A Scenario of Heavy Baryonic Dark Matter

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We consider a general class of models in which dark matter is a composite baryonic and antibaryonic particle of some hidden vector-like strong gauge theory. The model building provides simple answers to two basic questions: Annihilation between dark baryon and antibaryon saturates the unitarity bound, which in thermal freeze out predicts the scale of dark matter particle to be about 150 TeV. And the dark matter stability is a result of the accidental dark baryon number, which can still be violated by operators suppressed by large scales, leading to tiny decay rate. We show that annihilation between dark baryon and anti-baryon seems difficult to be detected in the galaxy center in the near future. On the other hand in the minimal model of $SU(3)$ hidden strong gauge group with a Planck scale suppression, the dark matter life time happens to be marginal to the current detection bound, and can explain the current AMS-02 antiproton results.

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INTRODUCTION

A lot of particle physics candidates have been worked out for dark matter (DM), which takes about 26% of the energy density of our universe [1]. While probably more models have DM candidates not as their primary motivation, all of them have, at least after tuning to certain parameters, to explain some basic facts such as the relic abundance, weakness of their interaction with the standard model (SM) matter, their stability and so on. Actually not all of the DM models have elegant answers to the requirements. In this letter we provide a new scenario according to our answer to the questions, in which DM is a baryonic or antibaryonic composite particle in a hidden strong gauge interaction.

Our composite DM model is basically a copy of quantum chromodynamics (QCD) at different scale. Some hidden strong gauge group at certain scales has exactly the same QCD phenomena of color confinement and chiral symmetry breaking, they form fermionic dark baryons as colorless bound states in totally antisymmetric representation. The dark baryon may annihilate with dark antibaryon, analogy to real QCD we know that their annihilation is governed by strong dynamics, and at low velocity the cross section saturates the unitarity bound. The QCD proton is stable empirically, even if the theory is promoted to the grand unified theory (GUT) and proton decay is allowed. Our dark baryon is also stable as a consequence of the accidental dark baryon number conservation.

The generally required new strong hidden gauge group can be only a part of the complete gauge group. In model building we consider the following criteria [2], that constituent quarks in the hidden sector are charged under some SM gauge groups of $SU(3)_c \times SU(2)_L \times U(1)_Y$, but the dark baryon itself must carry no net SM charges, in order to be sufficiently weakly interacting in current universe. Such model building allows interesting phenomena of DM scattering with, and annihilate into, and decay into ordinary matter. We will see that the minimal model we can construct has a $SU(3)_{\rm hid} \times SU(2)_R \times U(1)_Y$ gauge group, and this minimal model is especially interesting as it happens to give a decay life time close to the current bound and can fit to the observation.

This letter is basically divided into two parts. In Section 2 we discuss the annihilation process of the composite DM, from which the scale of the DM is determined, unrelated to a specification of the gauge group. Section 3 contains the building of the minimal $SU(3)_{\rm hid} \times SU(2)_R \times U(1)_Y$ model and consequently the discussion of the decay process, eventually it is fitted to the recent AMS-02 and Fermi-LAT extragalactic gamma ray background (EGB) observations. At last we conclude in Section 4.

DARK MATTER ANNIHILATION AND SCALE

The degree of freedom in low energy QCD are baryons and mesons, rather than quarks and gluons. At the lowest scale the dominant interaction is mediated by the lightest meson, namely the pion or the pseudo Nambu-Goldstone boson. The effective theory is the chiral perturbation theory, or an organized form of the naive dimensional analysis (NDA). We expect the same dynamics applies in the hidden sector. One difference is, according to the Gell-Mann-Oakes-Renner relation [3] the pion mass is not determined by the QCD scale alone, it also depends on the constituent quark mass which is completely free in our scenario, so in the dark sector the pion to baryon mass ratio will not generally adopt the SM value of about 0.14. The one pion exchange potential between dark baryon and antibaryon can be different in shape compared with a rescale of the real QCD one, if the pion to baryon mass ratio is varied.

However the chiral effective theory is actually not valid to describe the baryon antibaryon annihilation. The clearest example is, a calculation of the baryon antibaryon annihilation with the NDA will give a cross section larger than the s wave unitarity bound. The chiral effective theory should be valid in the limit of vanishing four momentum transfer, however the annihilation process has a typical four momentum transfer of order of the baryon mass. At this intermediate scale a lot of facts are contributing, such as RGE running of the axial current coupling, the two and more pion exchange, other heavier meson exchange and so on.

Indeed the annihilation cross section should be better approximated by the unitarity bound [4]

$$\sigma v \simeq \frac{(2\ell+1)\pi}{m_\chi^2 v}. \tag{1}$$

At low relatively velocity the unitarity bound of annihilation cross section σv scales as v^{-1} rather than a constant with v. Such a behavior can be recovered, *e.g.*, by the Sommerfeld enhancement mechanism [5, 6]. The annihilation has two primary applications: one is the thermal freeze out in the early universe, the other is the present indirect detection in the galaxy center. In the latter case the relative velocity of DM particle is order $10^{-4}c$, so the lowest s partial wave will be enough and the annihilation will be smaller than the s wave unitarity bound. On the other hand, in the former case the relative velocity is order $0.2c$, not guaranteeing merely the s wave approximation. Fortunately the real QCD experiments have measurement for the annihilation cross section in such a velocity region. In Figure 1 we see that in this velocity region the annihilation cross section is about a factor of two times larger than the s wave unitarity bound, scaling rather independently with the relative velocity.

It is well known that in the thermal freeze out in the early universe an annihilation cross section of 3×10^{-26} $\mathrm{cm^3\,s^{-1}}$ gives the correct relic abundance of $\Omega_\chi h^2 \simeq 0.12$. In our DM scenario the annihilation cross section can be tuned by varying the DM mass. Equating the above mentioned two times of the s wave unitarity bound to the required annihilation cross section, we get

$$m_\chi \simeq 150 \text{ TeV}. \tag{2}$$

This number is expected to be independent of the choosing of the gauge interaction.

In literature not too much work is done for such high scale DM. Naively all the model independent experimental constraints can be extrapolated to high scales. For example the DM spin independent scattering cross section bound with ordinary matter should be scaled as m_χ^{-1} for very large m_χ, as a consequence of the number density suppression for a fixed local energy density of 0.3 $\mathrm{GeV\,cm^{-3}}$ or so. We have checked that the NDA calculated spin independent scattering cross section is at the order of 10^{-45} $\mathrm{cm^2}$ projected into each nucleon, which can only be covered by the future expected LZ experiment.

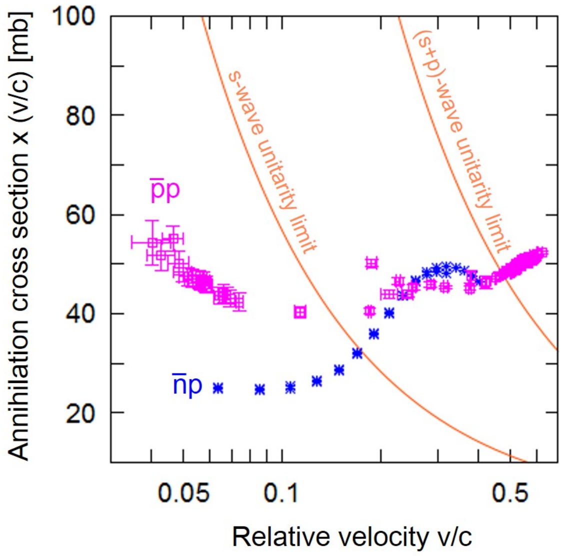

FIG. 1. The QCD measurement of baryon antibaryon annihilation cross section σv in the low relative velocity region. At higher relative velocity σv will exceed the s wave or the $(s+p)$ wave unitarity bound. $\bar{p}p$ data are taken from [8–11], and $\bar{n}p$ data are taken from [12, 13].

The aforementioned annihilation in the galaxy center as a DM indirect probe is also suffering the number density suppression, and it will be more serious since the annihilation rate scales with number density square. We have checked that even saturating the enhancement all the way to s wave unitarity bound, which for a typical galaxy center relative velocity $10^{-4}c$ means a factor of 2000 enhancement of the s wave unitarity bound at freeze out or 1000 enhancement of the 3×10^{-26} $\mathrm{cm^3\,s^{-1}}$, annihilation of a 150 TeV DM is still way too small to be detected, even at the future CTA experiment [14]. This is similar to [15], however in our composite DM scenario we also have to pay for the suppression from the branching ratio: instead of assuming a 100% branching ratio into two gamma photons, dark baryon and antibaryon will annihilate into several dark pions, among which only the neutral pions anomalous decay can give very hard gamma photons.

DARK MATTER DECAY

Suppose the hidden strong gauge group is an $SU(N)$ gauge group, the task is to determine the minimal N, which is an odd number for baryon to be a fermion. The major concern of the N choice is the DM stability. The baryon is in the totally antisymmetric representation of N dark quarks, and as the proton decay in the GUT the effective decay operator is at least $N+1$ fermions times together, with the new "1" being some other particle the dark baryon decay into, which we take the SM lepton. To be overall mass dimension 4 we need high scales suppression of power $\frac{3}{2}(N+1)-4$. This hidden strong gauge group has no relation with the postulated gauge coupling unification in the visible sector, so the only known large scale is the Planck scale.

We start with $N=3$, a Planck scale square suppression and the dark baryon mass of 150 TeV. Ignoring all the other numerical factors from dimensional analysis the decay width is given by $\Gamma \simeq m_\chi^5/\Lambda_{\rm Pl}^4 \approx (150\times 10^3)^5/(2.4\times 10^{18})^4 = 2.3\times 10^{-48}$ GeV, which corresponds to a decay life time of 2.9×10^{23} s. This estimation has already revealed an amazing coincidence, that the minimal model leads to a decay life time close to the current observational limit. A more detailed estimation of the decay width can be obtained by rescaling of [16] of the GUT proton decay calculation, which gives a factor of $1/(32\pi)$ from the phase space, and another dimensionless factor of about 10^{-2} as the lattice calculated matrix element amplitude 0.1 GeV^2 normalized by the QCD proton mass square. Putting altogether the decay life time is a few times 10^{27} s.

Let's take a closer look at the minimal model. We need to specify the whole gauge group in the hidden sector. The requirement that it is also charged under some SM gauge group is minimally satisfied for the SM $U(1)_Y$ group, and that will induce the SM electromagnetic interactions and the constituent quarks will be SM electromagnetically charged. To make the lightest component of the dark baryon multiplet electromagnetically neutral we need a splitting between up type and down type quark electric charges, the counterpart of the $SU(2)_L$ isospin gauge group is nothing but the $SU(2)_R$ gauge group. Note that if we choose the SM $SU(2)_L$ rather than the $SU(2)_R$, then the dark baryon is also charged under the SM $SU(2)_L$. This still suits the definition of "WIMP", but the scattering with ordinary matter will have quite different phenomena, and we do not consider this situation in our scenario.

Gauge	$SU(3)_H$	$SU(3)_c$	$SU(2)_R$	$SU(2)_L$	$U(1)$
Φ	1	1	3	1	$+1$
Q_L	3	1	2	1	$+\frac{1}{6}$
Q_R	3	1	2	1	$+\frac{1}{6}$
H	1	1	2	2	0
q_L	1	3	1	2	$+\frac{1}{6}$
q_R	1	3	2	1	$+\frac{1}{6}$
l_L	1	1	1	2	$-\frac{1}{2}$
l_R	1	1	2	1	$-\frac{1}{2}$

TABLE I. The new particle content and quantum numbers.

The model is shown in Table I. The triplet Φ gets a vacuum expectation value to break the $SU(2)_R$, also giving masses to the $SU(2)_R$ W boson and the right handed neutrino [18]. When the $SU(2)_R$ is added the dark baryon will come in a multiplet of dark proton and dark neutron, and the dark neutron is the DM candidate. The dark proton need to be heavier than the dark neutron, and after thermal freeze out decay early enough to it. Dimensional analysis suggests $\Gamma \propto \Delta m^5/m_W^4$ [17] where m_W is the SM ($SU(2)_R$) W boson mass for real QCD (the dark sector), and Δm is the mass difference between the SM (dark) proton and neutron. The mass difference between the dark proton and the dark neutron comes in two ways: One is the constituent quark mass differences, which can be generated by dimension-5 operator of $\bar{Q}\Phi^\dagger\Phi Q$. The other is the electromagnetic radiative self energy correction which applies only to charged proton. In real QCD the two happen to cancel with each other, while in our dark baryonic sector they can be additive. The simple requirement that the dark proton to dark neutron decay life time is before the big bang nucleosynthesis ($\lesssim 1$ s) corresponds to a constraint of

$$\Delta m \gtrsim 1.4\left(\frac{m_{W_R}}{10^9\ \text{GeV}}\right)^{\frac{4}{5}}\ \text{TeV}\ , \tag{3}$$

which is easily satisfied by the combination of two contributions.

The dark neutron will decay through the proton decay like chain of $N\to \ell_R^+\Pi^- \to \ell_R^+\bar{t}_R b_R$ where the Π is the dark pion and its decay is via an intermediate $SU(2)_R$ W^-, a mass induced chirality flipping mechanism similar to SM $W^\pm$ one applies so that the heaviest SM product of top bottom pair is dominant. The neutral decay mode of replacing the ℓ_R^+ by the (on-shell) right hand antineutrino is kinematically forbidden. The branching ratio for ℓ^+ is assumed equal for three families. The same but every particle replaced by antiparticle decay chain applies to dark antineutron.

For the most interesting decay product of top quark, the energy distribution can be determined analytically in the sequential two body decay. As a benchmark we fix the dark pion mass to be 1/10 of the dark baryon mass or 15 TeV, and ignore all the SM particle mass including the top quark. The charged lepton has a fixed energy of $E_\ell = (m_\chi^2 - m_\Pi^2)/(2m_\chi) = 74.25$ TeV, and the top and bottom will be evenly distributed in the energy region from $E_{q\rm min} = \frac{1}{2}(E_\Pi - \sqrt{E_\Pi^2 - m_\Pi^2})$ to $E_{q\rm max} = \frac{1}{2}(E_\Pi + \sqrt{E_\Pi^2 - m_\Pi^2})$, where $E_\Pi = (m_\chi^2 + m_\Pi^2)/(2m_\chi) = 75.75$ TeV. All the prompt cosmic ray spectra are then calculated by

$$\frac{dN_i}{dE} = \sum_{q=t,b}\int_{E_{q\rm min}}^{E_{q\rm max}} \frac{dE_q}{\sqrt{E_\Pi^2 - m_\Pi^2}}\left(\frac{dN_i}{dE}\right)_q'(m_\chi = E_q) + \frac{1}{3}\sum_{\ell=e,\mu,\tau}\left(\frac{dN_i}{dE}\right)_\ell'(m_\chi = E_\ell)\ , \tag{4}$$

where the primed $\frac{dN_i}{dE}$ are taken from the PPPC4 [19] for $i = p\bar{p}, e^+e^-, \gamma$ and so on.

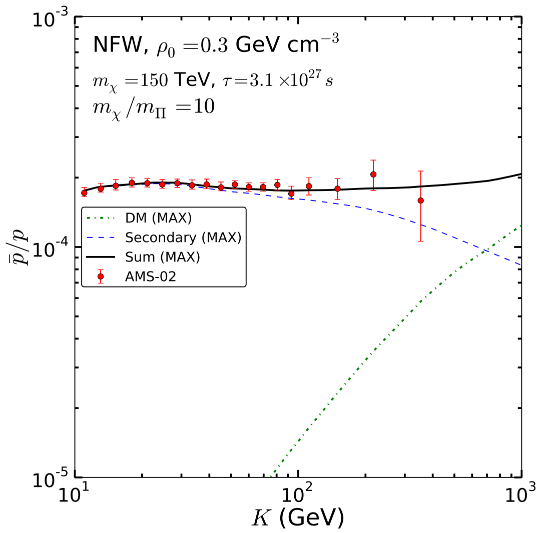

FIG. 2. The antiproton to proton ratio fitting to the AMS-02 data for the MAX propagation parameters. The DM alone, background alone, and sum of DM and background contributions are shown as green dashed-dotted line, blue dashed line and the black line respectively.

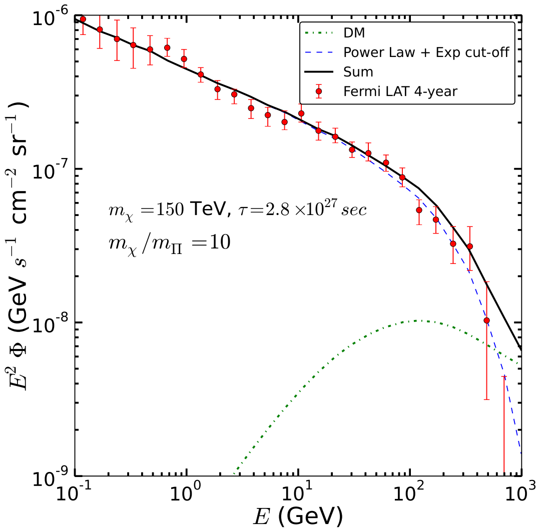

FIG. 3. The fitting to the Fermi-LAT EGB data. The DM alone, background alone, and sum of DM and background contributions are shown as green dashed-dotted line, blue dashed line and the black line respectively.

The antiproton fitting are shown in Figure 2, to the recent AMS-02 data [20] which shows a slight excess but still can be viewed as consistent with background. In the fitting we use the the NFW halo profile and the `MAX` propagation parameters [21, 22] for antiproton, as argued recently in [23]. The background is taken from [24].

The EGB[1] fitting to the Fermi-LAT 4 year data [27] are shown in Figure 3. In the fitting we ignored the local DM decay contribution such as that from our Milk Way, only working for redshift $z_{\rm min} = 10^{-4}$ to $z_{\rm max} = 2$ where the gamma ray is effectively cut off by the optical depth for all interested energy. We also ignore the contribution from inverse Compton scattering of our charged decay product with the CMB photons, which is less important in our interested high energy region and makes the result conservative. The gamma ray flux can be described by

$$\frac{d\Phi_\gamma}{dE} = \frac{c}{4\pi}\frac{\Omega_\chi \rho_c}{m_\chi \tau_\chi}\int_{z_{\rm min}}^{z_{\rm max}} dz \frac{e^{-\tau(z,E)}}{H(z)}\frac{dN_\gamma}{dE}(E^z)\ , \qquad (5)$$

where $H(z) = H_0\sqrt{(\Omega_\chi + \Omega_b)(1+z)^3 + \Omega_\Lambda}$ is the Hubble function and the data of $H_0, \Omega_\chi, \Omega_b, \Omega_\Lambda$ and critical density ρ_c are taken from [1]. The redshifted photon energy E measured at earth is related to the initial energy of $E^z = E(1+z)$ at production, and the optical depth suppression $e^{-\tau(z,E)}$ is taken of the min UV case in `PPPC4` [19]. For the background we use a power-law with cut-off, ignoring possible astrophysical sources such as Blazars, star-forming galaxies [28], and misaligned active galactic nuclei [29, 30].

SUMMARY AND DISCUSSIONS

We have proposed a new scenario of baryonic DM based on a strong hidden sector, and made predictions or fittings of the DM mass of 150 TeV, and the decay life time of a few 10^{27} s. While deep underground direct detection experiment and annihilation signals from the galaxy center seem unpromising, the decay signals from various channels will make it subject to future test.

Acknowledgments

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