Atmospheric Dark Matter from Inelastic Cosmic Ray Collision in Xenon1T

Liangliang Su,1,2 Wenyu Wang,3 Lei Wu,1 Jin Min Yang,4,5 and Bin Zhu2,6

1Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing, 210023, China
2School of Physics, Yantai University, Yantai 264005, China
3College of Applied Science, Beijing University of Technology, Beijing, China
4CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
5School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China
6Department of Physics, Chung-Ang University, Seoul 06974, Korea

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Very recently, the Xenon1T collaboration has reported an intriguing electron recoil excess, which may imply for light dark matter. In order to interpret this anomaly, we proposed the atmospheric dark matter (AMD) from the inelastic collision of cosmic rays with the atmosphere. Thanks to the boost effect of high energy CRs, we show that a $O(10)$ keV ADM can be fast-moving and successfully fit the observed electron recoil spectra observed through the ADM-electron scattering process. Meanwhile, our ADM predict the scattering cross sections $\sigma_e \sim O(10^{-37} - 10^{-38})$ cm$^2$, and thus can evade other direct detection constraints. The search for light meson rare decays, such as $\eta \rightarrow \pi + E_T$, would provide a complementary probe of our ADM in the future.

INTRODUCTION

The existence of dark matter (DM) has been established in cosmological and astrophysical experiments. Besides the gravitational effects, other possible interactions of dark matter are still unknown. The various searches for dark matter in the direct detection, indirect detection and collider experiments are in progress, however, no convincing signals have been observed. In particular, the direct detections [1] that aim for Weakly Interacting Massive Particle (WIMP) [2] have reached great sensitivities, which are approaching to the irreducible neutrino floor. Their null results produce very stringent limits on the WIMP DM-nucleus scattering cross section, and lead to a shift of focus towards light dark matter particles [3, 4].

As the average velocity of dark matter is around $10^{-3}c$ in the Milky Way halo, the sensitivity of traditional direct detections that measure nuclear recoils rapidly decreases for DM mass below $\sim 1$ GeV. In order to access the sub-GeV dark matter, many new techniques and new types of detectors have been proposed (see e.g. [5–12]). Among them, search for DM scattering off electrons has been demonstrated to be a useful way of improving the discovery potential of light dark matter. Concretely, since the electron is bound to the atom, it can have a non-negligible momentum. When the DMs scatter off these high-momentum electrons, the xenon atoms can be ionized in the liquid target. In these processes, the energy transfer to the detector is about $E_R \sim$ keV. Then such ionization (and scintillation) signals can be detectable at the dual-phase liquid Xenon detectors.

Very recently, with an exposure of 0.65 tonne-years and an unprecedentedly low background, the Xenon1T collaboration has reported about $3.5\sigma$ excess of events in the electron recoil range of $1 \text{ keV} < E_R < 7 \text{ keV}$ with 285 events over the backgrounds with $232 \pm 15$ events [13]. The main excess events appear in the 2-3 keV bins, while other bins are approximately consistent with the expected background events. In the analysis of Xenon1T, it is pointed out that the observed electron recoil spectrum can be fitted by the solar axion [14–16] with an axion-electron coupling $g_{ae} \simeq 3.7 \times 10^{-12}$, however, which is in tension with the stellar cooling constraint, $g_{ae} \lesssim 0.3 \times 10^{-12}$ [17]. Other speculations about this excess have been discussed in [13, 18–24]. Although the possibility of contamination from $\beta$ decay of tritium is not excluded, such an anomaly is still intriguing and may a sign of light dark matter.

Figure 1. Atmosphere dark matter from inelastic collision of CRs and atmosphere for Xenon1T electron recoil excess. Here the particle $\chi$ stands for the dark matter.
In general, the light dark matter bounded in galaxies moves with a low velocity, it is impossible to fit this Xenon1T electron data because of the small recoil energy. However, there are several astrophysical processes that can accelerate the dark matter to have velocities much higher than its galactic escape velocity [25–28]. This fast-moving dark matter will scatter with nucleus or electron of target in the direct detections, and produce the detectable signals. For example, the light dark matter can be boosted to (semi-)relativistic speeds through its elastic scattering with the high energy cosmic rays (CRs) [29–34]. However, if the DM scatters with the proton or Helium in CRs, this will cause the tension with direct detection bounds on DM-nucleus scattering cross section. On the other hand, if the DM only interacts with the electron, it is also hardly to produce the enough events to satisfy the Xenon1T data, due to the small flux of electron in the CRs. In this paper, we propose the light boosted dark matter produced in the inelastic collision of CRs with the atmosphere (c.f. Fig.1) to explain the Xenon1T excess. Different from the upscattering mechanism, this scheme is independent of the density of pre-existing dark matter, and thus naturally provides a sufficient source of boosted dark matter.

**ATMOSPHERIC DARK MATTER**

The main components of high energy CRs are protons and heliums, which can inelastically collide with the interstellar medium or the atmosphere on Earth. The latter is usually dominant source of the energetic dark matter [35]. For simplicity, we assume the protons as incoming cosmic ray flux and parameterize it as in Ref. [36]. The differential cosmic ray flux $d\phi_p(T_p, h)/dT_p$ is the function of proton energy $T_p$ and height from the ground level $h$, which will be diluted as traveling through the atmosphere,

$$\frac{d}{dh} \frac{d\phi_p(T_p, h)}{dT_p} = \sigma_{pN}(T_p)n_N(h) \frac{d\phi_p(T_p, h)}{dT_p}. \quad (1)$$

Here we assume the nitrogen as nuclei target in the atmosphere, $\sigma_{pN}$ is the inelastic proton-nitrogen cross section and $n_N$ is the number density of nitrogen. The initial value of the flux is evaluated at $h_{\text{max}} = 180\text{km}$.

Since the inelastic proton-nitrogen cross section is approximately constant in the relevant energy range, we can absorb the $h$-dependence of $\phi_p$ into a dilution factor $y_p(h)$ for simplicity,

$$\frac{d\phi_p(T_p, h)}{dT_p} = y_p(h) \frac{d\phi_p(T_p, h_{\text{max}})}{dT_p}, \quad (2)$$

where we set the boundary condition of suppression factor as $y_p(h_{\text{max}}=180\text{km} = 1$. Then, we can substitute the Eq. 2 into suppression function Eq.1 and yields,

$$\frac{dy_p(h)}{dh} = \sigma_{pN}n_N(h)y_p(h). \quad (3)$$

After integration over the height, we can obtain the dilution factor,

$$y_p(h) = \exp \left( -\sigma_{pN} \int_h^{h_{\text{max}}} d\tilde{h} n_N(\tilde{h}) \right). \quad (4)$$

In the numerical calculation, we simulate the collision of incoming CRs with the nitrogen via the process $pN \rightarrow X$ by the package CRMC [37–39], where $X$ denotes the meson produced in this inelastic collision. Then, these mesons will decay to the on-shell dark matter mediator $M$ plus the SM particles, such as $\eta \rightarrow \pi\chi$, which is followed by the sequent two-body decay $M \rightarrow \chi\chi$. In our study, we treat the branching ratio of meson decay $Br(\eta \rightarrow \pi\chi\chi)$ as a free parameter within the range allowed by the experiments.

After being produced from the decays of mesons, the flux of ADM will be further attenuated by the secondary scattering in the atmosphere. Similar to the above, the attenuation factor of dark matter can be written as

$$y_d(h, \theta, \phi) = \exp \left( -\sigma_{\chi N} \int_0^{l_d} dz \left[ n(r(z) - R_E) \right] \right) \quad (5)$$

where $n$ is the number density of nucleus, and $\sigma_{\chi N}$ is the elastic cross section between dark matter and nucleus. $R_E = 6378.1\text{km}$ is the value of Earth radius and $l_d$ denotes the line of sight distance between the point of dark matter production and the detector.

$$\ell_d^2(h, \theta) = (R_E + h)^2 + (R_E - h_d)^2 - 2(R_E + h)(R_E - h_d)\cos\theta \quad (6)$$

where $h_d = 1.4\text{km}$ is the depth of the detector, and $\theta$ is the angle between the point of dark matter production and the detector.

Including the dilution factor of cosmic ray $y_p$ and the attenuation factor of dark matter $y_d$, we can obtain the differential flux of ADM at the depth of $h_d$ below the surface of the Earth,

$$\frac{d\phi_{\chi X}}{dT_X} = G \int_{T_p_{\text{min}}}^{T_p_{\text{max}}} dT_p \frac{1}{\Omega(T_p)} \frac{d\phi_p(h_{\text{max}})}{dT_p} \frac{d\sigma_{pN\rightarrow\chi\chi}}{dT_X} \quad (7)$$

with the geometrical factor

$$G = \int_0^{h_{\text{max}}} dh \left( R_E + h \right)^2 \int_{-1}^{1} d\cos\theta \int_0^{2\pi} d\phi \int_{\ell_d(h, \theta)}^{\ell_d(h, \theta)} n_N(h) \cdot \frac{y_d(h, \theta, \theta_{\text{SI}}) y_p(h, \theta)}{\ell_d^2(h, \theta)} \quad (8)$$

where $\sigma_{\chi X}^{\text{SI}}$ is the spin-independent nucleon cross section in the attenuation and the inelastic differential cross section.
is given by
\[
\frac{d\sigma_{pN \rightarrow \pi \tilde{\chi}}}{dT_\chi} = \frac{d\sigma_{pN \rightarrow \pi \chi \pm}}{dT_\chi} \frac{\Gamma_{\pi \chi \pm}}{\Gamma_{\text{tot}}} \simeq \frac{\sigma_{pN}}{T_\chi} \text{BR}(\eta \rightarrow \pi \chi \pm) \tag{9}
\]
Here we assume an isotropic scattering and take a uniform distribution of the ADM kinetic energy.

In order to compare with the Xenon1T electron recoil data, we calculate the differential recoil rate by
\[
\frac{dR}{dE_R} = \epsilon(E_R) n_T \int_{T_{\text{min}}}^{T_{\text{max}}} \frac{d\phi}{dE_R} \frac{d\sigma_{\chi e}}{dE_R} \tag{10}
\]
where \(n_T = 4.2 \times 10^{27}\) is number density of Xenon per tonne and \(\epsilon(E_R)\) is detection efficiency [13]. The ADM flux \(d\phi/dT_\chi\) is given by Eq. 2. For a fixed DM velocity, the differential cross section of the ADM scattering with the electron can be written as,
\[
\frac{d\sigma_{\chi e}}{dE_R} = \frac{\sigma_e}{2m_e e^2} \sum_{nl} \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} a_0^2 q dq |F(q)|^2 |f_{nl}(q, E_R)|^2 \tag{11}
\]
where \(a_0 = 1/(\alpha m_e)\) is the Bohr radius. \(\sigma_e\) is the DM-free electron scattering cross section at fixed momentum transfer \(q = 1/a_0\). We attribute the momentum-dependent effect into the dark matter form factor \(F(q)\). In non-relativistic limit, the dark matter factor \(F(q) = (\alpha^2 m^2_e + m^2_M)/(q^2 + m^2_M)\). While for boosted dark matter, it will rely on the mediator mass \(m_M\) and the kinetic energy of dark matter \(T_\chi\),
\[
|F(q)|^2 = \frac{(\alpha^2 m^2_e + m^2_M)}{(2m_e E_R + m^2_M)^2} \frac{1}{2m_e m^2_\chi} \times \left[2m_e (m_\chi + T_\chi)^2 - E_R (m_\chi + m_e)^2 + 2m_e E_R T_\chi + m_e E^2_R\right] \tag{12}
\]
It can be seen that such a factor will behave like \((T_\chi/m_\chi)^2\), and thus be much larger than 1 when \(T_\chi \gg m_\chi\). The function \(f_{nl}(q, E_R)\) is the ionization form factor of an electron in the \((n, l)\) shell with the recoil \(E_R\). By using the given bound wave functions and unbound wave functions, this form factor for electron in the different shells is calculated in [40, 41]. The limits of integration of the momentum transfer \(q_{\text{min}}, q_{\text{max}}\) are given by
\[
q_{\text{min}, \text{max}} = m_\chi v_\chi \mp \sqrt{m^2_\chi v^2_\chi - 2m_\chi E_R}, \tag{13}
\]
where \(v_\chi\) is the velocity of ADM in its scattering with electron.

**NUMERICAL RESULTS AND DISCUSSIONS**

In Fig. 2, we show the flux of atmospheric dark matter for the benchmark point \(m_\chi = 50\text{keV}\) and \(m_M = 0.02\text{GeV}\). Due to the attenuation effect, the flux will exponentially decrease as the nucleon spin-independent cross section \(\sigma^{SI}_\chi \gtrsim 10^{-28}\) \(\text{cm}^2\). In our numerical calculations, we take \(\sigma^{SI}_\chi = 10^{-34}\) \(\text{cm}^2\), which can also evade the potential limits from the measurement of the nucleon spin-independent cross section [35]. Besides, if the mediator couples with the quarks, the ADM can be produced from the pion decay \(\pi \rightarrow \chi \gamma\) as well. However, its branching ratio is required to be less than \(1.9 \times 10^{-7}\) [42]. Thus, we can neglect its contribution to the flux of ADM. The charged meson decaying to the ADM are more model-dependent and will not be included in this study. On the other hand, there is no direct searches for the process \(\eta \rightarrow \pi^0 + E_T\). The current uncertainty of the decay width of \(\eta\) meson is around 3.8%. To be conservative, we assume \(\text{BR}(\eta \rightarrow \pi \chi) = 1 \times 10^{-3}\) [42]. From Fig. 2, it can be seen that the flux of ADM can have a peak in the (semi-)relativistic velocity region. As a comparison with the flux of cosmic ray upscattering DM, this mechanism have produce much more boosted DM. We also calculate the flux for the lighter ADM, such as \(m_\chi = 10\text{keV}\) and find that the slope of curves are slightly changed.

In Fig. 3, we perform the ADM fit of Xenon1T electron recoil data by using the Eq. 10. Thanks to the high energy CRs, the resulting ADM from the decay of mesons produced in the inelastic collision of CRs in the atmosphere can be fast-moving, for example, an ADM with the mass \(m_\chi = 50\text{keV}\) can have the kinetic energy \(T_\chi = 1\text{GeV}\) (corresponding to a velocity \(v \sim c\))
around the peak in the flux (c.f. Fig. 2). As expected, a $\mathcal{O}(10)$keV ADM can successfully fit the observed electron recoil spectra in Xenon1T. Besides, if the ADM mass is as light as keV, it will produce a peak at the lower recoil region. While for a $\mathcal{O}$(MeV) ADM, it also fails to give the required Xenon1T spectra because of the insufficient events.

In Fig. 4, we present the exclusion limits from Super-Kamiokande neutrino experiment, solar reflection and the XENON10/100 on the $\sigma_e$ versus $m_\chi$. We also show our benchmark points for the different ADM masses $m_\chi = 20, 50, 80$keV in this plot. All these points are required to fit the electron recoil spectra in Xenon1T. It can be seen that our samples can have the ADM-electron scattering cross sections $\sigma_e \sim \mathcal{O}(10^{-37} - 10^{-38})$ cm$^2$, which are much smaller than those exclusion limits. On the other hand, our $\sigma_e$ is sensitive to the branching ratio of meson decay. Therefore, we can expect the future precision measurements of the light meson rare decays, such as $\eta \rightarrow \pi + E_T$, would provide a complementary probe of our ADM.

**CONCLUSIONS**

The very recent Xenon1T electron recoil excess in the keV range may be the evidence of the light dark matter. We propose the atmospheric dark matter (AMD) from the inelastic collision of cosmic rays with the atmosphere to interpret this excess. Thanks to the acceleration effect from high energy cosmic rays, we find that a $\mathcal{O}(10)$keV ADM can obtain the enough kinetic energy and successfully fit the observed electron recoil spectrum scattering with the electron. Besides, due to the momentum-dependent relativistic atomic form factor, our ADM can also evade other direct detection constraints.

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