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On search for eV hidden sector photons in Super-Kamiokande and CAST experiments.

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Abstract

If light hidden sector photons (γ's) exist, they could be produced through kinetic mixing with solar photons in the eV energy range. We propose to search for this hypothetical γ'-flux with the Super-Kamiokande and/or upgraded CAST detectors. The proposed experiments are sensitive to the $\gamma - \gamma'$ mixing strength as small as $10^{-5} \gtrsim \chi \gtrsim 10^{-9}$ for the γ' mass region $10^{-4} \lesssim m_{\gamma'} \lesssim 10^{-1}$ eV and, in the case of non-observation, would improve limits recently obtained from photon regeneration laser experiments for this mass region.

1 Introduction

Several interesting extensions of the Standard Model (SM) suggest the existence of 'hidden' sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These sectors of particles do not interact with the ordinary matter directly and couple to it by gravity and possibly by other very weak forces. If the mass scale of a hidden sector is too high, it will be experimentally unobservable. However, there is a class of models with at least one additional $\mathrm{U_h}(1)$ gauge factor where the corresponding hidden gauge boson could be light. For example, Okun [1] proposed a paraphoton model with a massive hidden photon mixing with the ordinary photon resulting in various interesting phenomena. A similar model of photon oscillations has been considered by Georgi et al. [2]. Holdom [3] showed, that by enlarging the standard model by the addition of a second, massless photon one could construct grand unified models which contain particles with an electric charge very small compared to the electron charge [3]. These considerations have stimulated new theoretical works and experimental tests reported in [4]-[24] (see also references therein).

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In the Lagrangian describing the photon-hidden photon system the only allowed 'connection' between the hidden sector and ours is given by the kinetic mixing [1,3,4]

$$L_{int} = -\frac{1}{2}\chi F_{\mu\nu}B^{\mu\nu} \tag{1}$$

where $F^{\mu\nu}$, $B^{\mu\nu}$ are the ordinary and the hidden photon field strengths, respectively.

In the interesting case when B^{μ} has a mass $m_{\gamma'}$, this kinetic mixing can be diagonalized resulting in a non-diagonal mass term that mixes photons with hidden-sector photons. Hence, photons may oscillate into hidden photons, similarly to vacuum neutrino oscillations, with a vacuum mixing angle which is precisely χ.

Note that in the new field basis the ordinary photon remains unaffected, while the hidden-sector photon (here denoted as γ') is completely decoupled, i.e. do not interact with the ordinary matter at all [1,3,11].

Experimental bounds on these massive hidden photons can be obtained from searches for an electromagnetic fifth force, [1,25,26], from stellar cooling considerations [27,28], and from experiments using the method of photon regeneration [29]-[43]. Recently, new constrains on the mixing χ for the mass region 10^{-4} eV< $m_{\gamma'}$ < 10^{-1} eV have been obtained [44] from the results of the BMV [38] and GammeV [39] collaborations. The new results are a factor of two better than those obtained from the previous BFRT experiment [42]. The Sun energy loss argument has also been recently reconsidered [45]. It has been pointed out that helioscopes searching for solar axions are sensitive to the keV part of the solar spectrum of hidden photons and the latest CAST results [40,41] have been translated into limits on the $\gamma - \gamma'$ mixing parameter [45,46]. Strong bounds on models with additional new particles plus a γ' at a low energy scale could be obtained from astrophysical considerations [48]-[51]. However, such astrophysical constraints can be relaxed or evaded in some models, see e.g. [52]. Hence, it is important to perform independent tests on the existence of such particles in new laboratory experiments such, for example as ALPS [53], LIPSS [54], OSQAR [55], and PVLAS LSW [56].

Since γ's can be produced through mixing with real photons, it is natural to consider the Sun as a source of low energy γ's. It is well known that the total emission rate of the Sun is of the order of 3.8×10^{26} W. Moreover, the emission spectrum is also well understood. It has a broad distribution over energies up to 10 keV, and corresponds roughly to the black-body radiation at the temperature $T_0 \simeq 5800$ K (0.5 eV). The maximum in the solar power spectrum is at about 2.5 eV (500 nm), in the blue-green part of the visible region. As happens with solar neutrinos, the coherence length of the photon-hidden photon oscillations is much smaller than the distance from the Sun to the Earth. In this case the photon-hidden photon transition probability is just $2\chi^2$ and the spectral flux of hidden photons from the solar surface will be

$$\frac{d\Phi^s}{d\omega} \simeq \chi^2 \; 4.2 \times 10^{18} \frac{\omega^2}{e^{\omega/T_0} - 1} \; \frac{1}{\mathrm{eV}^3 \; \mathrm{cm}^2 \; \mathrm{s}} \; . \tag{2}$$

with the maximum at $\omega \simeq 1$ eV.

A considerably higher contribution to the flux of hidden photons is expected from $\gamma \to \gamma'$ oscillations in the solar interior. Here the usual suppression of the mixing angle due to refractive effects is balanced by a higher emitting volume and a higher temperature. Since the suppression of the mixing is more drastic as the density increases (and maximum at the solar center) it is certainly advantageous to search for low mass hidden sector photons with energies in the eV range, where the photon flux is maximal [45]. For $m_{\gamma'}$ well below the eV, one can use the following conservative estimate for the 'bulk' component of the hidden photon spectral flux at the Earth [46]:

$$\frac{d\Phi^b}{d\omega} \sim \chi^2 \left(\frac{m_{\gamma'}}{\mathrm{eV}}\right)^4 10^{32} \; \frac{1}{\mathrm{eV} \; \mathrm{cm}^2 \; \mathrm{s}} \qquad \text{for} \qquad \omega \in 1 \div 5 \; \mathrm{eV}, \tag{3}$$

which exceeds the surface contribution except for masses $m_{\gamma'} \lesssim 10^{-4}$ eV. A more detailed calculation will be given elsewhere [47].

In this note, we propose direct experimental searches for the flux of solar hidden photons. The experiment could be performed with the Super-Kamiokande neutrino detector, and/or in the CAST experiment at CERN upgraded with a new helioscope, and is based on the photon-regeneration method used at low energies.

2 Search for hidden photons in Super-Kamiokande

Among detectors suitable for such kind of search the most promising one is Super-Kamiokande (SK) [57]. This is a large, underground, water Cherenkov detector located in a mine in the Japanese Alps [57]. The inner SK detector is a tank, 40 m tall by 40 m in diameter. It is filled with $5{\times}10^4$ m^3 of ultra-pure water, the optical attenuation length $L_{abs} \gtrsim 70$ m, and is viewed by 11146 photomultiplier tubes (PMT) with 7650 PMTs mounted on a barrel (side walls) and 3496 PMTs on the top and bottom endcaps.

The PMTs (HAMAMATSU R3600-2) have $\simeq 50$ cm in diameter [57]. The full effective PMT photocathode coverage of the inner detector surface is 40%. The photocathode, the dynode system and the anode are located inside a glass envelope serves as a pressure boundary to sustain high vacuum conditions

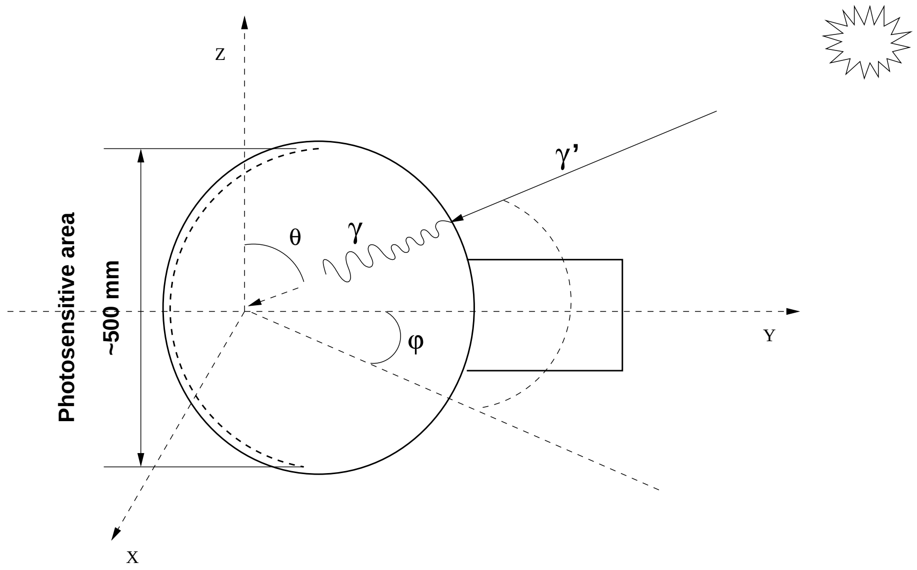

Fig. 1. *Schematic illustration of the direct search for light hidden-sector photons in the Super-K experiment. Hidden photons penetrate the Earth and convert into visible photons inside the vacuum volume of the Super-K PMTs. This results in an increase of the counting rate of those Super-K PMTs that are 'illuminated' by the Sun from the back, in comparison with those facing the Sun. If, for instance, the Earth rotates around the Z-axis, the counting rate is a periodic function of the angle* ψ, *i.e. is daily modulated.*

inside the almost spherical shape PMT. The photocathode is made of bialkali (Sb-K-Cs) that matches the wave length of Cherenkov light. The quantum efficiency is $\simeq 22\%$ at the typical wave length of Cherenkov light $\simeq 390$ nm. For the search for $\gamma - \gamma'$ oscillations it is important to have the ability to see a single photoelectron (p.e.) peak, because the number of photons arriving at a PMT will be exactly one. The single p.e. peak is indeed clearly seen (see e.g., Figure 9 in Ref. [57]) allowing to operate PMTs in the SK experiment at a low threshold equivalent to 0.25 p.e.. It is also important, that the average PMT dark noise rate at this threshold is just about 3 kHz.

Since γ's are long-lived noninteracting particles, they would penetrate the Earth shielding and oscillate into real photons in the free space between the PMT envelope and the photocathode, as shown in Figure 1. The photon then would convert in the photocathode into a single photoelectron which would be detected by the PMT. This could not happen for hidden photons coming from the water tank since, as we will see, the presence of the medium suppresses $\gamma \to \gamma'$ oscillations. Thus, the effect of $\gamma' \to \gamma$ oscillations could be searched for in the SK experiment through an increase of the counting rate of those PMTs that are 'illuminated' by the Sun *from the back*, as shown in Figure 1, in comparison with those facing the Sun. The increase of the counting rate in a particular PMT depends on its orientation with respect to the Sun and is daily modulated. Therefore, the overall counting rate of events from $\gamma' \to \gamma$

oscillations could also be daily modulated depending on the local SK position with respect to the Sun and the Earth rotation axis.

The number Δn_γ of expected signal events from $\gamma' \to \gamma$ conversion in SK is given by an integral over time, energy band, and the surfaces of all PMTs as

$$\Delta n_\gamma = \sum_1^N \int dt \int d\omega \, \frac{d\Phi}{d\omega} \, \eta(\omega) \int_{\text{cat.}} \vec{ds} \cdot \hat{r}_{\text{Sun}} P_{\gamma' \to \gamma}(\omega) \; . \tag{4}$$

Here, N_{PMT} is the number of SK PMTs, $\Phi = \Phi^s + \Phi^b$ is the total γ'-flux, η is the detection efficiency, $\vec{ds}$ is the photocathode surface element, $\hat{r}_{\text{Sun}}$ a unit vector pointing to the Sun and $P_{\gamma' \to \gamma}(\omega)$ is the $\gamma' \to \gamma$ vacuum transition probability given by:

$$P_{\gamma' \to \gamma}(\omega) = 4\chi^2 \sin^2\left(\frac{\Delta q l}{2}\right) \tag{5}$$

where l is the distance between the γ' entry point to the PMT and the PMT photocathode and Δq is the momentum difference between the photon and hidden photon:

$$\Delta q = \omega - \sqrt{\omega^2 - m_{\gamma'}^2} \approx \frac{m_{\gamma'}^2}{2\omega} \tag{6}$$

assuming $m_{\gamma'} \ll \omega$. In the absence of photon absorption, the maximum of the $\gamma' \to \gamma$ transition probability at a distance l corresponds to the case when $|\Delta q l| = \pi$. When $|\Delta q l| \ll \pi$ the photon and the hidden photon fields remain in phase and propagate coherently over the length l. In this case the transition probability degrades proportionally to $m_{\gamma'}^4$. For example, for $\omega \simeq 3$ eV and for the maximum distance $l \simeq 50$ cm, this will occur for $m_{\gamma'} \lesssim 10^{-3}$ eV.

The significance S of the γ' discovery with the Super-K detector scales as [58]

$$S = 2(\sqrt{\Delta n_\gamma + n_b} - \sqrt{n_b}) \tag{7}$$

where n_b is the number of expected background events. The excess of $\gamma' \to \gamma$ events in the Super-K detector can be calculated from the result of a numerical integration of eq.(4) over photon trajectories pointing to the PMT. In these calculations we use a simple model of PMTs, shown in Figure 1, without taking into account the PMT internal structure and dead materials which might results in some reduction of the signal due to the photon absorption and damping of $\gamma' - \gamma$ oscillations. We also assume that the Sun is located in the plane $\Theta = \pi/2$ and the Earth rotates around the Z-axis, which is the local vertical in SK, see Figure 1. In the PMT vacuum volume not all γ' energies effectively contribute to the signal because of its sinus dependence on Δq and l, see eq.(5). Assuming the main background source is the PMT dark noise gives

$$n_b = n_0 N' t \tag{8}$$

Here N' is the number of SK PMTs contributing to the signal, and $n_0 \simeq 3$ kHz is the average background counting rate of the PMTs [57]. Finally, taking $S = 3$, $N' \simeq 7 \times 10^3$, and $t \simeq 10^7$ s ($n_b = 2 \times 10^{14}$) results in a signal-to-background requirement of $\Delta n_\gamma / n_b \simeq 10^{-7}$.

For the case of non-observation, we have computed the corresponding exclusion region in the $(m_{\gamma'}, \chi)$ plane shown in Figure 2. The bound relaxes towards smaller hidden photon masses mainly because the flux (3) is suppressed. Below $m_{\gamma'} \sim 3$ meV an additional suppression adds up because hidden photons do not have enough space to oscillate inside the SK PMT, as noted above. The sensitive region of this experiment surpasses the already established CAST bounds at keV energies [45], and for masses above $m_{\gamma'} \simeq 10^{-3}$ eV also the limits recently obtained by Ahlers et al. [44] from laser experiments.

The sensitive search of γ's in the SK experiment is possible due to unique combination of several factors, namely, i) the presence of the large number of PMTs with a relatively large free vacuum volume; ii) the high efficiency of the single photon detection; and iii) the relatively low PMT dark noise. The statistical limit on the sensitivity of the proposed experiment is set by the number of PMTs and by the value of the dark noise (n_0) in the SK detector. The systematic errors are not included in the above estimate, however they could be reduced by the precise monitoring of the PMTs gain [57]. These estimates may be strengthened by more accurate and detailed Monte Carlo simulations of the proposed experiment.

Let us address the matter effects in $\gamma \to \gamma'$ oscillations. Neglecting photon absorption, the $\gamma \to \gamma'$ oscillation probability gets modified only by the refractive properties of the medium. We can parametrize them as a 'photon effective mass' m_γ, which accounts from deviations of the photon dispersion relation, namely $\omega^2 - k^2 \equiv m_\gamma^2$, with k the photon wavenumber. Consequently, we find that the mixing angle and the oscillation frequency of eq. (5) both get modified according to [28]

$$4\chi^2 \to \frac{4\chi^2 m_{\gamma'}^4}{\left(m_{\gamma'}^2 - m_\gamma^2\right)^2 + 4\chi^2 m_{\gamma'}^4} \quad ; \quad \Delta p \simeq \frac{m_{\gamma'}^2}{4\omega} \to \frac{\sqrt{(m_{\gamma'}^2 - m_\gamma^2)^2 + 4\chi^2 m_{\gamma'}^2}}{4\omega} \,. \tag{9}$$

Therefore (as it happens with neutrinos) a high refractivity ($m_\gamma \gg m_{\gamma'}$) decreases the amplitude of the oscillations, a resonant conversion is possible if eventually $m_\gamma = m_{\gamma'}$, and the rigorous definition of the vacuum case is $m_\gamma \ll m_{\gamma'}$.

In a completely ionized medium like the solar interior plasma, the plasma frequency $\omega_{\rm P}$ plays the role of the photon mass. Here $\omega_{\rm P}^2 = 4\pi\alpha N_e/m_e$, with α the fine structure constant and N_e, m_e the electron density and mass. Under the presence of bounded electrons the situation changes drastically, at least for photon energies around or below the atomic resonances (those relevant for us). An index of refraction n is more suitable to account for the refractive properties of these media, which gives $m_\gamma^2 \to -2\omega^2(n-1)$. The index of refraction is rarely smaller than one [2], so the mixing angle will be *always suppressed* with respect to the vacuum case (impeding unfortunately a resonant detection).

The high vacuum conditions of the SK photo-multipliers ($p \lesssim 10^{-7}$ Torr.) make this suppression harmless, at least for $m_{\gamma'} \gtrsim 10^{-5}$ eV (using $\omega = 10$ eV and water vapor as the main residual gas, with $n - 1 = 2.5\ 10^{-3}$ at normal conditions). On the other hand, in the SK water tank, with $n \sim 1.3$ for visible light under normal conditions, the $\gamma \to \gamma'$ oscillations get a suppression of the order $\sim m_{\gamma'}^4/(2.6\omega^2)^2$. In an optimistic case $\omega = 1$ eV and $m_{\gamma'} \sim 0.1$ eV this factor is $\lesssim 10^{-4}$! Even in the case when the SK tank is filled with air $|m_\gamma| \gtrsim 10^{-2}$ eV and the sensitivity of the experiment could not be improved and extended to the smaller γ' mass region by searching $\gamma - \gamma'$ oscillations in the inner SK detector volume.

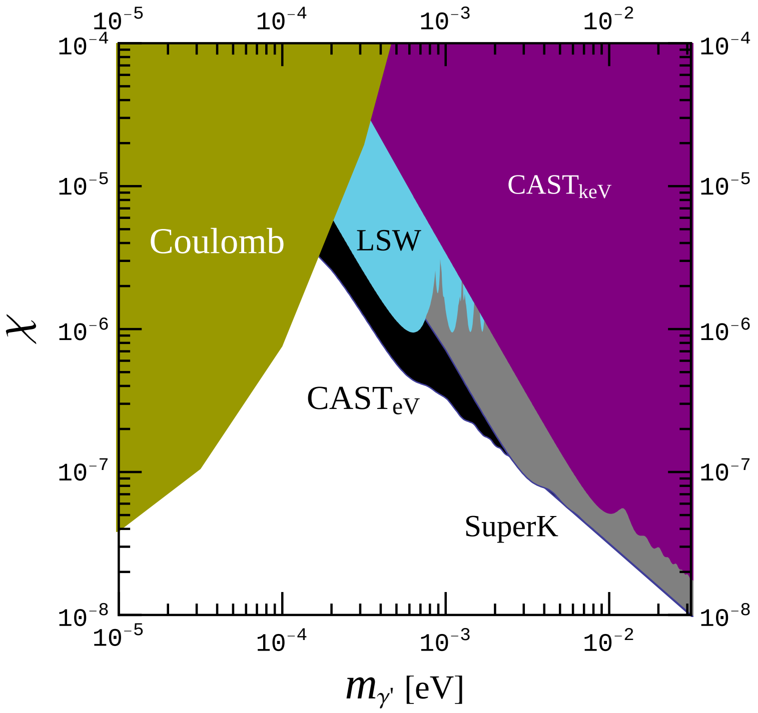

Fig. 2. *Regions in the $(m_{\gamma'}, \chi)$ plane which could be excluded by the proposed experiments: SuperK (gray region) and CAST$_{eV}$ (black). Also shown are the regions, with self explanatory labels, excluded by CAST in the keV range [45], by LSW experiments [44] and by searches of deviations of Coulomb's law [25,26].*

[2] The region of anomalous dispersion around the energy of an atomic transition could in principle exhibit such an unusual behavior, unfortunately light dispersion is very intense.

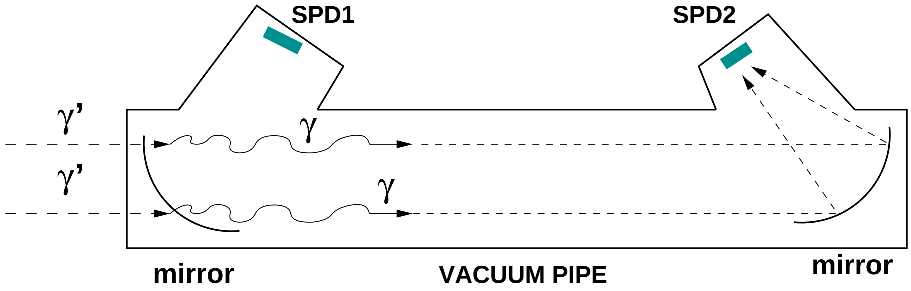

Fig. 3. *Schematic illustration of the direct search for solar γ'-flux in the CAST experiment. A vacuum pipe equipped from both sides by mirrors used to focus ordinary photons produced from $\gamma' \to \gamma$ oscillations on single photon detectors (SPDs). The manifestation of a signal would be an increase of the counting rate of the SPD that is 'illuminated' by the Sun compare to the other.*

3 Search for hidden photons in the upgraded CAST experiment

The CAST (Cern Axion Solar Telescope) experiment aims to detect solar axions through their conversion into detectable photons in the magnetic field of a 10 m long decommissioned LHC dipole magnet which is tracking the Sun. A detailed description of the experimental setup can be found in [59].

To search for eV hidden photons one can upgrade the CAST experiment with a simple helioscope detector schematically shown in Figure 3. Single photon detectors (SPDs), at both ends of a vacuum pipe, are looking for the single visible photons produced through oscillations of hidden photons inside the helioscope when it is pointing the Sun. We assume that the vacuum pipe has aperture with an effective diameter of $\simeq$ 50 cm and the length of 10 m. The whole helioscope detector could be mounted parallel to the LHC magnet on the CAST platform, allowing a movement of $\pm 8^o$ vertically and $\pm 40^o$ horizontally [59]. This allows tracking of the Sun during about 1.5 h at sunrise and the same time at sunset. The manifestation of a signal would be an excess of events in the eV energy spectrum during the Sun tracking, compared to the background runs spectrum.

For a high sensitivity of the proposed experiment to achieve a low background counting rate and a high efficiency for the single photon detection is crucial. The SPD used should have as large as possible sensitive area ($\gtrsim$ 1 cm^2), the high red extended quantum efficiency ($\gtrsim$ 30%), as small as possible noise counting rate ($\lesssim$ 10 Hz), a high gain ($\gtrsim 10^4$) and a good single photoelectron peak resolution. It is known, that one of main sources of noise, which also limits the SPD's single photon resolution, is the dark current originating from charge carriers thermally created in the sensitive volume of the SPD. This background can be reduced by the operating the SPD at a low temperature. Typically, the SPD dark rate decreases by several orders of magnitudes when the temperature decreases from the room one to $\simeq$ 100 K. Thus, to achieve a low background level ($\simeq 1$ Hz) the SPD has to be cooled down to, presumably cryogenic temperatures. Among several types of SPDs able to operate at such conditions, PMTs [60], silicon PMTs [61], large area avalanche photodiods [62], and a new type of hybrid photodetectors (HPD) [63] could be considered. In addition, optical mirrors, used to focus ordinary photons to a small spot, favour the use of a small size SPD detector and some improvement of the expected signal to background ratio, specially for the largest masses [45]. The technique of phase shift plates proposed for axion-like particle searches [64] could be also considered for increasing the sensitivity at higher masses.

Finally, performing integration over the spectra of eqs. (2) and (3) results in the hypothetical $\mathrm{CAST_{eV}}$ exclusion region shown in Figure 2. The calculations are performed for the HPD quantum efficiency taken from ref. [63] and assuming the spectral reflectivity of mirrors to be $\gtrsim 90\%$ for the considered wavelength region. The background counting rate is taken to be $n_0 \simeq 1$ Hz and the exposition time $t \simeq 10^6$ s. Note that the signal-to-background requirement of $\Delta n_\gamma / n_b \simeq 10^{-3}$ is significantly lower as compared to the SK case.

One can see that the proposed experiment improves the sensitivity of the SuperK at low masses due to the extra oscillation length. Around $m_{\gamma'} = 0.2$ meV, the hidden photon flux from the solar interior is strongly suppressed and the sensitivity of the experiment is dominanted by the surface contribution of eq.(2). Moreover, it surpasses the reach of already performed laser experiments [14] and certainly of the CAST keV search [45]. The vacuum requirements are somehow crucial. Using again water vapor as a possible residual gas in the helioscope pipe, we should ensure a pressure below $\simeq 10^{-4}$ Torr not to dump oscillations of $\gtrsim$ eV hidden photons with $m_{\gamma'} > 2\ 10^{-4}$ eV.

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