Constraints on cosmic-ray boosted DM in CDEX-10

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Abstract

Dark matter (DM) direct detection experiments have been setting strong limits on the DM-nucleon scattering cross section at the DM mass above a few GeV, but leave large parameter space unexplored in the low mass region. There is no reason why DM will generate nuclear recoils in direct detection experiments to offer observable signals but miss the chance to be boosted by relativistic cosmic rays in the expanding universe. Since low energy threshold detectors using Germanium have provided good constraints on GeV-scale DM, we re-analyze 102.8 kg×day data in the CDEX-10 experiment within the cosmic-ray boosted DM (CRBDM) framework. For the DM mass range 1 keV < m_χ < 1 MeV, we reach an almost flat floor limit at 7.24 × 10^{-30} cm^2 on spin-independent DM-nucleon scattering cross section at a 90% confidence level. The CDEX-10 result is able to close the gap in the parameter space between MiniBooNE and XENON1T which was partially hindered by the Earth attenuation effect.

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I. INTRODUCTION

Astrophysical and cosmological evidence points to the existence of DM \cite{11, 2}, yet it is puzzling to understand particle nature of DM often treated as one of new physics beyond Standard Model. Several decades have been spent on searching for DM directly with low-background detectors to register potential light, heat and charge signals in the deep underground laboratories on the Earth. Indirect searches put emphasis on the observation of the secondary SM particles originating from the DM annihilations \cite{3, 4}.

The fundamental working principle of DM direct detections shown in reference \cite{7} helps with identifications of the energy recoil spectrum generated by interactions between DM and detector target nuclei in the standard halo model (SHM) \cite{8} based on the simplest DM-nucleon scattering hypothesis. In sensitivity calculations, there are considerable uncertainties with regard to the astrophysical ingredients including DM density and velocity distributions, and nuclear physics to describe the response of bound nucleons in each nucleus. DM direct detection experiments prefer to distinguish nuclear recoils (NRs) and electronic recoils (ERs) with the noble gas liquid detectors such as PandaX \cite{9}, Xenon1T \cite{10} and LUX \cite{11} using liquid Xenon, DEAP-3600 \cite{12} and DarkSide \cite{13} using liquid Argon, while a few of complementary experiments has no capability of discriminating NRs and ERs, such as CoGeNT \cite{14} and CDEX \cite{15} using Germanium. Rapid progress has been made, but we have to be confronted with null results more often than not, except a few positive but controversial results from DAMA \cite{16}, CoGeNT \cite{17}, CDMS-Si \cite{18} and CRESST-II \cite{19}. As a result, stringent exclusion limits have be placed in the plane of the DM mass $m_\chi$ and the DM coupling strength $\sigma_\chi_0$, given the weakly interacting massive particle (WIMP) as a DM candidate. Suffering from the energy threshold in the current detector technology, we have to bear with a large space unexplored in the light DM scheme. In the high mass DM region, the neutrino floor caused by coherent neutrino-nucleus scatterings is around the corner and leads to intrinsic neutrino backgrounds for the next-generation large scale DM detectors \cite{20, 21}. Therefore, new detection strategies and deep theoretical understandings to probe the low mass DM have been proposed and actively discussed very recently, including lower-threshold detection techniques \cite{22, 23}, and Migdal effect \cite{24, 25, 26, 27}. Multiple component DM models can also provide boosted DM by heavy-generation annihilations \cite{28}.

One of the most interesting models is the cosmic ray boosted DM (CRBDM) mechanism proposed in recent studies \cite{29, 30, 31, 32}. In the galaxy, there is an isotropic and relativistic cosmic-ray stream \cite{33, 34} consisting of protons ($\sim 86\%$), helium nuclei ($\sim 11\%$), some other heavier nuclei and electrons ($\sim 3\%$). There is no reason why DM will generate nuclear recoils in direct detection experiments to offer observable signals but miss the chance to be boosted by relativistic cosmic rays in the expanding universe. Several studies have already investigated the CRBDM and offered relatively tight constraints on light DM, including the diurnal effect \cite{44}, DM-nucleon interactions propagated by various mediators \cite{45, 46} and the so-called reverse direct detection method \cite{49}. As we noticed in the study, there exists a gap in results from XENONE1T and MiniBooNE experiments \cite{50}. This study will focus on the CRBDM and present a method to close the gap with existing experimental data. Compared with other types of detector, Germanium detectors with the lower energy threshold and better energy resolution are effective means to set limits on $m_\chi$ $< 1$ GeV.

This article is organized as follows. In Sec. \ref{II} we review the mechanism of CRBDM and derive the theoretical energy recoil spectrum with the Earth attenuation effect taken into account. In Sec. \ref{III} we re-analyze the CDEX-10 data in the CRBDM hypothesis. Finally, we summarize and make conclusions in Sec. \ref{IV}.

II. COSMIC RAY BOOSTED DARK MATTER (CRBDM)

In a CRBDM model, cosmic rays and DM exchange their energy and momentum in the process of collisions, so that the boosted DM would become almost relativistic. Then, boosted DM particles traveling toward the detector on the Earth and scattering off the target nuclei, could generate enough recoil energy which would exceed the threshold energy. The schematic diagram to illustrate acceleration and detection processes is given in Fig. \ref{fig:1}. To study a scattering process, we need to know the information of the incident particle, the target, and the collision process. The local density of DM near the solar system is $\rho_0 \sim 0.3$ GeV/cm$^3$ according to the cosmological observations \cite{2}. The velocity distribution of DM in the standard halo model (SHM) \cite{8} approximates to the Maxwell-Boltzmann distribution whose the most probable velocity $v_0$ is about 220 km/s. In the following, we will discuss the CRs and review the collision process between CRs and DM.
A. Boosted DM flux from CRs

CRs might originate from some of the supernova remnant (SNR) in the Galactic Disk \[43\]. Fermi pointed out that CRs from SNR bounce constantly between the shock surface and the magnetic field behind the wave surface. To explain the highly isotropic distributions for energetic charged particles, the concept of CR diffusion was proposed, in which the Galactic magnetic field plays an important role in the process \[50\]. To calculate the differential CRs flux, two main components proton and helium nucleus are considered and marked with subscript $i$ in the following formula.

With the data from PAMELA, the fitting formula of the Local Interstellar Spectra (LIS) of CRs are parameterized \[51\] as follows:

$$\frac{d\Phi_i}{dR} \times R^{2.7} = \begin{cases} \sum_{j=0}^{5} a_j R^j & R \leq 1 \text{ GV} \\ b + \frac{c}{R} + \frac{d_1}{d_2 + R} + \frac{e_1}{e_2 + R} + \frac{f_1}{f_2 + R} + gR & R > 1 \text{ GV} \end{cases}$$

Here $R$ means the rigidity of each nucleus. For a particle with a proton number $Z$, the relationship between the rigidity $R$ and the kinetic energy of CR particle $T_i$ is: $\frac{T_i}{R} = Ze$. As we all know, the differential CR flux obeys a power law with an index $\sim -2.7$. As shown in Eqn. (1), $a$, $b$, $c$, $d$, $e$, $f$, $g$ are the numerical coefficients \[51, 52\] and we show the coefficients of proton and helium nucleus in Table I. Considering that CRs is isotropic in the interstellar, we integrate the volume to obtain the differential CR flux $d\Phi_i$:

$$d\Phi_i = 4\pi d\phi_i \frac{dT_i}{dT} = 4\pi \frac{d\Phi_i}{dR} \frac{dT_i}{dR} dR.$$

Compared with the relativistic velocity of CRs, DM at a velocity of $\sim 10^{-3} c$ in the SHM can be safely treated at rest. With the assumption that the collision of DM and CRs are elastic and isotropic, we relate the kinetic energy of DM at $T_\chi$ to that of CRs at $T_i$ by energy and momentum conservation in the following:

$$T_\chi = \frac{T_i^2 + 2m_i T_i}{T_i + \frac{(m_\chi + m_i)^2}{2m_\chi}} \frac{1 + \cos \theta}{2},$$

where $\theta$ is the scattering angle in the center of momentum frame, and $m_\chi$ is the mass for CR particle $i$. According to Eqn. (2), $T_\chi$ tends to decrease and is proportional to $m_\chi$ if $m_\chi \ll m_i$, while DM would gain more energy if $m_\chi$ is close to $m_i$. If $\theta$ is 0, we have back to back scattering and DM would gain the maximum recoil energy $T_\chi^{\text{max}}(T_i)$ given

|   | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $b$ | $c$ |
|---|-------|-------|-------|-------|-------|-------|-----|-----|
| p | 94.1  | -831  | 0     | 16700 | -10200| 0     | 10800| 8500|
| He| 1.14  | 0     | -118  | 578   | 0     | -87   | 3120 | -5530|

|   | $d_1$ | $d_2$ | $e_1$ | $e_2$ | $f_1$ | $f_2$ | $g$ |
|---|-------|-------|-------|-------|-------|-------|-----|
| p | 423000| 3190  | 274000| 17.4  | -30400| 0.464 | 0   |
| He| 3370  | 1.29  | 134000| 88.5  | -117000| 861  | 0.03|
in Eqn. (3a) and the minimum energy of the incident particle $T_{i\text{min}}(T_\chi)$ given in Eqn. (3b):

$$T_{\chi}^{\text{max}}(T_i) = \frac{T_i^2 + 2m_i T_i}{T_i + \frac{(m_i + m_\chi)^2}{2m_\chi}} \tag{3a}$$

$$T_{i\text{min}}^\chi(T_\chi) = \left(\frac{T_\chi}{2} - m_i\right) \left[1 \pm \sqrt{1 + \frac{2T_\chi (m_i + m_\chi)^2}{m_\chi (2m_i - T_\chi)^2}}\right]. \tag{3b}$$

Note that the sign $+/−$ applies to the case with $T_\chi > 2m_i$ or $T_\chi < 2m_i$.

When momentum transfer occurs in the scattering process, the internal structure of the nuclei will take effect. Therefore, the cross section varies with the exchange of momentum described by the form factor $G_i$: $\sigma_{xi} = \sigma_{0,xi} G_i^2(2m_\chi T_\chi)$, where $\sigma_{0,xi}$ is the cross section for zero momentum transfer. We adopt the Helm model for small momentum transfer. Considering that CRs and DM particle would exchange large momentum during the collision, we adopt the simplest dipole form [53]:

$$G_i(2m_\chi T_\chi) = \frac{1}{(1 + 2m_\chi T_\chi / \Lambda_i)^2}, \tag{4}$$

where $\Lambda_i$ is inversely proportional to the charge radius, and we set $\Lambda_p = 770$ MeV for proton and $\Lambda_{He} = 410$ MeV [54] for helium nucleus. It is generally believed that the DM couplings to the proton and nucleon are the same in most instances, so the cross section can be written as Eqn. (5) with dependence of mass number $A$ for the incident particle $i$:

$$\sigma_{xi} = \sigma_{0,xi} A^2 \frac{(m_i + m_p)}{m_p (m_i + m_\chi)}^2. \tag{5}$$

It is worth mentioning that the factor $A^2$ in Eqn. (5) is 16 for the helium nucleus and 1 for the proton, respectively. The Helium nucleus and proton make contributions at the same order of magnitude to the differential flux for DM (the helium nucleus account for 10% of CRs).

Based on the above information, we start to calculate the differential flux for boosted DM. Inside a volume $dV$, the collision rate with energy exchange $dT_i$ for CRs and $dT_\chi$ for DM is given by:

$$d\Gamma_{CR→\chi} = \sum_i \frac{\rho_\chi}{m_\chi} \times \frac{d\sigma_{0,xi}}{dT_\chi} G_i^2(2m_\chi T_\chi) \times \frac{d\Phi_i}{dT_i} dT_i dT_\chi dV, \tag{6}$$

where $\frac{d\Phi_i}{dT_i}$ is the differential flux for CRs. Without a loss of generality, we make an energy-independent assumption here with such a form factor untouched that energy transfer is uniformly distributed as $\frac{d\sigma_{0,xi}}{dT_\chi} = \sigma_{0,xi}^{\text{max}}$. By integrating the volume and the energy $T_i$, we obtain the differential flux for the boosted DM in Eqn. (7). In addition, the volume integral asks for the distribution of DM and CRs in the galaxy. We plan to take the Navarro-Frenk-White (NFW) profile [55] and the uniform distribution for DM density and for CRs as $\frac{d\Phi_i}{dT_i}$, respectively. Note that the integral needs to be divided by the factor $4\pi d^2$ to convert the volume to the line-of-sight integral, where $d$ is the distance between the collision place and the center of the galaxy. Conservatively, we follow the reference [36] and adopt the effective distance $D_{\text{eff}} = 1$ kpc as the line-of-sight integral result:

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{1}{4\pi} \int d\Omega \int_{T_{\text{min}}}^{\infty} \frac{d\sigma_{0,xi}}{dT_\chi} \frac{d\Phi_i}{dT_i} dT_i = D_{\text{eff}} \frac{\rho_\chi}{m_\chi} \sum_i \sigma_{xi} \int_{T_{\text{min}}}^{\infty} \frac{d\Phi_i}{dT_i} T_{\chi,\text{max}}(T_i) dT_i, \tag{7}$$

where $T_{\text{min}}$ and $T_{\text{max}}(T_i)$ are shown in Eqn. (3). To further study the boosted DM, we can make a comparison between the boosted DM flux induced by CRs and the DM flux under the SHM in the same reference frame:

$$\frac{d\Phi_{\chi,\text{SHM}}}{dT_\chi} = \frac{\rho_\chi}{m_\chi} v f(v) \frac{dv}{dT_\chi} = \rho_\chi v m_\chi f(v) \frac{1}{(T_\chi + m_\chi)^2}, \tag{8}$$

where $f(v)$ is the Maxwellian velocity distribution with the most probable velocity at $v_0 = 220$ km/s and the galactic escape velocity at $v_{\text{escape}} = 540$ km/s [56]. Here the velocity distribution in SHM is taken as follows:

$$f(v) = \frac{1}{4\pi v^2} e^{-v^2/v_0^2} \Theta(v - v_{\text{escape}}), \tag{9}$$
where $k$ is the normalization factor. The numerical results for the CRBDM fluxes are compared and shown in Fig. 2.

As the DM density in space is fixed, the smaller DM mass results in the larger number density of DM. Compared with the DM flux under the SHM hypothesis, the flux intensity boosted by CRs is a small portion of the total flux. This fact guarantees that the CRBDM mechanism can easily survive in the cosmological constraints.

### B. Attenuation

As DM particles could collide with ordinary matter, the DM flux from space to the detector would be blocked by the atmosphere and the rock, which causes energy loss or de-acceleration for DM. We simply estimate the mean free path for DM: $\lambda = 1/\sigma_{\chi N} n_N$. Taking the mean mass number $\bar{A} = 20$ in the Earth crust, the mean density $\rho_{\text{crust}} = 2.7 \text{ g/cm}^3$ in the crust \cite{57} and $\sigma_{\chi 0} = 10^{-30} \text{ cm}^2$ as parameters, we get the the mean free path: $\lambda \sim 0.1 \text{ km}$. In order to suppress backgrounds from cosmic rays, direct detection experiments are usually located deep underground. For example, China Jinping Underground Laboratory to host the CDEX experiment has the rock overburden at $z \sim 2.4 \text{ km}$. Then it is time to establish a model to analyze the Earth attenuation effect.

Under the assumption of energy independence: $\frac{d\sigma_{\chi N}}{dT_r} = \frac{\sigma_{\chi N}}{T_r^{\max}}$, we obtain the energy loss for DM crossing the crust:

$$\frac{dT_r}{dz} = - \sum_N n_N \int_0^{T_r^{\max}} \frac{d\sigma_{\chi N}}{dT_r} T_r dT_r = - \frac{1}{2} \sum_N n_N \sigma_{\chi N} T_r^{\max},$$

where $T_r^{\max}$ is the maximal recoil energy between the DM particle and the nucleus $N$. Here the form $T_r^{\max}$ is similar to Eqn. (3) by a replacement of $m_\chi \to m_N$ and $m_i \to m_\chi$. We have to solve the differential equation in Eqn. (10) to establish the relationship between DM energy in the space and detector: $T_r(z) = T_r(0)(T_{\chi}^z)$. After that, we will get the attenuated DM flux spectrum as follows:

$$\frac{d\Phi_\chi}{dT_r} = \frac{d\Phi_\chi}{dT_r^{\max}} \frac{dT_r^{\max}}{dT_r^z}.$$

Adopting the nuclear composition of the Earth crust given in the reference \cite{57} and the crust thickness as 2400 m, we present the DM flux with/without the Earth attenuation effect in Fig. 2. The comparison of different line colors tells us the interesting features associated with the DM mass while the solid and dashed lines highlight the attenuation effect. Under the same assumption for the cosmic ray acceleration mechanism, we see the low mass DM gets boosted.
Theoretically predicted CRBDM spectrum
\[ m_\chi = 1 \text{ MeV}, \sigma_{\chi_0} = 7.0 \times 10^{-30} \text{ cm}^2 \]

Figure 3. The measured energy recoil spectrum in CDEX-10 with black data points plus error bars \cite{15}, a flat background assumption in blue dashed line versus the predicted CRBDM recoil spectrum in red solid line for \( m_\chi = 1 \text{ MeV} \) and \( \sigma_{\chi_0} = 7 \times 10^{-30} \text{ cm}^2 \). Here "eVee" represents electron equivalent energy derived from a charge calibration.

To obtain the recoil spectrum from CRBDM, we focus on the elastic and isotropic collision of DM and target particle in the detector. By neglecting energy dependence, we get the recoil spectrum by integrating the kinetic energy of DM particle \( dT_\chi \):

\[
\frac{dR}{dE_R} = \frac{1}{m_N} \int_{T_{\chi_0}^{E_R}}^{\infty} \frac{\sigma_{\chi_0} N}{E_R^{\max}} \frac{d\Phi_\chi}{dT_\chi} \, dT_\chi ,
\]

where \( T_\chi \) and \( \frac{d\Phi_\chi}{dT_\chi} = \frac{dT_\chi}{d\Phi_\chi} \) are the kinetic energy of DM and the DM flux in the detector with depth of \( z \), respectively. We will follow the similar expression in Eqn. (3) to calculate \( T_{\chi_0}^{E_R} \) and \( E_R^{\max} \). For scintillation and ionization detectors calibrated with \( \gamma \) sources, the observable nuclear recoil energy \( E_v \) differs from the true recoil energy \( E_R \): \( E_v = f_n(E_R)E_R = F(E_R) \), where \( f_n \) is called the quenching factor as a function of \( E_R \) calculated by the TRIM software package \cite{58-60} and \( F(E_R) \) is more convenient to make the derivation. Besides, because of a finite detector energy resolution and electronic noise, recoils at energy \( E_R' \) would be observed as a Gaussian distribution. Consequently, we will obtain the modified recoil spectrum:

\[
\frac{dR}{dE_v} = \frac{1}{\sqrt{2\pi}} \frac{1}{\Delta E_v} \frac{dR}{dE_R} \frac{dE_R}{dE_v} \exp \left[-\frac{(E_v' - E_v)^2}{2\Delta E_v^2}\right] dE_v = \frac{1}{\sqrt{2\pi}} \int \frac{1}{\Delta E_v} \frac{dR}{dE_R} \frac{dF}{dE_R} \frac{1}{|F^{-1}(E_v)|} dE_v ,
\]

where \( \Delta E_v \) is the energy resolution. As a demonstration, Fig. 3 shows the energy recoil spectrum from CDEX-10 data, and the predicted recoil spectrum for DM with \( m_\chi = 1 \text{ MeV} \) and \( \sigma_{\chi_0} \). Note that the quenching factor and the energy resolution are included in the calculation of theoretical predictions.
III. CONSTRAINTS WITH CDEX-10 DATA

The CDEX-10 experiment located at China Jinping Underground Laboratory (CJPL) with about 2400 m of rock overburden makes use of p-type point contact Germanium (pPCGe) to reconstruct the ionization signal generated by the collision between DM and target particles [61]. With the energy threshold lowered to 160 eVee, CDEX-10 improves limits on $\sigma_{\chi^0}$ down to $m_\chi$ of 2 GeV. To obtain the constraints, we adopt the minimum-$\chi^2$ analysis as the statistical method. Considering that high energy $\gamma$–rays from ambient radioactivity produce flat electron-recoil backgrounds at low energy [59, 62], two free and positive parameters $\sigma_{\chi^0}$ and b, which characterize the flat backgrounds and the spin-independent DM-nucleon scattering cross section $\sigma_{\chi^0}$, are used to construct the statistical measure such as:

$$\chi^2(\sigma, b) \equiv \sum_k \left( \frac{S_{Th}^k + b - S_{Ex}^k}{\sigma_k^2} \right)^2,$$

where $S_{Ex}^k$ is the experimental data with the uncertainty $\sigma_k$, and $S_{Th}^k$ stands for the theoretical predictions in each bin, respectively. In a likelihood analysis, the allowed parameter space is obtained by $\chi^2$ as follows:

$$\chi^2(\sigma, b) \leq \chi^2_{\text{min}} + \Delta\chi^2,$$

where $\chi^2_{\text{min}}$ is the minimum value of $\chi^2$ and $\Delta\chi^2$ is associated with the number of considered parameters. For two parameters in $\chi^2(\sigma, b)$, we adopt 4.61 as $\Delta\chi^2$ to obtain the excluded parameter regions at a 90% confidence level. To be conservative, the DM mass and maximally allowed cross section to satisfy conditions in Eqn. (15) are represented as a point in the parameter space. Scanning over the interested low-mass DM range, we then figure out the exclusion limit for the spin-independent cross section $\sigma_{\chi^0}$, and the DM mass $m_\chi$.

Following this strategy, we take the CDEX-10 experiment as a demonstration and reanalyze their data to obtain constraints on the DM mass $m_\chi$ and the cross section $\sigma_{\chi^0}$ in the CRBDM hypothesis at a 90% C.L. as shown in Fig. 4. Compared with the Migdal effect, the CRBDM framework will reach much lower mass region but suffer from the Earth attenuation effect. For the DM mass range 1 keV $< m_\chi < 1$ MeV, we reach the almost flat floor limit at $7.24 \times 10^{-30}$ cm$^2$ on spin-independent DM-nucleon scattering cross section, while this limit turns up for $m_\chi > 1$ MeV and converges towards the ceiling limit caused by Earth attenuation. The current result from CDEX-10 is one order of magnitude better than the neutrino experiment MiniBooNE but not comparable to the XENON1T data. Due to the attenuation, there will be a narrow gap for the excluded parameter regions from MiniBooNE and XENON1T. We have to bear in mind that the effective distance in the line-of-sight integral can enlarge the excluded regions for each experiment.

Figure 4. Constraints on spin-independent cross section of DM-nucleon interactions from CDEX-10 (gray), XENON1T (purple) and MiniBooNE (blue) [36] in the framework of CRBDM at a 90% C.L. As a comparison, we also include the exclusion limit from EDELWEISS [32] based on the Migdal effect.
With the current CRBDM hypothesis, the CDEX-10 result can close the gap in a nice manner. This fact highlights the importance of multiple detection technologies and combined analysis to examine the CRBDM model.

IV. SUMMARY AND CONCLUSION

Given that DM could elastically scatter with target nuclei in detectors, it is straightforward to think of the collisions between relativistic cosmic rays and low-speed DM in the galaxy. In this way, CRBDM would become more energetic to make the recoil energy above the threshold in detectors, especially for DM in the low mass range. We have reviewed the theoretical framework to accelerate a portion of DM by cosmic rays, including the modification of DM fluxes, the Earth attenuation effect and the energy recoil spectrum for the general detector target nuclei. We have re-analyzed 102.8 kg×day data from the CDEX-10 experiment based on the CRBDM model, and obtained constraints on the spin-independent DM-nucleon cross section in the low mass range \(1 \text{ keV} < m_\chi < 1 \text{ GeV}\), surpassing the detector energy threshold limitations in classical analysis. Similar analyses were performed in other studies for the neutrino detector MiniBooNE and the DM direct detection experiment XENON1T. Excluded parameter regions from MiniBooNE and XENON1T are not incorporated with each other partially due to the fact that the Earth attenuation effect will dilute the experimental constraints. Our analysis for CDEX-10 can beautifully cover such a gap in the low-mass DM parameter space. Migdal effect can also lead to constraining the light DM but is still not comparable to the CRBDM model. For future direct detection experiments, the same strategy for the CRBDM model could be applied. Our work should encourage the experimental collaborations to press forward with development of the next generation Germanium detector and joint analysis with different detection technologies. Recently, the XENON collaboration reported the low-energy ER excess \[63\], which might be DM signals deviating from the conventional assumptions. In a CRBDM model, the light DM in the interstellar can also be accelerated by electrons in CRs and produce the observable ER in the detector \[38, 64\]. The ER excess in XENON1T might be explained as signals from the light DM in a CRBDM to be examined by low-threshold Germanium detectors, apart from the fact that careful study on backgrounds is to be surveyed by LXe detection techniques like PandaX \[65\].

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