Physics Letters B 740 (2015) 61–65

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Probing new physics with underground accelerators and radioactive sources

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ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form 18 November 2014
Accepted 18 November 2014
Available online 21 November 2014
Editor: M. Trodden

ABSTRACT

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

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

http://dx.doi.org/10.1016/j.physletb.2014.11.037

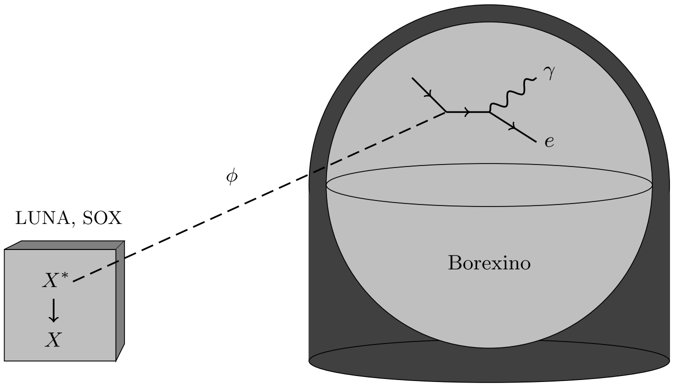

Fig. 1. Schematic figure of ϕ production in a "LUNA"-type underground accelerator via $p + {}^{19}\mathrm{F} \to ({}^{16}\mathrm{O}^* \to {}^{16}\mathrm{O} + \phi) + \alpha$ or a "SOX"-type radioactive source via ${}^{144}\mathrm{Ce} \to {}^{144}\mathrm{Pr}(\bar{\nu}_e) \to \mathrm{Nd}^* \to \mathrm{Nd}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

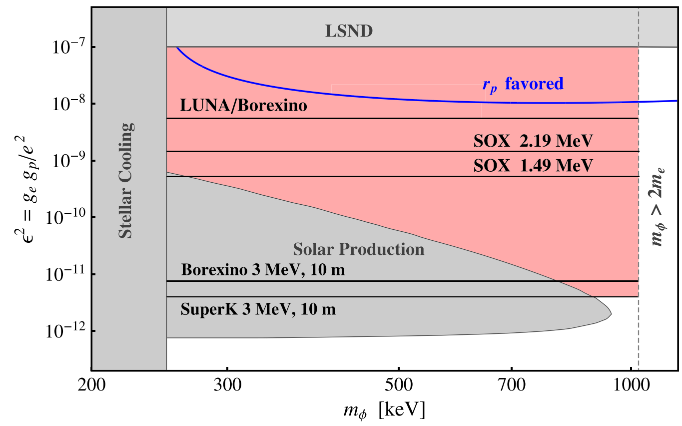

Fig. 2. Sensitivity projections for various experimental setups in terms of $\epsilon^2 = g_p g_e/e^2$ and m_ϕ, which parametrize the NP explanation of the r_p anomaly in Eq. (4); the blue band is the parameter space that resolves the puzzle. The "LUNA/Borexino" curve assumes a 400 keV proton beam with 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 ~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]

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

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 $\Delta r_p^2|_{\mu\mathrm{H}} - \Delta r_p^2|_{e\mathrm{H}}$ 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