Constraints on dark photons from π^0 decays

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Several models of dark matter suggest the existence of hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. The interaction between the ordinary and hidden sectors could be transmitted by new Abelian $U'(1)$ gauge bosons A' (dark or hidden photons) mixing with ordinary photons. If such A''s have masses below the π^0 meson mass, they would be produced through $\gamma - A'$ mixing in the $\pi^0 \to \gamma\gamma$ decays and be observed via decays $A' \to e^+e^-$. Using bounds from the SINDRUM experiment at the Paul Scherrer Institute that searched for an excess of e^+e^- pairs in $\pi^- p$ interactions at rest, the area excluding the $\gamma - A'$ mixing $\epsilon \gtrsim 10^{-3}$ for the A' mass region $25 \lesssim M_{A'} \lesssim 120$ MeV is derived.

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The origin of dark matter is still a great puzzle in particle physics and cosmology. Several models dealing with this problem suggest the existence of "hidden" sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These sectors do not interact with our world directly and couple to it by gravity. It is also possible that there exist new very-weak forces between the ordinary and dark worlds transmitted by new Abelian $U'(1)$ gauge bosons A' (dark or hidden photons for short) mixing with our photons [1], as discussed first by Okun in his model of paraphotons [2]. In a class of recent interesting models the $\gamma - A'$ mixing strength may be large enough to be experimentally tested. This makes searches for A''s very attractive; for a recent review see Ref. [3] and references therein.

It should be noted that many models of physics beyond the Standard Model—such as Grand Unified Theories [4], superstring models [5] (see also Ref. [6]), supersymmetric models [7], and models including the fifth force [8]—also predict an extra $U'(1)$ factor and the corresponding new gauge X boson. The X's could interact directly with quarks and/or leptons. If the X mass is below the pion mass, the X could be effectively searched for in the decays $P \to \gamma X$, where $P = \pi^0$, η, or η'. This is due to the fact that the decay rate of $P \to \gamma +$ any new particles with spin 0 or $\frac{1}{2}$ is proved to be negligibly small [9]. Hence, an observation of these decay modes could unambiguously signal the discovery of a new spin-1 boson, in contrast with other searches for new light particles in rare K, π, or μ decays [9–11].

The allowed $\gamma - A'$ interaction is given by the kinetic mixing [2,3,12,13]

$$L_{\rm int} = -\frac{1}{2}\epsilon F_{\mu\nu}A'^{\mu\nu}, \tag{1}$$

where $F^{\mu\nu}$, $A'^{\mu\nu}$ are the ordinary and the dark photon fields, respectively, and ϵ is their mixing strength. In some recent dark matter models the dark photon could be massless; see, e.g., Refs. [14,15]. If the A' has a mass, the kinetic mixing of Eq. (1) can be diagonalized, resulting in a nondiagonal mass term and $\gamma - A'$ mixing. Hence, any γ source could produce a kinematically allowed massive A' boson according to the appropriate mixings. Then, if the mass difference is small, ordinary photons may oscillate into dark photons—similarly to neutrino oscillations—or, if the mass difference is large, dark photons could decay, e.g., into e^+e^- pairs.

Experimental constaints on dark photons in the meV-keV mass range can be derived from searches for the fifth force [2,16,17], from experiments based on the photon regeneration technique [18–22], and from astrophysical considerations [23,24]. For example, the results of experiments searching for solar axions [25,26] can be used to set limits on the $\gamma - A'$ mixing in the keV part of the solar spectrum of dark photons [27–30]. Stringent bounds on the low mass A''s could be obtained from astrophysical considerations [31–33]. There are plans to test the existence of sub-eV dark photons at new facilities, such as, for example, SHIPS [34] and IAXO [35].

The A''s with masses in the sub-GeV range (see, e.g., Refs. [36–38]) can be searched for through their $A' \to e^+e^-$ decays in beam-dump experiments [39–44] or in particle decays [45–48]. Recently, stringent bounds on the mixing ϵ have been obtained from searches for decay modes π^0, η, $\eta' \to \gamma A'(X)$, $A'(X) \to e^+e^-$ with existing data from neutrino experiments [49,50]. These limits are valid for the relatively long-lived A''s with a mixing strength in the range $10^{-4} \lesssim \epsilon \lesssim 10^{-7}$. The goal of this paper is to show that new bounds on the decay $\pi^0 \to \gamma A'$ of neutral pions into a photon and a short-lived A' followed by the rapid decay $A' \to e^+e^-$ due to the relatively large $\gamma - A'$ mixing can be obtained from the results of sensitive searches for an excess of single isolated e^+e^- pairs from decays of the weakly interacting neutral boson X by the SINDRUM Collaboration at the Paul Scherrer Institute (PSI, Switzerland) [51].

The SINDRUM experiment—specifically designed to search for rare particle decays in the SINDRUM magnetic spectrometer—was performed by using the $\pi^- p$ interactions at rest as the source of π^0's. The π^0's were produced in the charge-exchange reaction $\pi^- p \to \pi^0 n$ of 95 MeV/c π^-'s stopped in a small liquid hydrogen target in the center of the SINDRUM magnetic spectrometer. The magnetic field was 0.33 T, resulting in a transverse-momentum threshold of roughly 17 MeV/c for particles reaching the scintillator hodoscope surrounding the target. The trigger required an e^+e^- pair with an opening angle in the plane perpendicular to the beam axis of at least 35°; this corresponds to a lower threshold in the invariant mass of 25 MeV/c [51]. A total of 98400 $\pi^0 \to \gamma e^+e^-$ decays were observed. The signature of the $X \to e^+e^-$ decay would be seen as a peak in the continuous e^+e^- invariant mass distribution.

No such peak events were found, and upper limits on the branching ratio $\mathrm{Br}(\pi^0 \to \gamma X, X \to e^+e^-) = \frac{\Gamma(\pi^0\to\gamma X, X\to e^+e^-)}{\Gamma(\pi^0\to\gamma\gamma)}$ in the range $\simeq 10^{-6}$–10^{-5} have been placed for the X-mass region $25 \lesssim M_X \lesssim 120$ MeV. The corresponding 90% C.L. exclusion area in the $(M_X; \mathrm{Br}(\pi^0 \to \gamma X, X \to e^+e^-))$ plane is shown in Fig. 1. The limits were obtained assuming the X lifetimes to be in the range

$$10^{-23} \lesssim \tau_X \lesssim 10^{-11}\ \mathrm{s}. \tag{2}$$

For lower values of τ_X in Eq. (2) the e^+e^- mass peak would be smeared out beyond recognition; for larger values most X's would decay outside the target region and thus the detector would not be triggered [51].

If the A' exists and is a short-lived particle, it would decay in the SINDRUM target and be observed in the detector via the $A' \to e^+e^-$ decay, similar to the decays of X's. The occurrence of $A' \to e^+e^-$ decays would appear as an excess of e^+e^- pairs in the SINDRUM spectrometer above those expected from standard decays of π^0 produced in $\pi^- p$ interactions. As the final states of the decays $\pi^0 \to \gamma X$, $X \to e^+e^-$ and $\pi^0 \to \gamma A'$, $A' \to e^+e^-$ are identical, the results of the searches for the former can be used to constrain the latter for the same e^+e^- invariant mass regions.

For a given number N_{π^0} of π^0's produced in the target the expected number of $A' \to e^+e^-$ (or $X \to e^+e^-$) decays occuring within the fiducial volume of the SINDRUM detector is given by

$$\begin{aligned} N_{A'\to e^+e^-}(M_{A'}) &= \int f\left[1 - \exp\left(-\frac{rM_{A'}}{P\tau_{A'}}\right)\right]\zeta A dr d\Omega \\ &= N_{\pi^0}\mathrm{Br}(\pi^0 \to \gamma A')\mathrm{Br}(A' \to e^+e^-)\zeta A, \end{aligned} \tag{3}$$

where $M_{A'}$, P, f, r, $\tau_{A'}$ are the A' mass, momentum, flux, the distance between the A' decay vertex and the target, and the lifetime at rest, respectively, and ζ and A are the e^+e^- pair reconstruction efficiency and the acceptance of the SINDRUM spectrometer, respectively [51]. Here it is assumed that the A' is a short-lived particle with $\frac{rM_{A'}}{P\tau_{A'}} \gg 1$ for r values larger than the effective size of the target, in accordance with Eq. (2). Taking Eq. (3) into account and using the relation $N_{A'\to e^+e^-}(M_{A'}) < N^{90\%}_{e^+e^-}(M_{A'})$, where

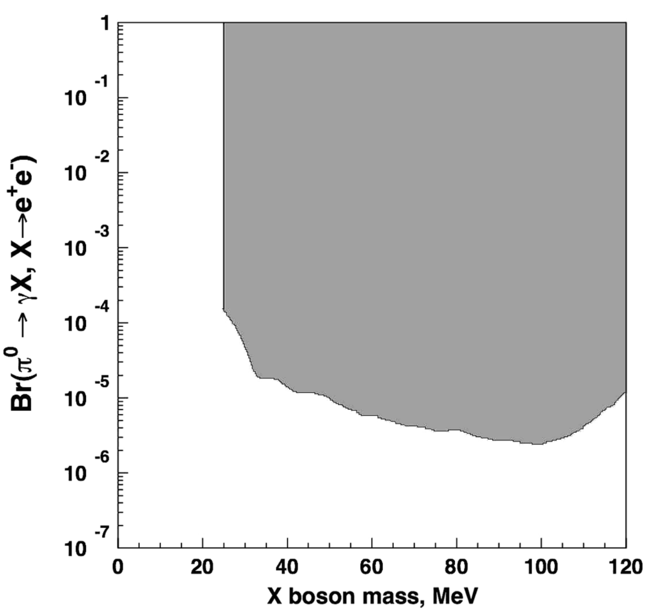

FIG. 1. The 90% C.L. area (shaded) in the $(M_X; \mathrm{Br}(\pi^0 \to \gamma X, X \to e^+e^-))$ plane excluded by the SINDRUM experiment (from Ref. [51]).

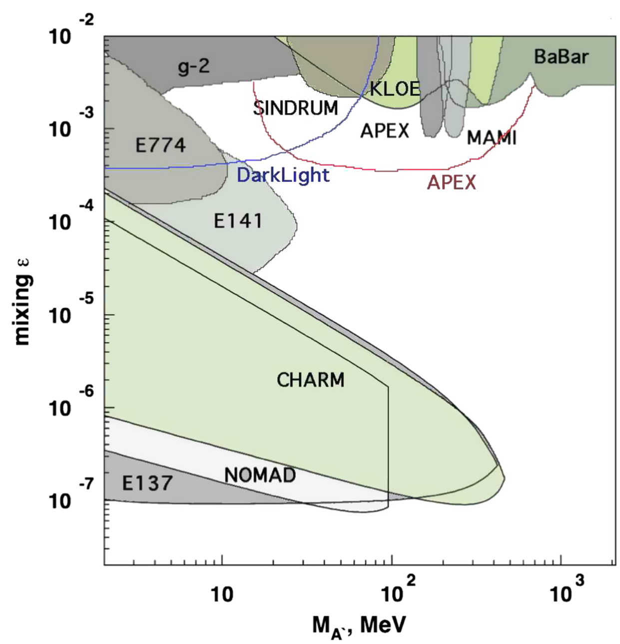

FIG. 2 (color online). Exclusion region in the $(M_{A'}; \epsilon)$ plane obtained in the present work from the results of the SINDRUM experiment [51]. Shown are areas excluded from the muon (g-2) considerations by the results of the electron beam-dump experiments E137 [39,41], E141 [42], E774 [43], the searches in APEX [44], KLOE [46], *BABAR* [47], and MAMI [48], and from the data of the neutrino experiments NOMAD [49] and CHARM [50]. Expected sensitivities of the planned APEX (full run) and DarkLight experiments are also shown for comparison. For a review of all experiments, which intend to probe a similar parameter space, see Ref. [52] and references therein.

$N^{90\%}_{e^+e^-}(M_{A'})$ is the 90% C.L. upper limit for the number of signal events from the decays of the A' with a given mass $M_{A'}$, results in the 90% C.L. exclusion area in the $(M_{A'}; \mathrm{Br}(\pi^0 \to \gamma A', A' \to e^+e^-))$ plane obtained by the SINDRUM experiment and shown in Fig. 1. The upper limit $N^{90\%}_{e^+e^-}$ as a function of $M_{A'}$ was obtained from the fit of the measured e^+e^- mass distribution in the vicinity of each selected value of $M_{A'}$ to a sum of the signal peak from the $A' \to e^+e^-$ decays and a flat background distribution.

The obtained results can be used to impose bounds on the $\gamma - A'$ mixing strength as a function of the dark photon mass. For A' masses smaller than the mass M_{π^0} of the π^0 meson, the branching fraction of the decay $\pi^0 \to \gamma A'$ is given by Batell *et al.* [36]

$$\mathrm{Br}(\pi^0 \to \gamma A') = 2\epsilon^2 \mathrm{Br}(\pi^0 \to \gamma\gamma)\left(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\right)^3. \quad (4)$$

Assuming that the dominant A' decay is into a e^+e^- pair, the corresponding decay rate is given by

$$\Gamma(A' \to e^+e^-) = \frac{\alpha}{3}\epsilon^2 M_{A'}\sqrt{1 - \frac{4m_e^2}{M^2_{A'}}}\left(1 + \frac{2m_e^2}{M^2_{A'}}\right). \quad (5)$$

Taking into account Eq. (4), one can determine the 90% C.L. exclusion area in the $(M_{A'}; \epsilon)$ plane from the results of the SINDRUM experiment. This area is shown in Fig. 2, together with regions excluded by the results of the electron beam-dump experiments E137, E141, E774 [39,41–43], by recent measurements from APEX [44], KLOE [46], *BABAR* [47], and MAMI [48], and from the data of the neutrino experiments NOMAD [49] and CHARM [50]. For a recent, more detailed review of existing and planned limits, see Refs. [52–54]. The shape of the exclusion contour from the SINDRUM experiment corresponding to the A' masses $M_{A'} \gtrsim 100$ MeV is defined mainly by the phase-space factor in Eq. (4). The A' lifetime values calculated by using Eq. (5) for the mass range $25 \lesssim M_X \lesssim 120$ MeV are found to be within the allowed range of Eq. (2). Note that since the A' is a short-lived particle, the sensitivity of the search is $\propto \epsilon^2$, differently from the case of a long-lived A', where the number of signal events is $\propto \epsilon^4$; see, e.g., Refs. [49,50].

In summary, using results from the SINDRUM experiments on the search for weakly interacting X bosons produced in $\pi^- p$ interactions at rest and decaying into e^+e^- pairs, new bounds on a hidden-sector gauge A' boson produced in the decay $\pi^0 \to \gamma A'$ were derived. The obtained exclusion area covers the A' mass region $25 \lesssim M_{A'} \lesssim 120$ MeV and the $\gamma - A'$ mixing strength $\epsilon \gtrsim 10^{-3}$.

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