Dark Matter and the XENON1T electron recoil excess

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We show that the electron recoil excess around 2 keV claimed by the XENON collaboration can be fit by DM or DM-like particles having a fast component with velocity of order ~ 0.1. Those particles cannot be part of the cold DM halo of our Galaxy, so we speculate about their possible nature and origin, such as fast moving DM sub-haloes, semi-annihilations of DM and relativistic axions produced by a nearby axion star. Feasible new physics scenarios must accommodate exotic DM dynamics and unusual DM properties.

INTRODUCTION

The XENON collaboration reported results of searches for new physics with low-energy electronic recoil data recorded with the XENON1T detector [1]. They claim an excess of events over the known backgrounds in the recoil energy $E_R$ range 1-7 keV, peaked around 2.4 keV. The local statistical significance is around 3-4σ, although part of the excess could be due to a small tritium background in the XENON1T detector [1].

The statistical significance of the excess is 3.5σ when interpreted in terms of axions [2–4] emitted by thermal nuclei [1, 12] or by DM DM scattering be-

In this work we demonstrate that a flux of fast DM can provide a good fit to the XENON1T excess, and determine the necessary flux and velocity. Our results show that adding a free tritium abundance to the detector does not improve the fit. We later speculate about possible origins of such a fast DM component.

FAST DM FIT TO XENON1T DATA

We consider an elastic DM $e \rightarrow DM'_{e'}$ scattering between a DM particle with initial velocity $v_{DM}$ and an electron with initial velocity $v_e$ that acquires final velocity $v_{e'}$. Assuming, for simplicity, that they are parallel and non-relativistic, the transferred recoil energy is

$$E_R = E_{e'} - E_e = 2\mu_{rel}v_{CM}$$

$$\approx \begin{cases} 2m_{DM}v_e(v_{DM} - v_e) & \text{for } m_{DM} \ll m_e, \\ 2m_e v_{DM}(v_{DM} - v_e) & \text{for } m_{DM} \gg m_e, \end{cases}$$  

and the transferred momentum is

$$q = m_{DM}(v'_{DM} - v_{DM}) = -2\mu_{rel}$$

$$\approx \begin{cases} 2m_{DM}(v_{DM} - v_e) & \text{for } m_{DM} \ll m_e, \\ 2m_e(v_{DM} - v_e) & \text{for } m_{DM} \gg m_e, \end{cases}$$

where $v_{CM} = (m_e v_e + m_{DM} v_{DM})/(m_e + m_{DM})$ is the center-of-mass velocity, $v_{rel} = v_{DM} - v_e$ is the relative velocity, and $\mu = m_e m_{DM}/(m_e + m_{DM})$ is the reduced mass. We see that the desired $E_R \sim 2.4$ keV can be obtained for $m_{DM} \gg m_e$ with $v_{DM} \approx 0.1$ or for $m_{DM} \ll m_e$ and faster DM, that becomes relativistic for $m_{DM} \sim 0.1m_e$. Notice that $E_R \approx q v_{CM}$ so that $q^2 \approx (40 \text{keV})^2$. 

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We validate the above estimates by performing a detailed computation taking into account the Xe atomic structure, along the lines of [15, 16]. In particular, we use the relativistic wave-functions for the ionization factor provided in [16].

For a fixed DM velocity $v_{DM}$ (hereafter denoted by $v$ to simplify the notation), the differential cross-section is

$$\frac{d\sigma v}{dE_R} = \frac{\sigma_e}{2m_e v} \int_{q_-}^{q_+} q dq |F(q)|^2 K(E_R, q),$$

(3)

where $\sigma_e$ is the free electron cross-section at fixed momentum transfer $q = 1/a_0$, where $a_0 = 1/(\alpha m_e)$ is the Bohr radius. The limits of integration are

$$q_{\pm} = m_{DM} v \pm \sqrt{m_{DM}^2 v^2 - 2m_{DM} E_R}.$$  

(4)

We assume the DM form factor $F(q) = 1$ obtained, e.g., from heavy mediators. The atomic excitation factor $K(E_R, q)$ is taken from [17] and includes the relativistic corrections, relevant at large momentum exchange. For $E_R \sim$ keV recoil energies, the excitation factor is dominated by the $n = 3$ and $n = 4$ atomic shells, the former starting at $E_R > 1.17$ keV. The differential rate is given by

$$\frac{dR}{dE_R} = n_T n_{DM} \frac{d\sigma v}{dE_R},$$

(5)

where $n_T \simeq 4.2 \times 10^{27}$/ton is the number density of Xenon atoms, and $n_{DM}$ is the number density of the fast DM component. The rate depends on the product $n_{DM}\sigma_{\epsilon}$, which we fit to the XENON1T excess. To compare the spectra with the XENON1T data, we smear them by a detector resolution $\sigma_{\text{det}} = 0.45$ keV [18], approximated as constant, multiply by the efficiency given in [1] and bin them as the available data in [1]. We perform the fit both with negligible and free tritium abundance. In the latter case, the tritium signal shape is taken from [18] and its magnitude is fitted.

Fig. 1 compares the XENON1T data to sample spectra of the electron excess, computed for some values of the DM mass and velocity.

Fig. 2 shows which values of these parameters best fit the energy spectrum of the excess. We find that DM heavier than the electron with velocities $v_{DM} \sim 0.1$ fits the excess well. On the other hand, lower masses do not provide sufficiently high electron recoil (unless the DM velocity is increased to relativistic values), whereas slower DM (even if heavier, to provide sufficient recoil) tends to give a too large signal in the first bin 1–2 keV. Allowing for a free amount of tritium background (dotted contours in fig. 2) does not shift significantly the best-fit regions because tritium reproduces the energy spectrum of the excess well less than fast DM.

Fig. 3 shows the values of the number density of the fast DM component times its cross section on electrons needed to reproduce the excess rate claimed by XENON1T.
DISCUSSION AND SPECULATIONS

We have seen that the XENON1T electron recoil excess can be interpreted as due to a flux of high velocity particles. Their velocities have to be so high that these particles cannot be gravitationally bound to the DM halo of our Galaxy. Here we will speculate about possible physical origins of such flux of fast DM-like particles. One needs to consider non-trivial DM dynamics, that must be consistent with all constraints. For example, DM up-scattering by cosmic rays [19] seems not to be consistent with other experiments.

One possibility is that the Earth is currently passing through a DM (sub-)halo that moves with a very high speed relative to us. The origin of such halo is, however, unclear, as the required velocities \( v \gtrsim 0.05 \) are an order of magnitude larger than the velocity dispersions in nearby rich galaxy clusters.

Another possibility is that a flux of fast DM is produced by semi-annihilation processes (see e.g. [20–24]) such as \( \phi \phi \to \phi X \), where \( \phi \) denotes the DM particle and \( X \) is extra particles. In case \( X \) has a negligible mass, a mono-energetic flux with \( v_{DM} = 0.6 \) is produced. The speed can be different if, instead of \( \phi \), the final state contains a particle \( \phi' \) with a different mass (and possibly different interactions with electrons and SM particles). A continuous spectrum is obtained if multiple particles \( X \) are involved in the process. DM heavier than \( T/v_{esc} \sim 1 \) GeV can accumulate in the Sun or the Earth through elastic scattering with SM particles. The resulting rate of semi-annihilation process in their centers is at most equal to the capture rate, that is at most geometric. In the most optimistic limit where all DM particles are captured the equilibrium flux of fast DM particles from the Earth is \( \Phi_{DM} = \rho_{DM} v_{DM} / (8 \sigma_{DM} m_{DM}) \), where \( \rho_{DM} \approx 0.3 \) GeV/cm\(^3\) is the usual density of DM particles with \( v_{DM} \sim 10^{-3} \). The XENON excess rate can be reproduced, for example, if the DM cross section on electrons is a few orders of magnitude below \( 10^{-36} \) cm\(^2\), the critical value for efficient capture by the Earth, consistently with experimental bounds [25]. Similarly, one can consider radioactive DM that slowly decays into energetic dark particles.

Another possibility is that DM contains structures similar to matter, with a lighter faster dark-electron coupled by some dark photon to slower and heavier dark-nuclei, possibly in the form of dark-atoms (see e.g. [26]).

As another example, some DM may consist of axions in the form of axion stars [27–29], in addition to DM in the form of smooth halos. This implies that some fraction of the DM mass is confined in the compact star-like objects, and the observed DM halos contain axion stars. As is well known, scenarios of this kind require some hypothetical mechanism of axion star formation. The generic prediction of axion star dynamics is that they oscillate and emit both relativistic axions as well as photons in the form of radio bursts [28, 30]. The axion-electron coupling \( g_{ae} \) (needed to explain the XENON1T results) can differ from the axion-photon coupling \( g_{a\gamma} \) (which produces radio bursts and other axion signatures involving photons and electric and magnetic fields). So one can conceive scenarios of axion stars that satisfy bounds from photon signals. If a nearby axion star exists, such as the hypothetical Planet 9 [31–33], it may be invisible and yet produce the required relativistic flux of axions without being excluded. Whether such exotic axion stars exist or not requires a dedicated study.

CONCLUSIONS

The excess in the electron recoil energy spectrum around 2 keV claimed by the XENON1T collaboration could be produced by fast DM or DM-like particles hitting electrons with DM velocity \( v \sim 0.1 \). A fast DM component is needed because the cold DM with \( v \sim 10^{-3} \) recoiling on electrons produces an excess at lower energies. This result persists the XENON1T is partly due to tritium background. We speculated about possible exotic DM dynamics that produces the needed fast DM component.
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