Search for boosted dark matter with high-Z material in underground experiments

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We propose to search for a boosted dark matter (DM) particle from astrophysical sources using an emulsion detector in deep underground facilities. We further propose using high-Z material such as lead for a larger DM-nucleus coherent scattering cross section above a threshold. The boosted DM will scatter into an excited DM. While the nuclear recoil energy is not detected, the decay products from the excited DM can be recorded by the proposed detector. Backgrounds such as the nuclear recoil, and an $e^+e^-$ pair from an excited DM decay) in Super-K was proposed, for a better background suppression. However, when an incoming DM is not energetic enough to "knock out" on a proton or electron, the collision is DM-nucleus elastic and the signature consists of only two rings instead of three. When the DM energy is even lower, interaction will be turned off. The threshold energy for the interaction to happen depends on the nucleus mass, and it is lower when the nucleus is heavier. A heavier nucleus has another advantage in that the coherent DM-nucleus scattering cross section scales with $Z^2$, where $Z$ is the atomic number of the target nucleus. In this paper, we propose to use a high-Z material to search for a BDM through its coherent scattering into an excited DM, whose decay products (a pair of $e^+e^-$) can be detected in an underground DM detector. This kind of signal may escape detection in a large volume detector such as Super-K.

I. INTRODUCTION

With compelling gravitational evidences for the existence of dark matter (DM) from astrophysical observations, searching for a DM particle either indirectly through their annihilations, or directly through their interaction with target nuclei, have been an endeavor of many experiments. DM particles are usually assumed to be massive and cold, with a typical velocity of $\mathcal{O}(10^{-3})$. At this low speed, direct detection is very hard since the energy transferred from the DM to a target nucleus is below MeV level, and consequently demands low energy threshold and low radioactivity background in the deep underground experiments. However, it is not impossible that DM sector has multiple components (in analogy to the SM), one of which may have a relativistic speed, so that its detection at underground experiments is easier. The multi-component DM is used to explain several issues in cosmology. In its simplest form \textsuperscript{[1]}, it has a heavy seceded component with no direct coupling to the SM particles (so to evade the direct detection), and a light boosted component which interacts with SM, and assists the thermalization of the heavy one with it. Although subdominant in the universe, the light DM can be constantly produced through the annihilation of the heavy ones in the Galactic center, inside the Sun or the Earth \textsuperscript{[2]}, where the heavy DM’s are trapped and have a higher abundance to annihilate. Such a boosted DM (BDM) has been searched for in the Super-K experiment \textsuperscript{[3]} with an energy threshold above 100 MeV. This threshold was used to reduce the spallation background induced by muons, and background from neutrino collisions. In \textsuperscript{[4]}, a novel search for a BDM scattering into an excited DM state leading to a three-ring signature (induced by a proton or electron recoil, and an $e^+e^-$ pair from an excited DM decay) in Super-K was proposed, for a better background suppression. However, when an incoming DM is not energetic enough to "knock out" on a proton or electron, the collision is DM-nucleus elastic and the signature consists of only two rings instead of three. When the DM energy is even lower, interaction will be turned off. The threshold energy for the interaction to happen depends on the nucleus mass, and it is lower when the nucleus is heavier. A heavier nucleus has another advantage in that the coherent DM-nucleus scattering cross section scales with $Z^2$, where $Z$ is the atomic number of the target nucleus. In this paper, we propose to use a high-Z material to search for a BDM through its coherent scattering into an excited DM, whose decay products (a pair of $e^+e^-$) can be detected in an underground DM detector. This kind of signal may escape detection in a large volume detector such as Super-K.

II. BOOSTED DARK MATTER ENERGY SPECTRUM

For simplicity and without losing generality, we assume the two-component scalar DM model with a contact action

$$\lambda \phi_A \phi_A^* \phi \phi^*, \tag{1}$$

where $\phi_A$ is the dominant heavy DM scalar (with mass $m_A$), and $\phi$ is the subdominant light one (with mass $m$) being produced from the annihilation of $\phi_A^* \phi_A$. When the velocity of $\phi_A$ is non-relativistic, the $\phi$’s energy is almost a delta function, $\delta(E - m_A)$, jittered by each $\phi_A$’s thermal velocity. Suppose the velocities of the two initial state DM particles are $v_1$ and $v_2$, then up to the first power of these velocities, the outgoing $\phi$’s energy can be expressed as

$$E = m_A + \sqrt{m_A^2 - m^2} v \cos \theta, \tag{2}$$

where $v$ is the velocity of $\phi_A$.
where \( \mathbf{v}_s = (\mathbf{v}_1 + \mathbf{v}_2)/2 \) is the total velocity of the \( \phi_1 \phi_1^* \) system, \( \theta \) is the polar angle between \( \mathbf{v}_s \) and the velocity \( \mathbf{v} \) of one \( \phi \) (defined as \((\mathbf{v}_1 - \mathbf{v}_2)/2\)) in the center-of-mass (CM) frame of the \( \phi_1 \phi_1^* \) pair. The differential production rate of \( \phi \) is proportional to

\[
\sigma \nu f(\mathbf{v}_1) d^3 \mathbf{v}_1 f(\mathbf{v}_2) d^3 \mathbf{v}_2, \tag{3}
\]

where \( \sigma \) is the \( \phi_1 \phi_1^* \) annihilation cross section, \( f(\mathbf{v}) = \pi^{-3/2} v_0^{-3} e^{-v_0^2/m^2} \) is the probability function defined in the DM Standard Halo Model \(^5\), with \( v_0 \approx 235 \text{ km/s} \) being the most probable speed \(^9\). The \( \sigma \nu \) in Eq. \((3)\) is nearly a constant, so the energy spread of \( \phi \) around \( E = m_A \) can be calculated as

\[
\langle (\Delta E)^2 \rangle = \frac{m_A^2 - m^2}{2} \int v_s^2 \cos^2 \theta f(\mathbf{v}_1) f(\mathbf{v}_2) d^3 \mathbf{v}_1 d^3 \mathbf{v}_2 d \cos \theta.
\]

To give a typical estimation, for \( m_A = 50 \text{ MeV} \) and \( m = 10 \text{ MeV} \), \( \Delta E \) is about 26 keV.

### III. MASS SPLITTING FOR THE LIGHT DM

We assume the following realization of light dark scalar \( \phi \) mass splitting

\[
\mathcal{L} \supset -\frac{1}{4} X_{\mu \nu} X^{\mu \nu} + \frac{1}{2} m_X^2 X_{\mu \nu} X^{\mu \nu} - \epsilon \epsilon Q_f X_{\mu \nu} \bar{f} \gamma^\mu f +
(D_{\mu} \phi)^* D^\mu \phi - \mu^2 \phi^* \phi - \frac{1}{2} \rho^2 (\phi^* \phi + \phi \phi^*), \tag{5}
\]

where \( X \) is a dark photon mediator, \( f \) is the SM fermion with charge \( Q_f \), \( \epsilon \) is the mixing parameter between the \( U(1)_Y \) and \( U(1)_D \) gauge fields, \( D_{\mu} = \partial_{\mu} + i g_D X_{\mu} \) is the covariant derivative with dark coupling parameter \( g_D \), \( \phi = (\phi_1 + i \phi_2)/\sqrt{2} \) is the light complex scalar in Eq. \((1)\).

The dark photon mass term results from a spontaneous \( U(1)_D \) breaking, whose detailed realization is not specified here. Additionally, the last term in Eq. \((3)\) explicitly violates \( U(1)_D \) and causes a mass splitting for \( \phi \). To see this, substituting \( \phi_1, 2 \) for \( \phi \) to obtain

\[
\mathcal{L} \supset \frac{1}{2} \partial_{\mu} \phi_1 \partial^{\mu} \phi_1 + \frac{1}{2} \partial_{\mu} \phi_2 \partial^{\mu} \phi_2 - \frac{1}{2} (\mu^2 + \rho^2) \phi_1^2 \\
- \frac{1}{2} (\mu^2 - \rho^2) \phi_2^2 - g_D X_{\mu} (\phi_2 \partial^{\mu} \phi_1 - \phi_1 \partial^{\mu} \phi_2)
+ \frac{1}{2} g_D^2 X_{\mu} X_{\mu} (\phi_1^2 + \phi_2^2). \tag{6}
\]

It is evident that two real scalars \( (\phi_1, \phi_2) \) emerge, with mass \( m_1 = \sqrt{\mu^2 + \rho^2} \) and \( m_2 = \sqrt{\mu^2 - \rho^2} \), respectively. It is also possible to achieve a similar mass splitting for a fermionic dark matter by the presence of Majorana mass terms \(^7\), but the scalar model we are studying will be general enough to cover similar kinematics.

We consider the mass degeneracy case where \( m_A \approx m_1 \), so that \( \phi \)s predominantly decays into \( \phi_2 \), and the excited state \( \phi_1 \) can be hardly produced at Super-K.

### IV. BOOSTED DARK MATTER SCATTERING INTO EXCITED DARK MATTER

When the energy transfer between \( \phi_2 \) and nucleus is about a few tens of MeV, the scattering is elastic and we assume the target atom is a scalar boson (its spin is not important). The vertex reads

\[
\frac{i e F(q^2)(P_1 + P_f)_{\mu}}{2} \tag{7}
\]

where \( q^2 \) is the momentum transfer squared, \( P_1, f \) are the target atom’s initial and final state 4-vectors, \( F(q^2) \) accounts for the \( q^2 \)-dependent form factors. Suppose the scattering process is \( \phi_2 (E_2) + T (m_T) \rightarrow \phi_1 (E_1) + T (E_T) \), where \( T \) denotes the target atom with mass \( m_T \) and the particle’s energy is indicated in the parentheses, the differential scattering cross section can be then expressed as

\[
\frac{d \sigma_{\text{scat.}}}{d t} = \frac{\alpha e^2 g_D^2}{16 \pi m_T^2} \frac{(4m_T E_2 - m_1^2 - m_2^2 - t)^2}{(E_2^2 - m_2^2)^2} G_2(t), \tag{8}
\]

where \( \alpha \) is the fine structure constant, \( t = -q^2 = 2m_T (E_2 - E_1) \geq 0 \), and \( G_2(t) \) is an overall elastic form factor defined as \(^8\)

\[
G_2(t) = \left( \frac{a^2 t}{1 + a^2 t} \right)^2 \left( \frac{1}{1 + t/d} \right)^2 Z^2, \tag{9}
\]

where the first term accounts for the atomic form factor due to electron screening, and the second one for the nuclear elastic form factor. According to the simple parameterization in \(^8\), \( a = 111.7 Z^{-1/3}/m_e \), and \( d = 0.164 A^{-2/3} \) GeV\(^2 \) with \( A \) being the target atomic mass number. There is also an inelastic scattering part whose contribution is small and can be neglected at low momentum transfer, since we are focusing on the enhanced coherent scattering. The upper and lower bounds for \( t \) read

\[
t^\pm = \frac{m_T}{s} \left[ (2E_2^2 - m_1^2 - m_2^2) m_T - (m_1^2 - m_2^2) E_2 \right.
\]

\[
\pm \sqrt{(E_2^2 - m_2^2)^2}, \tag{10}
\]

where \( s = 2m_T E_2 + m_1^2 + m_2^2 \) is the CM energy of the initial \( \phi_2 + T \) system, and \( \lambda = (2m_T E_2 - m_1^2 - m_2^2)^2 - 4m_T^2 m_2^2 \). The cross section decreases rapidly as \( t \) increases, as Eq. \((8)\) indicates, but it is the range of low \( t \) values that gives the most important contributions. The differential cross section for a particular set of parameter values is shown in Fig. \((1)\) where \( E_2 \) is 10 keV above the threshold energy introduced below. The total scattering cross section can be obtained by integrating Eq. \((8)\) over the range of \( t \) determined by Eq. \((10)\).

For the scattering process to happen, the minimum threshold energy required for the incoming \( \phi_2 \) is

\[
E_2^{\text{th}} = m_1 + m_2^2 - m_2^2, \tag{11}
\]
3

from which it is evident that, different from the usual elastic scattering process where lighter nucleus mass is favored for larger nuclear recoil energy (as in the contact interaction models), in the case of excited DM, there is a threshold energy that decreases with larger nucleus mass. As a result, high-Z materials are more effective to detect this type of DM scattering than low-Z ones. In Fig. 2 the probability distribution of incoming $\phi_2$ energy according to Eq. 4 and the scattering energy thresholds for lead (Pb) and Oxygen (O) target atoms according to Eq. 11 are shown for $m_A = m_1 = 50$ MeV and $m_2 = 10$ MeV. The Oxygen is the main target atom of the purified water at Super-K (the contribution from hydrogen atoms can be neglected). It is evident that in the case of $m_A \lesssim m_1$, due to the higher threshold, the available BDM flux above it is severely suppressed.

V. DECAY OF THE EXCITED DARK MATTER

Depending on the $\phi_1$’s mass $m_1$, the decay process $\phi_1 \to \phi_2 e^+ e^-$ proceeds either an on-shell (if $m_1 > m_2 + m_X$) or an off-shell (if $m_1 < m_2 + m_X$) dark photon $X$. For the off-shell $X^*$ three-body decay of $\phi_1$, the partial decay width reads

$$
\frac{d\Gamma_{\phi_1}}{dE_{ee}} = \frac{\alpha e^2 g_D^2}{24\pi^2 m_1^3 (m_{ee} - m_X) m_{ee}^2} \left[ (m_1^2 - m_2^2 - m_{ee}^2)^2 - (m_{ee} + m_2^2) - 4m_{ee}^2 m_2^4 - 8m_{ee}^2 m_2^2 m_{ee}^2 \right],
$$

(12)

where $m_{ee}$ denotes the $e^+ e^-$ pair’s invariant mass, whose allowed range is $2m_e \leq m_{ee} \leq (m_1 - m_2)$. With $(m_1, m_2, m_X) = (50, 10, 50)$ MeV and $(\epsilon, g_D) = (10^{-3}, 0.5)$, the intrinsic lifetime of $m_1$ is about $1.2 \times 10^{-11}$ s. With the $\phi_2$ produced nearly at rest, the decay length is well below 1 mm. The 2-D probability distribution of the outgoing electrons’ energy from a three-body $\phi_1 \to \phi_2 e^+ e^-$ decay, taking into account Eq. 12 and different angles between the particle flight direction in CM frame and the boost direction, is shown in Fig. 3. A typical Lorentz boost factor of $\gamma_1 = 1.00041$ is chosen for $\phi_1$.
of $X \rightarrow e^+ e^-$ can be expressed as

$$\Gamma(X \rightarrow ee) = \frac{1}{3} \alpha e^2 m_X \left(1 + \frac{2m_e^2}{m_X^2}\right) \left(1 - \frac{4m_e^2}{m_X^2}\right)^{\frac{5}{2}}. \quad (13)$$

With $\epsilon = 10^{-3}$ and $m_X = 20$ MeV, the intrinsic lifetime of $X$ is about $1.4 \times 10^{-14}$ s. Even with a boost factor of 1.4 for $X$ (from $\phi_1 \rightarrow \phi_2 X$ decay), its decay length is at the level of a few $\mu$m’s. To compare with Fig. 3, the 2-D probability distribution of the outgoing electrons’ energy from the decay $\phi_1 \rightarrow \phi_2 X(e^+ e^-)$ is shown in Fig. 4. It is seen that the energy distribution of $e^+$ or $e^-$ is more confined in this case due to an on-shell dark photon.

![FIG. 4. The probability distribution of the outgoing electrons’ energy from a two-body cascade decay $\phi_1 \rightarrow \phi_2 X \rightarrow \phi_2 e^+ e^-$, for a particular set of parameter values indicated in the plot. The absolute color scale is arbitrary.](image)

**VI. DETECTING BOOSTED DM WITH EXCITED DM DECAY**

To detect the $e^+ e^-$ pair from the excited DM decay after the scattering of a cosmological BDM with a target nucleus, we propose to use an emulsion detector with Pb as the target and absorber material at the same time. Emulsion detectors have been used in the Opera [11], DsTau [12] and FASERν [13] experiments. We propose the dimension of a subdetector to be $30 \times 30 \times 108$ cm$^3$, consisting of 1800 layers, with each layer 0.6 mm thick. Each layer is comprised of a 0.3 mm thick lead plate and 0.3 mm thick emulsion layer. Each emulsion layer consists of a 200 $\mu$m thick base (made of, e.g., cellulose acetate), sandwiched between two emulsion films of 50 $\mu$m thickness, as illustrated in Fig. 5. The emulsion films consist mainly of AgBr (about 66%) and gelatin material (34%). The silver bromide crystals are sensitive to ionization by charged particles passing through it (with an energy band gap of 2.5 eV), and have a typical size of 0.2 $\mu$m. Therefore, the emulsion can have a position measurement of tracks with a precision below 1 $\mu$m, which makes it ideal for our purpose of detecting a pair of $e^+ e^-$ with an energy above $\sim$5 MeV with good tracking performance. We propose to make 9 identical subdetectors, with each one having a cross section area of $30 \times 30$ cm$^2$. The total sensitive target mass will be about 5 tons with 0.875 m$^3$ effective volume. After particle events are recorded by the emulsion detector for an accumulated period, the films will be developed and the AgBr grains positions will be read out by dedicated microscopes. The film on each side of the emulsion layer can provide a position measurement. At the reconstruction level, sequences of aligned grains will be recognized and form tracks for the electrons.

![FIG. 5. The illustration of one emulsion layer of the proposed detector.](image)

The lead is used instead of, e.g. tungsten, apart from its high-Z, is because it is relatively inexpensive, and an electron can travel longer to form a longer track. The main radioactive contamination in lead is $^{210}$Pb, which decays into $^{210}$Bi and $^{210}$Po. There is a 1.16-MeV $\beta$ ray from $^{210}$Bi, but electron of this energy can hardly travel more than one detector layer according to our simulation, and the $^{210}$Pb contamination can be controlled in the production pathway.

We propose to place the detector in a deep underground facility, so the cosmic muon background can be suppressed as much as possible. On the other hand, high energy muons going through the detector will cause a long track from one side of the detector to another side, and can be more easily identified and removed than other experiments that have not as much precise tracking ability, such as Super-K.

Solar neutrino is an important background for this search. Most solar neutrinos have energy below 2 MeV, except for those from the $^8$B reaction chain that extends to about 13 MeV. The most serious interaction for our search is $\nu_e n \rightarrow e^- p$, with a cross section of about $10^{-41}$ cm$^2$. The total solar neutrino flux with $E_\nu \gtrsim$ 10 GeV is about $10^5$ cm$^{-2}$s$^{-1}$ [14], taking into the neutrino oscillation effect. The proposed detector will see about 60 such high energy neutrino interactions per year. Figure 6 shows a 2-D view of the 3-D track of a 10 MeV single electron (from neutrino background) and those for a $e^+ e^-$ pair with an energy of 15 MeV each [15], simulated.
The total signal yield can be calculated as
\[ N_{\text{sig}} = \mathcal{L} t \sigma_{\text{scat}} N_T, \] (14)
where \( \mathcal{L} \) is the BDM flux, \( t \) is the exposure time and \( N_T \) is the number of target nuclei. An integration over a probability function is needed when \( \mathcal{L} \) is energy dependent like in Fig. 2. Some predictions for \( \mathcal{L} \) is at \( O(10^{-7} - 10^{-4}) \) cm\(^{-2}\)s\(^{-1}\) [1, 2, 17]. When we take \( \mathcal{L} = 10^{-4} \) cm\(^{-2}\)s\(^{-1}\), which is Gaussian distributed with a resolution \( \Delta E \) according to Eq. 4, \( \epsilon = 10^{-3} \) and \( g_D = 1 \), the predicted signal yields with 5 years’ exposure time for the proposed detector and Super-K, are given in Tab. I. It can be seen that smaller \( m_X \) leads to larger yields, and larger mass splitting \( (m_1 - m_2) \) leads to smaller yields. However, the signal with larger mass splitting will also give more outstanding signatures in the emulsion detector (more energetic \( e^+e^- \) pair). Moreover, as either or both of \( m_1 \) and \( m_2 \) increase, the signal yields also decrease, and the expected yields at Super-K diminish towards zero while an observation is still possible with the proposed detector.

TABLE I. The expected BDM signal yields with 5 years’ exposure time for the proposed emulsion detector and Super-K, for several different sets of parameters together with \( \epsilon = 10^{-3}, \ g_D = 1, \ \mathcal{L} = 10^{-4} \) cm\(^{-2}\)s\(^{-1}\) and Gaussian distributed with an energy resolution \( \Delta E \) according to Eq. 4.

| \( (m_A, m_1, m_2, m_X) \) | \( \mathcal{L} \) | \( t \) | \( N_{\text{sig}} \) |
|--------------------------|----------|--------|----------------|
| all in MeV               | Emul. Det. | Super-K |
| (50, 10, 50)             | 8.3      | 11.9   |
| (50, 10, 20)             | 25.3     | 36.5   |
| (75, 10, 20)             | 5.2      | 0.02   |
| (100, 10, 20)            | 1.3      | 9.1 \( \times 10^{-4} \) |
| (100, 50, 20)            | 3.6      | 2.7 \( \times 10^{-4} \) |

Finally, the parameter space of at least one signal event expected is shown in Fig. 7 for \( \mathcal{L} = 10^{-4} \) cm\(^{-2}\)s\(^{-1}\), \( m_A = m_1 = 50 \) MeV, \( m_2 = 10 \) MeV (with \( \Delta E = 26 \) keV), and two different values for \( m_X \). It is seen that there is a large parameter space to be explored. The grey area is where \( g_D > \sqrt{4\pi} \) and perturbativity fails. The expected BDM signal yields with 5 years’ exposure time for the proposed detector and Super-K, are given in Tab. I. It can be seen that smaller \( m_X \) leads to larger yields, and larger mass splitting \( (m_1 - m_2) \) leads to smaller yields. However, the signal with larger mass splitting will also give more outstanding signatures in the emulsion detector (more energetic \( e^+e^- \) pair). Moreover, as either or both of \( m_1 \) and \( m_2 \) increase, the signal yields also decrease, and the expected yields at Super-K diminish towards zero while an observation is still possible with the proposed detector.

VIII. CONCLUSION

In this paper, we propose an emulsion detector placed in deep underground facilities to search for a boosted dark matter from various astrophysical sources (from dark matter annihilation in the Galactic center, Sun, Earth, or even the cosmic rays [18]). We further propose a high-Z material such as Pb as the target, which coherently scatters the BDM into an excited DM, whose decay product (a \( e^+e^- \) pair) can be recorded by the detector (in this case the nuclear recoil is too small to be detected).
We assume an Gaussian distributed BDM energy spectrum, can estimated the signal yields with different parameter settings. We find that the proposed detector can detect a BDM with a sub-GeV mass, and in some cases the signal has no chance to be found in Super-K at all while an observation in the proposed detector is possible. The largest background for this search is the high energy solar neutrinos, but can be controlled by track topologies reconstructed in the emulsion detector. The proposed search will certainly complement the existing DM search experiments and deepen our understanding of the dark matter physics.

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