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Probing new physics with underground accelerators and radioactive sources

Eder Izaguirre [a], Gordan Krnjaic [a,*], Maxim Pospelov [a,b]

[a] Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
[b] Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada

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A B S T R A C T

New light, weakly coupled particles can be efficiently produced at existing and future high-intensity accelerators and radioactive sources in deep underground laboratories. Once produced, these particles can scatter or decay in large neutrino detectors (e.g. Super-K and Borexino) housed in the same facilities. We discuss the production of weakly coupled scalars ϕ via nuclear de-excitation of an excited element into the ground state in two viable concrete reactions: the decay of the 0^+ excited state of ^{16}O populated via a (p, α) reaction on fluorine and from radioactive ^{144}Ce decay where the scalar is produced in the de-excitation of ^{144}Nd*, which occurs along the decay chain. Subsequent scattering on electrons, $e(\phi, \gamma)e$, yields a mono-energetic signal that is observable in neutrino detectors. We show that this proposed experimental setup can cover new territory for masses 250 keV $\le m_\phi \le 2m_e$ and couplings to protons and electrons, $10^{-11} \le g_e g_p \le 10^{-7}$. This parameter space is motivated by explanations of the "proton charge radius puzzle", thus this strategy adds a viable new physics component to the neutrino and nuclear astrophysics programs at underground facilities.

1. Introduction

In recent years, there has emerged a universal appreciation for new light, weakly-coupled degrees of freedom as generic possibilities for New Physics (NP) beyond Standard Model (SM). Considerable effort in "intensity frontier" experiments is now devoted to NP searches [1]. In this paper we argue that there is a powerful new possibility for probing these states by combining large underground neutrino-detectors with either high luminosity underground accelerators or radioactive sources.

Underground laboratories, typically located a few km underground, are shielded from most environmental backgrounds and are ideal venues for studying rare processes such as low-rate nuclear reactions and solar neutrinos. Thus far, these physics goals have been achieved with very different instruments: nuclear reactions relevant for astrophysics involve low-energy, high-intensity proton or ion beams colliding with fixed targets (such as the LUNA experiment at Gran Sasso), while solar neutrinos are detected with large volume ultra-clean liquid scintillator or water Cerenkov detectors (SNO, SNO+, Borexino, Super-K, etc.).

In this paper we outline a novel experimental strategy in which light, "invisible" states ϕ are produced in underground accelerators or radioactive materials with O(MeV) energy release, and observed in nearby neutrino detectors in the same facilities as depicted in Fig. 1:

$$X^* \to X + \phi, \qquad \text{production at "LUNA" or "SOX"} \tag{1}$$

$$e + \phi \to e + \gamma, \qquad \text{detection at "Borexino".} \tag{2}$$

Here X^* is an excited state of element X, accessed via a nuclear reaction initiated by an underground accelerator ("LUNA") or by a radioactive material ("SOX").[1] In the "LUNA"-type setup a proton beam collides against a fixed target, emitting a new light particle that travels unimpeded through the rock and scatters inside a "Borexino"-type detector. Alternatively, in the "SOX" production scenario, designed to study neutrino oscillations at short baselines, a radioactive material placed near a neutrino detector gives rise to the reaction in Eq. (1) as an intermediate step of the radioactive material's decay chain.

We study one particularly well-motivated NP scenario with a $\lesssim$ MeV scalar particle, very weakly $O(10^{-4})$ coupled to nucleons

* Corresponding author.
E-mail address: gkrnjaic@perimeterinstitute.ca (G. Krnjaic).

[1] Our idea is very generic, not specific to any single experiment or location, which is why quotation marks are used.

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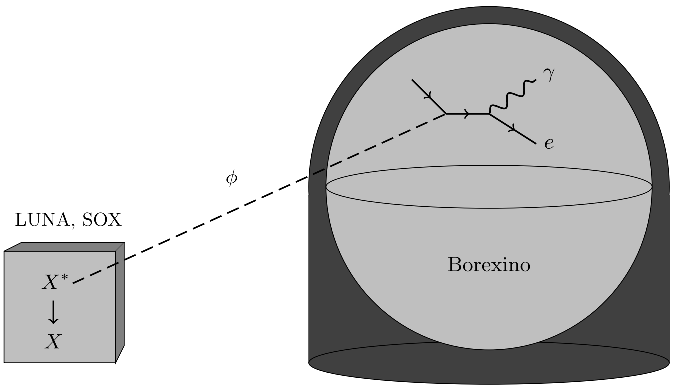

Fig. 1. Schematic figure of ϕ production in a "LUNA"-type underground accelerator via $p + {}^{19}\mathrm{F} \to ({}^{16}\mathrm{O}^* \to {}^{16}\mathrm{O} + \phi) + \alpha$ or a "SOX"-type radioactive source via ${}^{144}\mathrm{Ce} \to {}^{144}\mathrm{Pr}(\bar{\nu}_e) \to \mathrm{Nd}^* \to \mathrm{Nd} + \phi$. Subsequent detection at "Borexino" proceeds via $\phi e \to e\gamma$ scalar conversion.

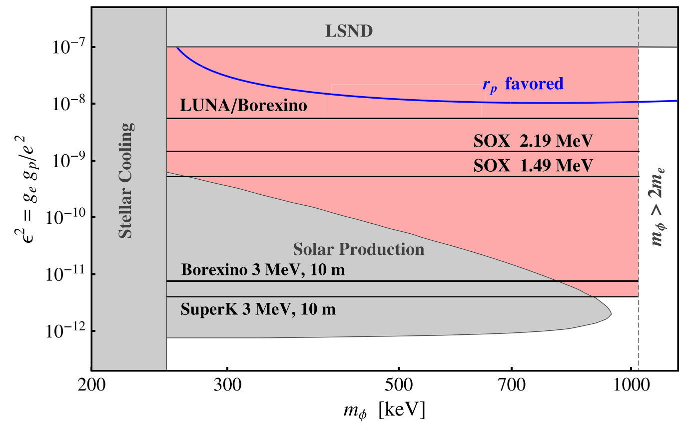

Fig. 2. Sensitivity projections for various experimental setups in terms of $\epsilon^2 = g_p g_e/e^2$ and m_ϕ, which parametrize the NP explanation of the r_p anomaly in Eq. (4); the blue band is the parameter space that resolves the puzzle. The "LUNA/Borexino" curve assumes a 400 keV proton beam with 10^{25} POT incident on a C_3F_8 target to induce $p + {}^{19}\mathrm{F} \to ({}^{16}\mathrm{O}^* \to {}^{16}\mathrm{O} + \phi) + \alpha$ reactions 100 m away from Borexino and yield 10 signal events ($>3\sigma$) above backgrounds [9]. The Borexino 3 MeV and Super-K 3 MeV lines assume the same setup with a 3 MeV p-accelerator 10 m away from each detector. The Super-K projection shows 100 signal events ($>3\sigma$) above backgrounds at 6.05 MeV [10]. The SOX lines assume a radioactive ${}^{144}\mathrm{Ce}$–${}^{144}\mathrm{Pr}$ source 7.15 m away from Borexino with 50 and 165 events ($>3\sigma$) above backgrounds for 2.19 and 1.49 MeV lines respectively. Shaded in gray are constraints from solar production [9], LSND electron–neutrino scattering [11], and stellar cooling [12], for which we assume $g_e = (m_e/m_p)g_p$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and electrons. This range of masses and couplings is not excluded by astrophysical or laboratory bounds, and is motivated by the persistent proton charge-radius anomaly. Two concrete, viable possibilities for producing light scalars are considered:

- For the LUNA-type setup, we show that such light particles can be efficiently produced by populating the first excited 6.05 MeV 0^+ state of ${}^{16}\mathrm{O}$ in (p, α) reactions on fluorine.
- For the SOX-type setup we find similarly powerful sensitivity from the ${}^{144}\mathrm{Ce}$–${}^{144}\mathrm{Pr}(\bar{\nu}_e)$ radioactive source, which can produce a scalar with 2.19 or 1.49 MeV energies from the ${}^{144}\mathrm{Nd}^*$ de-excitation that occurs along the decay chain.

The subsequent detection of a mono-energetic release in a Borexino-type detector with 6.05, 2.19, or 1.49 MeV will be free from substantial environmental backgrounds. The strategy proposed in this Letter is capable of advancing the sensitivity to such states by many orders of magnitude, completely covering the parameter space relevant for the r_p puzzle.

2. Scalar particles below 1 MeV

New particles in the MeV and sub-MeV mass range are motivated by the recent 7σ discrepancy between the standard determinations of the proton charge radius, r_p, based on e–p interactions [2], and the recent, most precise determination of r_p from the Lamb shift in muonic Hydrogen [3,4]. One possible explanation for this anomaly is a new force between the electron (muon) and proton [5–7] mediated by a $\sim$100 fm range force (scalar- or vector-mediated) that shifts the binding energies of Hydrogenic systems and skews the determination of r_p. Motivated by this anomaly, we consider a simple model with one light scalar ϕ that interacts with protons and leptons,

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2 \phi^2 + (g_p \bar{p}p + g_e \bar{e}e + g_\mu \bar{\mu}\mu)\phi, \tag{3}$$

and define $\epsilon^2 \equiv (g_e g_p)/e^2$. We assume mass-weighted couplings to leptons, $g_e \propto (m_e/m_\mu)g_\mu$, and no couplings to neutrons. The apparent corrections to the charge radius of the proton in regular and muonic hydrogen are [5–7]

$$\Delta r_p^2\big|_{eH} = -\frac{6\epsilon^2}{m_\phi^2}; \qquad \Delta r_p^2\big|_{\mu H} = -\frac{6\epsilon^2 (g_\mu/g_e)}{m_\phi^2} f(am_\phi) \tag{4}$$

where $a \equiv (\alpha m_\mu m_p)^{-1}(m_\mu + m_p)$ is the μH Bohr radius and $f(x) = x^4(1+x)^{-4}$. Equating $\Delta r_p^2|_{\mu H} - \Delta r_p^2|_{eH}$ to the current discrepancy of $-0.063 \pm 0.009\ \mathrm{fm}^2$ [4], one obtains a relation between m_ϕ and ϵ. Thus, for $m_\phi = 0.5$ MeV, the anomaly suggests $\epsilon^2 \simeq 1.3 \times 10^{-8}$. For $m_\phi > 2m_e$, the $\phi \to e^+e^-$ process is highly constrained by searches for light Higgs bosons [1], so we consider the $m_\phi < 2m_e$ region, which is relatively unconstrained. Since $g_e \ll g_p$, the $\phi - e$ coupling is suppressed relative to that of a massive photon-like particle, so precision measurements of α and $(g-2)_e$ do not constrain this scenario.

We would like to emphasize that currently, there are no good models of new physics capable of fitting Δr_p discrepancy and not suffering from additional fine-tuning issues, especially if one tries to find a satisfactory description for such models at or above the electroweak scale. Thus, models with very light vector mediators have to be constructed to avoid couplings with neutrinos [7], but these cannot avoid the tuning of the muon $g-2$ and the atomic parity violation constraints [8]. In that sense, a sub-MeV scalar may be presenting the least amount of tuning [5]. Still, the vanishing coupling to neutrons (constrained in neutron scattering experiments to be below 10^{-4} level), is challenging to achieve: the only possibility at hand seems to be a fine-tuning of $\phi\bar{u}u$ and $\phi\bar{d}d$ operators at the quark level. This in turn, would correspond to tuning of dimension five operators, when $\phi\bar{q}q$ are generalized to the full SM gauge invariance. To summarize this discussion, we take model (3) as a phenomenological model, capable of resolving Δr_p discrepancy, but not free of fine-tuning issues.

The astrophysical and fixed-target constraints depend on the cross section for $e\phi \to e\gamma$ conversion, which for $m_\phi \ll m_e$ with a stationary electron target is

$$\frac{d\sigma}{dE} = \frac{\pi (g_e/e)^2 \alpha^2 (E - m_e)}{m_e Q^4 (Q - E + m_e)^2}\Big[E\big(Q^2 - EQ - 2m_e Q - 2m_e^2\big) + m_e\big(3Q^2 + 3Q m_e + 2m_e^2\big)\Big], \tag{5}$$

where E is the electron recoil energy and Q is the ϕ energy. At $Q \gg m_e$, this leads to a total cross section of

$$\sigma_{e\phi} \simeq \frac{\pi (g_e/e)^2\alpha^2}{2m_e Q} = 13\text{ mb} \times \frac{5\text{ MeV}}{Q} \times \left(\frac{g_e}{e}\right)^2, \quad (6)$$

which determines the in-medium ϕ-absorption probability. Absorption competes with the $\phi \to \gamma\gamma$ decay, proceeding through loops of fermions f with the width given by a standard formula,

$$\Gamma(\phi \to \gamma\gamma) = \frac{\alpha^2 m_\phi^3}{512\pi^3}\left|\sum_f \frac{g_f}{m_f} N_c Q_f^2 A_{1/2}(\tau_f)\right|^2, \quad (7)$$

where Q_f is the fermion charge, $\tau_f \equiv m_\phi^2/4m_f^2$, and

$$A_{1/2}(\tau) = 2\tau^{-2}\left[\tau + (\tau - 1)\arcsin\sqrt{\tau}\right]. \quad (8)$$

An approximate proportionality to particle masses ensures that couplings to neutrinos are negligible.

Processes (5), (7) define the gross features of ϕ-phenomenology in cosmological and astrophysical settings. The ensuing constraints are summarized as follows:

- Energy loss in stars via $e\gamma \to e\phi$ (red giants, white dwarfs, etc.) is exponentially suppressed for $m_\phi > T_{\rm star}$. We calculate a bound of $m_\phi \gtrsim 250$ keV, for the fiducial range of couplings.
- The decay of ϕ in the early Universe at $T \sim m_\phi$ results in a negative shift of the "effective number of neutrinos." For $m_\phi >$ 250 keV the shift is moderate, $N_{\rm eff} \sim -0.5$ [13], and can be easily compensated by the positive contributions from other light particles (e.g. sterile neutrinos).
- SN physics: Low masses and sizable couplings, $g_{e,p} \sim 10^{-4}$, ensures the ϕ are trapped during the explosions, and neither take energy from the explosive zones nor degrade the neutrino energies on account of $g_\nu = 0$.
- Emission of ϕ in solar nuclear reactions can be constrained using the Borexino search for solar axions [9], and disfavors some fraction of the parameter space with ϵ^2 in between 10^{-12} and 10^{-10}, as shown in this work.

In addition to astrophysical constraints, bounds on ϵ from direct searches of very light scalars typically probe $\epsilon^2 \gtrsim 10^{-7}$. When combined, existing constraints leave an unexplored part of the parameter space for the scalar model, 250 keV $\lesssim m_\phi < 2m_e$, $10^{-10} \lesssim \epsilon^2 \lesssim 10^{-7}$, and the Δr_p-motivated range falls in the middle of this allowed territory. The existing constraints are summarized in Fig. 2.

3. Production of scalars in nuclear reactions

Searches of light scalar particles in nuclear reactions, such as ^{3}H$(p,\gamma)^4$He and ^{19}F$(p,\alpha)^{16}$O* have been successfully implemented [14,15] on the surface, where the main background comes from cosmic events. For sub-MeV masses of ϕ, the latter reaction is especially advantageous as ϕ is produced in the de-excitation of the 0^+ state:

$$^{16}\text{O}^*(6.05) \to {}^{16}\text{O} + \phi, \quad (9)$$

with energy release $Q = 6.05$ MeV. In the SM, the single-γ decay of this state is not possible due to angular momentum conservation, and the main de-excitation process is $^{16}\text{O}^* \to {}^{16}\text{O} + e^+e^-$ with the long lifetime 96 ± 7 ps [16]; thus, the relative branching to new physics can be greatly enhanced. Following [17] for $m_\phi \ll Q$, the NP branching ratio $\Gamma_\phi/\Gamma_{e^+e^-}$ is

$$\mathcal{B}r_\phi = \frac{8\pi(g_p/e)^2 Q^5}{\alpha b(s)(Q - 2m_e)^3(Q + 2m_e)^2} \simeq 4 \times 10^3\left(\frac{g_p}{e}\right)^2, \quad (10)$$

where $s = (Q - 2m_e)/(Q + 2m_e)$ and $b(s) \approx 0.92$ is defined in [17]. The excited state ^{16}O* can be efficiently produced in $\sim$100 keV–MeV p accelerators.

To estimate the ϕ yield from $p + {}^{19}\text{F} \to {}^{16}\text{O}^*(6.05) + \alpha$, we model the cross section below 3 MeV using [18,19] and extrapolate to the Coulomb-suppressed region. Specifically, we take $\sigma(E) \simeq \sigma_0 f(E)$, with $\sigma_0 = 18$ mbn and model the Coulomb repulsion with

$$f(E < E_0) = \sqrt{\frac{E_0}{E}}\exp\left(\sqrt{E_g/E_0} - \sqrt{E_g/E}\right), \quad (11)$$

in the $E < E_0 \equiv 1.5$ MeV range. Here $E_g = 2(\pi\alpha Z_F)^2\mu = 45.5$ MeV is the Gamow energy and μ is the proton–fluorine reduced mass, E is the c.o.m. energy, and normalization ensures continuity at $f(E_0) = 1$, where repulsion can be neglected.

The signal yield for a proton beam of energy E_p (i.e. the probability to produce a quantum of ϕ per each injected proton) and target material of fluorine number-density n_F is

$$N_\phi(E_p) = \mathcal{B}r_\phi \times n_F \int_0^{E_p} dE\, \frac{\sigma_p(E)}{|dE/dx|}. \quad (12)$$

$|dE/dx|$ depends on the material that includes fluorine, and is readily available in [20]. For example, for the C_3F_8 material, the probability of producing one ϕ per injected proton is $N_\phi(3\text{ MeV}) \sim 3 \times 10^{-2}(g_p/e)^2$.

The angular distribution of emerging ϕ is fully isotropic as nuclear recoil velocities are negligible, and the flux at the position of the detector is given by $\Phi_\phi = N_\phi(E_p) \times (dN_p/dt)/4\pi L^2$. Inside the detector, the emitted ϕ scatter off electrons through $e\phi \to e\gamma$ with cross sections given by (5). Thus, the only remaining free parameters (distance L, number of accelerated protons per second dN_p/dt, their energy E_p as well as the number of electrons in the detector volume) are location, source, and detector-specific.[2]

4. Production of light states in radioactive decays

An alternative realistic mechanism for producing light weakly coupled particles is using the high-intensity radiative sources placed near a neutrino detector. In particular, we focus on the specific radioactive source ^{144}Ce–^{144}Pr$(\bar\nu_e)$ motivated by the SOX proposal by the Borexino Collaboration. The production of the scalar in this reaction proceeds via $^{144}\text{Ce} \to \beta\bar\nu + {}^{144}\text{Pr}$ followed by $^{144}\text{Pr} \to \beta\bar\nu + ({}^{144}\text{Nd}^* \to {}^{144}\text{Nd} + \phi)$. Once produced, the scalar can be detected at a neutrino detector.

5. Possible accelerator realizations

All the ingredients for a successful realization of our idea currently exist at the underground Laboratori Nazionali del Gran Sasso (LNGS) in Italy, home of both the LUNA accelerator and Borexino detector. In addition, there are several other facilities of interest including SNOLAB in Canada and the Kamioka Observatory in Japan. Both SNO+ and Super-K detectors in these laboratories could be sensitive to new sub-MeV states if a proton accelerator were to be placed in their vicinity. Furthermore, the Sanford Underground Research Facility (SURF) has current plans to host the Dual Ion Accelerators for Nuclear Astrophysics (DIANA), which are expected

[2] Depending on the UV model assumptions that yield the effective theory in (3), the $\phi \to \gamma\gamma$ decay may dominate the signal yield inside the detector. However, this is highly model-dependent, so we conservatively restrict our focus to the model-independent scattering signal that depends only on the couplings $g_{e,p}$ in the IR effective theory.

to deliver 10–100 mA 3 MeV proton beams. SURF is also home to the Large Underground Xenon (LUX) experiment, which despite its smaller volume compared to Borexino and Super-Kamiokande, could also be sensitive to new sub-MeV states.

The LUNA accelerator [21] can deliver mA currents of MeV scale proton energies [22]. Our main results and the plot with sensitivity projections assume a target which is not currently used by the LUNA experiment (e.g. C_3F_8), but can easily be installed. In Fig. 2 we show a realistic scenario assuming the existing 400 keV accelerator $L = 100$ m away in the canonical LUNA scenario. We also show projections for an upgraded 3 MeV beam [23] 10 m away from the Borexino detector in the Gran Sasso service tunnel. For all our accelerator projections we optimistically assume 10^{25} protons-on-target (POT), achievable with a 50 mA beam running for one year. Very importantly, at 6.05 MeV energy Borexino is almost background-free and has good energy resolution, so that even a handful of events ($\sim$10) would show a significant excess in the corresponding energy bin, and constitute a discovery.

One practical limitation of this proposal could be a requirement of not increasing the neutron background in LNGS. In our example, the main source of neutrons is α nuclei produced in each reaction step, which yield neutrons in secondary collisions with target nuclei. Using [24], we estimate the neutron yield from ^{19}F (α, n) ^{23}Na in our setup to be $\sim O$(few Hz). Such low rates are irrelevant at LNGS, which can accommodate 10^3 Hz, but might matter if alternate production methods are employed, thus requiring extra shielding.

The Super-Kamiokande (Super-K) detector [25] in Kamioka, Japan, contains a 50,000-ton water Čerenkov detector. In Fig. 2 we show the expected ϵ sensitivity of a high-intensity 3 MeV proton source, assuming a C_3F_8 target 10 m away from the detector. Despite a penalty due to a relatively high threshold for the electron energy in Super-K, one can see an incredibly strong potential for the reach to new physics.

6. Possible radioactive source realizations

For scalar production via radioactive decays, one possibility is phase B of the SOX proposal by the Borexino Collaboration [26], which intends to deploy a $\sim$2 PBq source of ^{144}Ce–^{144}Pr 7.15 m from the Borexino center. Roughly 2% of ^{144}Ce decays are accompanied by the γ-radiation from the decay of the metastable Nd* daughter nuclei described above. The 1.49 and 2.19 MeV transition energies are well above the Borexino threshold, so this method covers the full mass range of interest, generating $\sim 10^{13}(g_p/e)^2$ ϕ-particles per second. Given the planned exposures [26], we estimate the Borexino reach in this case, and add corresponding sensitivity lines on Fig. 2.

7. Existing constraints

While many of the past beam-dump experiments can be sensitive to sub-MeV particles, we concentrate on the one that is able to constrain the product of $g_p g_e$, namely the LSND experiment at Los Alamos. Its measurement of the elastic electron–neutrino cross section [11] is also sensitive to light scalars that induce $e\gamma$ events due to scattering on electrons. This analysis has previously been used to constrain new vector particles produced in π^0 decays to dark sector states [27,28]. In our scenario, a scalar ϕ cannot be produced from pseudoscalar π^0 decays. Instead, the dominant process is π^- absorption via $\pi^- p \to n\phi$. The analogous SM process $\pi^- p \to n\gamma$ has branching ratio $\sim$35% [29], so we approximate the ϕ branching as $\sim\epsilon^2 \times 35\%$. Taking the π^- production rate at LSND to be roughly 10% of the π^+ production implies $\sim 10^{22}\pi^-$ for the exposure in [11]. Assuming isotropic ϕ emission and the scattering cross section in Eq. (5) with $Q \to m_p + m_{\pi^-} - m_n \simeq m_\pi$, and implementing the cuts from this analysis, we obtain a roughly flat bound $\epsilon^2 \lesssim 10^{-8}$ for $m_\phi <$ MeV as shown in Fig. 2. This sensitivity exceeds even the bounds from $(g-2)_e$ from [30], which only imply $\epsilon^2 \lesssim 10^{-7}$ over this mass range, assuming mass weighted couplings $g_p = (m_p/m_e)g_e$; for $g_e = g_p$, the bounds from $(g-2)_e$ are comparable to those set by LSND.

In the 100 keV–MeV mass window ϕ's cannot be produced thermally in the solar interior, but can be produced in nuclear reactions. A particularly relevant process is $p + d \to {}^3\text{He} + \phi$ (that accompanies the $d(p,\gamma)^3$He reaction occurring for every individual pp event of energy generation). If ϕ is sufficiently long lived, and not absorbed in the solar interior, it will reach the Earth and deposit 5.5 MeV of energy in Borexino. The absence of such events [9] sets an important constraint on our model.

The solar flux of 5.5 MeV ϕ particles at Borexino is approximated using the pp-neutrino flux via

$$\Phi_{\phi,\text{solar}} \simeq \epsilon^2 P_\text{esc} P_\text{surv} \Phi_{pp\nu}, \tag{13}$$

where $\Phi_{pp\nu} = 6.0 \times 10^{10}$ cm^{-2} s^{-1} [9]. The probability of escaping the sun is $P_\text{esc} = \exp(-\int^{R_\odot} dr\, n_\odot \sigma_{e\phi})$, the probability that the scalar does not decay between the Sun and the Earth is $P_\text{surv} = \exp(-\ell_\odot/\ell_\phi)$, where $\ell_\phi = Qc/m_\phi \Gamma(\phi \to \gamma\gamma)$ is the boosted decay length, and $\ell_\odot$ is the Earth–Sun distance. The Borexino rate is

$$\dot{N}_{\phi e} = \Phi_{\phi,\text{solar}} n_B \sigma_{e\phi} V_B \tag{14}$$

where $n_{\odot,B}$ are mean-solar and Borexino e^- densities, V_B is the Borexino volume, and the cross section off electrons is given in (6). The current limits on this process are $O(5)$ events [9] and the constraint is depicted by the oval region in Fig. 2. For $\epsilon^2 \gtrsim 10^{-10}$, scattering off electrons prevents ϕ from leaving the Sun and for $\epsilon^2 \lesssim \times 10^{-12}$ the production and scattering are insufficient to yield an appreciable signal at Borexino.

The constraints from thermal energy loss in red giants and white dwarfs follow the standard considerations. Calculating the thermal energy loss $\propto g_e^2 \exp(-m_\phi/T_\text{star})$ and reinterpreting the axion constraints from [12], we exclude the $m_\phi \lesssim 250$ keV parameter space for all ϵ of interest.

To conclude, in this paper we have proposed a novel strategy to hunt for sub-MeV particles produced in underground accelerators and radioactive sources located 10–100 m away from large underground neutrino detectors. This experimental program offers unprecedented sensitivity to a variety of NP scenarios including those that resolve the r_p puzzle.

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