Hunting up low-mass bosons from the Sun using HPGe detector

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Abstract

In this experiment we aim to look for keV-mass bosons emitted from the Sun, by looking at a process analogous to the photoelectric/Compton effect inside the HPGe detector. Their coupling to both electrons and nucleons is assumed. For masses above 25 keV, the mass dependence of our limit on the scalar-electron coupling reveals a constraint which proves stronger than that obtained recently and based on the very good agreement between the measured and predicted solar neutrino flux from the $^7$B reaction. On the other hand, the mass dependence of our limit on the scalar-proton/electron coupling together entails a limit on a possible Yukawa addition to the gravitational inverse square law. Such a constraint on the Yukawa interactions proves much stronger than that derived from the latest AFM Casimir force measurement.

Keywords: Solar scalars, Dark matter, Equivalence principle

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The existence of new light particles (notably in the sub-eV regime), coupled extremely weakly to ordinary matter, seems quite feasible in extensions of the Standard Model to very high energy scales. Besides exploring the TeV scale, currently underway via the Large Hadron Collider at CERN, there are also overwhelming reasons (like neutrino masses and the dark energy of the universe) to search for new physics in low energy experiments. Amongst the light bosonic 4-dimensional particles inherently connected to physics at very high energy scales, the QCD axion with pseudoscalar coupling [1], axion-like particles (like string moduli) [2] as well as gauge bosons from the hidden sector of string theory [3], leap out. Examples of bosons with scalar coupling are the scalar components of the flavon fields [4], the scalar familion [5] and the sgoldstino [6].

Yet another motivation to study hypothetical bosons (this time with keV masses) is the possibility that such particles may account for a dark matter in the universe [7]. Moreover, they may account for a dark matter component in the galactic halo as well, arising thus naturally as a solution to the observed model-independent annual modulation signal in the DAMA/Libra experiment [8]. Besides, the theoretical paradigm for the formation of structure in the universe needs a keV-mass particle for the galactic scale [9].

Finally, a nonzero bosonic coupling to ordinary matter would induce a violation of the Newtonian Inverse Squared Law (ISL) through new boson-exchange forces. Such contribution gives forces between unpolarized bodies that violates the Weak Equivalence Principle and in experimental tests of the gravitational ISL can be distinguished from forces arising in higher-dimensional theories [10].

In the present paper, we aim to observe light boson particles with mass in the keV range, coming from the Sun and emitted in a Compton-like process $\gamma + f \rightarrow f + \phi$ with the solar-plasma constituents, where “f” designates electrons (e) or protons (p). Although a direct production via bremsstrahlung process $e + f \rightarrow e + f + \phi$ turns out to give three times larger total emission in the Sun [11], the Compton-like process has a much harder spectrum for energies $\gtrsim O(\text{keV})$. Thus, for keV mass particles, the use of the Compton-like process alone will suffice. Our experimental setup has been designed such as to capture scalars from the Sun in the HPGe detector, in the photoelectric-like process (if scalars couple only to electrons) or in the Compton-like process (if scalars couple only to protons). Then we compare our limit on the interaction strength $g_{\text{sec}}(m_\phi)$ with that obtained recently from the SNO constraint on nonstandard energy losses [12]. Also, our limit $g_{\text{opp}}(m_\phi)$ is used to infer constraints on the Yukawa interactions in the parameter range covered by Casimir/van der Waals force measurements [13].

The scalar bosons couple to ordinary matter via formula

$$\mathcal{L} = g_{\text{eff}} \bar{\psi} \gamma \phi \psi .$$

(1)

In the limit of nonrelativistic electrons (protons) with mass

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[1] Although the interpretation of the DAMA annual modulation in terms of keV-mass pseudoscalars is no longer viable, the solution in the scalar case coupled to nucleons still does apply [2].

The contribution of the Compton-like process with helium nuclei is also taken into account when the solar flux due to a scalar-proton coupling is calculated.
mass $m_f \gg E_f$ (photon energy), the cross section for the Compton-like process is expressed as \[ (2) \]
\[ \sigma_{\gamma f \rightarrow e\gamma} = \frac{1}{4\pi} \sigma_{T_h} \times \beta^2, \]
where $\sigma_{T_h}$ is the cross section for Thomson scattering ($\sigma_{T_h} = 6.65 \times 10^{-25}$ cm$^2$ and $\sigma_{T_h}^{137} = 1.97 \times 10^{-31}$ cm$^2$), $\beta = \sqrt{1 - (m_\gamma/E)^2}$ is the velocity of the outgoing $\phi$-boson, and $\alpha \simeq 1/137$ is the fine structure constant (natural units with $\hbar = c = k_B = 1$ are used through this paper). An appreciable amount of the Sun's protons are bound inside $^4$He nuclei and these protons have to be taken into account. Eq. \[ (2) \], being nonrelativistic, is valid for the $\gamma$-$^4$He scattering too (with $\sigma_{^4\text{He}}^{10} = 5 \times 10^{-32}$ cm$^2$ and $g_{\text{eff}} \equiv g_{\text{eff}}$). The recoil effects are neglected so that the photon and the scalar energies are taken to be equal, $E_\gamma = E$, where $E$ is the total energy of the scalar particle. The differential solar flux of scalar bosons at the Earth is given by
\[ (3) \]
\[ \frac{d\Phi_{\phi}}{dE} = \frac{1}{4\pi d_\odot^2} \int_0^{R_\odot} dr 4\pi r^2 n_\gamma(E_\gamma) \sigma_{\gamma f \rightarrow e\gamma} N_f. \]
Here $n_\gamma(E_\gamma) = E_\gamma^2 / \pi^2 (e_{\gamma T} / T - 1)$ is the differential number density of photons in the Sun (number of photons per energy interval per volume), $d_\odot$ is the average Sun-Earth distance, while $R_\odot$ is the solar radius. The electron, proton, and $^4$He number densities $N_e$, $N_p$, and $N_{^4\text{He}}$, respectively, as well as the temperature $T$ are functions of $r$, the distance from the solar center. They are calculated using BS05 Standard Solar Model data \[ (14) \]. For example, Fig. \[ 1 \] shows differential flux of the solar scalars at the Earth for different scalar masses and the scalar-electron coupling strength of $10^{-13}$. When we consider the flux due to the scalar-proton interactions, we consider a sum of the proton and $^4$He contribution in Eq. \[ (3) \].

In this paper, we report results of our search for scalars which could be produced in the Sun by the Compton-like processes and detected in the single spectrum of an HPGe detector as a result of the photoelectric-like effect (if scalars couple only to electrons) or the Compton-like effect (if scalars couple only to protons) on germanium atoms. The X-rays originating from the Compton-like process with protons or accompanying the photoelectric-like effect will be (subsequently) absorbed in the same crystal, and the energy of the particular outgoing signal equals the total energy of the incoming scalar. The expected number of events in the detector, differential with regard to the scalar energy $E$ is given as
\[ (5) \]
\[ \frac{dN_\phi}{dE} = \frac{d\Phi_{\phi}}{dE} \sigma_{\phi \text{Ge-Ge} \rightarrow e\gamma} N_{\text{Ge}} t, \]
where $N_{\text{Ge}}$ is the number of germanium atoms in the detector and $t$ is the data collection time. The cross section for the photoelectric-like effect in Eq. \[ (4) \] is calculated from the photoabsorption cross section $\sigma_{\gamma \text{Ge-Ge} \rightarrow e\gamma}$ as
\[ (6) \]
\[ \sigma_{\phi \text{Ge-Ge} \rightarrow e\gamma} = \frac{g_{\text{eff}}^2}{4\pi} \sigma_{\text{Ge-Ge} \rightarrow e\gamma} \times \beta^2, \]
with data for $\sigma_{\phi \text{Ge-Ge} \rightarrow e\gamma}$ taken from Ref. \[ (12) \], while the cross section for the Compton-like process is given by
\[ (7) \]
\[ \sigma_{\phi \text{Ge-Ge} \rightarrow \gamma} = \frac{g_{\text{eff}}^2}{4\pi} \sigma_{\text{Th} \rightarrow \phi} \times \beta, \]
where $\sigma_{\text{Th} \rightarrow \phi} = \sigma_{\text{Th}} (m_\phi/m_{\text{Ge}})^2 Z_{\text{Ge}}^2$ is the Thomson cross section for a Ge nucleus.

Because in our experimental set-up the target and the detector are the same, the efficiency of the system for the expected signal is \( \approx 1 \). 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. Energy calibration was obtained with calibrated radioactive sources of $^{241}\text{Am}$, $^{109}\text{Cd}$, and $^{55}\text{Fe}$. For the energy region of interest in this experiment (below 60 keV) the detector resolution was about 660 eV for the 3.9 keV escape peak and 820 eV for 13.9 keV and 59.5 keV gamma-rays of $^{241}\text{Am}$. Data were accumulated in a 1024-channel analyzer, with an energy dispersion of 63.4 eV/channel and with data collection time of $2.38 \times 10^7$ s. In these long-term running conditions, the knowledge of the energy scale is allocated by continuously monitoring the positions and resolution of indium $24.14$ keV ($K_\alpha$) and $27.26$ keV ($K_\beta$) peaks which are present in the measured energy distribution, as is seen in Fig. \[ 2 \]. Drifts were $< \pm 1$ channel and a statistical accuracy of better than 0.4% per channel was attained.

The evaluation for upper limits on the scalar-electron (proton) coupling follows the most conservative assumption, by requiring the predicted signal in an energy bin to be less than or equal to the recorded counts. Similar approaches have been used by other groups \[ (24) \].
a case like this where direct background measurement is not possible (the Sun cannot be switched off) and the signal shape is a broad smooth spectrum on top of an unknown background spectrum. For fixed $m_{\phi}$, the theoretically expected spectrum of scalar-induced events has been calculated by means of Eq. (6), where $g_{\phi\gamma\gamma}^{2\text{eff}}$ is the only free parameter which is then used to fit the maximal value of the expected spectrum to the measured one. Figure 2 shows a comparison between the experimental data and the calculated spectrum for scalar-electron interactions, for scalar masses of 3 keV (red dashed line) and 30 keV (blue dashed line). The corresponding upper limits on the scalar-electron (proton) coupling strength obtained in this work are displayed in Fig. 3. One can see that for masses above 25 keV, the mass dependence of our $g_{\phi\gamma\gamma}$ limit reveals a constraint which proves stronger than that obtained recently [12] and based on the very good agreement between the measured and predicted solar neutrino flux from the $^8\text{B}$ reaction. The possibility of decay of the scalar particle into two photons, with a lifetime of $64\pi/(g_{\phi\gamma\gamma}^2 m_{\phi}^2)$ and $|g_{\phi\gamma\gamma}| = 2 g_{\phi\gamma\gamma}^2/\sqrt{3Î� m_{\phi}}$ [12], during its traversal from the Sun to the Earth sets an upper bound on the scalar mass to be less than about 50 keV.

We note that from our limit on the extension of the Standard Model $g_{\phi\gamma\gamma}(m_{\phi})$, one can infer also a constraint on a deviation from Newtonian physics. Indeed, a spin-0 exchange contribution to the static gravitational energy, described by the lagrangian density $\mathcal{L}$, is given by a Yukawa addition to the familiar Newton potential between two point masses $m_1$ and $m_2$,

$$V(r) = -G \frac{m_1 m_2}{r} \left[ 1 + \alpha_N e^{-r/\lambda_{\phi}} \right].$$

Here $\alpha_N$ is proportional to the squared product of the appropriate coupling constants, $\alpha_N \simeq g_{\phi\gamma\gamma}^2/(16\pi G m_{\phi}^2)$. This constant characterizes the strength of non-Newtonian interaction compared to the Newtonian one with a gravitational constant $G = 1/M_{\odot}^2$. The interaction range $\lambda_{\phi} = 1/m_{\phi}$ has the meaning of the Compton wavelength of the spinless particle. The fact that matter-scalar coupling constants in $\mathcal{L}$ are species-dependent, reflects a violation of the Weak Equivalence Principle. The region in the plane $(\lambda_{\phi}, |\alpha_N|)$, excluded by various torsion-balance experiments as well as theoretical prediction from string-like theories are collected in [11]. On the other hand, since experiments searching for $\alpha_N$-dependent term in $\mathcal{L}$ are only sensitive when $r \sim \lambda_{\phi}$, the experiments that are setting the best limits for separations $\lesssim 10^{-4}$ m are those testing the Casimir force law. This is so since in that regime Casimir forces, and not gravity, provide the dominant background force. Our limit $g_{\phi\gamma\gamma}(m_{\phi})$, when expressed in the $(\lambda_{\phi}, |\alpha_N|)$ plane, just fits the regime covered by Casimir force measurements. As seen from Fig. 4, the constraints from various Casimir force measurements are considerably weaker than ours for $\lambda_{\phi} \lesssim 10^{-8}$ m. Thus, all the existing constraints in the plane $(\lambda_{\phi}, |\alpha_N|)$ for $\lambda_{\phi} \lesssim 10^{-8}$ m should be superseded by the currently derived ones.

In conclusion, we have performed an experimental search
Figure 4: Upper limits on new forces from potentials of the form given by Eq. (5). Our results corresponding to scalar-proton and scalar-electron interactions are shown by the blue and the green line, respectively. The gray curves represent the limits from various van der Waals/Casimir force measurements [13, 16–19].

for low-mass bosons coming from the Sun. For bosons coupling to protons, our limit comfortably extends to masses beyond the solar central temperature, encompassing thus marginally the allowed region for the presence of scalar dark matter in the galactic halo. Also, our limits are complementary to those obtained recently from the accurate knowledge of the solar interior. Finally, our limits tighten up constraints on non-Newtonian gravity much more efficiently than those obtained from the Casimir force measurements.

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