma_L t_2}$$

$$\zeta = \mathbf{p}^2 / \kappa$$

# The κ-deformed decay intensity

- We compute the decay intensity

$$I = |\langle f_1, t_1; f_2, t_2 | H | \psi \rangle_\kappa|^2$$

- and after integrating over $T = t_1 + t_2$ from $\Delta t = | t_1 - t_2 |$ to infinity we obtain

$$I_\kappa(\Delta t) = |C(\Delta t)|^2 + |W(\Delta t)|^2 + 2\Re[C(\Delta t) W(\Delta t)^*]$$

"Correct" terms

$|K_S\rangle |K_L\rangle$

"Wrong" terms

$|K_S\rangle |K_S\rangle$ $|K_L\rangle |K_L\rangle$

# The κ-deformed decay intensity

- Explicit expressions

$$|C(\Delta t)|^2 = \frac{2}{\overline{\Gamma}}|f_L|^2|f_S|^2\big(1+\cos(\zeta\Delta t)\big)\left[e^{-\Gamma_L\Delta t}+e^{-\Gamma_S\Delta t}-2e^{-\overline{\Gamma}\Delta t}\cos(\Delta E\Delta t)\right],$$

$$|W(\Delta t)|^2 = 2\big(1-\cos(\zeta\Delta t)\big)\Bigg[\frac{|f_L|^4}{\Gamma_L}e^{-\Gamma_L\Delta t}+\frac{|f_S|^4}{\Gamma_S}e^{-\Gamma_S\Delta t}$$

$$-2\Re\left(f_L^2\bar{f}_S^2\right)\frac{e^{-\overline{\Gamma}\Delta t}}{\overline{\Gamma}^2+(\Delta E)^2}\big(\Delta E\sin(\Delta E\Delta t)-\overline{\Gamma}\cos(\Delta E\Delta t)\big)\Bigg]$$

- The decay amplitudeof $K_L \to \pi^+\pi^-$ is supressed with respect to $K_S \to \pi^+\pi^-$ by the factor

$$|\eta_{+-}| = \left|\frac{f_L}{f_S}\right| \simeq 2\times 10^{-3}$$

# The setup

- We know that κ-deformation effects vanish when momenta of particle go to zero. This makes it possible to use the DaΦne/CLOE data, obtained in the case of the Φ resonance created at rest.
- Then we boost with the large boost parameter γ to magnify the κ-deformation effects. Decay widths contract as Γ' = Γ/γ, decay times dilate as t'= γ t and energies increase as E' = γ m. Therefore, the arguments ΓΔt of exponentials are Lorentz-invariant.

$$(\Delta E \Delta t)' = \gamma^2 \, \Delta m \Delta t$$

$$(\zeta \Delta t)' = \gamma^3 m^2 \Delta t/\kappa.$$

# Large boosts

- We are interested in the limit of large boosts, $\gamma \approx 10^2 - 10^5$. Neglecting $1/\gamma$ terms we get the final expression for decay intensities (the interference term is negligible)

$$|C(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2 |f_S|^4}{\overline{\Gamma}} 2\big(1+\cos(\zeta\Delta t)\big)\left[e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2e^{-\overline{\Gamma}\Delta t}\cos(\Delta E \Delta t)\right]$$

$$|W(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2 |f_S|^4}{\overline{\Gamma}} \big(1-\cos(\zeta\Delta t)\big)\left[|\eta_{+-}|^2 e^{-\Gamma_L \Delta t} + \frac{1}{|\eta_{+-}|^2} e^{-\Gamma_S \Delta t}\right]$$

- We see that, surprisingly, since $|\eta_{+-}| \approx 10^{-3}$ the `wrong' amplitude is enhanced compared to the `correct' one. This makes the effect observable, in principle.

# Phenomenology

- The modifications of decay intensity of kaons were not observed experimentally, but no dedicated analysis was ever performed.
- Let us discuss potentially observable effects, and the bounds that zero result would provide. There are three classes of potentially observable effects:
  1. Frequency of deformed oscillations.
  2. Intensity of wrong-parity oscillations.
  3. Resonant oscillations.

# Frequency of deformed oscillations

$$|C(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2|f_S|^4}{\overline{\Gamma}} 2\big(1+\cos(\zeta\Delta t)\big)\left[e^{-\Gamma_L\Delta t}+e^{-\Gamma_S\Delta t}-2e^{-\overline{\Gamma}\Delta t}\cos(\Delta E\Delta t)\right]$$

$$|W(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2|f_S|^4}{\overline{\Gamma}}\big(1-\cos(\zeta\Delta t)\big)\left[|\eta_{+-}|^2\, e^{-\Gamma_L\Delta t}+\frac{1}{|\eta_{+-}|^2}\, e^{-\Gamma_S\Delta t}\right]$$

- If we just concentrate on oscillations, we see that there are ones governed by $1\pm\cos(\zeta\Delta t)$ superimposed on the standard $\cos(\Delta E\Delta t)$. These modulations can be observed provided that the deformed oscillations with frequency $\zeta$ are not too slow compared to the undeformed ones with the frequency $\Delta E$.

- The boosted periods of normal oscillations, amounting to $1/\Delta E$, extend from $10^{16}$ GeV$^{-1}$ down to $10^{10}$ GeV$^{-1}$ for the corresponding Lorentz $\gamma$ in the range from $10^2$ to $10^5$. For the same range of $\gamma$, assuming $\kappa \approx M_{Pl}$ , the boosted deformed oscillation period $1/\zeta$ extends from $10^{13}$ GeV$^{-1}$ down to $10^{10}$ GeV$^{-1}$. It is thus seen that the two oscillation periods, $1/\Delta E$ and $1/\zeta$, become comparable only for large $\gamma \approx 10^5$, corresponding to protons of an energy of 100 TeV, yet unattainable in accelerators.

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# Frequency of deformed oscillations

- The unobservability of deformed oscillations can provide us an upper limit for. If one requires that $\cos(\zeta \Delta t)$ varies very slowly compared to $\cos(\Delta E \Delta t)$, which means $\zeta \ll \Delta E$, one translates this inequality into condition

$$\kappa \gg \gamma \times 0.5 \times 10^{14}\ \mathrm{GeV}$$

- For example, using energy of 10 TeV one gets a lower limit of at most $10^{17}$ GeV, still located below the Planck energy scale $10^{19}$ GeV. This provides us with an exciting possibility to limit $\kappa$ experimentally by pushing further up future accelerating technologies.

# Intensity of wrong-parity oscillations

$$|C(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2|f_S|^4}{\overline{\Gamma}} 2\big(1+\cos(\zeta\Delta t)\big) \left[e^{-\Gamma_L\Delta t} + e^{-\Gamma_S\Delta t} - 2e^{-\overline{\Gamma}\Delta t}\cos(\Delta E\Delta t)\right]$$

$$|W(\Delta t)|^2 \simeq \frac{|\eta_{+-}|^2|f_S|^4}{\overline{\Gamma}} \big(1-\cos(\zeta\Delta t)\big) \left[|\eta_{+-}|^2 e^{-\Gamma_L\Delta t} + \frac{1}{|\eta_{+-}|^2} e^{-\Gamma_S\Delta t}\right]$$

- In order to make the wrong parity unobservable, it must small compared to the correct one we must assume

$$1-\cos(\zeta\Delta t) < 10^{-6}$$

$$\kappa > 10^3 \, \frac{\gamma^3 m^2 \Delta t_r}{2}$$

- With currently available time resolutions and $\gamma = 10^3$ we get the bound

$$\kappa > 0.2 \times 10^{18} \text{ GeV}$$

# Resonant oscillations

- One can look for the resonant oscillations, which happen when the frequency $\zeta$ is exactly equal the frequency $\Delta E$. Denoting by $\gamma^*$ the boost for which it happens, we find

$$\kappa = \gamma^* \times 0.45 \times 10^{14} \ \mathrm{GeV}$$

- Looking for the resonance might be an efficient way to find the deformation parameter.

# Conclusions

- The distinctive feature of the model of Lorentz invariance deformations is that the magnitude of deviations from the predictions of the standard, undeformed, CPT-invariant theory is proportional to the momenta carried by kaons, and, if real, can be in principle observed.
- Together with the previous analysis of muon decay it shows that there seems to be a great potential to search for possible traces of Lorentz invariance deformations in high-energy accelerator experiments.
- It remains to be seen whether the required sensitivity can be achieved with the currently available accelerator/detector technologies, or whether we will have to wait for the next generation of machines.

# And that's it.
# Thank you.