On-shell mediator dark matter models and the Xenon1T anomaly

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We present a dark matter model to explain the excess events in the electron recoil data recently reported by the Xenon1T experiment. In our model, dark matter $\chi$ annihilates into a pair of on-shell particles $\phi$ which subsequently decay into $\psi\psi$ final state; $\psi$ interacts with electron to generate the observed excess events. Due to the mass hierarchy, the velocity of $\psi$ can be rather large and can have an extended distribution, which provides a good fit to the electron recoil energy spectrum. We estimated the flux of $\psi$ from dark matter annihilations in the galaxy and further determined the interaction cross section which is sizable but small enough to allow $\psi$ to penetrate the rocks to reach the underground labs.

Introduction: Recently, the XENON collaboration reported a new result in the low energy electron recoil data in the Science Run 1 (SR1) data collected by the Xenon1T experiment from February 2017 to February 2018 with an exposure of 0.65 tonne-years: 285 events are observed in the electron recoil energy between 1 keV and 7 keV, while the background expectation is $232 \pm 15$ events [1]. Various backgrounds for the excess events are studied by the XENON collaboration [1]. The uncertainty in the Pb-214 background is found not big enough to explain the excess [1]. Although the $\beta$ emission of tritium gives a good fit to the excess data, the amount of tritium due to cosmogenic activation is found to be much smaller than needed for the excess [1]. But there could be some other sources of tritium inside the Xenon1T detector.

Axions produced from the Sun and neutrinos with magnetic moment can provide a good fit to the excess events with a significance of 3.5 $\sigma$ and 3.2 $\sigma$ respectively [1]. However, the solar axion explanation is strong tension with the stellar cooling constraint [2–5], and neutrinos with magnetic moment are also constrained [1]. Axion-like particles [6], and dark matter (DM) particles with very large velocity [7] are proposed to explain the excess data.

In this paper, we present a DM model which can explain the excess events in the Xenon1T low energy electron recoil data. This model, DM particle $\chi$ annihilates into a pair of on-shell particles $\phi$ which subsequently decays into $\psi\psi$ final state, as shown by the diagram on Fig. (1). We refer to this model as the on-shell mediator model (see e.g. [8–13] for early studies). We assume that $\psi$ has a sizeable interaction cross section with electron. The produced $\psi$ particle can have rather large velocity leading to a ~keV electron recoil energy to be recorded by the Xenon1T detector.

We show that the $\psi$ particle can have an extended velocity distribution due to the mass hierarchy, which provides a good fit to the excess spectrum in the Xenon1T electron recoil data. We further estimate the flux of $\psi$ and the interaction cross section with the electron. We find that the flux of $\psi$ is consistent with the expectation from DM annihilation in the galaxy, and the interaction cross section needed for the excess is small enough such that $\psi$ is not stopped by the rock on top of the underground labs.

On-shell mediator model: We consider a hidden sector that contains three particles $\chi$ which is the DM, $\phi$, and $\psi$. We assume the following mass hierarchy $m_\chi > m_\phi > 2m_\psi$ so that DM $\chi$ can annihilate in the following way

$$\chi\chi \rightarrow \phi\phi \rightarrow \psi\psi\psi\psi$$

(1)

Assuming $\psi$ is isotropically produced the rest frame of $\phi$, the energy spectrum of the $\psi$ particle has a box-shape in the energy range

$$E_- < E_\psi < E_+$$

(2)

where $E_\pm = (m_\chi/2)(1 \pm xy)$ with $x = \sqrt{1 - m_\phi^2/m_\chi^2}$ and $y = \sqrt{1 - 4m_\psi^2/m_\phi^2}$. This leads to a velocity distribution of $\psi$ as follows

$$\int_{v_-}^{v_+} dv_\psi f(v_\psi) = \int_{v_-}^{v_+} \frac{dv_\psi}{(E_+ - E_-)(1 - v_\psi^2)^{3/2}} 3$$

(3)

1 A different mass hierarchy can lead to the following process $\chi\chi \rightarrow \psi\psi$ where $\psi$ is mono-energetic.
where \( v_\psi(E_\psi) = \sqrt{1 - m_\psi^2/E_\psi^2} \) is the velocity of \( \psi \), and \( v_\pm = v_\psi(E_\pm) \).

**Electron recoil events:** The differential rate due to scattering between \( \psi \) and electron can be computed by [14–17]

\[
\frac{d\sigma v_\psi}{dE_R} = \frac{\bar{\sigma} v_\psi}{2m_e} \int d\psi f(v_\psi) \int_{q^-}^{q^+} \alpha_0^2 q dq |F(q)|^2 K(E_R, q),
\]

where \( f(v_\psi) \) is the \( \psi \) velocity distribution given in Eq. 3, \( F(q) \) is the dark matter form factor which is assumed to be unity in this analysis, \( E_R \) is the electron recoil energy, \( K(E_R, q) \) is the dimensionless atomic excitation factor [16, 17] and \( \bar{\sigma} v_\psi \) is the free electron cross section at fixed momentum transfer \( q = 1/a_0 \) with \( a_0 = 1/(m_e \alpha) \) being the Bohr radius. The integration limits on the momentum transfer is given by [14–16]

\[
q_\pm = m_\psi v_\psi \pm \sqrt{m_\psi^2 v_\psi^2 - 2m_\psi E_R}.
\]

The differential event rate then can be obtained by

\[
\frac{dR}{dE_R} = N_T m_\psi \frac{d\sigma v_\psi}{dE_R} \epsilon(E_R),
\]

where \( N_T \) is the number of atoms in the target material, and \( m_\psi \) is the number density of the incident \( \psi \) particle. We take \( N_T \approx 4.2 \times 10^{27} \text{ ton}^{-1} \) for Xenon atoms.

The number of events are then calculated by

\[
N_S = \text{exposure} \int_{E_1}^{E_2} \frac{dR}{dE_R} \text{d}E_R \epsilon(E_R),
\]

where the exposure is 0.65 tonne years, and \( \epsilon(E_R) \) is the total efficiency given in the Xenon1T experiment [1].

**Fitting to excess events:** We use the on-shell mediator models to fit the excess events in the electron recoil energy range 1-7 keV on Fig. 2. We take the background from the Xenon1T paper [1]. We considered four benchmark model points on Fig. 2. The product of the number density of \( \psi \) and its interaction cross section with electron is fixed to be \( n_\psi \sigma_{e\psi} = 10^{-43.5}/\text{cm} \) for all benchmark model points on Fig. 2.

We carry out a simple chi-square analysis by analyzing only the six low energy electron recoil data points shown on Fig. 2, where \( \chi^2 \) is calculated by

\[
\chi^2 = \sum \frac{(N_{i,\text{exp}}^i - N_{i,\text{th}}^i)^2}{\delta N_{i,\text{exp}}^2},
\]

where \( i \) denotes for bins, \( N_{i,\text{exp}}^i \) and \( \delta N_{i,\text{exp}}^i \) are the number of observed events and its uncertainty taken from Xenon1T [1]. \( N_{i,\text{th}}^i \) is the number of signal events calculated in Eq. 7 plus the expected background taken from Xenon1T [1]. It is found that the benchmark model point B has the best-fit significance of 3.5\( \sigma \) among the four points; the benchmark model points A, C, D yields a significances of 2.7\( \sigma \), 3.0\( \sigma \) and 3.2\( \sigma \) respectively.

Also, comparing the BP B and C, it is found that the peak bin tends to shift to the right when \( x \) and \( y \) have bigger values. Lower masses BPs result in a smaller number of events in the excess region.

Figure 2. The binned signal events from four benchmark points (A, B, C, D) in the on-shell mediator model. The black dots are the observed events and the gray line is the expected background [1]. \( n_\psi \sigma_{e\psi} = 10^{-43.5}/\text{cm} \) is assumed for these benchmark model points.

We further carry out a scan in the projected parameter space spanned by \( m_\psi \) and \( (m_\chi - m_\phi) \), both in the range of 0.001 GeV to 10 GeV. The relation \( m_\phi = 2m_\psi + 0.1 \) MeV is used in in the scan. The model points equally distributed on both dimensions in the log scale.

Figure 3 shows the fit to the Xenon1T excess as function of the \( m_\psi \) and \( (m_\chi - m_\phi) \). It is found that \( \chi^2 = 1.2 \) for the best-fit model point at \( (m_\psi, m_\chi - m_\phi) = (0.99, 0.009) \) GeV. The red and blue contours represent the 68% and 95% C.L. which, in a two dimensional parameter space,
corresponds to $\Delta \chi^2 = 2.3$ and $\Delta \phi^2 = 5.99$ respectively.

For smaller mass gap between $\chi$ and $\phi$ particles, the final state particle $\psi$ has higher velocity; thus in order to produce enough excess events in the small electron recoil energy range (1-7 keV), smaller mass values of $\psi$ are needed. This result in a tendency shape in Fig. 3. We found that in order to generate the Xenon1T excess, the $\psi$ velocity has to be in the range of $v_{\psi}/c \sim (0.01, 0.1)$.

**Particle flux of $\psi$:** To compute the flux of $\psi$ from DM annihilations, we assume an NFW profile for the Milky Way DM halo

$$\rho_\chi(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$  \hspace{1cm} (9)

where we take $\gamma = 1$, $\rho_s = 0.31 \text{ GeV/cm}^3$, and $r_s = 21$ kpc. The flux of $\psi$ is given by

$$\Phi_{\psi} = 4 \frac{\langle \sigma v \rangle}{8 \pi m_\chi^2} J$$  \hspace{1cm} (10)

where the total J-factor is $J = \int d\Omega \int ds \rho_\chi^2 \approx 10^{23}$ GeV$^2$/cm$^3$, and $\rho_\chi$ is the DM annihilation cross section. The total $\psi$ flux is $\Phi_{\psi} \approx 10^{-3}$ cm$^{-2}$ s$^{-1}$ for $m_\chi \approx \text{GeV}$ if the canonical thermal cross section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$/s is assumed. We note the particle flux of $\psi$ can be further enhanced if there exists some DM subhalos in the vicinity of the solar system.

Using the benchmark model points B and C on Fig. 2, we determine the interaction cross section to be $\sigma_{\psi e} \approx 10^{-32}$ cm$^2$. This is much larger than the dark matter direct detection upper limit $\sigma_{\text{DM-e}} \lesssim 10^{-38}$ cm$^2$ [18]. However, the particle flux of $\psi$ is about 8 order of magnitude smaller than the local DM flux $\Phi_\chi \approx 10^5$ cm$^{-2}$ s$^{-1}$ for $m_\chi \approx \text{GeV}$. Thus $\psi$ with $\sigma_{\psi e} \approx 10^{-32}$ cm$^2$ is allowed by DM direct detection limits.

However, if the interaction cross section between $\psi$ and electron is so large that it is absorbed by the rock on top of the underground labs. In order to reach the underground labs, the interaction cross section has to satisfy $\sigma_{\psi e} \lesssim 10^{-23}$ cm$^{-2}$ [19]. Thus $\psi$ with $\sigma_{\psi e} \approx 10^{-32}$ cm$^2$ can enter the Xenon1T to generate the excess events.

**Discussion:** A possible realization of the on-shell mediator model discussed is a hidden sector model in which $\chi$ and $\psi$ are fermions charged under the hidden $U(1)$ gauge boson $\phi = \phi_\mu$. Both $\chi$ and $\psi$ are stable due to the hidden $U(1)$.

The interaction Lagrangian is given by

$$g_\ell \phi_\mu (\bar{\chi} \gamma^\mu \chi + \bar{\psi} \gamma^\mu \psi)$$  \hspace{1cm} (11)

$\psi$ can either interact with electron via some electrophilic interaction, or interact with the standard model fermions via another gauge boson $A_\mu$ which is kinetically mixed with the standard model hypercharge boson. We note that such models can be searched for in $e^+ e^-$ colliders.

The mass hierarchy $m_\chi > m_\phi > 2m_\psi$ leads to the box-shape energy spectrum of $\psi$. If $m_\phi > m_\chi$, the annihilation process $\chi \chi \rightarrow \phi \rightarrow \psi \psi$ dominates; the energy spectrum of $\psi$ is a delta function, smeared by the small kinetic energy of DM $\chi$. The velocity distribution in the $\chi \chi \rightarrow \phi \rightarrow \psi \psi$ case has been investigated in Ref. [7].

**Conclusion:** We have analyzed the on-shell mediator DM models to fit the excess events in the low energy electron recoil data observed by Xenon1T. We find that the on-shell mediator DM models can provide a good fit to the Xenon1T data. The benchmark models that can explain the Xenon1T excess are consistent with the expected flux arising from DM annihilations in the Milky Way DM halo. Although the interaction cross section needed for the excess is sizable, it is small enough such that $\psi$ can penetrate the rock to reach the underground labs.

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