Interpretation of XENON1T excess with MeV boosted dark matter*

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Abstract: The XENON1T excess of keV electron recoil events may be induced by the scattering of electrons and long-lived particles with an MeV mass and high speed. We consider a tangible model composed of two scalar MeV dark matter (DM) particles, S_A and S_B, to interpret the XENON1T keV excess via boosted S_B. A small mass splitting $m_{S_A} - m_{S_B} > 0$ is introduced, and the boosted S_B can be produced using the dark annihilation process of $S_A S_A^\dagger \to \phi \to S_B S_B^\dagger$ via a resonant scalar ϕ. S_B−electron scattering is intermediated by a vector boson X. Although the constraints from Big Bang nucleosynthesis, cosmic microwave background (CMB), and low-energy experiments set the X−mediated S_B−electron scattering cross section to be $\lesssim 10^{-35}\text{cm}^2$, the MeV scale DM with a resonance enhanced dark annihilation today can still provide sufficient boosted S_B and induce the XENON1T keV excess. The relic density of S_B is significantly reduced by the s-wave process $S_B S_B^\dagger \to XX$, which is permitted by the constraints from CMB and 21-cm absorption. A very small relic fraction of S_B is compatible with the stringent bounds on un-boosted S_B-electron scattering in DM direct detection, and the S_A-electron scattering is also allowed.

Keywords: boosted dark matter, XENON1T excess, dark matter direct detection

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I. INTRODUCTION

The existence of dark matter (DM) has been established through extensive cosmological and astronomical observations. However, the microscopic properties of DM beyond the Standard Model (SM) are largely unknown. Recently, the XENON collaboration reported an excess of electronic recoil events with an energy of approximately 2–3 keV [1], and the event distribution has a broad spectrum for the excess. They collected low-energy electron recoil data from the XENON1T experiment with an exposure of 0.65 tonne-years and analyzed various backgrounds for the excess events. Although a small tritium background fits the excess data well [1], bosonic DM can also provide a plausible source for the peak-like excess.

The excess of electron recoil events may be induced by new long-lived particle scattering with electrons in a detector. The lifetime of the new particle must be sufficiently long to reach a detector on Earth after its production and it has an appreciable interaction with electrons. The mass of the new long-lived particle should be $\gtrsim$ MeV and the velocity should at the level of $O(0.1)c$ [2]. Meanwhile, it should be compatible with the structure formation of the universe and the constraints from Big Bang nucleosynthesis (BBN) as well as the cosmic microwave background (CMB). Thus, an exotic mechanism is required to produce many long-lived particles with a high speed. A plausible scenario for the electron excess events is boosted DM produced in the present universe via dark sector annihilation or decay [2–9]. Meanwhile, a fraction of the un-boosted DM with a regular velocity distribution (with a velocity of $\sim 10^{-3}\,c$ in the galaxy) can also be present today and is detectable via the scattering off electron. Thus, the direct detection experiments would set stringent bounds on the un-boosted DM-electron scattering for the recoil energy of a few eV [10–14]. These bounds must be evaded when interpreting the XENON1T keV excess.

In the interpretation of the XENON1T excess via the scattering between electron and boosted DM, the nature of the intermediating particle and interaction becomes a

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key aspect. For a long-lived light mediator with keV∼MeV mass, BBN and CMB would place stringent constraints [15, 16]. If the new mediator has a short lifetime, because of the constraint from BBN, its mass should be $\gtrsim$ 10 MeV, and its lifetime is much shorter than a second [17–20]. In addition, the constraints from low-energy experiments, such as NA48/2 [21] and NA64 [22], should be considered. However, the new mediator and interaction may leave some traces in anomalous processes; for example, a new vector boson of about 17 MeV [23, 24], predominantly decaying into e^+e^-, was suggested by two anomalous transitions of ^{8}Be [25] and ^{4}He [26]. Here, we consider a light vector boson X in general, which primarily decays into e^+e^- and intermediates the scattering between electron and the boosted DM. Considering the constraints from low-energy experiments [21, 22], when 14 MeV $\lesssim m_X \lesssim$ 30 MeV, as shown in Fig. 5 of Ref. [22], a part of the parameter ϵ_e (the X-electron coupling is parameterized as $\epsilon_e e$) in the range of $10^{-4} \lesssim \epsilon_e \lesssim 10^{-3}$ is still permitted by the experiments. Note that the rapid fluctuations in the NA48/2 limit [21] cause some uncertainty of the NA48/2 limit. Here we take the NA48/2 limit in a smooth way as shown in Fig. 5 of Ref. [22] instead of the rapid fluctuations. For instance, the range of $5\times10^{-4} \lesssim \epsilon_e \lesssim 10^{-3}$ is permitted for $m_X \sim 20$ MeV of our interest.

In this paper, we introduce two complex scalar DM particles, S_A and S_B, to interpret the XENON1T excess with a light vector mediator X. The DM particles S_A and S_B are under possible dark symmetry in the hidden sector with $m_{S_A} \simeq m_{S_B}$, and some dark sector numbers are carried by both S_A and S_B to maintain the stability of DM. S_B is dark charged and S_A is neutral with a small mass splitting $m_{S_A} - m_{S_B} > 0$, which can be introduced from radiative corrections or substructures. The pair $S_B S_B^\dagger$ can be produced via the dark annihilation process of $S_A S_A^\dagger \to S_B S_B^\dagger$ mediated by a new scalar ϕ. Thus, the present dark annihilation can provide a source of boosted S_B. The scattering between electron and boosted S_B mediated by the X boson may explain the keV electron excess observed by XENON1T. In addition to the boosted S_B accounting for the XENON1T keV excess, there would be a fraction of un-boosted S_B around the Earth. The relic abundance of S_B can be significantly reduced by the transition of $S_B S_B^\dagger \to XX$. Thus, it will be compatible with the stringent bound on un-boosted S_B−electron scattering in DM direct detections. This tangible approach is explored in this paper.

II. DM INTERACTIONS AND TRANSITIONS

In this paper, we consider a scalar DM model to interpret the XENON1T excess. In this model, S_A is dark neutral, and S_B is charged under possible dark symmetry in the hidden sector. S_B is intermediated by a new vector boson X to interact with an electron. X is assumed to couple to SM charged leptons, and the effective couplings are expressed as

$$\mathcal{L}_X \supset e X_\mu \sum_\ell \epsilon_\ell \bar{\ell}\gamma^\mu \ell \,. \tag{1}$$

X is considered to be a light vector boson in general; here, we do not specify a scenario such as a kinetic mixing portal or a new gauged $U(1)$. The dark charged S_B couples to the X boson via

$$\mathcal{L}_X \supset -e_D X_\mu J^\mu_{\rm DM} + e_D^2 X^\mu X_\mu S_B^\dagger S_B \,, \tag{2}$$

where $J^\mu_{\rm DM}$ is the charged current of scalar DM S_B and is given by

$$J^\mu_{\rm DM} = {\rm i}[S_B^\dagger(\partial^\mu S_B) - (\partial^\mu S_B^\dagger) S_B] \,.$$

Here, we assume that the X particle has a mass $\gtrsim$ 14 MeV [22] and predominantly decays into e^+e^-.

We also assume a real dark field ϕ coupled to both S_A and S_B, and it mediates the transition between S_A and S_B. In addition to the kinetic energy terms, the scalar Lagrangian is given by

$$\begin{aligned} -\mathcal{L}_{\rm scalar} \supset & \frac{1}{2} m_\phi^2 \phi^2 + \lambda_4 \phi^4 + \mu_{S_A} S_A S_A^\dagger \phi + \lambda_{S_A} S_A S_A^\dagger \phi^2 \\ & + \mu_{S_B} S_B S_B^\dagger \phi + \lambda_{S_B} S_B S_B^\dagger \phi^2 \,, \end{aligned} \tag{3}$$

The parameters $\mu_S \equiv \mu_{S_A} = \mu_{S_B}$ and $\lambda_S \equiv \lambda_{S_A} = \lambda_{S_B}$ are adopted. Here, we assume $m_\phi > m_{S_A} \simeq m_{S_B} > m_X$ for simplicity, and a small mass splitting Δ between S_A and S_B is introduced, i.e., $\Delta = m_{S_A} - m_{S_B} > 0$. To avoid the over-abundance of ϕ in the early universe, we adopt $m_\phi > 2m_X$; thus, the decay mode $\phi \to XX$ is generated at loop level from the $\phi S_B S_B^\dagger$ coupling and the charged current of S_B. For $m_{S_B} > m_X$, the relic fraction of S_B can be significantly depleted when the on-shell annihilation mode $S_B S_B^\dagger \to XX$ is opened. In addition, possible ϕ−SM Higgs mixing is neglected here for simplicity (for the mixing case, the mixing with a rough upper limit of $\sin^2\theta \ll 10^{-3}$ can be permitted by experiments [27]). Please note that there may be more particles in the new sector, and here we only consider the particles with key roles in transitions between the SM and dark sector.

To induce the keV electron scattering events via boosted S_B, the dark annihilation process of $S_A S_A^\dagger \to \phi \to S_B S_B^\dagger$ is considered to be dominant in $S_A S_A^\dagger$ annihilation. The annihilation cross section is given by

$$\sigma_0 v_r \simeq \frac{\mu_S^4}{32\pi m_{S_A}^2}\frac{\beta_f}{(s-m_\phi^2)^2+m_\phi^2\Gamma_\phi^2}\,, \tag{4}$$

where v_r is the relative velocity, and s is the squared total invariant mass. In the non-relativistic limit, the phase space factor β_f is

$$\beta_f=\sqrt{1-\frac{4m_{S_B}^2}{s}}\approx\sqrt{\frac{v_r^2}{4}+\frac{2\Delta}{m_{S_A}}}\,. \tag{5}$$

The decay width of ϕ is

$$\Gamma_\phi=\frac{\mu_X^2}{8\pi m_\phi}\sqrt{1-\frac{4m_X^2}{m_\phi^2}}\left(\frac{m_\phi^4}{4m_X^4}-\frac{m_\phi^2}{m_X^2}+3\right). \tag{6}$$

The annihilation of dark charged DM S_B is primarily governed by $S_BS_B^\dagger\to XX$ via the S_B-X coupling in Eq. (2). The annihilation cross section is

$$\sigma_1 v_r\simeq\frac{e_D^4\sqrt{1-4m_X^2/s}}{16\pi m_{S_B}^2}\frac{8m_{S_B}^4-8m_{S_B}^2m_X^2+3m_X^4}{(2m_{S_B}^2-m_X^2)^2}\,. \tag{7}$$

The p-wave process $S_BS_B^\dagger\to X\to e^+e^-$ is suppressed by ϵ_e^2 and is negligible compared with the above annihilation process (see Ref. [19] for this p-wave dominant case).

III. BOOSTED DM FOR THE XENON1T EXCESS

Assuming that the main component of DM is S_A, which has a Navarro-Frenk-White (NFW) profile, the boosted DM particles S_B can be produced by the present dark annihilation process of $S_AS_A^\dagger\to S_BS_B^\dagger$. To obtain the benchmark velocity $v_b\sim 0.06$ in Ref. [3] for boosted S_B, the value of Δ/m_{S_A} is required to be ~ 0.0018 as $\Delta\simeq\frac{1}{2}m_{S_B}v_b^2\approx\frac{1}{2}m_{S_A}v_b^2$. The flux of the boosted DM S_B over the full sky can be expressed as [28]

$$\Phi_{\rm BDM}^{4\pi}=1.6\times10^{-4}{\rm cm}^{-2}{\rm s}^{-1}\left(\frac{1\ {\rm GeV}}{m_{S_A}}\right)^2\times\frac{\langle\sigma_0 v_r\rangle_0}{5\times10^{-26}{\rm cm}^3{\rm s}^{-1}}\,, \tag{8}$$

where $\langle\sigma_0 v_r\rangle_0$ is today's thermally averaged annihilation cross section of $S_AS_A^\dagger$ and is suppressed by the phase space factor β_f. Together with the flux of boosted DM S_B hitting the earth detectors, the number of signal events $N_{\rm sig}$ via boosted DM S_B-electron scattering is

$$N_{\rm sig}\propto\sigma_{\rm elec}\times\Phi_{\rm BDM}^{4\pi}\,, \tag{9}$$

where $\sigma_{\rm elec}$ is the boosted S_B-electron scattering cross section mediated by the X boson:

$$\sigma_{\rm elec}\simeq\frac{4\alpha e_D^2\epsilon_e^2\mu_{eS_B}^2}{m_X^4}\,, \tag{10}$$

with μ_{eS_B} being the reduced mass of m_e and m_{S_B}.

The signal events $N_{\rm sig}$ observed by XENON1T is about 40–70 events. In this case, the required scattering cross section $\sigma_{\rm elec}$ is [3]

$$\sigma_{\rm elec}=2.1\times10^{-31}{\rm cm}^2\left(\frac{10^{-4}{\rm cm}^{-2}{\rm s}^{-1}}{\Phi_{\rm BDM}^{4\pi}}\right)\left(\frac{N_{\rm sig}}{70}\right). \tag{11}$$

To obtain a large cross section in Eq. (10), the mass m_X (parameter ϵ_e) should be as small (large) as possible. Substituting the mediator's mass $m_X=17$ MeV, $e_D=1$, and $\epsilon_e\lesssim10^{-3}$ into Eq. (10), we observe that the scattering cross section $\sigma_{\rm elec}\lesssim10^{-35}$ cm^2 for $m_{S_B}\gg m_e$, and this value is smaller than the scattering cross section required by Eq. (11) even when DM mass as light as $\gtrsim$ 20 MeV. Thus, there is insufficient boosted S_B flux to produce the XENON1T excess for ordinary annihilations of S_A. However, if today's dark annihilation of S_A is enhanced, the result is different. We consider the annihilation of S_A is close to the ϕ resonance with the mass $2m_{S_A}$ slightly above m_ϕ. Thus, today's dark annihilation $\langle\sigma_0 v_r\rangle_0$ will be significantly enhanced and can produce a large flux of boosted $S_BS_B^\dagger$. Moreover, for DM mass $\lesssim$ 10 MeV, the scattering cross section required by Eq. (11) can be significantly lowered, while such light DM particles will be in tension with constraints from BBN and CMB.

Now, we introduce a parameter $\xi\equiv m_\phi/2m_{S_A}$ in which ξ is slightly smaller than 1. The cross section $\langle\sigma_0 v_r\rangle_0$ is sensitive to the value of $1-\xi$. The decay width is negligible in DM annihilations when $1-\xi\gg\Gamma_\phi/4m_\phi$ is satisfied. In the early universe, DM chemically decouples from the thermal bath when the reaction rate $\Gamma(n\langle\sigma v_r\rangle)$ of DM particles decreases below the Hubble expansion rate H. For $\langle\sigma_1 v_r\rangle\gg\langle\sigma_0 v_r\rangle$ considered here, the DM S_B freeze-out occurs slightly later compared with the DM S_A. As the mass difference between S_A and S_B is very small, the number density is $n_{S_B}\simeq n_{S_A}^{\rm eq}$ during the freeze-out period of S_A. Considering contributions from the $S_BS_B^\dagger\to S_AS_A^\dagger$ transition, the effective annihilation cross section of DM S_A is equivalent to $2\times\sigma_0 v_r$ during the freeze-out period (see Appendix A for details). The relic density of DM is determined by the annihilation cross section, and it can be evaluated using the general method without s-wave approximation [29–31]. The coupling parameter μ_S as a function of $1-\xi$ is derived with the relic density of $S_AS_A^\dagger$ nearly equal to the total DM relic density $\Omega_Dh^2=0.120\pm0.001$ [32], as shown in Fig. 1.

Today's $S_A S_A^\dagger$ annihilation $\langle\sigma_0 v_r\rangle_0$ as a function of $1-\xi$ is shown in Fig. 2, with the value of $1-\xi$ varying in a range of $10^{-3}-10^{-1}$. Note that the relative velocity v_r in the galaxy is $\sim 10^{-3}$, and $\langle\sigma_0 v_r\rangle_0$ is insensitive to v_r in $s-m_\phi^2$ or the phase space factor β_f in $\sigma_0 v_r$ in Eq. (4) for the range of $1-\xi$ of concern. In Fig. 2, the solid curve is the corresponding $\langle\sigma_0 v_r\rangle_0$ for a given $1-\xi$, and we observe that the annihilation is enhanced when ξ is very close to 1. The dot-dashed and dashed curves are the annihilation cross sections required by the XENON1T excess for two benchmark values of [m_X = 17 MeV, $\epsilon_e = 1\times10^{-3}$] and [$m_X$ = 19 MeV, $\epsilon_e = 0.85\times10^{-3}$] adopted here, respectively. We can observe that the resonance enhanced dark annihilation of today can produce large boosted S_B flux to account for the XENON1T excess.

Next, we briefly discuss the annihilation of S_B. S_B contributes only to a very small fraction f_{S_B} of the total DM relic density, and the relic fraction f_{S_B} (both S_B and $S_B^\dagger$ included) can be obtained using the relation $f_{S_B} \simeq 4.4\times10^{-26}$ cm$^3 s^{-1}/\ \langle\sigma_1 v_r\rangle$ [33, 34]. The annihilation of $S_B S_B^\dagger$ is suppressed by the factor $f_{S_B}^2$ in observations, and revised annihilation cross section $f_{S_B}^2\langle\sigma_1 v_r\rangle/2$ is shown in Fig. 3 for $e_D = 1$ and 0.5. For two benchmark values of m_X = 17 and 19 MeV, the dark matter masses m_{S_B} (m_{S_A}) in a range of m_{S_B} (m_{S_A}) $> m_X$ are permitted by the constraint from CMB [35] and the typical upper limit set by the anomalous 21-cm absorption [36], as depicted in Fig. 3. Given m_{S_A} = 20 MeV and $e_D = 1$, f_{S_B} is of order $\sim 10^{-10}$ for $m_X \approx 17-19$ MeV.

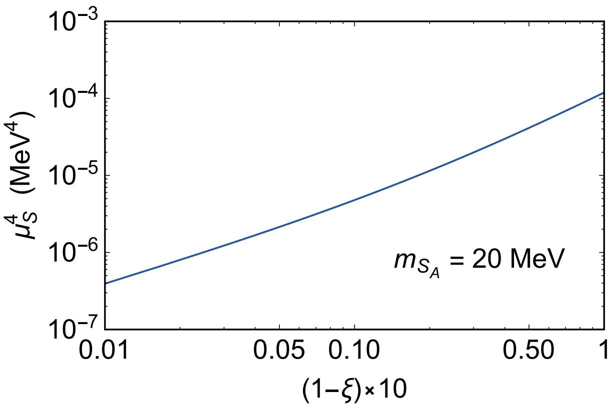

Fig. 1. (color online) Coupling parameter μ_S^4 as a function of $1-\xi$ for m_{S_A} = 20 MeV. Here, the relic density of $S_A S_A^\dagger$ equal to 0.120 is adopted.

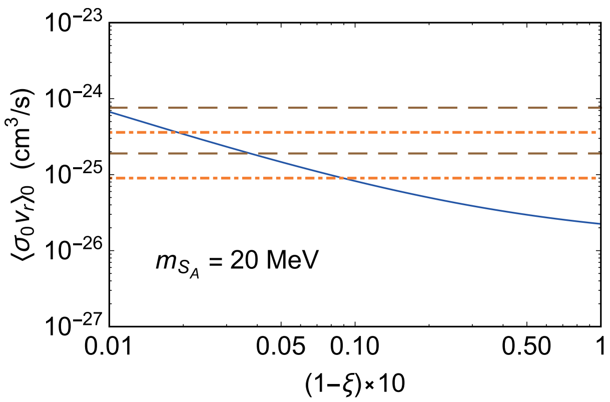

Fig. 2. (color online) Relation between $\langle\sigma_0 v_r\rangle_0$ (solid curve) and $1-\xi$ for m_{S_A} = 20 MeV. The dot-dashed and dashed curves are for m_X = 17 and 19 MeV, respectively. The lower (upper) limit of the dot-dashed and dashed curves corresponds to the annihilation cross sections required by the XENON1T excess for $e_D = 1$ (0.5).

IV. DIRECT DETECTION OF UN-BOOSTED DM

In addition to the boosted S_B accounting for the XENON1T keV excess, a large amount of S_A and S_B with a regular velocity distribution are present around the earth. Now, we discuss the un-boosted DM-electron scattering. First, we consider the un-boosted S_A. S_A-electron scattering occurs at two-loop level from the $\phi-XX$ transition and X-electron coupling. The scattering cross section is significantly below the neutrino floor [37, 38] in DM direct detections.

For the un-boosted S_B, the S_B-electron scattering is primarily contributed by the tree level process mediated by the X boson. The corresponding scattering cross section is

$$\bar{\sigma}_{eS_B} \simeq \frac{4\alpha e_D^2 \epsilon_e^2 \mu_{eS_B}^2}{m_X^4}\,, \tag{12}$$

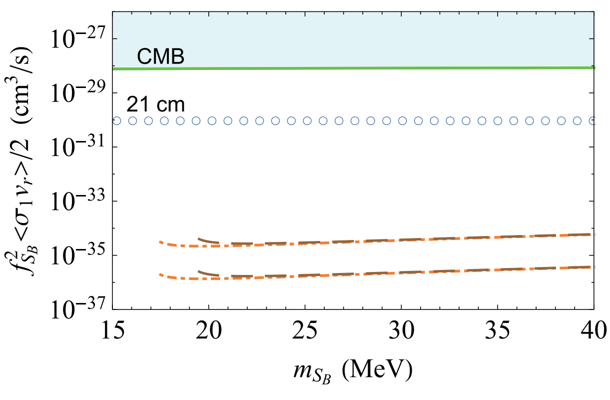

Fig. 3. (color online) Revised annihilation cross section $f_{S_B}^2\langle\sigma_1 v_r\rangle/2$ as a function of m_{S_B}. The dot-dashed and dashed curves are the revised annihilation cross sections for m_X = 17 and 19 MeV, respectively. The lower (upper) limit of the dot-dashed and dashed curves corresponds to the annihilation cross sections for $e_D = 1$ (0.5). The solid curve is the constraint from CMB [35], and the empty dotted curve is the typical upper limit set by the anomalous 21-cm absorption with $T_m < 4$ K at $z = 17.2$ [36].

with the form factor $F_{\rm DM}(q)=1$ [39]. For m_X = 17 MeV, $e_D=1$, and $\epsilon_e=10^{-3}$, the scattering cross section is $\simeq 10^{-35}{\rm cm}^2$, which is above the bound set by XENON10/100 [10, 11]. This is why the ordinary interpretation of the XENON1T keV excess via DM-electron scattering appears to be in tension with DM direct detections, although DM mass is as low as $O(10)$ MeV. In this paper, the DM particles $S_BS_B^\dagger$ constitutes only a very small fraction f_{S_B} of the total DM; thus, the tension can be relaxed owing to the effective scattering cross section being $f_{S_B}\bar{\sigma}_{eS_B}$ in DM direct detections. The result of the effective scattering cross section $f_{S_B}\bar{\sigma}_{eS_B}$ is shown in Fig. 4. We can observe that the benchmarks we consider above can evade the constraints from CMB, 21 cm absorption, and DM direct detections.

Moreover, for $m_{S_B}<m_X$, sufficiently boosted S_B can also be produced, and it induces the XENON1T keV excess. The mass m_{S_B} should be $\lesssim$ 13 MeV given the constraints from DM direct detections, as shown by the dotted curve in Fig. 4. Meanwhile, for S_A and S_B, the mass m_{S_B} (m_{S_A}) should be $\gtrsim$ 13 MeV with the bound from BBN [17]. Thus, a very small parameter space remains for the case of $m_{S_B}<m_X$ when interpreting the XENON1T keV excess, and this case is beyond the scope of this paper.

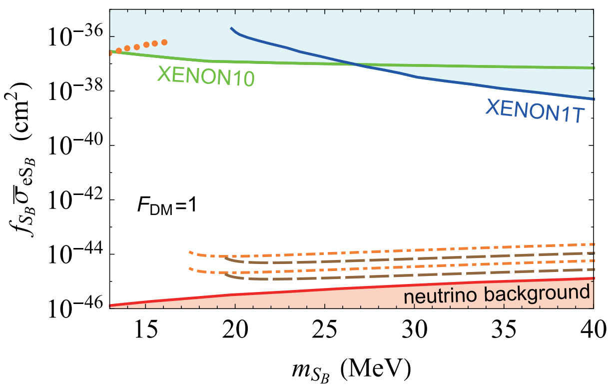

Fig. 4. (color online) Effective scattering cross section $f_{S_B}\bar{\sigma}_{eS_B}$ as a function of m_{S_B} for un-boosted $S_BS_B^\dagger$ in DM direct detections. The dot-dashed and dashed curves are the effective scattering cross section for the benchmark values as labeled in Figs. 2 and 3. The lower (upper) limit of the dot-dashed and dashed curves correspond to the cross sections for $e_D=1\,(0.5)$. The upper two solid curves are the upper limits from XENON10 [11] and XENON1T [13]. For comparison, the dotted curve on the top left is for $m_{S_B}<m_X=16.7$ MeV [19]. The lower solid curve is the neutrino background [37].

V. CONCLUSION

The boosted DM with a high speed of about 0.05-0.1 c and with a large DM-electron scattering cross section (as large as 10^{-29} cm^2 [3]) can interpret the XENON1T electron-event anomaly, as discussed in Refs. [2, 3]. However, can the boosted DM with such a large DM-electron scattering cross section be compatible with the present stringent bounds, such as the BBN, low energy experiments, and DM direct detections? This key question should be answered when proposing a model to explain the XENON1T anomaly. In this paper, we attempt to answer this question. The proposed GeV DM has a large scattering cross section (10^{-29} cm^2) between DM and an electron [3]. The required mediator mass is as light as 0.1 MeV. Such a light mediator is excluded by the BBN, which sets a lower mass bound on new thermal equilibrium particles, that is, the mass of a new particle should be above 10 MeV. Considering the constraints from BBN and low energy experiments, we observe that the scattering cross section between DM and an electron is smaller in reality, approximately smaller than 10^{-35} cm^2. We observe that light DM in the MeV scale with an enhanced annihilation source and a scattering cross section of 10^{-35} cm^2 can produce sufficient keV electron excess events observed by XENON1T and be permitted by present DM direct detections.

We have investigated an interpretation of the XENON1T excess using two scalar DM particles, S_A and S_B. S_A is neutral and S_B is dark charged in the hidden sector. The boosted S_B can be produced by the annihilation $S_AS_A^\dagger\to\phi\to S_BS_B^\dagger$ mediated by a scalar ϕ. S_B-electron scattering is intermediated by a vector boson X. We focus on the range $m_\phi>m_{S_A}\simeq m_{S_B}>m_X$. Although the constraints from BBN, CMB, and low-energy experiments require the boosted S_B-electron scattering cross section mediated by X to be $\lesssim 10^{-35}$ cm^2, MeV-scale DM with a resonance enhanced dark annihilation today can still produce sufficient boosted DM and induce the XENON1T keV electron excess. The relic density of S_B can be significantly reduced by the s-wave process of $S_BS_B^\dagger\to XX$; thus, this s-wave annihilation is permitted by the constraints from CMB and 21-cm absorption. A very small relic fraction of S_B is compatible with the stringent bound on un-boosted S_B-electron scattering in DM direct detections. The S_A-electron scattering occurs at loop level, and the scattering cross section is below the neutrino floor in direct detections. We look forward to the further investigation of MeV DM and the corresponding new interactions in the future.

APPENDIX A: THE FREEZE-OUT OF S_A

For $\langle\sigma_1 v_r\rangle\gg\langle\sigma_0 v_r\rangle$, the freeze-out of DM S_A occurs first, and the DM S_B decouples from the thermal bath later. For the DM particle S_A, the evolution of the number density n_{S_A} is given by

$$\frac{\mathrm{d}n_{S_A}}{\mathrm{d}t}+3n_{S_A}H=-\langle\sigma_0 v_r\rangle_{S_AS_A^\dagger\to S_BS_B^\dagger}(n_{S_A}^2-(n_{S_A}^{\mathrm{eq}})^2)+\langle\sigma_0 v_r\rangle_{S_BS_B^\dagger\to S_AS_A^\dagger}\left(n_{S_B}^2-\frac{(n_{S_B}^{\mathrm{eq}})^2}{(n_{S_A}^{\mathrm{eq}})^2}n_{S_A}^2\right),\quad \text{(A1)}$$

where $n_{S_A}^{\mathrm{eq}}$ and $n_{S_B}^{\mathrm{eq}}$ are the equilibrium number densities, and H is the Hubble parameter. The DM particle S_B is still in the thermal equilibrium with the thermal bath during the freeze-out period of S_A, and in this case, we obtain the number density $n_{S_B}=n_{S_B}^{\mathrm{eq}}\simeq n_{S_A}^{\mathrm{eq}}$ with ignorable mass difference between S_A and S_B. Thus, Eq. (A1) can be rewritten as

$$\frac{\mathrm{d}n_{S_A}}{\mathrm{d}t}+3n_{S_A}H\simeq-2\langle\sigma_0 v_r\rangle_{S_AS_A^\dagger\to S_BS_B^\dagger}(n_{S_A}^2-(n_{S_A}^{\mathrm{eq}})^2).\quad \text{(A2)}$$

For DM S_A, the effective annihilation cross section is equivalent to $2\times\sigma_0 v_r$ during the freeze-out period for the $S_BS_B^\dagger\to S_AS_A^\dagger$ transition considered.

References

[1] E. Aprile *et al.* (XENON), Phys. Rev. D **102**(7), 072004 (2020), arXiv:2006.09721[hep-ex]
[2] K. Kannike, M. Raidal, H. Veermäe *et al.*, Phys. Rev. D **102**(9), 095002 (2020), arXiv:2006.10735[hep-ph]
[3] B. Fornal, P. Sandick, J. Shu *et al.*, Phys. Rev. Lett. **125**(16), 161804 (2020), arXiv:2006.11264[hep-ph]
[4] M. Du, J. Liang, Z. Liu *et al.*, Chin. Phys. C **45**(1), 013114 (2021), arXiv:2006.11949[hep-ph]
[5] L. Delle Rose, G. Hütsi, C. Marzo *et al.*, JCAP **02**, 031 (2021), arXiv:2006.16078[hep-ph]
[6] H. Alhazmi, D. Kim, K. Kong *et al.*, JHEP **05**, 055 (2021), arXiv:2006.16252[hep-ph]
[7] H. Davoudiasl, P. B. Denton, and J. Gehrlein, Phys. Rev. D **102**(9), 091701 (2020), arXiv:2007.04989[hep-ph]
[8] P. Van Dong, C. H. Nam, and D. Van Loi, Phys. Rev. D **103**, 095016 (2021), arXiv:2007.08957[hep-ph]
[9] J. Cao, X. Du, Z. Li *et al.*, arXiv: 2007.09981[hep-ph]
[10] J. Angle *et al.* (XENON10), Phys. Rev. Lett. **107**, 051301 (2011), arXiv:1104.3088[astro-ph.CO]
[11] R. Essig, T. Volansky, and T. T. Yu, Phys. Rev. D **96**(4), 043017 (2017), arXiv:1703.00910[hep-ph]
[12] P. Agnes *et al.* (DarkSide), Phys. Rev. Lett. **121**(11), 111303 (2018), arXiv:1802.06998[astro-ph.CO]
[13] E. Aprile *et al.* (XENON), Phys. Rev. Lett. **123**(25), 251801 (2019), arXiv:1907.11485[hep-ex]
[14] L. Barak *et al.* (SENSEI), Phys. Rev. Lett. **125**(17), 171802 (2020), arXiv:2004.11378[astro-ph.CO]
[15] T. R. Slatyer and C. L. Wu, Phys. Rev. D **95**(2), 023010 (2017), arXiv:1610.06933[astro-ph.CO]
[16] M. Kawasaki, K. Kohri, T. Moroi *et al.*, JCAP **12**, 048 (2020), arXiv:2006.14803[hep-ph]
[17] C. M. Ho and R. J. Scherrer, Phys. Rev. D **87**(2), 023505 (2013), arXiv:1208.4347[astro-ph.CO]
[18] C. Boehm, M. J. Dolan, and C. McCabe, JCAP **08**, 041 (2013), arXiv:1303.6270[hep-ph]
[19] L. B. Jia and X. Q. Li, Eur. Phys. J. C **76**(12), 706 (2016), arXiv:1608.05443[hep-ph]
[20] A. Berlin, D. Hooper, G. Krnjaic *et al.*, Phys. Rev. Lett. **121**(1), 011102 (2018), arXiv:1803.02804[hep-ph]
[21] J. R. Batley *et al.* (NA48/2), Phys. Lett. B **746**, 178-185 (2015), arXiv:1504.00607[hep-ex]
[22] D. Banerjee *et al.* (NA64), Phys. Rev. D **101**(7), 071101 (2020), arXiv:1912.11389[hep-ex]
[23] J. L. Feng, B. Fornal, I. Galon *et al.*, Phys. Rev. Lett. **117**(7), 071803 (2016), arXiv:1604.07411[hep-ph]
[24] J. L. Feng, T. M. P. Tait *et al.*, Phys. Rev. D **102**(3), 036016 (2020), arXiv:2006.01151[hep-ph]
[25] A. J. Krasznahorkay, M. Csatlós, L. Csige *et al.*, Phys. Rev. Lett. **116**(4), 042501 (2016), arXiv:1504.01527[nucl-ex]
[26] A. J. Krasznahorkay, M. Csatlós, L. Csige *et al.*, arXiv: 1910.10459[nucl-ex]
[27] L. B. Jia, Phys. Rev. D **94**(9), 095028 (2016), arXiv:1607.00737[hep-ph]
[28] K. Agashe, Y. Cui, L. Necib *et al.*, JCAP **10**, 062 (2014), arXiv:1405.7370[hep-ph]
[29] P. Gondolo and G. Gelmini, Nucl. Phys. B **360**, 145-179 (1991)
[30] E. W. Kolb and M. S. Turner, Front. Phys. **69**, 1-547 (1990)
[31] K. Griest and D. Seckel, Phys. Rev. D **43**, 3191-3203 (1991)
[32] N. Aghanim *et al.* (Planck), Astron. Astrophys. **641**, A6 (2020), arXiv:1807.06209[astro-ph.CO]
[33] G. Steigman, B. Dasgupta, and J. F. Beacom, Phys. Rev. D **86**, 023506 (2012), arXiv:1204.3622[hep-ph]
[34] L. B. Jia and T. Li, Chin. Phys. C **45**(6), 063101 (2021), arXiv:2006.13357[hep-ph]
[35] T. R. Slatyer, Phys. Rev. D **93**(2), 023527 (2016), arXiv:1506.03811[hep-ph]
[36] H. Liu and T. R. Slatyer, Phys. Rev. D **98**(2), 023501 (2018), arXiv:1803.09739[astro-ph.CO]
[37] J. Billard, L. Strigari, and E. Figueroa-Feliciano, Phys. Rev. D **89**(2), 023524 (2014), arXiv:1307.5458[hep-ph]
[38] D. M. Mei, G. J. Wang, H. Mei *et al.*, Eur. Phys. J. C **78**(3), 187 (2018), arXiv:1708.06594[physics.ins-det]
[39] R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D **85**, 076007 (2012), arXiv:1108.5383[hep-ph]