3.5 keV X-rays as the “21 cm line” of dark atoms, and a link to light sterile neutrinos

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The recently discovered 3.5 keV X-ray line from extragalactic sources may be evidence of dark matter scatterings or decays. We show that dark atoms can be the source of the emission, through their hyperfine transitions, which would be the analog of 21 cm radiation from a dark sector. We identify two families of dark atom models that match the X-ray observations and are consistent with other constraints. In the first, the hyperfine excited state is long-lived compared to the age of the universe, and the dark atom mass is relatively unconstrained; dark atoms could be strongly self-interacting in this case. In the second, the excited state is short-lived and viable models are parameterized by the value of the dark proton-to-electron mass ratio R: for R = 10^4 − 10^5, the dark atom mass is predicted to be in the range 350 − 1300 GeV, with fine structure constant \( \alpha' \approx 0.1 − 0.6 \). In either class of models, the dark photon is expected to be massive with \( m_{\gamma'} \sim 1 \text{ MeV} \) and decay into \( e^+ e^- \). Evidence for the model could come from direct detection of the dark atoms. In a natural extension of this framework, the dark photon could decay predominantly into invisible particles, for example \( \sim 0.5 \text{ eV} \) sterile neutrinos, explaining the extra radiation degree of freedom recently suggested by data from BICEP2, while remaining compatible with BBN.

1. Introduction. Evidence for a 3.5 keV X-ray line has been found in XMM-Newton data from the Andromeda galaxy and the Perseus galaxy cluster [1], as well as in the stacked spectra of 73 galaxy clusters [2]. Since a line at this energy is not attributable to any known atomic transitions, there has been considerable interest in trying to explain it in terms of dark matter scattering or decays [3]. In most of these models, the dark matter is very light, with mass of order a few keV. Alternatively, an excited metastable state of dark matter could decay to its ground state with the emission of a 3.5 keV photon, or an unstable state of this type could be excited through inelastic dark matter scatterings [4, 5].

In the present note we point out that dark atoms provide an interesting example of the latter two kinds, due to the relative ease of inducing hyperfine excitations through their self-scatterings. This idea was also considered in [3], but the difficulties for massless dark photons that we highlight and overcome here were not spelled out definitively in that paper. Although atomic dark matter is an old idea, originally arising in theories of mirror symmetry (see [6] for a review), it has experienced a revival in the larger context of hidden sectors [7]−[16], since any U(1) gauge symmetry with sufficiently light mediators should give rise to atom-like bound states. We find it appealing that atomic dark matter can naturally explain the X-ray line, without giving up on the WIMP paradigm, by identifying the low 3.5 keV energy scale with the hyperfine splitting:

\[
\Delta E = \frac{8}{3} \alpha' \frac{m_e^2 m_p}{m_H} = 3.5 \text{ keV} \quad (1)
\]

Here \( e, p \) and \( H \) respectively denote the dark electron, proton (assumed to be elementary particles), and hydrogen atom, with fine structure constant \( \alpha' \) and \( m_H = m_e + m_p \).

In the following we identify two regimes in which the decay of the hyperfine excited state can explain the X-ray line, both requiring the dark photon to be massive with \( m_{\gamma'} \sim 1 \text{ MeV} \). If the decays are relatively fast, then \( m_H \sim 350 − 1300 \text{ GeV} \) and \( \alpha' \sim 0.1 − 0.6 \) for \( R \equiv m_{\gamma'}/m_e \sim 10^2 − 10^4 \), in order to satisfy eq. (1) plus the observed strength of the 3.5 keV line, and constraints from perturbativity and from recombination in the dark sector. If the decays are slower \( \sim 10^{-17} \text{ s}^{-1} \), the line intensity depends on the fractional electric charge of the dark constituents, and there is more freedom in choosing consistent parameter values.

2. Strength of X-ray line from scatterings. Ref. [4] shows that the observed 3.5 keV X-ray line strength can be explained by mildly inelastic DM scatterings followed by fast decays of the excited state if the cross section satisfies

\[
(\sigma v) BR \sim 10^{-21} \text{ cm}^3 \text{s}^{-1} \left( \frac{m_H}{\text{GeV}} \right)^2 \quad (2)
\]

(in units \( \hbar = c = 1 \)). Here \( BR \) denotes the branching ratio for the excited state to decay into visible photons as opposed to dark photons. If the dark photon was massless and mixed with the visible photon through the kinetic mixing term \( (\epsilon/2) F_{\mu} F^{\mu} \), then the dark electron and proton would get fractional charges \( \mp e \) and we would find that \( BR = \epsilon^2 \alpha'/\alpha \). This scenario is ostensibly
Figure 1: Constraints on fractional charge $\epsilon$ of dark atom constituents. Left: lower (dashed) curves are LUX [17] constraint on $\epsilon$ for $R = 2$ and $R = 1000$, while the upper (dotted) lines show the values of $\epsilon$ required by the observed 3.5 keV X-ray line strength in the massless dark photon case. The solid line labeled "LUX" is the LUX upper limit [8] on $\epsilon$ in the massive dark photon model with $R$ fixed by eq. (6). Also shown (dot-dashed) is the lower limit [8] from requiring fast decays of the excited state ("decays too slow"), and the region where $\alpha'$ becomes nonperturbative. Right: constraints on $\epsilon$ from direct detection, in the case $R = 1$ (equal dark proton and electron masses), for $m_{\text{H}} < 8$ GeV. For SuperCDMS [15], only the region where it provides a stronger constraint than CDMSlite [19] is shown.

ruled out as we will explain in sect. 6. Therefore we instead assume that the dark photon has a mass $m_{\gamma'} > 3.5$ keV so that the hyperfine excited state can decay only into photons. Hence we take $BR = 1$.

In sect. 9 we will show that the cross section for spin excitations is of the same order as the elastic cross section, which was found in ref. [15] to be of order

$$\sigma_{\text{el}} \approx 100 a_0^2 = \frac{100}{(\alpha'\mu_{\text{H}})^2} \frac{f(R)^2}{(\alpha'\mu_{\text{H}})^2}$$

(3)

where $a_0$ is the dark sector Bohr radius, $\mu_{\text{H}} = m_p/m_e/m_{\text{e}}$ is the reduced mass, $R = m_p/m_e \geq 1$ and $f(R) = m_{\text{H}}/\mu_{\text{H}} = R + 2 + R^{-1}$. It was shown that the coefficient estimated here as 100 varies only moderately with $R$ for $R \lesssim 2000$. With these definitions, eq. (4) implies the constraint

$$\alpha' = 0.034 \left(\frac{m_{\text{H}}}{\text{GeV}}\right)^{-1/4} f(R)^{1/2}$$

(4)

Equating (3) to the cross section in (2), assuming a relative velocity $v \sim 2000$ km/s appropriate for galaxy clusters, and using (4) to eliminate $\alpha'$ allows us to solve for the dark atom mass as a function of $R$:

$$m_{\text{H}} = 137 [f(R)/4]^{2/7} \text{GeV}$$

(5)

We will see in sect. 8 that $R \gtrsim 100$ is needed to get efficient recombination in the dark sector to form atoms. Then eq. (4) gives $\alpha' \gtrsim 0.08$. Eqs. (4) and (5) together imply that $\alpha' > 1$ for $R > 5 \times 10^4$, invalidating a perturbative treatment; hence our preference for $R \lesssim 10^4$.

3. Line strength from slow decays. If the lifetime $\tau_{hf}$ of the hyperfine excited state is greater than the age of the universe, $\tau_u$, the line strength is determined differently. The dark atoms form with a 3:1 ratio of spin states (since the temperature when they recombine is large compared to $\Delta E$), and this ratio is preserved for of order 1 decay time. So if $\tau_{hf} \gtrsim \tau_u$, then a fraction of order unity of the atoms is hyperfine-excited, independently of the scattering rate. Previous analyses showed that under these circumstances, the observed line strength requires a decay rate of [12] $\tau_{hf}^{-1} = 2.3 \times 10^{-21} \text{s}^{-1} (m_{\text{H}}/100 \text{GeV})$ whereas the predicted rate is

$$\tau_{hf}^{-1} = \frac{\alpha e^2}{3} \frac{\Delta E^3}{\mu_{\text{H}}^2}$$

(6)

(Recall that we have assumed that the decays to dark photons $\gamma'$ are kinematically blocked since $m_{\gamma'} > \Delta E$.) Equating the two rates gives the required value of the dark fractional charge:

$$\epsilon = 1.2 \times 10^{-14} \left(\frac{m_{\text{H}}}{\text{GeV}}\right)^{3/2} \frac{f(R)}{4}^{-1}$$

(7)

4. Constraints on fractional charges. If the hyperfine state is longer lived than the age of the universe, the required fractional charge (7) of $e$ and $p$ is well below laboratory bounds. Otherwise, we rely upon scatterings to populate the excited state, and the requirement that $\tau_d < \tau_u$ puts a lower bound on $\epsilon$:

$$\epsilon > 3 \times 10^{-10} \left(\frac{m_{\text{H}}}{100 \text{GeV}}\right)^{-5/2}$$

(8)

where we used (5) to eliminate $f(R)$.

There are upper limits on $\epsilon$ from the interactions of dark atoms with nuclei by photon exchange. (Due to interference between visible and dark photon exchange, the parameter actually constrained by direct detection is $\epsilon_{\text{eff}} \equiv \epsilon + g'\delta/\epsilon$; see sect. 7 for definition of $\delta$. Since $\delta$ is much less than the experimentally allowed value of
the Compton wavelength of the dark photon is greater than the required range of its interaction, \( m_{\gamma'} \ll a_0^{-1} = \alpha' m_H / f \), the photon mass will not significantly change the dark atom binding properties. For our preferred parameter values, this implies \( m_{\gamma'} \ll 100 \text{ MeV} \). However, for recombination we need \( m_{\gamma'} \) to be less than the binding energy so that excited states of the \( H \) atom can radiatively decay to the ground state. This requires \( m_{\gamma'} \ll \frac{1}{2} \alpha'^2 m_e \approx 7 \text{ MeV} \) (this numerical value applies in the models with fast decays of the excited state).

A simpler alternative to spontaneous breaking of the gauge symmetry through a dark Higgs VEV is to suppose that the mass arises from the Stueckelberg mechanism, as discussed in ref. [21]. This alternative also has string theoretic motivations [22]. The couplings of the visible and dark photons to matter in the two sectors is a function of the kinetic mixing parameter \( \delta \) and the ratio \( \epsilon \) of Stueckelberg masses. In the basis where the kinetic and mass matrices are diagonal, the interactions become

\[
\mathcal{L} = A_\mu (J^{\mu'} + (\epsilon - \delta) J_\mu') + A_\mu (J^\mu - \epsilon J'_\mu) \tag{11}
\]

where \( A' (A) \) denotes the dark (visible) photon vector potential and \( J' (J) \) the current of the dark (visible) constituents. (Couplings of the \( Z \) boson to \( J' \) are further suppressed by the small ratio \( \frac{m_{\gamma'}/m_Z}{\epsilon} \).) Defining \( \tilde{\epsilon} = (\epsilon/g)\epsilon \), the dark constituents get fractional charges given by \( \pm \tilde{\epsilon}e \), while the dark gauge boson couples to electrons with strength \( (\epsilon - \delta) \equiv \delta e \). It would require fine tuning \( \delta = \tilde{\epsilon} \) to eliminate the coupling \( \delta \) between \( A' \) and electrons, whereas \( |\delta| \) could naturally be much larger than \( \epsilon \) if \( \delta \gg \tilde{\epsilon} \).

However, various constraints on \( \delta \) from astrophysics and from fixed-target experiments are stronger than those on \( \epsilon \). We will be interested in \( m_{\gamma'} \sim 1 \text{ MeV} \) (which is still consistent with the need for excited dark atoms to radiate), since constraints on \( \delta \) are even more stringent at lower \( m_{\gamma'} \). For \( m_{\gamma'} \sim 1 \text{ MeV} \), supernova cooling restricts \( \delta \lesssim 6 \times 10^{-11} \) [23]. Then the theoretically most natural situation is that this constraint is nearly saturated.

One may wonder whether the dark photon can have an effect on big bang nucleosynthesis (BBN) by its contribution to the energy density. If \( m_{\gamma'} > 2 m_e \), it decays into \( e^+ e^- \) with rate \( \Gamma_{ee} = (1/3) \alpha \delta^2 m_{\gamma'} g(x) \) where \( x = (m_e/m_{\gamma'})^2 \) and \( g(x) = (1 + 2x)/(1 - 4x)^{1/2} \approx 1 \). Then for example with \( m_{\gamma'} = 3 m_e \) and \( \delta \) saturating the supernova constraint, the lifetime is 54 s which could be problematic for BBN. However we find that Thomson scattering \( \gamma e \leftrightarrow \gamma' e \) is too slow to ever bring \( \gamma' \) into equilibrium, given the constraint \( \delta < 6 \times 10^{-11} \). The corresponding process on dark electrons, \( \gamma e \leftrightarrow \gamma' e \), also fails to come into equilibrium because of the limit [21] on \( \epsilon \). Thus the abundance of \( \gamma' \) is suppressed when it decays.

In sect. 10, we will estimate this abundance based on assumptions about reheating of the dark sector, and show how decays of \( \gamma' \) into sterile neutrinos can be consistent with hints from the CMB of an extra neutrino species, while simultaneously satisfying BBN constraints.
8. Dark recombination. Another important requirement for the consistency of our proposal is that the dark constituents recombined efficiently into atoms, with a sufficiently small residual ionized fraction at the end. The recombination of dark atoms has been considered in references [7] and [12]. Ref. [10] numerically fit the results of [1] for the ionization fraction as

\[ X_e \sim \left( 1 + 10^{10} \alpha' / \xi_0 \right)^{-1} \]  

while [12] obtained a similar estimate but with an extra factor \( \alpha'/\xi_0 \) multiplying \( \alpha'/\xi_0 \), where \( \xi \) is the ratio of dark to visible photon temperatures, which suppresses \( X_e \). In sect. 10, we will estimate that \( \xi = 0.6 \) in our model. To be conservative, we use [12] without this correction. Eliminating \( \alpha' \) and \( m_H \) using [3] and [5], we find that \( X_e \sim 60 R^{-15/7} \), so that \( X_e < 3 \times 10^{-3} \) for \( R > 100 \). This is small enough to consider that the dark constituents are mostly recombined, and the unscreened dark Coulomb scattering of the ionized fraction will have a negligible effect on the shape of dark matter halos as they evolve.

9. Spin excitation cross section. The cross sections for hyperfine excitations are related to those of elastic scattering through \[ \sigma^+ = \frac{\pi}{2k^2} \sum_{\ell = 0} \left( 2\ell + 1 \right) \sin^2(\delta_\ell - \delta_s) \]  

where \( \delta_{s,\ell} \) are the electron singlet and triplet channel phase shifts that were computed for dark atoms in ref. [13], and \( \ell \) refers to \( \Delta F = 2, 1 \) changes in the total hyperfine state \( F \) of the two atoms. A linear combination \( (\sigma^++2\sigma^-)/4 \) is relevant for finding the rate of hyperfine-exciting transitions. For our purposes, it is sufficient that \( \sigma^+ \) (which dominates) is of the same order as the unpolarized elastic cross section, which at low energies is dominated by the \( \ell = 0 \) phase shifts.

10. Link to sterile neutrinos. It is possible that the dark photon \( \gamma' \) has an invisible decay channel in addition to its \( \delta \)-suppressed decays into \( e^+e^- \). These decays could therefore provide a source of dark radiation as well as avoiding BBN constraints on \( \gamma' \). The recent BICEP2 measurement of \( B \)-mode polarization in the CMB [28] reveals a tension with Planck determinations of the power spectrum (for caveats, see [29]), that can be alleviated if there is an additional radiation species [30]. In particular, sterile neutrinos with a mass \( \sim 0.5 \) eV have been shown to give a good fit to the data [31, 53] (however ref. [34] disagrees with this conclusion). Here we consider the effect of such particles coupling to the dark photon and whether they can naturally contribute \( \Delta N_{\text{eff}} \sim 1 \) to the effective number of neutrino species.

Decays of \( \gamma' \) into \( \nu_s \) could arise from a one-loop effect if there is a dark analog of the weak interactions coupling \( \nu_s \) to e and a \( W' \) boson with strength \( g_{\mu'} \). If \( \nu_s \) is a Majorana particle, then the effective operator induced is the anapole moment

\[ \frac{1}{2} g_{\mu'} \bar{\nu}_s \gamma^\mu \delta \nu_{\alpha'} \partial^\alpha F'_{\alpha\mu} \]  

where \( a_{\nu} \equiv g_{\mu'} / (16\pi^2 m_{W'}^2) \). For massive on-shell photons the Proca equation gives \( \partial^\mu F'_{\mu
u} = m_{W'}^2 A'_{\nu} \), leading to the dimensionless coupling \( a_{\nu} m_{W'}^2 \) and a decay rate for \( \gamma' \rightarrow \nu_s \bar{\nu}_s \) of \( \Gamma_{\nu_s} = a_{\nu}^2 m_{W'}^5 / 24\pi \).

To find the \( \Delta N_{\text{eff}} \) of \( \nu_s \) following these decays, we need to know the abundance of \( \gamma' \) when it decays: \( Y_{\gamma'} = n_{\gamma'}/s \) where \( s \) is the visible sector entropy density. Previously we established that \( \delta \) and \( \epsilon \) are too small for \( \gamma' \) to come into equilibrium with the standard model; hence we content ourselves with making a reasonable assumption about its initial temperature after reheating. Namely if the dark and visible sectors were initially heated to the same temperature \( T \gg 100 \) GeV, and the dark sector consists only of e, p, \( \gamma' \), \( \nu_s \), \( W' \) and a dark Higgs, then \( Y_{\gamma'} = (45\zeta(3)/2\pi^4)(13.74/106.75) = 0.036 \), corresponding to a temperature of \( T_{\gamma'} / T_e = (7 Y_{\gamma'})^{1/3} = 0.63 \). Here 13.74 is the number of dark entropy degrees of freedom that end up as \( \gamma' \) as opposed to \( \nu_s \) (before \( \gamma' \) decays), while 106.75 is the number of SM degrees of freedom.

Ref. [35] (see their fig. 3) has determined the contribution of such a decaying dark photon to \( \Delta N_{\text{eff}} \) in the CMB as a function of \( Y_{\gamma'} m_{\gamma'} \) and the lifetime of \( \gamma' \) (assuming it decays only into dark radiation). For example with \( Y_{\gamma'} = 0.036 \) and \( m_{\gamma'} = 1 \) MeV, \( \Delta N_{\text{eff}} = 1 \) in the CMB is achieved if \( \tau_{\gamma'} = 40 \) s, while the contribution to \( N_{\text{eff}} \) relevant for BBN is within the constraints. A lifetime is compatible with reasonable values of the parameters entering [14]: if \( g_{\mu'} = 1 \) and \( g_{\mu'}^2 / 4\pi = 0.1 \), then \( m_{W'} = 17.5 \) GeV. In this example \( \gamma' \) is too light to decay into \( e^+e^- \) and \( \gamma' \rightarrow \nu_s \bar{\nu}_s \) is the only decay channel. If \( m_{\nu_s} = 3m_{\nu} \) with other parameters being the same, then \( \delta \) need only be \( 10^{-10} \) to allow decays into \( \nu_s \) to dominate over those into \( e^+e^- \).

11. Conclusions. We have outlined a scenario in which the tentative discovery of a 3.5 keV X-ray line in galactic clusters could be identified as the dark analog of 21 cm emission. The dark constituents have a small coupling \( ee \) to ordinary photons. If the hyperfine excited state lifetime is greater than the age of the universe, very small values of \( \epsilon \), eq. [3], are sufficient to give the observed line intensity, and the dark atoms could be relatively light, \( 30 - 160 \) GeV, having strong self-interactions (eq. [10]), which could alleviate problems of cold dark matter with respect to structure formation at small scales.

Otherwise, for faster-decaying excited states, the observed X-ray energy and intensity, combined with the need to have a small ionized fraction of the dark constituents and to satisfy direct dark matter searches, more strongly constrain the parameter space of the model: the dark atom mass is expected to be in the range \( 350 - 1300 \) GeV, with dark electron masses \( 3.5 - 0.1 \) GeV, corresponding to dark proton-to-electron mass ratios \( R \sim 100 - 10^4 \), and U(1)’ couplings \( \alpha' = 0.08 - 0.57 \). The fractional charges obey \( \epsilon \lesssim 10^{-8} \), which if saturated would make the dark atoms close to being discovered by the LUX experiment.

Moreover the dark photon should have mass \( m_{\gamma'} \sim 1 \)
MeV to block the invisible decays of the hyperfine excited states and allow them to decay only to visible photons despite the smallness of $\epsilon$. The Stueckelberg mechanism is assumed to give rise to the mass, as well as to a small coupling $\delta e$ of $\gamma'$ to visible electrons with $\delta < 6 \times 10^{-11}$ from supernova constraints. Smaller values of $m_{\gamma'}$ could be permitted, at the expense of stronger constraints on $\delta$. In the fast-decay scenario, this would require greater fine tuning with respect to the theoretical expectation that $\delta \gtrsim \epsilon$, whereas in the slow-decay models that expectation is more easily satisfied.

Recent suggestions of a sterile neutrino of mass 0.5 eV to reconcile BICEP and Planck determinations of the CMB power spectrum can naturally be incorporated into our dark sector. An anapole moment coupling of $\nu_s$ to the dark photon could allow for decays of $\gamma'$ predominantly into $\nu_s$ rather than electrons, leading to the desired density of $\nu_s$, compatible with BBN constraints. Such a coupling would suggest that the dark sector has a broken $SU(2)'$ gauge symmetry in analogy to the weak interactions, in addition to the $U(1)'$ that binds the dark atoms.

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