On search for hidden sector photons in Super-Kamiokande

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Abstract

If hidden sector photons($\gamma'$) exist, they could be produced through oscillations of photons emitted by the Sun. We show that a search for these particles could be performed in Super-Kamiokande due to the presence in this detector of a large number of photomultiplier’s (PMTs) with a relatively low noise and big size. The $\gamma'$s would penetrate the Earth shielding and would be detected by PMTs through their oscillations into real photons inside the PMTs vacuum volume. This would result in an increase of the PMT counting rate and its daily variations depending on the Earth position with respect to the Sun. The proposed search for this effect is sensitive to the $\gamma - \gamma'$ mixing strength as small as $\chi \lesssim 10^{-6}$ for the $\gamma'$ mass region $10^{-3} \lesssim m_{\gamma'} \lesssim 10^{-1}$ eV and, in the case of nonobservation, could improve limits recently obtained from photon regeneration laser experiments for this mass region.

Several interesting extensions of the Standard Model (SM) suggest the existence of ”hidden” sectors consisting of $SU(3) \times SU(2) \times U(1)$ 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 is experimentally unobservable and indeed is hidden. However, there is a class of models with at least one additional $U'(1)$ 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 adding 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).

In the Lagrangian describing photon- hidden photon system the so-called kinetic mixing term is given by [1,3,4]

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

(1)

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where $F^\mu$, $B^\mu$ are the ordinary and the hidden photon field strength, respectively. In the case when $U'(1)$ is a broken symmetry, 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, similar to vacuum neutrino oscillations. Note that in the new field basis the ordinary photon remain unaffected, while the hidden-sector photon ($\gamma'$) is completely decoupled, i.e. do not interact with the ordinary matter at all [13,14].

Experimental bounds on $\gamma'$s can be obtained from searches for the 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 $\gamma - \gamma'$ mixing strength for the $\gamma'$ mass region $10^{-4} < m_{\gamma'} < 10^{-2}$ have been obtained [44] from the results of laser experiments BMV [38] and GammeV [39], looking for the photons regeneration through their interactions with light axion-like particles. The new results are a factor two better then the results obtained from the BFRT experiment [42]. The Sun energy loss arguments has also been recently reconsidered [45]. It has been pointed out that helioscopes searching for solar axions are sensitive to the solar flux of hidden photons and the new limits on the $\gamma - \gamma'$ mixing parameter for the mass range $m_{\gamma'} \simeq 0.01 - 1$ eV obtained from the recent results of the CAST collaboration [40,41] have been reported [45]. Strong bounds on new physics with $\gamma'$ at low energy scale could be obtained from astrophysical considerations [46]-[49]. However, such astrophysical constraints can be relaxed or evaded in some models, see e.g. [50]. Hence, it is important to perform independent tests on the existence of such particles in new experiments such, for example, as ALPS [51], LIPSS [52], OSQAR [53], and PVLAS LSW [54].

In this note, we propose a direct experimental search for $\gamma'$ particles which might be present in the photon flux from the Sun. The experiment could be performed with the Super-Kamiokande neutrino detector and is based on the photon-regeneration method, used at low energies.

If $\gamma'$s can be produced through oscillations of real photons, it is naturally to consider the Sun as a source of low energy $\gamma'$s. Indeed, it is well known that the total emission rate of the Sun is of the order of $3.8 \times 10^{26}$ W. The emission photon energy spectrum is well understood. It has a broad distribution over energies up to 10 keV, and corresponds roughly to the black-body radiation at the temperature $\simeq 5800$ K. The maximum in the solar emission spectrum is at about 500 nm, in the blue-green part of the visible spectrum. Direct visible photons arrive at the Earth at a rate of $\simeq 4 \times 10^{17}/cm^2/s$. Thus, if $\gamma - \gamma'$ transitions occur it might be advantageous to search for hidden sector photons through regeneration of real photons using the visible part of the emission spectrum from the Sun, where the photon flux is maximal.

Among detectors suitable for such kind of search the most promising one is
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 example, the Earth rotates around the Z-axis, the counting rate is a periodic function of the angle $\psi$, i.e. is daily modulated.

Super-Kamiokande (SK) \[55\]. This is a large, underground, water Cherenkov detector located in a mine in the Japanese Alps \[55\]. The inner SK detector is a tank, 40 m tall by 40 m in diameter. It is filled with $5\times10^4$ m$^3$ of ultra-pure water, the optical attenuation length $L_{\text{abs}} \gtrsim 70$ 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\[55\]. The full effective PMT photocathode coverage of the inner detector surface is 40%. The photo cathode, the dynode system and the anode are located inside a glass envelope serves as a pressure boundary to sustain high vacuum conditions 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 is exactly one. The single p.e. peak is indeed clearly seen (see e.g., Figure 9 in Ref. \[55\]) 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.

If $\gamma'$s are long-lived noninteracting particle, 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. 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 $\Delta n_{\gamma}$ of expected signal events from $\gamma' \to \gamma$ conversion in SK is given by the following expression:

$$\Delta n_{\gamma} = \sum_{i} N_{i} \int_{\omega_{1}}^{\omega_{2}} I_{\gamma}(\omega) \cdot \eta(\omega) \cdot P_{\gamma \to \gamma'}(m_{\gamma'}, \omega) \cdot P_{\gamma' \to \gamma}(m_{\gamma'}, \omega) \cdot d\omega d\Omega \quad (2)$$

Here, $N$ is the number of SK PMTs, $I_{\gamma}$ and $\omega$ are the photon flux and energy, respectively, $\eta$ is the detection efficiency, and $P_{\gamma \to \gamma'}(m_{\gamma'}, \omega)$ and $P_{\gamma' \to \gamma}(m_{\gamma'}, \omega)$ are the $\gamma \to \gamma'$ and $\gamma' \to \gamma$ transition probabilities, respectively, given by:

$$P_{\gamma \to \gamma'}(\omega, m_{\gamma'}) = 4\chi^{2} \sin^{2}\left(\frac{\Delta q L}{2}\right) \quad (3)$$

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

where $L, l$ are the distances between the Sun and the Earth, and between the $\gamma'$ entry point to the PMT and the PMT photocathode, respectively, and $\Delta q$ is the momentum difference between the photon and hidden photon:

$$\Delta q = \omega - \sqrt{\omega^{2} - m_{\gamma'}^{2}} \approx \frac{m_{\gamma'}^{2}}{2\omega} \quad (5)$$

assuming $m_{\gamma'} \ll \omega$. In the absence of photon absorption, the maximum of the $\gamma \to \gamma'(\gamma' \to \gamma)$ transition probability at a distance $l$ corresponds to the case when $|\Delta q l| \simeq \pi$. 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 is proportional to $l^{2}$. For $\omega \simeq 3\text{eV}$ and for the maximum distance $l \simeq 50 \text{cm}$, the smallest $\gamma'$-mass which can be effectively explored at the Super-K detector with the photon-regeneration method is $m_{\gamma'} \simeq 10^{-3} \text{eV}$. For the mass range $m_{\gamma'} \gtrsim 10^{-3} \text{eV}$ and for $L \simeq 10^{13} \text{cm}$,

$$\frac{m_{\gamma'}^{2} L}{4\omega} \gg 1 \quad (6)$$
thus, the sinus of Eq.(3) is averaged to 1/2 and Eq.(2) reads

$$\Delta n_\gamma = 8\chi^4\Sigma_i^N \int_{\omega_1}^{\omega_2} I_\gamma(\omega) \cdot \eta(\omega) \cdot \sin^2\left(\frac{m_\gamma^2 l}{4\omega}\right)d_\omega d\Omega$$  (7)

The significance $S$ of the $\gamma'$ discovery with the Super-K detector scales as 

$$S = 2(\sqrt{\Delta n_\gamma + n_b} - \sqrt{n_b})$$  (8)

where $n_b$ is the number of expected background events. The excess of $\gamma' \rightarrow \gamma$ events in the Super-K detector can be calculated from the result of a numerical integration of Eq.(7) over photon trajectories pointing to the PMT. In this calculation we use a simple model of PMTs, shown in Figure 11 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. The Sun emission spectrum is described by the Planck’s law of black-body radiation. 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. For the considered mass range $10^{-3} < m_{\gamma'} < 10^{-1}$ the shape of the $\gamma'$ energy spectrum arriving at the Earth is the same as for solar photons due to the large distance between the Sun and the Earth. In the PMT vacuum volume not all $\gamma'$ energies effectively contribute to the signal because of its sinus dependence on $\Delta q$ and $l$, see Eq.(4). The total number of expected events from $\gamma - \gamma'$ oscillations collected in the SK experiment during the exposition time $t$ is estimated for the solar flux $I_\gamma \simeq 1.4 \times 10^3 \text{ W/m}^2$ and taking into account the overall detection efficiency, which includes the quantum efficiency of the photocathode, the secondary electron collection efficiency, the detection threshold, and the geometrical acceptance. Assuming the main background source is the PMT dark noise gives

$$n_b = n_0 N' t$$  (9)

Here $N'$ is the number of SK PMTs contributing to the signal, and $n_0 \simeq 3 \text{ kHz}$ is the average background counting rate of the PMTs [55]. Finally, taking $S = 3$, $N' \simeq 7 \times 10^3$, and $t \simeq 10^7 \text{ s}$ results in the exclusion region in the $(m_{\gamma'}, \chi)$ plane shown in Figure 2. For the mass region $m_{\gamma'} \gtrsim 10^{-3} \text{ eV}$ the limit for the mixing parameter is

$$\chi < 8.3 \times 10^{-7}$$  (10)

The limit estimated for the configuration when the Sun is located at $\Theta = 0$ is comparable than the one of Eq.(10).

We see that the sensitive search of $\gamma'$'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 [55]. For the mass region $10^{-3} \lesssim m_{\gamma'} \lesssim 10^{-1} \text{eV}$ the estimated upper limit of Eq.(10) is slightly better than the limits recently obtained by Ahlers et al. [44] from laser experiments. This estimate may be strengthened by more accurate and detailed Monte Carlo simulations of the proposed experiment.

Finally note, that in the presence of photon absorption, the probability for a hidden photon to pass through a conversion region of a length $L'$ and to arrive to a detector as an ordinary photon is given by [45], see also [32,33]:

$$P_{\gamma' \rightarrow \gamma}(\omega, m_{\gamma'}) = \frac{\chi^2 m_{\gamma'}^4}{(m_{\gamma}^2 - m_{\gamma'}^2)^2 + (\omega \Gamma)^2} \left(1 + e^{-\Gamma L} - 2e^{-\Gamma L'/2} \cos \Delta q L' \right)$$

In the above formula, $\Delta q = (m_{\gamma}^2 - m_{\gamma'}^2)/2\omega$ is the difference between the $\gamma'$ and the photon momenta in the medium for a photon energy $\omega$; $m_{\gamma}$ plays the role of the plasma frequency (photon mass) in a target medium: $m_{\gamma}^2 = 4\pi \alpha N_e/m_e$ with $N_e$ the electron number density and $m_e$ the electron mass. For the SK water target $m_{\gamma} \simeq 20 \text{eV}$, and the photon absorption rate is $\Gamma \simeq 1/L_{abs} \simeq 3 \times 10^{-9} \text{eV}$. Thus, although photon absorption in the target is small, the transition probability of Eq.(11) is suppressed for the mass region $m_{\gamma'} \ll 1 \text{eV}$ by the high photon mass in the target medium. Even in the case when the SK tank is filled with air, the target photon mass is $m_{\gamma} \gtrsim 10^{-2} \text{eV}$ and the sensitivity of the experiment cannot be improved and extended to the smaller mass region.
γ′ mass region by searching γ − γ′ oscillations in the inner SK detector volume.

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