Probing New Physics with Underground Accelerators and Radioactive Sources

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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 $\phi$ 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 $^{16}\text{O}$ populated via a $(p,\alpha)$ reaction on fluorine and from radioactive $^{144}\text{Ce}$ decay where the scalar is produced in the de-excitation of $^{144}\text{Nd}^*$, 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 set-up can cover new territory for masses $250\text{keV} \leq m_\phi \leq 2m_e$ and couplings to protons and electrons, $10^{-11} \leq g_\phi g_\mu \leq 10^{-7}$. 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.

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. In this Letter 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 Letter we outline a novel experimental strategy in which light, “invisible” states $\phi$ are produced in underground accelerators or radioactive materials with $O(\text{MeV})$ energy release, and observed in nearby neutrino detectors in the same facilities as depicted in Fig. [1].

\begin{equation}
X^* \rightarrow X + \phi, \quad \text{production at “LUNA” or “SOX”} \quad (1)
\end{equation}

\begin{equation}
e + \phi \rightarrow e + \gamma, \quad \text{detection at “Borexino”}. \quad (2)
\end{equation}

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”). 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 $\lesssim \text{MeV}$ scalar particle, very weakly $O(10^{-4})$ coupled to nucleons 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 $^{16}\text{O}$ in $(p,\alpha)$ reactions on fluorine.
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]. One possible explanation for this anomaly is a new force between the electron(muon) and proton $[3][4]$ mediated by a ~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 $\phi$ that interacts with protons and leptons,

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

and define $e^2 \equiv (g_e g_\mu)/e^2$. We assume mass-weighted couplings to leptons, $g_e \propto (m_e/m_\mu)g_\mu$, and no couplings to neutrinos. UV completing such a theory is challenging, so we regard this as a purely phenomenological model. The apparent corrections to the charge radius of the proton in regular and muonic hydrogen are $[5][7]$.

$$\Delta r_p^2|_{\text{pH}} = \frac{6e^2}{m_\phi^2} ; \quad \Delta r_p^2|_{\mu\text{H}} = -\frac{6e^2}{m_\phi^2} (e^2/m_\phi) f(a m_\phi), \quad (4)$$

where $a \equiv (\alpha m_\mu/m_p)^{-1}(m_\mu + m_p)$ is the $\mu$H Bohr radius and $f(x) = x^4(1 + x)^{-4}$. Equating $\Delta r_p^2|_{\text{pH}} - \Delta r_p^2|_{\mu\text{H}}$ to the current discrepancy of $-0.063 \pm 0.009$ fm$^2$ [3], one obtains a relation between $m_\phi$ and $e$. Thus, for $m_\phi = 0.5$ MeV, the anomaly suggests $e^2 \simeq 1.3 \times 10^{-8}$. For $m_\phi > 2m_e$, the $\phi \rightarrow e^+e^-$ 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 $g_e \ll g_\mu$, the $\phi - e$ coupling is suppressed relative to that of a massive photon-like particle, so precision measurements of $\alpha$ and $(g - 2)_e$ do not constrain this scenario.

The astrophysical and fixed-target constraints depend on the cross section for $e\phi \rightarrow e\gamma$ conversion, which for $m_\phi < 2m_e$ with a stationary electron target is

$$\frac{d\sigma}{dE} = \frac{\pi (g_e/e)^2 \alpha^2(E - m_e)}{m_e Q^2 (Q - E + m_e)^2} \left[ E(Q^2 - EQ - 2m_e Q - 2m_e^2) + m_e(3Q^2 + 3Qm_e + 2m_e^2) \right], \quad (5)$$

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

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

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

$$\Gamma(\phi \rightarrow \gamma\gamma) = \frac{\alpha^2 m_\phi^3}{512 \pi^3} \sum_f \frac{Q_f}{m_f} N_f Q_f^2 A_{1/2}(\tau_f)^2, \quad (7)$$

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

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

An approximate proportionality to particle masses ensures that couplings to neutrinos are negligible. Processes $[5][7]$ define the gross features of $\phi$-phenomenology in cosmological and astrophysical settings. The ensuing constraints are summarized as follows:

- Energy loss in stars via $e\gamma \rightarrow e\phi$ (red giants, white dwarfs etc) is exponentially suppressed for...
\( m_\phi > T_{\text{star}} \). This places a strong bound for \( m_\phi \lesssim 250 \text{ keV} \), for the fiducial range of couplings.

- The decay of \( \phi \) in the early Universe at \( T \sim m_\phi \) results in a negative shift of the “effective number of neutrinos.” For \( m_\phi > 250 \text{ keV} \) the shift is moderate, \( N_{\text{eff}} \sim -0.5 \) \([12]\), and can be easily compensated by the positive contributions from other light particles (e.g. sterile neutrinos).

- SN physics: Low masses and sizable couplings, \( g_{e,\nu} \approx 10^{-4} \), ensures the \( \phi \) 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 \( \phi \) in solar nuclear reactions can be constrained using the Borexino search for solar axions \([8]\), and disfavors some fraction of the parameter space with \( c^2 \) in between \( 10^{-12} \) and \( 10^{-10} \), as shown in this work.

In addition to astrophysical constraints, bounds on \( \epsilon \) 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, \( 250 \text{ keV} \lesssim m_\phi < 2m_e, 10^{-10} \lesssim c^2 \lesssim 10^{-7} \), and the \( \Delta r_\mu \)-motivated range falls in the middle of this allowed territory. The existing constraints are summarized in Fig. 2.

**Production of scalars in nuclear reactions.** Searches of light scalar particles in nuclear reactions, such as \( ^3\text{H}(p,\gamma)^4\text{He} \) and \( ^{19}\text{F}(p,\alpha)^{16}\text{O}^* \) have been successfully implemented \([13,14]\) on the surface, where the main background comes from cosmic events. For sub-MeV masses of \( \phi \), the latter reaction is especially advantageous as \( \phi \) is produced in the de-excitation of the \( 0^+ \) state:

\[
^{16}\text{O}^*(6.05) \rightarrow ^{16}\text{O} + \phi ,
\]

with energy release \( Q = 6.05 \text{ MeV} \). In the SM, the single-\( \gamma \) decay of this state is not possible due to angular momentum conservation, and the main de-excitation process is \( ^{16}\text{O}^* \rightarrow ^{16}\text{O} + e^+e^- \) with the long lifetime \( 96 \pm 7 \text{ ps} \) \([15]\); thus, the relative branching to new physics can be greatly enhanced. Following \([16]\) for \( m_\phi \ll Q \), the NP branching ratio \( \Gamma_\phi/\Gamma_{e^+e^-} \) is

\[
BR_\phi = \frac{8\pi (g_\mu/e)^2 Q^5}{\alpha b(s)(Q - 2m_e)^3(Q + 2m_e)^2} \approx 4 \times 10^3 \left( \frac{g_\mu}{e} \right)^2 ,
\]

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

To estimate the \( \phi \) yield from \( p + ^{19}\text{F} \rightarrow ^{16}\text{O}^*(6.05) + \alpha \), we model the cross section below 3 MeV using \([17,18]\) and extrapolate to the Coulomb-suppressed region. Specifically, we take \( \sigma(E) \approx \sigma_\alpha f(E) \), with \( \sigma_\alpha = 18 \text{ mb} \) and model the Coulomb repulsion with

\[
f(E < E_0) = \frac{E_0}{E} \exp \left( \sqrt{E_g/E_0} - \sqrt{E_g/E} \right) ,
\]

in the \( E < E_0 \approx 1.5 \text{ MeV} \) range. Here \( E_0 = 2(\sigma_\alpha Z_F)^2 \mu = 45.5 \text{ MeV} \) is the Gamow energy and \( \mu \) 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 \( \phi \) per injected proton) and target material of Fluorine number-density \( n_F \) is

\[
N_\phi(E_p) = BR_\phi \times n_F \int_0^{E_p} dE \frac{\sigma_p(E)}{|dE/dx|} .
\]

\(|dE/dx|\) depends on the material that includes Fluorine, and is readily available in \([19]\). For example, for the \( ^{13}\text{F} \) material, the probability of producing one \( \phi \) per injected proton is \( N_\phi(3 \text{ MeV} \approx 3 \times 10^{-2} (g_\mu/e)^2 \).

The angular distribution of emerging \( \phi \) is fully isotropic as nuclear recoil velocities are negligible, and the flux at the position of the detector is given by \( f_\phi = N_\phi(E_p) \times (dN_p/dt) / 4\pi L^2 \).

Under the detector, the emitted \( \phi \) scatter off electrons through \( e\phi \rightarrow e\gamma \) 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.

**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 \(^{144}\text{Ce} \rightarrow ^{144}\text{Pr} (\nu_e) \) motivated by the SOX proposal by the Borexino collaboration. The production of the scalar in this reaction proceeds via \(^{144}\text{Ce} \rightarrow \beta\bar{\nu} + ^{144}\text{Pr} \) followed by \(^{144}\text{Pr} \rightarrow \beta\bar{\nu} + ^{144}\text{Nd}^* \rightarrow ^{144}\text{Nd} + \phi \). Once produced, the scalar can be detected at a neutrino detector.

**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 SNO-LAB 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 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 \([20]\) can deliver mA currents of MeV scale proton energies \([21]\). Our main results and the plot with sensitivity projections assume a target which is not currently used by the LUNA experiment,
(e.g., C$_3$F$_8$), 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 [22] 10m 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 $\alpha$ 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 ($\alpha$, n) $^{23}$Na in our setup to be $\sim O(\text{few Hz})$. Such low rates are irrelevant at LNGS, which can accommodate $10^{34}$Hz, but might matter if alternate production methods are employed, thus requiring extra shielding.

The Super Kamiokande (SuperK) detector [24] in Kamioka, Japan contains a 50,000-ton water Čerenkov detector. In Fig. 2 we show the expected $\epsilon$ sensitivity of a high-intensity 3 MeV proton source, assuming a C$_3$F$_8$ target 10 m away from the detector. Despite a penalty due to a relatively high threshold for the electron energy in SuperK, one can see an incredibly strong potential for the reach to new physics.

Possible radioactive source realizations. For scalar production via radioactive decays, one possibility is phase B of the SOX proposal by the Borexino collaboration [25], 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 $\gamma$-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 $\sim 10^{13} (g_p/e)^2$ $\phi$-particles per second. Given the planned exposures [25], we estimate the Borexino reach in this case, and add corresponding sensitivity lines on Fig. 2.

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 $g_p\sigma_e$, namely the LSND experiment at Los Alamos. Its measurement of the elastic electron-neutrino cross section [10] is also sensitive to light scalars that induce $\gamma$ events due to scattering on electrons. This analysis has previously been used to constrain new vector particles produced in $\pi^0$ decays to dark sector states [26, 27]. In our scenario, a scalar $\phi$ cannot be produced from pseudoscalar $\pi^0$ decays. Instead, the dominant process is $\pi^-\phi$ absorption via $\pi^-p \rightarrow n\phi$. The analogous SM process $\pi^-p \rightarrow n\gamma$ has branching ratio $\sim 35\%$ [28], so we approximate the $\phi$ branching as $\sim \epsilon^2 \times 35\%$. Taking the $\pi^-$ production rate at LSND to be roughly 10% of the $\pi^+$ production implies $\sim 10^{22} \pi^-$ for the exposure in [10]. Assuming isotropic $\phi$ emission and the scattering cross section in Eq. (6) with $Q \rightarrow m_p + m_n - m_e$, and implementing the cuts from this analysis, we obtain a roughly flat bound $\epsilon^2 \lesssim 10^{-8}$ for $m_\phi < 2$ MeV as shown in Fig. 2. This sensitivity exceeds even the bounds from $(g-2)_e$ from [29], 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 $\phi$’s cannot be produced thermally in the solar interior, but can be produced in nuclear reactions. A particularly relevant process is $p + d \rightarrow ^3\text{He} + \phi$ (that accompanies the $d(p,\gamma)^3\text{He}$ reaction occurring for every individual pp event of energy generation). If $\phi$ 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 [8] sets an important constraint on our model.

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

$$\Phi_{\phi, \text{solar}} \simeq \epsilon^2 P_{\text{esc}} P_{\text{surv}} \Phi_{\text{ppv}},$$

where $\Phi_{\text{ppv}} = 6.0 \times 10^{10}\text{cm}^{-2}\text{s}^{-1}$ [8]. The probability of escaping the sun is $P_{\text{esc}} = \exp(-\int_{R_\odot}^{R_{\odot}} d\rho \cdot \sigma_{\phi,e})$, the probability that the scalar does not decay between the Sun and the Earth is $P_{\text{surv}} = \exp(-\ell_{\odot}/\ell_\phi)$, where $\ell_\phi = Q/e(m_\phi/\Gamma(\phi \rightarrow \gamma\gamma))$ is the boosted decay length, and $\ell_\odot$ is the Earth-Sun distance. The Borexino rate is

$$N_{\phi e} = \Phi_{\phi, \text{solar}} n_B \sigma_{\phi,e} V_B$$

where $n_{B,\odot}$ 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 [8] and the constraint is depicted by the oval region in Fig. 2. For $\epsilon^2 \gtrsim 10^{-10}$, scattering off electrons prevents $\phi$ from leaving the Sun and for $\epsilon^2 \lesssim 10^{-12}$ 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 $\propto g_\phi^2 \exp(-m_\phi/T_{\text{star}})$ and reinterpreting the axion constraints from [11], we exclude the $m_\phi \lesssim 250$ keV parameter space for all $\epsilon$ of interest.

To conclude, in this Letter 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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