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Direct and Indirect Constraints on Isospin-Violating Dark Matter

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Abstract

The scenario of isospin-violating dark matter (IVDM) with destructive interference between DM-proton and DM-neutron scatterings provides a potential possibility to reconcile the experimental results of DAMA, CoGeNT and XENON. We explore the constraints on the IVDM from other direct detection experiments such as CRESST and SIMPLE, etc. and from the indirect DM searches such as the antiproton flux measured by BESS-Polar II. The results show that the relevant couplings in IVDM scenario are severely constrained.

Keywords: Dark Matter, Isospin-Violating Interaction, Cosmic-Ray Antiproton

Some of the recent dark matter (DM) direct detection experiments such as DAMA [1, 2, 3], CoGeNT [4, 5] and CRESST-II [6] have reported events which cannot be explained by conventional backgrounds. The excesses, if interpreted in terms of DM particle elastic scattering off target nuclei, may imply light DM particles with mass around 8-10 GeV and scattering cross section around 10^{-40} cm^2. Other experiments such as CDMS-II [7, 8], XENON10/100 [9, 10], and SIMPLE [11] etc., have reported null results in the same DM mass range.

A commonly adopted assumption on interpreting the DM direct detection data is that in spin-independent scatterings the DM particle couplings to proton (f_p) and to neutron (f_n) are nearly the same, i.e. $f_n \approx f_p$, which makes it straight forward to extract the DM-nucleon scattering cross sections. It is a good approximation for neutralino DM and DM models with Higgs portal, e.g, the scalar DM in left-right models[12, 13, 14, 15] and 4th generation Majorana neutrino DM [16]. However, in generic cases, the interactions may be isospin-violating [17, 18, 19, 20, 21, 22, 23]. In this scenario, the DM particle couples to proton and neutron with different strengths, possible destructive interference between the two couplings can weaken the bounds of XENON10/100 and move the signal regions of DAMA and CoGeNT to be closer to each other [21, 22]. In order to reconcile the data of DAMA, CoGeNT and XENON10/100, a large destructive interference corresponding to $f_n/f_p \approx -0.7$ is required [21].

Possible constraints on IVDM from the cosmic neutrinos and gamma ray on IVDM have been discussed previously in Refs. [24, 25, 26]. Recently the BESS-Polar II experiment has measured the antiproton flux in the energy range from 0.2 GeV to 3.5 GeV [27] which have higher precision compared with that from PAMELA [28] at low energies. In this talk, we discuss on the direct and indirect constraints on IVDM with focus on the cosmic-ray antiproton constraints. The details of our analysis can be found in Ref. [29].

For a DM particle χ elastically scattering off a target nucleus, the differential scattering cross section can be written as

$$\frac{d\sigma}{dE_R} = \frac{m_A F^2(E_R)}{2\mu_A^2 v^2}\sigma_0 , \qquad (1)$$

where $F(E_R)$ is the form factor of the nucleon and $\mu_A = (m_\chi m_A)/(m_\chi + m_A)$ is the DM-nucleus reduced

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mass. The quantity σ_0 can be understood as the total scattering cross section at the limit of zero-momentum transfer which is related to $f_{p(n)}$ through

$$\sigma_0 = \frac{\mu_A^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 , \quad (2)$$

where Z is the atomic number and A is the atomic mass number. Under the assumption that the scattering is isospin conserving (IC), i.e., $f_n \approx f_p$, the total cross section σ_0 is independent of Z and only proportional to A^2. One can define a cross section σ_p^{IC} which is the value of σ_p extracted from σ_0 under the assumption of IC interaction as

$$\sigma_p^{IC} \equiv \frac{\mu_p^2}{\mu_A^2 A^2}\sigma_0 . \quad (3)$$

In the generic case where $f_n \neq f_p$, the true value of σ_p will differ from σ_p^{IC} by a factor $F(f_n/f_p)$ which depends on the ratio f_n/f_p and the target material

$$\sigma_p = F(f_n/f_p)\sigma_p^{IC}. \quad (4)$$

If the target material consists of N kind of relevant nuclei with atomic numbers Z_α ($\alpha = 1,\ldots,N$) and fractional number abundances κ_a, and for each nucleus Z_α there exists M type of isotopes found in nature with atomic mass number $A_{\alpha i}$ and fractional number abundance $\eta_{\alpha i}$ ($i = 1,\ldots,M$), the expression of $F(f_n/f_p)$ can be explicitly written as

$$F(f_n/f_p) = \frac{\sum_{\alpha,i}\kappa_\alpha\eta_{\alpha i}\mu_{A_{\alpha i}}^2 A_{\alpha i}^2}{\sum_{\alpha,i}\kappa_\alpha\eta_{\alpha i}\mu_{A_{\alpha i}}^2[Z_\alpha + (A_{\alpha i} - Z_\alpha)f_n/f_p]^2} , \quad (5)$$

where $\mu_{A_{\alpha i}}$ is the reduced mass for the DM and the nucleus with atomic mass number $A_{\alpha i}$. For a given target material T, there is a particular value of f_n/f_p which corresponds to the maximal possible value of $F(f_n/f_p)$

$$\xi_T \equiv = -\frac{\sum_{\alpha,i}\kappa_\alpha\eta_{\alpha i}\mu_{A_{\alpha i}}^2(A_{\alpha i} - Z_\alpha)Z_\alpha}{\sum_{\alpha,i}\kappa_\alpha\eta_{\alpha i}\mu_{A_{\alpha i}}^2(A_{\alpha i} - Z_\alpha)^2} . \quad (6)$$

The value of ξ_T varies with target material. In Tab. 1, we list the values of ξ_T for some typical material utilized by the current or future experiments.

If the ξ_T values of the target material used by two experiments are very close to each other, the tension between the two experimental results, if exists, is less affected by the effect of isospin violation. From Tab. 1 one finds that $\xi_{\rm Na} \approx \xi_{\rm C_2ClF_5} = -0.92$, $\xi_{\rm Xe} \approx \xi_{\rm CsI} \approx -0.7$ and $\xi_{\rm Si} \approx \xi_{\rm Ca(W)O_4} = -1.0$. Thus the tension between DAMA signal from Na recoil and the upper bound from SIMPLE is unlikely to be alleviated by isospin violation, which can be clearly seen in Fig. 1. Similarly, if there exists contradictions between XENON and KIMS, CoGeNT and the Ar based experiments such as DarkSide, it can hardly be explained by isospin violating scattering. The SIMPLE result is also useful in comparing with the CRESST-II which utilizes $\rm Ca(W)O_4$ which has $\xi_{\rm Ca(W)O_4} = -1.0$. Obviously, for the experiments use the same target material, the possible tension between them cannot be relaxed by isospin violation, such as the tension between CoGeNT and CDMS-II, as both use germanium as target nucleus.

In Fig. 1, the allowed regions by the current experiments are shown in the (σ_p, m_χ) plane for $f_n/f_p = -0.70$. It can be seen that the overlapping region between GoGeNT and DAMA may still be consistent with the exclusion curve from the XENON100 2011 data [10]. However, If one considers the recently updated upper bounds from XENON100 [30], the main bulk of the overlapping region is excluded for both the GoGeNT results with and without surface event rejection corrections, which challenges the IVDM as a scenario to reconcile the results of DAMA, CoGeNT and XENON. The overlapping region between DAMA and CoGeNT seems also to be excluded by the results of SIMPLE [11] and CDMS-II independently [7, 8]. Note however that there still exists controversies regarding the detector stability of SIMPLE experiments [31, 32], the recoil energy calibration of CDMS experiment [33] and the extrapolation of the measured scintillation efficiency to lower recoil energy in the previous XENON100 data analysis [34, 35].

We assume that the DM particles interact with the SM light quarks through some heavy mediator particles much heavier than the DM particle such that both the scattering and the annihilation processes can be effectively described by a set of high dimensional contact operators

$$\mathcal{L} = \sum_{i,q} a_{iq}O_{iq} . \quad (7)$$

If the DM particles are Dirac fermions, the relevant operators arising from scalar or pseudoscalar interactions are given by

$$\begin{aligned} O_{1q} &= \bar\chi\chi\bar q q, O_{2q} = \bar\chi\gamma^5\chi\bar q q, \\ O_{3q} &= \bar\chi\chi\bar q\gamma^5 q, O_{4q} = \bar\chi\gamma^5\chi\bar q\gamma^5 q. \end{aligned} \quad (8)$$

The operators from vector or axial-vector type interac-