Physics Letters B 773 (2017) 121–124

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Strong CMB constraint on P-wave annihilating dark matter

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ARTICLE INFO

Article history:
Received 26 September 2016
Received in revised form 7 August 2017
Accepted 10 August 2017
Available online 16 August 2017
Editor: S. Dodelson

ABSTRACT

We consider a dark sector consisting of dark matter that is a Dirac fermion and a scalar mediator. This model has been extensively studied in the past. If the scalar couples to the dark matter in a parity conserving manner then dark matter annihilation to two mediators is dominated by the P-wave channel and hence is suppressed at very low momentum. The indirect detection constraint from the anisotropy of the Cosmic Microwave Background is usually thought to be absent in the model because of this suppression. In this letter we show that dark matter annihilation via bound state formation occurs through the S-wave and hence there is a constraint on the parameter space of the model from the Cosmic Microwave Background.

1. Introduction

The Standard Model (SM) has no acceptable dark matter (DM) candidate. As its name implies DM must be uncharged and various direct detection as well as astrophysical and cosmological constraints exist on its couplings to ordinary matter as well as its self interactions. These constraints motivate a class of very simple extensions of the SM that contain a dark sector with particles that carry no SM gauge quantum numbers. For thermal DM the minimal dark sector model consists of the DM and a mediator that the DM annihilates into in the early universe. There are various possibilities for the Lorentz quantum numbers of the DM and mediator. Two well studied examples are a Dirac fermion with a mediator that is either a new massive $U(1)_D$ gauge boson (the dark photon) or a massive scalar. In the first case communication with the SM degrees of freedom occurs through the vector portal (via kinetic mixing between the $U(1)_D$ and $U(1)_Y$ field strength tensors) and in the latter case through the Higgs portal.

Constraints on the parameter space of these models occur from the so-called indirect detection signals. Annihilation of DM in the early universe at the time of recombination injects energy into the plasma of SM particles elongating the recombination process and changing expectations for the cosmic microwave background (CMB) radiation anisotropy. Annihilation of DM today in our galaxy contributes to electromagnetic and charged particle astrophysical spectra observed, for example, by the Fermi satellite.

In a recent paper [1], we have highlighted the role that DM bound state formation can play on indirect detection signals from DM annihilation in our galaxy when the mediator is a dark photon (there bound state formation was not important for the CMB constraint). In this *letter*, we again consider the influence of DM bound state formation on indirect signals but focus on the case where the mediator is a real scalar and on the CMB constraint. We impose a parity symmetry on the dark sector with the real scalar mediator having even parity. Then, the Lagrange density for the DM sector is,

$$\mathcal{L} = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_D\bar{\chi}\chi - g\bar{\chi}\chi\phi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2\,, \quad (1)$$

where χ and ϕ are the DM and the dark mediator and the Higgs portal couplings are omitted. This model has been well studied for various reasons [2–19]. For DM heavier than 5–10 GeV, direct detection experiments [20] and the requirement that ϕ decays before BBN set the lower bound, $m_\phi > 2m_\mu \simeq 0.2$ GeV. In our calculations below, we assume a thermal DM relic density, which fixes the value of $\alpha_D = g^2/(4\pi)$ as a function of the DM mass, m_D.

The most often considered DM annihilation process in this model is $\chi\bar{\chi} \to \phi\phi$. The parity of a 2ϕ system must be even and so does the $\chi\bar{\chi}$ system because parity is conserved by the Lagrange density in Eq. (1). Therefore this annihilation is mostly P-wave for slow DM and anti-DM particles.[1] With the P-wave

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[1] If parity was not conserved S-wave annihilation would be possible.

http://dx.doi.org/10.1016/j.physletb.2017.08.010
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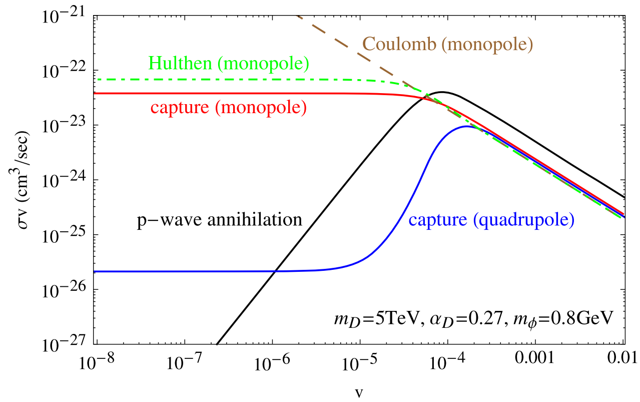

Fig. 1. DM relative velocity dependence in various cross sections. The black curve is the p-wave direct annihilation cross section for $\chi\bar{\chi} \to \phi\phi$. The red curve is the $(\chi\bar{\chi})$ bound state formation cross section via monopole transition, evaluated numerically using Eqs. (4) and (5). The blue curve stands for quadrupole transition counterpart. The brown line is the monopole transition cross section in the Coulomb limit, while the green curve is based on the Hulthén potential which gives a quite good approximation to the realistic Yukawa potential. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Sommerfeld enhancement factor [21] included, the cross section times velocity can be written as

$$(\sigma v)_A^{P\text{-wave}} = \frac{3\pi\alpha_D^2 v^2}{8m_D^2} \times \left| \sqrt{\frac{3}{4\pi p^2}} \frac{dR_{p1}}{dr}(r=0) \right|^2 , \qquad (2)$$

where $p = m_D v/2$, v is the relative velocity. $R_{p\ell}$ is defined as the radial part of the initial scattering wave function (with the relative momentum aligned along the z-axis), $\Psi_{\vec{p}=p\hat{z}}(\vec{r}) = \sum_\ell R_{p\ell}(r) Y_{\ell 0}(\hat{r})$, and $\Psi_{\vec{p}}(\vec{r})$ is asymptotic to $\exp(i\vec{p}\cdot\vec{r})$ at infinity. A typical curve of $(\sigma v)_A^{P\text{-wave}}$ as a function of v is the black curve in Fig. 1. As v gets smaller, $(\sigma v)_A^{P\text{-wave}}$ first grows as $1/v$ due to the Sommerfeld enhancement, and then at around $v \sim m_\phi/m_D$, $(\sigma v)_A^{P\text{-wave}}$ gets strongly suppressed. The drop-off is due to the *effective* potential barrier at $r \sim m_\phi^{-1}$ generated by the sum of the attractive Yukawa potential and the repulsive centrifugal potential. The transmission coefficient for tunneling through the barrier diminishes as v^2 in the small v limit, as illustrated by Fig. 1.

After thermal freeze out (chemical decoupling), DM can still maintain kinetic equilibrium with the ϕ particles in the universe. The DM velocity only red-shifts linearly with the expansion after the kinetic decoupling. For DM mass in the TeV range, their relative velocity v during recombination is extremely small, $v \ll \sqrt{T_{\rm rec}/m_D} \sim 10^{-6}$, where $T_{\rm rec}$ is the temperature of the universe at the recombination era. Hence it has been thought that there will be no CMB constraint for the P-wave annihilating DM in this model. In this *letter*, we show that this is not the case. In some regions of parameter space, a pair of free DM particles can capture into a DM bound state via the emission of a ϕ particle, and then annihilate into ϕ's inside the bound state. The bound state formation process dominantly occurs in an S-wave and therefore is not suppressed at low velocity due to the absence of the centrifugal potential barrier. The mediator eventually decays to SM particles via the Higgs portal resulting in a CMB constraint on the region of the parameter space in the model where the kinematics allows for bound state formation.

2. Bound state formation cross section

The Hamiltonian for a non-relativistic DM–anti-DM system interacting with the mediator field is (in the center of mass frame)

$$H_{\rm int} = g\left[\phi(\vec{r}/2) + \phi(-\vec{r}/2)\right] - g\left[\phi(\vec{r}/2) + \phi(-\vec{r}/2)\right]\frac{\nabla^2}{2m_D^2} , \qquad (3)$$

where g is the dark Yukawa coupling. $\vec{r}$ is the relative position of the DM-and-anti-DM particles, and ϕ is the Schrödinger picture mediator field. In the bound state formation transition amplitude a mediator particle is created by the field ϕ. The mode expansion of the mediator field has exponential dependence on the wave-vector $\vec{k}$ that can be expanded, $e^{\pm i\vec{k}\cdot\vec{r}/2} = 1 \pm i\vec{k}\cdot\vec{r}/2 - (\vec{k}\cdot\vec{r})^2/8 + \cdots$. In the first line of Eq. (3), due to the orthogonality between the initial and final states, the leading order contribution vanishes. The contributions at the $i\vec{k}\cdot\vec{r}$ order from DM and anti-DM cancel with each other. The contribution from the $(\vec{k}\cdot\vec{r})^2$ order yields both monopole and quadrupole transitions. The second line of Eq. (3) represents the leading relativistic correction, which contributes to the monopole transition at the zeroth order in $\vec{k}\cdot\vec{r}$.

The bound state formation cross section times the relative velocity can be written as

$$\sigma v = \sum_f \sum_{\mathfrak{M}=M,Q} \int \frac{d^3\vec{k}}{(2\pi)^3 2k^0}(2\pi)\delta(E_f + k^0 - E_i)|V_{fi}^{\mathfrak{M}}|^2 , \qquad (4)$$

where E_i and E_f are the energies of the initial and final states of the DM–anti-DM system. The sum over f is over final bound state azimuthal, magnetic, and principal quantum numbers, but because we have aligned the dark matter relative momentum along the z-axis only the magnetic quantum number $m = 0$ contributes. Here we are neglecting the spin degrees of freedom for the dark matter. Including them would give a factor of $1/4$ from spin averaging and then for each $f = n, l, m$ there would be four final bound states; one with spin 0 and three with spin 1.

For the monopole (M) transition,

$$|V_{fi}^M|^2 = g^2 \left| \int drr^2 \left[\frac{1}{12}k^2 r^2 + \frac{\alpha_D e^{-m_\phi r}}{m_D r}\right] R_{n\ell}(r) R_{p\ell}(r) \right|^2 , \qquad (5)$$

where $k \equiv |\vec{k}|$, $R_{k\ell}$ and $R_{n\ell}$ are the initial and final radial wave functions. For quadrupole transition,

$$|V_{fi}^Q|^2 = \frac{g^2 k^4}{120}\left[\frac{(\ell+1)(\ell+2)}{(2\ell+1)(2\ell+3)}\left|\int drr^4 R_{n\ell}^*(r) R_{p\ell+2}(r)\right|^2 + \frac{2\ell(\ell+1)}{3(2\ell-1)(2\ell+3)}\left|\int drr^4 R_{n\ell}^*(r) R_{p\ell}(r)\right|^2 + \frac{\ell(\ell-1)}{(2\ell-1)(2\ell+1)}\left|\int drr^4 R_{n\ell}^*(r) R_{p\ell-2}(r)\right|^2\right]. \qquad (6)$$

During the time of recombination the DM and anti-DM particles have negligible kinetic energy, hence to emit an on-shell ϕ, $m_\phi < \alpha_D^2 m_D/(4n^2)$ is required in the Coulomb limit. This indicates $m_\phi \ll \alpha_D m_D/(2n)$. Therefore, the relevant bound state wave functions can be treated as Coulombic for the computation of the bound state formation cross section. On the other hand, we solve for the scattering state wave functions numerically using the shooting method described in [1].

From numerical solutions, we find that after summing over the azimuthal quantum number ℓ, for both the monopole and quadrupole transitions, $(\sigma v) \sim n^{-2}$ roughly. For $m_D = 5.0$ TeV, $\alpha_D = 0.27$, $m_\phi = 0.8$ GeV, the numerical solution of total cross sections times velocity for the monopole and quadrupole transitions are shown as the red and blue curves in Fig. 1 respectively.

For $v > m_\phi/m_D$, σv goes like v^{-1} and agrees with the result from the Coulomb potential scattering states which is shown by