Light new particles at the kaon experiments

Kohsaku Tobioka[a,b]

[a] Department of Physics, Florida State University, Tallahassee, FL 32306, USA
[b] KEK Theory Center, IPNS, KEK, Tsukuba 305–0801, Japan

E-mail: ktobioka@fsu.edu

Abstract. Feebly interacting light particles are an attractive addition to the SM because they appear in the broad context of new physics models that address significant issues of the standard model. Searches for the light particles using kaons benefit from their small total decay widths and the availability of enormous datasets. Recently, the comprehensive studies that connect experimental probes with theoretical models in Ref. [1]. In this presentation, we overview the reference and highlight a few examples.

1. Introduction

The kaon physics has been a powerful probe to discover several foundations of the standard model and constrained physics beyond the standard models (BSM). Conventionally, the kaon precision measurements have been utilized to constrain the effective operators which arise from heavy new physics. TeV or heavy BSM physics is well motivated by the hierarchy problem of the weak scale and the WIMP dark matter candidates. However, it is conceivable that new light degrees of freedom appear, and the effective field theory (EFT) approach breaks down. Instead, the kaon experiment can directly search for them from the rare kaon decays. The motivations of the light particles case broad: the QCD axion can solve the strong CP problem; sterile neutrinos are related to the non-zero neutrino masses, and various anomalies; and the long-standing anomaly of muon g-2 can be explained by O(10-100MeV) scale new particles.

The kaon experiments are interesting because the kaons, especially K^+ and K_L have narrow widths, which enhances the new physics decay branching ratio. Also, the new particle X that the kaon decays can produce have limited SM decay products $(\gamma, e, \mu, \pi, \nu)$. Most importantly, one can conduct new analyses with more data at the NA62 and KOTO experiments.

The challenge of having the new particle X is that the experimental signature strongly depends on the nature of X, such as the production mode, the decay patterns, and the lifetime. Therefore, generic studies like the EFT studies are impossible, and one has to employ model-dependent approaches. In this context, it is essential to connect experimental probes with specific models in a comprehensive manner. This literature [1] was written to accomplish that goal. Note that 64 researchers from the experiment and theory communities synergistically contributed to the paper.

2. Physics Cases

We can categorize the scenarios of X into roughly three categories:

(i) X, which decays into SM particles. Production of X is flavor-conserving.

(ii) X is effectively invisible in the kaon experiments. Production of X is flavor-conserving.

(iii) X is cosmologically long-lived. Production of X is flavor violating ($\Delta S = 1$).

If the X has any additional flavor violation, especially $\Delta S = 1$, at the production $K \to X + \mathrm{SM}$, generally, there is a stringent constraint to such a flavor violation, which enforces the allowed coupling to be extremely feeble. Therefore the lifetime X is cosmologically long, in the category (iii). On the other hand, the X coupling to the SM is flavor conserving, and there is still viable parameter space with a relatively large coupling. Then there are two interesting regions. In (i), X is short-lived, as it decays within the detectors. Generically, there are two competing bounds: one from the beam-dump experiments and the other from cosmology and Big Bang nucleosynthesis (BBN). In category (ii), the kaon experiments can test the gap region between these bounds.

To make the detailed connection between the models and the signatures at the kaon experiments, the readers can refer to Table 9 of [1]. We highlight specific examples for categories (i-iii) separately.

(i) Visible X: axions
The axion is the most compelling solution to the strong CP problem. It should be light as a pseudo-NG boson of Peccei-Quinn symmetry, making the axion a representative example of light new particles. In the context of kaon observables, the heavy QCD axion is attractive where the axion is heavier than the conventional mass relation $m_a \simeq m_\pi f_\pi / f_a$ where f_a is the breaking scale of PQ symmetry. Variants of axion are proposed in other BSM physics models, and they are dubbed axion-like particles (ALPs). With $K \to \pi a$ and the subsequent decay $a \to \gamma\gamma, e^+e^-$, the kaon experiments will have unique sensitivities to the poorly covered parameter space [].

(ii) Lab-invisible X: axions, Higgs portal scalar, leptonic force, and heavy neutral leptons.
The particle is effectively invisible in the experiments for the smaller coupling X in a flavor-conserving manner. The ongoing searches $K_L \to \pi^0 X_{\rm inv}$ and $K^+ \to \pi^+ X_{\rm inv}$ probe the different parameter space of the axion/ALPs as well as the parameter space of the light Higgs portal scalar. Leptonic decay modes of charged kaon, $K^+ \to \mu^+ \nu X_{\rm inv}, e^+ X_{\rm inv}$, are sensitive to the leptonic force motivated by the muon g-2 anomaly and the heavy neutral leptons.

(iii) Cosmologically stable X, flavor violating production.
In the presence of flavor violation of X coupling, we get strong bounds from the precision observables such as $\bar{K}^0$-K^0 mixing. Therefore the allowed coupling (scale of the higher dimensional operator) should be very feeble (high), which means the particle X always looks invisible in the direct searches at the kaon experiments. At least two cases are interesting. The first one is the QCD axion with generic quark couplings. In this case, the supernova cooling bound is stronger than the $\bar{K}^0$-K^0 mixing bound. On top of them, the $K^+ \to \pi^+ X_{\rm inv}$ search gives an even stronger bound, so the kaon probe is unique. If the dark photon is massless, the leading interaction to the SM may be from the dimension five dipole operator with flavor violation. In this case, the kaon probes, the SN bound, and the kaon mixing bound are complementary. Interestingly, this scenario suggests a few unexplored but feasible final states of the kaon decays.

3. Conclusions

The new light particles are favored in various BSM models, and they can be probed by the kaon decays. Unlike the EFT analysis, the model dependence of the searches is inevitable since the experimental signature strongly depends on the production and decay patterns of the new particle and its lifetime. Therefore, explicitly connecting the specific models and the specific signatures is essential. The purpose of review paper [1] is to achieve this goal. In this presentation, we further categorize the physics cases by the flavor violation and the lifetime, and we highlighted limited examples, and for more details, see references in [1].

Acknowledgments
KT is supported by in part the US Department of Energy grant DE-SC0010102 and JSPS Grant-in-Aid for Scientific Research (Grant No. 21H01086).

References

[1] Goudzovski E *et al.* 2022 (*Preprint* 2201.07805)