



Constraining solar hidden photons using HPGe detector

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ABSTRACT

In this Letter we report on the results of our search for photons from a U(1) gauge factor in the hidden sector of the full theory. With our experimental setup we observe the single spectrum in a HPGe detector arising as a result of the photoelectric-like absorption of hidden photons emitted from the Sun on germanium atoms inside the detector. The main ingredient of the theory used in our analysis, a severely constrained kinetic mixing from the two U(1) gauge factors and massive hidden photons, entails both photon into hidden state oscillations and a minuscule coupling of hidden photons to visible matter, of which the latter our experimental setup has been designed to observe. On a theoretical side, full account was taken of the effects of refraction and damping of photons while propagating in Sun's interior as well as in the detector. We exclude hidden photons with kinetic couplings $\chi > (2.2 \times 10^{-13} - 3 \times 10^{-7})$ in the mass region $0.2 \text{ eV} \lesssim m_{\gamma'} \lesssim 30 \text{ keV}$. Our constraints on the mixing parameter χ in the mass region from 20 eV up to 15 keV prove even slightly better than those obtained recently by using data from the CAST experiment, albeit still somewhat weaker than those obtained from solar and HB stars lifetime arguments.

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The models of SUSY-breaking most often involve dynamics of a hidden sector, which uses to communicate the SUSY-breaking scale (usually larger than the weak scale) to the visible sector with aid of operators having always the appropriate loop or Planck-scale suppression. Otherwise the gauge hierarchy would be destabilized. If a U(1) gauge factor is contained in the hidden sector, a new communication mechanism [1] in the form of an operator that mixes two U(1)'s opens up, having a potential to destabilize any model for SUSY-breaking. Since this operator is a renormalizable one, it comes with no suppression by the large mass scale and therefore the mixing parameter χ must be small. The fact that both in field theory and in string theory settings an appreciable amount of χ can be generated [1], one may recognize the kinetic mixing operator as an important ingredient in these fundamental theories.

Introduction of an explicit mass term for hidden photons (thereby not upsetting the renormalizability of the theory) together with the kinetic mixing term mentioned above would lead to a model of photon oscillations (photons–hidden photons) [2] similar to the much more popular neutrino flavor oscillations. To this end, one gets rid of the kinetic mixing term by the appropriate rotation of states, introducing in such a manner a truly sterile state with respect to gauge interactions. This generates a nondiagonal mass

matrix in the sector of two photons, a necessary ingredient for the oscillation phenomenon. A thorough analysis of finding appropriate propagating states in vacua as well as in a matter background has been done recently [3,4]. Thus, the flavor (or interacting) states (one truly sterile while the other with the full gauge coupling to charged matter particles) can be expressed as a linear combination of propagating states in vacua/matter. As a consequence, a sterile propagating state would gain a tiny coupling to ordinary matter of order χ in vacua, while in matter such a coupling depends on both the real and imaginary part of the photon self-energy at finite temperature/density. This is crucial for our experimental setup (see below), since after being oscillated into a sterile state and (presumably) quick absorption of the active component in ordinary matter, it is just the sterile propagating state that leaves material background and travels unscathed towards a region where it is to be detected.

In the present Letter, we aim to observe sterile photon states (hereafter denoted as γ') in a few keV range and coming from the Sun by observing the photoelectric-like process on germanium atoms inside the HPGe detector. So far the most stringent limits on the hidden-photon mixing, in the mass region relevant for our investigation, are obtained by experiments using the Sun as a source of hidden photons [3] as well as by astrophysical arguments regarding the solar lifetime [3] and HB stars lifetime [5].

The low-energy effective Lagrangian for the two-photon system with kinetic mixing reads [6]

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$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 A'^\mu A'_\mu - eA^\mu J_\mu, \quad (1)$$

where $F^{\mu\nu}$ and $F'^{\mu\nu}$ are the photon (A^μ) and hidden photon (A'^μ) field strengths, respectively, J^μ is the current of electrically charged matter while $m_{\gamma'}$ is the hidden-photon mass that could arise from a Higgs or Stückelberg mechanism [7]. For transversely polarized hidden photons of energy sufficiently above the plasma frequency ω_p (in the solar model, $1 \text{ eV} \lesssim \omega_p \lesssim 295 \text{ eV}$) we can write the differential flux at the Earth as [3]

$$\frac{d\Phi_{\gamma'}}{dE_{\gamma'}} = \frac{1}{\pi^2 R_{\text{Earth}}^2} \int_0^{R_\odot} dr r^2 \frac{E_{\gamma'} \sqrt{E_{\gamma'}^2 - \omega_p^2}}{e^{E_{\gamma'}/(k_B T)} - 1} \times \frac{\chi^2 m_{\gamma'}^4}{(\omega_p^2 - m_{\gamma'}^2)^2 + (E_{\gamma'} \Gamma)^2} \Gamma, \quad (2)$$

where $E_{\gamma'}$ is the hidden-photon energy, the plasma frequency $\omega_p = \sqrt{4\pi\alpha N_e/m_e}$, k_B is the Boltzmann constant, T is the solar plasma temperature, $R_\odot$ is the solar radius, $R_{\text{Earth}} \approx 1.5 \times 10^{13} \text{ cm}$ is the average Sun–Earth distance, and Γ is the damping factor given by [3]

$$\Gamma = \frac{16\pi^2\alpha^3}{3m_e^2 E_{\gamma'}^3} \sqrt{\frac{2\pi m_e}{3k_B T}} N_e \left[1 - \exp\left(-\frac{E_{\gamma'}}{k_B T}\right) \right] \times \sum_i Z_i^2 N_i \bar{g}_{\text{ff},i} + \frac{8\pi\alpha^2}{3m_e^2} N_e. \quad (3)$$

The first term is the bremsstrahlung contribution to the damping, where index “i” designates protons or alphas, while the second term is the Compton contribution. Here it is assumed that all hydrogen and helium are completely ionized. The thermally averaged Gaunt factors $\bar{g}_{\text{ff},i}$ are taken from [8] which presents an accurate analytic fitting formula for the nonrelativistic exact Gaunt factor. The calculation is also checked using another exact formula (with numerical integration over Maxwellian distribution) [9]. The r -dependent quantities, T , N_e , N_p , and N_α are calculated using BS05 Standard Solar Model [10]. Our experiment is the most sensitive to hidden photons of around 1.6 keV (see below), and since they are created mostly in Sun’s inner layers (as shown in Fig. 1), Eqs. (2) and (3) (ionization neglected) can be reliably applied to calculate the expected flux of hidden photons. The contribution of different solar layers to the hidden-photons flux, depicted in Fig. 1 for $m_{\gamma'} = 100 \text{ eV}$, exhibits a narrow peak at $r = 0.28 R_\odot$ corresponding to the resonant contribution, $\omega_p^2(r) = m_{\gamma'}^2$, in the integrand of Eq. (2). The plasmon mass is maximal at Sun’s center, $\omega_p(0) \simeq 290 \text{ eV}$. For $m_{\gamma'} \gtrsim 290 \text{ eV}$ there is no resonant contribution in Eq. (2) (and there would have been no peak in Fig. 1 had it drawn for $m_{\gamma'} \gtrsim 290 \text{ eV}$). This causes a sudden drop in sensitivity for $m_{\gamma'} \gtrsim 290 \text{ eV}$ what can be clearly seen in Fig. 3.

Our experiment involves searching for the particular energy spectrum in the measured data,

$$\frac{dN_{\gamma'}}{dE_{\gamma'}} = \frac{d\Phi_{\gamma'}}{dE_{\gamma'}} \sigma_{\gamma' \text{Ge} \rightarrow \text{Ge}^* e}(E_{\gamma'}) N_{\text{Ge}} t, \quad (4)$$

produced if the hidden photons from the Sun are detected via photoelectric-like effect on germanium atoms. Here N_{Ge} is the number of germanium atoms in the detector and t is the data collection time. The cross section for the hidden-photon absorption, $\gamma' + \text{Ge} \rightarrow \text{Ge}^* + e$, can be expressed via the cross section for the ordinary photoelectric absorption as (see, e.g., Ref. [11])

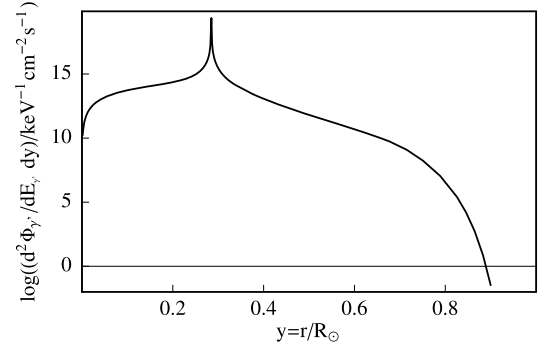


Fig. 1. Flux of solar hidden photons at the Earth as a function of the normalized radial coordinate $y = r/R_\odot$ for $E_{\gamma'} = 1.6 \text{ keV}$, $m_{\gamma'} = 100 \text{ eV}$, and $\chi = 3 \cdot 10^{-13}$.

$$\sigma_{\gamma' \text{Ge} \rightarrow \text{Ge}^* e}(E_{\gamma'}) = \frac{\chi_{\text{eff}}^2}{\beta_{\gamma'}} \sigma_{\gamma \text{Ge} \rightarrow \text{Ge}^* e}(E_{\gamma'}), \quad (5)$$

where

$$\chi_{\text{eff}}^2 = \chi^2 \left| \frac{m_{\gamma'}^2}{m_{\gamma'}^2 + 2E_{\gamma'}^2 (n(E_{\gamma'}) - 1)} \right|^2, \quad (6)$$

and $\beta_{\gamma'} = \sqrt{1 - m_{\gamma'}^2/E_{\gamma'}^2}$ is the velocity of the hidden photons and the data for $\sigma_{\gamma \text{Ge} \rightarrow \text{Ge}^* e}$ are taken from Ref. [12]. The effective mixing parameter χ_{eff} takes into account the media (germanium) influence on the photon–hidden-photon mixing. This is essentially the fraction in the second line of Eq. (2) with ω_p and Γ expressed via the more commonly used complex refractive index n as $2E_{\gamma'}^2(1 - n) = \omega_p^2 - iE_{\gamma'}\Gamma$ (see, e.g., Ref. [13]). The germanium refractive index data are taken from Ref. [14]. Because in our experimental setup the target and the detector are the same, the efficiency of the system for the expected signal is ≈ 1 . The X-rays accompanying the photoelectric-like effect will be thereafter absorbed in the same crystal, so the energy of the particular outgoing signal equals the total energy of the incoming hidden photon.

The experimental setup used in this search for solar hidden photons has been described elsewhere [15–17]. Here we only recall that the HPGe detector with an active target mass of 1.5 kg was placed at ground level, inside a low-radioactivity iron box with a wall thickness ranging from 16 to 23 cm. The box was lined outside with 1 cm thick lead. A low threshold on the output provided the online trigger, ensuring that all the events down to the electronic noise were recorded. Various calibrated sources have been used to study the linearity and energy resolution and, in particular, in the lowest-energy region mainly a ^{241}Am source. The detector resolution was about 820 eV for the 13.9 keV gamma-rays and 660 eV for their 3.9 keV escape peak. Data were accumulated in a 1024-channel analyzer, with an energy dispersion of 63.4 eV/channel and with data collection time of $2.38 \times 10^7 \text{ s}$. In these long-term running conditions, the knowledge of the energy scale is allocated by continuously monitoring the positions and resolution of indium X-ray peaks of 24.14 keV and 27.26 keV, which are present in the measured spectra.

As can be seen from Fig. 2, showing the total energy spectrum, there is no evidence for any excess of photon-like events due to the hidden photon–electron interactions. The expected spectrum (red line) has a step at $E_{\gamma'} \sim 1.3 \text{ keV}$, corresponding to the threshold in photoelectric cross section on germanium L electrons. There is no sign of such a step in the measured spectrum that could positively identify a hidden-photon signal. Therefore, our evaluation for upper limits on the mixing parameter follows the most conservative assumption, by requiring the predicted signal $N_{\gamma'}(k)$ in every energy bin k to be less than or equal to the recorded

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