

Search for a mirror hidden sector with neutral kaons at NA64

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Mirror matter from the dark hidden sector with the same particle content and gauge interactions as in the standard model is still an interesting candidate for dark matter. Several experiments on the search for positronium and neutron oscillations into their mirror partner have been conducted recently. In this work, we consider the transitions $K^0 - K_m^0$ of a neutral kaon into a hidden mirror kaon. It is shown that their probability can be probed with the sensitivity of $P(K^0 - K_m^0) \lesssim 10^{-7}$ from the search for missing-energy events in the NA64 experiment at the CERN SPS with $\sim 10^{11}$ K^+ on target. This would result in a limit on the $K^0 - K_m^0$ mixing parameter much stronger than the similar bound estimated from the cosmological considerations.

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I. INTRODUCTION

Mirror matter from the dark mirror sector with a particle content and gauge interactions, which is a mirror copy of the standard model, is still a valuable candidate for dark matter; for a recent review, see [1] and also [2–4]. In this class of models, the mirror symmetry could be either unbroken, resulting in the mirror particles having the same masses as in the standard model (SM) [5–11], or the symmetry could be spontaneously broken, and mirror sector particles have masses which are similar to the SM particles [12,13]. Already long ago, Kobzarev *et al.* [6] found out that the interaction between the SM and mirror particles cannot be strong or electromagnetic. They interact presumably via gravity, and possibly by other feeble forces. Such new interactions induced, e.g., by the photon-mirror photon kinetic mixing [14,15], would result in positronium—mirror positronium oscillations as was first pointed out by Glashow [16]; see also [17,18]. Several experiments motivated by this observation searched for the effect [19–24]; see also [25]. Another possibility proposed in Ref. [26] was the neutron mixing with the mirror neutron resulting in oscillations between the two states. This process has been looked for in experiments [27–33] that provided a stringent upper limit on the mixing parameter for the case of unbroken mirror symmetry. (See, e.g.,

Refs. [30,31], and also study the case where the neutron and mirror neutron have substantial mass splitting, i.e., the case of broken mirror symmetry. Also see the recent result from the experiment at the ILL reactor [33]). The mirror model for sterile neutrinos giving a subdominant contribution to solar neutrino physics was studied in Refs. [34,35].

The possibility of a K^0 to mirror K_m^0 transition was first discussed by Nikolaev and Okun [36]. They proposed searching for these transformations in an experiment *à la* “light shining through the wall.” Namely, the primary K^0 beam producing a flux of mirror kaons due to the $K^0 - K_m^0$ conversion in flight is fully absorbed in a shield installed upstream of a detector. The signal in the detector is produced by the decays of the ordinary K^0 ’s regenerated in the beam due to the $K_m^0 - K^0$ transitions of mirror kaons that are sterile and penetrate the shield without interactions. In this approach, the signal rate is proportional to $\sim a^4$; here, a is the amplitude of the $K^0 \rightarrow K_m^0$ conversion, where one small factor a^2 came from the $K^0 \rightarrow K_m^0$ transition before the shield, and another small factor a^2 is from the $K_m^0 \rightarrow K^0$ regeneration after the shield. Below, we consider another type of experiment based on the active target plus missing-energy approach developed for the search for invisible decays of dark photons [37,38]. Its advantage is that the signal rate is $\sim a^2$; thus, many fewer kaons on target are required to reach the same level of sensitivity as in the proposal of Ref. [36].

The rest of the paper is organized as follows: The phenomenology of the $K^0 - K_m^0$ system is described in Sec. II. The experimental method, the setup, and the expected sensitivity of the proposed search are presented

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in Sec. III. Cosmological constraints are discussed in Sec. IV. Section V summarizes and provides concluding remarks.

II. PHENOMENOLOGY OF THE $K^0 - \bar{K}_m^0$ SYSTEM

Let us introduce a mirror world of particles by assuming that the total Lagrangian is invariant under CPM transformation. Here, C , P , M are charge conjugation, space inversion, and an *ordinary particles* $\leftrightarrow$ *mirror particles* transformation. The following states with definite CP for the ordinary and mirror world can be introduced:

$$K_1 = \frac{K^0 + \bar{K}^0}{\sqrt{2}}, \quad K_{1m} = \frac{K_m^0 + \bar{K}_m^0}{\sqrt{2}}, \quad CP = +1, \quad (1)$$

$$K_2 = \frac{K^0 - \bar{K}^0}{\sqrt{2}}, \quad K_{2m} = \frac{K_m^0 - \bar{K}_m^0}{\sqrt{2}}, \quad CP = -1, \quad (2)$$

and the following states with definite CPM ,

$$K_1^+ = \frac{K_1 + K_{1m}^0}{\sqrt{2}}, \quad K_2^+ = \frac{K_2 - K_{2m}}{\sqrt{2}}, \quad CPM = +1, \quad (3)$$

$$K_1^- = \frac{K_1 - K_{1m}^0}{\sqrt{2}}, \quad K_2^- = \frac{K_2 + K_{2m}}{\sqrt{2}}, \quad CPM = -1, \quad (4)$$

which are associated with particles of definite and distinct mass m_1^+ , m_2^+ , m_1^- , and m_2^- , and mean lifetimes τ_1^+ , τ_2^+ , τ_1^- , and τ_2^- .

We know that in the ordinary world only CPT appears to be an exact symmetry of nature, while C , P , and T are known to be violated. Within the Wigner-Weisskopf approximation, the time evolution of the neutral kaon system is described by

$$i \frac{d\Phi(t)}{dt} = H\Phi(t) = \left(M - i \frac{1}{2} \Gamma \right) \Phi(t), \quad (5)$$

where M and Γ are 2×2 Hermitian matrices, which are time independent, and $\Phi(t)$ is a two-component state vector in the $K^0 - \bar{K}^0$ space. Denoting by m_{ij} and Γ_{ij} the elements of M and Γ in the $K^0 - \bar{K}^0$ basis, CPT invariance implies

$$m_{11} = m_{22} \quad (\text{or} \quad m_{K^0} = m_{\bar{K}^0}) \quad \text{and} \quad \Gamma_{11} = \Gamma_{22} \quad (\text{or} \quad \Gamma_{K^0} = \Gamma_{\bar{K}^0}). \quad (6)$$

The eigenstates of Eq. (5) called K_S and K_L are given by

$$K_S = \frac{1}{\sqrt{2(1 + |\epsilon_S|^2)}} (K_1 + \epsilon_S K_2), \quad (7)$$

$$K_L = \frac{1}{\sqrt{2(1 + |\epsilon_L|^2)}} (K_2 + \epsilon_L K_1), \quad (8)$$

where, assuming CPT conservation, the parameter $\epsilon = \epsilon_S = \epsilon_L$ describing CP violation, in terms of the elements of M and Γ , is

$$\epsilon = \frac{\text{Im}(\Gamma_{12}) + i \text{Im}(M_{12})}{\Gamma_S - \Gamma_L - 2i\Delta m}, \quad (9)$$

where $\Gamma_S(\Gamma_L)$ is the $K_S(K_L)$ decay rate, and Δm is the $K_L - K_S$ mass difference.

Assuming the existence of the mirror matter, similar to Eqs. (7) and (8), the short-lived and long-lived states can be defined as [36]

$$K_S^{+(-)} = \frac{1}{\sqrt{2(1 + |\epsilon^{+(-)}|^2)}} \left(K_1^{+(-)} + \epsilon^{+(-)} K_2^{+(-)} \right), \quad (10)$$

$$K_L^{+(-)} = \frac{1}{\sqrt{2(1 + |\epsilon^{+(-)}|^2)}} \left(K_2^{+(-)} + \epsilon^{+(-)} K_1^{+(-)} \right) \quad (11)$$

with the corresponding eigenvalues $\lambda_{S,L}^{+(-)} = m_{S,L}^{+(-)} - i \frac{1}{2} \Gamma_{S,L}^{+(-)}$. Note that $\lambda_{S,L}^+ \neq \lambda_{S,L}^-$.

A. $K^0 - \bar{K}_m^0$ mixing

Let us consider the phenomena associated with $K^0 - \bar{K}_m^0$ mixing. Suppose we produce K^0 in an experiment at $t = 0$ in a typical strong charge-exchange reaction

$$K^+ + n \rightarrow K^0 + p \quad (12)$$

by irradiating a target followed by a hermetic detector that absorbs all secondary particles in the final state and located at some distance from it. The energy deposit in the detector by K^0 or its decay product is equal to the primary K^+ energy as the recoil proton energy is typically much smaller.

Taking into account Eqs. (2)–(12), the K^0 state at $t = 0$ is then

$$|\psi(0)\rangle = |K^0\rangle = \frac{1}{\sqrt{2}} [(1 - \epsilon^+)(|K_S^+\rangle + |K_L^+\rangle) + (1 - \epsilon^-)(|K_S^-\rangle + |K_L^-\rangle)]. \quad (13)$$

For simplicity, let us ignore CP violation

$$|\psi(0)\rangle = |K^0\rangle = \frac{1}{\sqrt{2}} [(|K_S^+\rangle + |K_L^+\rangle) + (|K_S^-\rangle + |K_L^-\rangle)]. \quad (14)$$

After a propagation time t along the kaon beam to the detector, the wave function of K^0 is

$$\begin{aligned}
|\psi(t)\rangle &= \frac{1}{\sqrt{2}}[(|K_S^+(t)\rangle + |K_L^+(t)\rangle) + (|K_S^-(t)\rangle + |K_L^-(t)\rangle)] \\
&= \frac{1}{\sqrt{2}}[(|K_S^+(t)\rangle e^{-\lambda_S^+ t} + |K_L^+(t)\rangle e^{-\lambda_L^+ t}) \\
&\quad + (|K_S^-(t)\rangle e^{-\lambda_S^- t} + |K_L^-(t)\rangle e^{-\lambda_L^- t})]. \quad (15)
\end{aligned}$$

If the K^0 time of flight is much greater than the lifetime of the short-lived components $t \gg \tau_S^{+,-} = 1/\Gamma_S^{+,-}$, we have

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-i\lambda_L t} (|K_L(t)\rangle + |K_{Lm}(t)\rangle), \quad (16)$$

where

$$\begin{aligned}
|K_L(t)\rangle &\approx |K_2(t)\rangle, & |K_{Lm}(t)\rangle &\approx i\delta\lambda_L t |K_{2m}(t)\rangle \\
\lambda_L &= \frac{1}{2}(\lambda_L^+ + \lambda_L^-), & \delta\lambda_L &= \frac{1}{2}(\lambda_L^+ - \lambda_L^-). \quad (17)
\end{aligned}$$

The mirror K_m^0 fraction of the beam for $t \ll \tau_L^{+,-} = 1/\Gamma_L^{+,-}$ is just

$$\begin{aligned}
f(K_{2m}) &= |\langle K_{2m} | \psi(t) \rangle|^2 \\
&= \frac{1}{4} e^{-(\Gamma_L^+ + \Gamma_L^-)t/2} |\delta\lambda_L|^2 t^2 \approx \frac{1}{4} |\delta\lambda_L|^2 t^2. \quad (18)
\end{aligned}$$

The mirror component is sterile and hence would penetrate the detector without interaction resulting in a striking experimental signature—complete disappearance of the primary beam energy in the experiment with the signal sensitivity $\propto |\delta\lambda_L|^2 t^2$. As mentioned in Sec. I, this makes the approach based on searching for events with a large missing energy (see Sec. III) more advantageous compared to the one based on the light-shining-through-the-wall technique proposed in Ref. [36]. The sensitivity of the latter is $\propto |\delta\lambda_L|^4$ due to the additional small extra factor $\propto |\delta\lambda_L|^2$ related to the regeneration of the ordinary K^0 's.

B. Dumping of the K_m^0 wave function

Let us assume that in an experiment K^0 is formed in a target of a material and then propagates in air not in vacuum. After ejection from the target, the K^0 meson can lose its energy due to elastic collisions, while the mirror component K_m^0 is sterile and does not interact with the air. The significant difference in properties of K^0 and K_m^0 could lead to the effect that after each collision the $K^0 - K_m^0$ system becomes an incoherent mixture of K^0 and K_m^0 . It is easy to show that if one starts with a pure K^0 state, the probability of a $K^0 - K_m^0$ conversion will be

$$P(K^0 \rightarrow K_m^0) \simeq \frac{|\Delta\lambda_L|^2 t^2}{2(\omega_c t)}, \quad (19)$$

where ω_c is the K^0 collision rate in air. Thus, the $K^0 \rightarrow K_m^0$ transition rate will be reduced by a factor $N_{col} \simeq \omega_c t$ compared to the vacuum rate, where N is the number of

K^0 -nuclei collisions during the propagation time to the detector t .

Let us estimate the average number of K^0 collisions in the air. The average number of collisions is determined by the formula

$$N_{col} = N_{av} \rho_{air} \sigma_{tot} L. \quad (20)$$

Here, $N_{av} = 6.02 \times 10^{23} \text{ mole}^{-1}$ is the Avogadro number, ρ_{air} is the density of air, σ_{tot} is the cross section of the K^0 meson on the “air molecules” (mainly the mixing of O_2 and N_2 molecules), and L is the length of the K^0 meson propagation. In our estimates, we take $L = 5 \text{ m}$, $\sigma_{tot} = 20 \text{ mb}$, and the air density at room temperature $\rho_{air} = 1.3 \times 10^{-3} \text{ g/cm}^3$. We take the average atomic number of the air molecules $A_{air} = 29$. For the estimation of the kaon air molecules cross section, we use the additive approximation $\sigma_{tot}(K^0 \text{ air}) = A_{air} \sigma_{tot}(K^0 \text{ nucleon})$. As a consequence of the formula (20), we find the average number of collisions is

$$N_{col} \approx 8 \times 10^{-3}. \quad (21)$$

It means that the effects of K^0 collisions are small, and we can neglect them in the study of the $K^0 - K_m^0$ transitions.

III. AN EXPERIMENT TO SEARCH FOR $K^0 - K_m^0$ TRANSFORMATION

The detector specifically designed to search for the $K^0 - K_m^0$ transitions is schematically shown in Fig. 1. This experimental setup is complementary to the one proposed for the search for invisible decays of dark photons at the SPS at CERN [37,38]. The experiment could employ, e.g., the H4 hadron beam, which is produced in the target T2 of the CERN SPS and transported to the detector in an evacuated beamline tuned to a freely adjustable beam momentum from 40 to 100 GeV/c [39]. The typical maximal beam intensity at ≈ 50 –100 GeV is of the order of $\approx 10^7 \pi^\pm$ and $\approx 3 \times 10^5 K^\pm$ for one SPS spill with 10^{12} protons on target. The typical SPS cycle for fixed-target (FT) operation lasts 14.8 s, including 4.8 s spill duration. The maximal number of FT cycles is four per minute.

The beam of incident charged kaons is defined by the scintillating counters $S_{1,2}$. The momentum of the beam is additionally selected with a momentum spectrometer consisting of a dipole magnet and a low-density tracker made of a set of Micromegas chambers MM_{1-4} . The K^0 's are produced in beam kaons scattering off nuclei in the active target (T). The T is surrounded by the veto system consisting of a set of high-efficiency scintillating counters (V), an electromagnetic calorimeter (ECAL), and a veto hadronic calorimeter (VHCAL₁) used against photons or charged secondaries that could escape the target at a large angle. The three VHCAL₂₋₄ modules are used to form a decay volume (DV) of the length $L = 5 \text{ m}$ for development

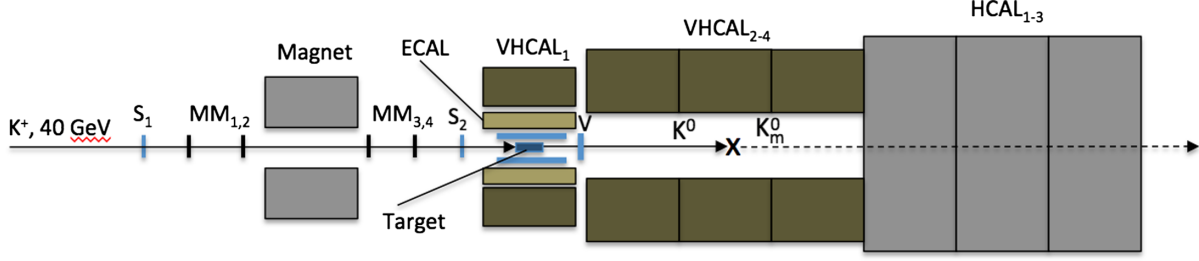


FIG. 1. Schematic illustration of the NA64 setup to search for the $K^0 \rightarrow K_m^0$ conversion in flight (see text).

of the $K^0 \rightarrow K_m^0$ transformations. In addition, $VHCAL_{2-4}$ modules and three massive hadronic calorimeter modules ($HCAL_{1-3}$) located at the end of the setup are used as a fully hermetic calorimeter system to detect energy deposited by secondaries from the primary interactions $K^+A \rightarrow$ anything of K^+ 's with nuclei A in the target. For searches at low energies, Cherenkov counters to enhance the incoming hadron tagging efficiency can be used.

The method of the search is as follows: The source of the K^0 's is the charge-exchange reaction (12) of high-energy kaons on nucleons of an active target where the neutral kaon is emitted mainly in the forward direction with the beam momentum, and the recoil nucleon carries away a small fraction of the beam energy. If the process of $K^0 \rightarrow K_m^0$ transitions exist, the K_m^0 component produced in the beam during time of flight $t(=L/c\gamma$ in K^0 c.m.s.) would penetrate the rest of the detector without interaction and any energy deposition in the HCAL. The occurrence of the $K^0 \rightarrow K_m^0$ transition produced in $K^\pm$ interactions would appear as an excess of events with a signal in the T ; see Fig. 1 and zero energy deposition in the rest of the detector (i.e., above that expected from the background sources).

A. Expected sensitivity

To estimate the sensitivity of the proposed experiment, a simplified feasibility study based on GEANT4 [40] Monte Carlo simulations has been performed for 40 GeV kaons. In this simulation, the ECAL is an array of 3×3 lead-scintillator counters of the Shashlyk type ($X_0 \simeq 2$ cm) (see, e.g., Ref. [38]), each with the size of $36 \times 36 \times 400$ mm³, allowing for accurate measurements of the lateral energy leak from the target. The target itself is the ECAL central cell with thickness $\simeq 0.1\lambda_{\text{int}}$, and the surrounding counters serve as the veto counters, which should detect a small energy deposit. A new high-resolution active target made of lead tungstate crystals [41] has been also considered. The veto system's inefficiency for the minimum ionizing particle detection is conservatively assumed to be $\lesssim 10^{-4}$. Each VHCAL module is a sandwich of 40 alternating layers of copper and scintillator with thicknesses of 25 and 4 mm, respectively, and with a lateral size of 60×60 cm² and central hole of 12×12 cm². Each HCAL module consists of 48 alternating layers of iron and scintillator with thicknesses of 25 and 4 mm, respectively,

and a lateral size of 60×60 cm² and a total thickness of $\simeq 7\lambda_{\text{int}}$. The hadronic energy resolution of the HCAL calorimeters as a function of the beam energy is taken to be $\frac{\sigma}{E} \simeq \frac{60\%}{\sqrt{E}}$. The energy threshold for the zero energy in the HCAL is 0.1 GeV.

To estimate the expected sensitivities, simulations are used to calculate fluxes and energy distributions of mesons produced in the target by taking into account the relative normalization of the yield of K^0 from Refs. [42,43]. The K^0 production cross section of the reaction (12) is $\frac{d\sigma(K^+n \rightarrow K^0p)}{dq} \simeq \frac{\sigma(K^-p \rightarrow \bar{K}^0n)}{dq}$, and the latter can be expressed as [42]

$$\begin{aligned} & \frac{\sigma(K^-p \rightarrow \bar{K}^0n)}{dq} \\ &= (1 - Gt)(\exp[c_\rho q] + R^2 \exp[c_A q]) \\ & \quad - 2R[\cos \phi_+ - GT \cos \phi_-] \exp[(c_\rho + c_A)q/2], \end{aligned} \quad (22)$$

where q is the four-momentum transfer squared, $G = (33.5 \pm 1.3)$ GeV⁻², $c_\rho = (15.5 \pm 0.3)$ GeV⁻², $c_A = (8.8 \pm 0.1)$ GeV⁻², $R = 0.83 \pm 0.05$, $\cos \phi_+ = -0.08 \pm 0.07$, and $\cos \phi_- = 0.23 \pm 0.02$. This parametric form gives the charge-exchange cross sections for the K^0 production over the full phase space, up to $|q| \gtrsim 0.3$ GeV⁻². The K^0 production cross sections in the target were calculated from the linear extrapolation of (22) to the target atomic number. For the total number of incident kaons $n_{K^+} \simeq 10^{11}$ with the energy $E_0 = 40$ GeV, the number of produced K^0 's is $n_{K^0} \gtrsim 10^7$ which are emitted in the forward direction with the energy $E_{K^0} \simeq E_0$. The calculated fluxes and energy distributions of mesons produced in the target are used to predict the number of signal events in the detector.

For a given number of primary kaons n_{K^+} , the expected total number of mirror K_{2m} kaons produced within the decay volume of a length L and resulting in zero energy deposition in the detector is given by

$$\begin{aligned} n_{K_{2m}} &= n_{K^+} \cdot \int \frac{\sigma(K^+n \rightarrow K^0p)}{dq} \\ & \quad \times \left[1 - \exp\left(-\frac{L}{c\tau_{K_L}\gamma}\right) \right] P(K^0 \rightarrow K_{2m}) \zeta \epsilon_{\text{tag}} dq \\ &\simeq \zeta \epsilon_{\text{tag}} P(K^0 \rightarrow K_{2m}) n_{K^0}, \end{aligned} \quad (23)$$

where coefficient k is a normalization factor that was tuned to obtain the total cross section of the meson production $P(K^0 \rightarrow K_{2m}) = \frac{1}{4} |\delta\lambda_L|^2 t^2$ [see Eq. (18)], and, neglecting the K_S component, $c\tau_{K_L}\gamma$ is the K_L decay length, respectively, $\zeta \simeq 0.9$ is the signal reconstruction efficiency, $\epsilon_{\text{tag}} \gtrsim 90\%$ is the tagging efficiency of the final state, and n_{K^0} is the total number of the produced K^0 's. The estimation of background based on the analysis performed in Ref. [44] and taking into account the recent results of NA64 on the search for the $\eta, \eta' \rightarrow$ invisible decays with the similar signature [45] results in the sensitivity for signal events with the full missing energy to be at the level $\lesssim 10^{-11}$ per incoming kaon. Thus, in the case of no signal observation, the expected sensitivity of the proposed search for $K^0 \rightarrow K_m^0$ conversion can be defined by using the relation $n_{K_{2m}} < n_{90\%}^{\text{inv}}$, where $n_{90\%}^{\text{inv}} (= 2.3 \text{ events})$ is the 90% CL upper limit for the number of signal events. Using Eq. (23), the limit for the conversion probability is

$$P(K^0 \rightarrow K_m^0) \lesssim 10^{-7} \quad (24)$$

for $\simeq 10^{11}$ incident kaons. This results in a bound on the $K^0 - K_m^0$ mixing parameter

$$|\delta\lambda_L| \lesssim 3 \times 10^{-19} \text{ GeV}, \quad (25)$$

which is 4 orders of magnitude less compared to the value of the $K_L - K_S$ mass difference [46]. The statistical limit on the sensitivity of the proposed experiment is mostly set by the number of accumulated events. It could be further improved by utilizing a more careful design of the experiment. For example, the primary reaction $\pi^- + p \rightarrow K^0 + \Lambda^0$ which has a larger cross section, can be used as a source of well-tagged K^0 's allowing us to improve limits of (24) and (25) by an order of magnitude. In the case of the signal observation, several methods could be used to cross-check the result. For instance, one could perform measurements with different DV lengths. In this case, the expected number of signal events should vary as $n_S \sim t^2$.

IV. COSMOLOGICAL CONSTRAINTS

Consider now cosmological bounds on the mixing parameter $\delta\lambda_L$ [47]. Note that similar estimates have been performed in Ref. [26] for the case of neutron-mirror neutron oscillations; see also [25]. For the effective four fermion interaction

$$L_{\text{eff}} = \frac{1}{M_X^2} [\bar{d}\gamma^\mu \gamma_5 s \bar{d}^m \gamma_\mu \gamma_5 s^m + \text{H.c.}]. \quad (26)$$

Connecting our K_L mesons and mirror K_L^m mesons, the equilibrium temperature between our mirror worlds is determined by the equation

$$n\sigma = H, \quad (27)$$

where $H = k_H \frac{T_{\text{eq}}^2}{M_{PL}} (k_H = 1.7g_*^{1/2}, g_* \sim 100)$ is the Hubble expansion rate, and $n = k_n T_{\text{eq}}^3 (k_n = O(1))$, $\sigma = k_\sigma \frac{T_{\text{eq}}^2}{M_X^2} (k_\sigma = O(1))$ are the density and annihilation cross section. As a consequence of Eq. (27), we find

$$T_{\text{eq}} = \left(\frac{M_X^4 k_H}{M_{PL} k_n k_\sigma} \right)^{1/3}. \quad (28)$$

From the requirement that the equilibrium temperature t_{eq} is larger, the reheating temperature $T_r = 0.5 \text{ TeV}$, $T_{\text{eq}} \geq T_r$ [26], we find that

$$M_X \geq \frac{O(1)}{3} 10^7 \text{ GeV}. \quad (29)$$

For the effective interaction (26), the mixing parameter (25) is $\delta\lambda_L \sim \frac{f_K^2 m_K}{M_X^2}$. Here, $f_K \simeq 0.16 \text{ GeV}$ is the kaon decay constant. As a consequence of the inequality (29), we find

$$|\delta\lambda_L| \leq O(1) 10^{-15} \text{ GeV}. \quad (30)$$

The obtained bound (30) is much weaker than the estimated projection bound (25) from the NA64 experiment.

V. SUMMARY

Mirror matter from the dark hidden sector with identical particle and gauge interactions content as the standard model is still an interesting candidate for dark matter. Because of their specific properties, neutral kaons are still one of the most interesting probes of physics beyond the standard model from both theoretical and experimental viewpoints. In this work, the transformations of an ordinary neutral kaon K^0 meson into a sterile mirror K_m^0 meson are considered. We show that their probability can be probed with the sensitivity $P(K^0 - K_m^0) \lesssim 10^{-7}$ for $\simeq 10^{11}$ K^+ mesons on target in the NA64 experiment at the CERN SPS using the missing-energy signature. Interestingly, the estimated projection bound on the mixing parameter (25) from the NA64 experiment is much stronger than the similar bound (30) estimated from the cosmological considerations. The transition probability is proportional to the square of the K^0 time of flight $\sim t^2$ allowing an effective cross-check of the result in the case of a signal observation.

As the experimental signature of the signal is identical to the one from $K^0 \rightarrow$ invisible transitions, the proposed experiment can also search for $K_{S,L} \rightarrow$ invisible decays, which are a powerful tool for probing new physics in the kaon sector [48–50]. Note that these decays modes have never been sensitively tested. Only recently has the BESIII

Collaboration set the first modest bounds on their existence [51]. It is also important to stress that the first results from a proof-of-concept search for dark sectors via invisible decays of pseudoscalar η and η' mesons using the π^- charge-exchange reaction on nuclei as their source have being recently reported by NA64h; see Ref. [45]. Finally, the analysis presented above gives an illustrative order of magnitude for the sensitivity of the proposed experiment and may be strengthened by more detailed simulations and optimization of the beam energy and experimental setup.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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