Constraints on dark photons from $\pi^0$ 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 $\pi^0$ 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) 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 $3$ and references therein.

It should be noted, that many models of physics beyond the Standard Model (SM) such as GUTs $4$, superstring models $3$ (see also Ref.$[5]$), supersymmetric $7$, 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 $P = \pi^0, \eta, \text{or } \eta'$. This is due to the fact that the decay rate of $P \to \gamma + \text{any new particles with spin } 0 \text{ or } \frac{1}{2}$ 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 $K, \pi \text{ or } \mu$ decays $6,10$.

The allowed $\gamma - A'$ interaction is given by the kinetic mixing

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

where $F^{\mu\nu}$, $A'^{\mu\nu}$ are the ordinary and the dark photon fields, respectively, and $\epsilon$ 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 $\gamma$-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 constraints on dark photons in the meV-keV mass range can be derived from searches for the fifth force $2,14,17$, 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 $27,28$. 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 the masses in the sub-GeV range, see e.g. $36,38,39$, can be searched for through their $A' \to e^+ e^-$ decays in beam-dump experiments $39,44$, or in particle decays $47,48$. Recently, stringent bounds on the mixing $\epsilon$ have been obtained from searches for decay modes $\pi^0, \eta, \eta' \to \gamma A'(X)$, $A'(X) \to e^+ e^-$ with existing data of 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 note 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 $\pi^0$'s. The $\pi^0$'s were produced in the charge exchange reaction $\pi^- p \to \pi^0 n$ of 95 MeV/c $\pi^-$'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 $35^\circ$; this corresponds to a lower threshold in the invariant mass of 25 MeV/c [51]. A total of 98 $\pi^0 \to \gamma_{e^+e^-}$ 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 $Br(\pi^0 \to \gamma_{X}, X \to e^+e^-) = f(\pi^0 \to \gamma_{X}, X \to e^+e^-)$ in the range $10^{-6} - 10^{-5}$ have been placed for the $X$-mass region $25 \lesssim M_X \lesssim 120$ MeV. The corresponding 90% C.L. exclusion area in the $(M_X; Br(\pi^0 \to \gamma_{X}, X \to e^+e^-))$ plane shown in Fig. 1. The limits were obtained assuming the $X$ lifetimes to be in the range

$$10^{-23} \lesssim \tau_X \lesssim 10^{-11} \text{ s.} \quad (2)$$

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

$$N_{A' \to e^+e^-}(M_{A'}) = \int f \left[ 1 - \exp \left( -\frac{rM_{A'}}{P\tau_{A'}} \right) \right] A dr d\Omega$$

$$= N_{\pi^0} Br(\pi^0 \to \gamma_{A'}) Br(A' \to e^+e^-) \zeta A \quad (3)$$

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 $\zeta$ 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 $rM_{A'} / \tau_{A'} \gg 1$ 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'}) <
$N^{90\%}_{\epsilon \pi^0}(M_A)$, where $N^{90\%}_{e^+ e^-}(M_A)$ 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 $(M_A; Br(\pi^0 \to \gamma A', A' \to e^+ e^-))$ 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 $M_{\pi^0}$ of the $\pi^0$ meson, the branching fraction of the decay $\pi^0 \to \gamma A'$ is given by [33]:

$$Br(\pi^0 \to \gamma A') = 2e^2 Br(\pi^0 \to \gamma \gamma) \left( 1 - \frac{M_A^2}{M_{\pi^0}^2} \right)^3.$$ (4)

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

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

Taking into account Eq. (3), 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 [45], BaBar [46], 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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