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Mirror matter as self-interacting dark matter

R. N. Mohapatra
Department of Physics, University of Maryland, College Park, Maryland 20742

S. Nussinov
Department of Physics, Tel-Aviv University, Tel Aviv, Israel

V. L. Teplitz
Department of Physics, Southern Methodist University, Dallas, Texas 75275
and Office of Science and Technology Policy, Executive Office of the President, Washington, D.C. 20502
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It has been argued that the observed core density profile of galaxies is inconsistent with having a dark matter particle that is collisionless and that alternative dark matter candidates which are self-interacting may explain observations better. One new class of self-interacting dark matter that has been proposed in the context of mirror universe models of particle physics is the mirror hydrogen atom, whose stability is guaranteed by the conservation of mirror baryon number. We show that the effective transport cross section for mirror hydrogen atoms has the right order of magnitude for solving the ''cuspy'' halo problem. Furthermore, the suppression of dissipation effects for mirror atoms due to a higher mirror mass scale prevents the mirror halo matter from collapsing into a disk, strengthening the argument for mirror matter as galactic dark matter.

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I. INTRODUCTION

It has recently been pointed out [1] that the dark matter particles constituting the galactic halo need to satisfy a new constraint in order to avoid singular cusps [2]. One way to quantify this constraint is to demand that the mean free paths of these particles be less than typical galactic sizes (say 0.1 Mpc), i.e., $\lambda_{DM} \sim 1/n_{DM}\sigma_{DM} \leqslant 0.1$ Mpc. This equation implies that the typical cross section for the dark matter particle must be of the order $\sigma_{DM} \simeq m_{DM}/\text{GeV} \times 10^{-24}\ \text{cm}^2$. This cross section is large and it grows with the mass of the dark matter particle linearly. Some favorite long standing candidates such as the neutralino lightest supersymmetric particle (LSP) of 50–100 GeV mass [3] would then need to have a scattering cross section of $10^{-22}\ \text{cm}^2$, a requirement which is not met by any of the exsiting supersymmetric models. Barring some new long range interactions, such a large cross section for particles of such high mass would be in conflict with unitarity bounds [4] for a pointlike dark matter particle scattering via S waves.

The growth of cross section with mass is generic to solitonic structures and it has been noted that Q balls originally suggested in a different context [5] can, for a certain range of parameters, satisfy this constraint [6].

An alternative and natural candidate arises in mirror matter models where it is postulated that there is a parallel standard model which duplicates all the matter and forces and coexists, in our universe, with the familiar standard model. The mirror and familiar particles in such models are connected only by gravity [7–10]. In particular, the asymmetric mirror model [8,11], where both the weak scale as well as the QCD scale in the mirror sector are about 20–30 times the corresponding scales in the the familiar sector, has been studied extensively in connection with neutrino physics and the explanation of the microlensing events [11].[1] A particularly interesting feature of these models is that the lightest mirror baryon p' (in the form of the mirror hydrogen atom) is ideally suited to be the dark matter of the universe and as such would be the dominant constituent of the dark halo of the galaxies. If the QCD scale parameter in the mirror sector $\Lambda' \approx 30\Lambda$, the corresponding scale in the familiar sector, then $m_{p'} \approx 30 m_p$, and using the slightly lower reheat temperature of the mirror sector [required to satisfy the big-bang-nucleosynthesis (BBN) constraints arising from $\gamma', \nu'_{e,\mu,\tau}$], we find that $\Omega_{B'}/\Omega_B \approx (T'/T)^3 m_{p'}/m_p$. The BBN constraint requires that $T'/T \approx (1/10.75)^{1/4} \sim 0.5$. Using this we get $\Omega_{B'} \sim 4\Omega_B$. For $\Omega_B \sim 0.05$ this would lead to 20% dark matter and about 75% dark energy. This is of the right order of magnitude for the required fraction of the dark matter in the universe.

A very important property that distinguishes the mirror baryon from other dark matter candidates is that mirror matter has self-interaction. It was suggested in a recent paper by two of the authors (R.N.M. and V.L.T.) [13] that this might help resolve the core density problem. We further pursue this question in this brief note. Specifically taking account of the important distinction between total and transport cross sections, we show that the parameters of the model suggested by considerations of Ω_{DM} yield scattering of mirror hydrogen atoms in the right range suggested in Ref. [1].

[1]One can show that the asymmetry between the two QCD scales owes its origin to the asymmetry between the weak scales [12]. The main reason the first asymmetry follows from the second is that the mirror quarks are much heavier than the familiar quarks and therefore decouple earlier from the evolution of the QCD couplings in the mirror sector. This helps to speed up the rise of the mirror QCD fine structure constant.

We then comment briefly on the question of the shape of the dark halo if it is made up of mirror dark matter particles. Mirror symmetry requires that the coupling parameters in the mirror sector be identical to those of the familiar sector. This has led to the suspicion that, if halos were to be made up of mirror baryons, they would collapse due to dissipation of their transverse energy and become disk shaped, in contradiction to observations. The point, however, is that even though the couplings are identical due to mirror symmetry, the masses are different, i.e., the mirror matter masses are a factor of 30 or so higher. As a result, the processes such as bremsstrahlung responsible for dissipation of transverse energy are reduced by a factor of 1000, preventing the collapse of the mirror halo to a disk.

II. EFFECTIVE SCATTERING CROSS SECTION FOR MIRROR HYDROGEN

For small relative velocities of atoms of the order of $\beta_{virial}\sim 10^{-3}$, the total atom-atom elastic scattering cross sections are of the order of πR^2_{atom}. For H or He atoms, $R_{atom}\sim 0.55$ Å, leading to $\sigma_{\mathrm{HH}}\simeq 10^{-16}$ cm^2. If we take the mirror scale factor to be about 30–100, then the Bohr radius of the corresponding hydrogen atoms will scale inversely with it and will give $\sigma_{\mathrm{H'H'}}\simeq 10^{-19}$–$10^{-20}$ cm^2. This value is higher than the value apparently required for solving the core density problem by a factor of 100–1000. The new observation in this note is that the naive use of the cross section is not adequate for our discussion and there is indeed a substantial suppression factor which arises from a more careful analysis.

The main point is that the cross section relevant for avoiding the catastrophic accumulation of dark matter particle particles is *not* the total elastic cross section σ_{el} but the transport cross section σ_{tr}, to which large angle scattering contributes more strongly, i.e.,

$$\sigma_{tr}=\frac{1}{4\pi}\int d\Omega(1-\cos\theta)\frac{d\sigma}{d\Omega}. \tag{1}$$

For isotropic (say S-wave) or slightly backward hard sphere scattering, σ_{el} and σ_{tr} are roughly the same. This is not the case, however, for H-H or H′-H′ scattering at a relative velocity of $\beta\approx 10^{-3}$. Here many partial waves up to $\ell_{eff}=m_H v r_{Bohr}\approx m_{\mathrm{H}'} v r'_{Bohr}\approx 200$ contribute, allowing for strongly forward peaked elastic differential cross sections. To estimate this cross section, note that (i) the large number of partial waves suggests a quasiclassical WKB treatment; (ii) the collision virial velocity is smaller than the velocity of the electron in the atom, i.e., $10^{-3}c\approx\beta_{virial}c<\alpha_{em}c$, where $c\alpha_{em}$ is the velocity of the electron in the atom. Hence we can adopt an adiabatic Born-Oppenheimer type approximation. The interatomic potential can be computed for each atom-atom configuration denoted by the impact parameter b and the position of the H′ along its path (assumed to be a straight line) $z(t)$. The interatomic distance is then given by $R(t)=\sqrt{z^2(t)+b^2}$. The magnitude of the interatomic potential $V_{\mathrm{HH}}(R)\approx m_e\alpha^2_{em}\approx 27$ eV is about 20 times smaller than the kinetic energy of the collision $\frac{1}{2}m_H\beta^2\sim 500$ eV (the same ratio applies to the mirror sector since both terms get scaled by a common factor). Hence, for such velocities, atoms are "soft" and interpenetrate quite a bit. As we indicate, the scattering angle $\Delta p/p$ is approximately given by $\Delta p/p \sim V/(1/2 m_e\beta^2)\simeq 1/20$. The classical deflection angle which may be appropriate here is

$$\theta\approx\frac{\Delta p_y}{p}=\frac{\int F_y(z(t),b)dt}{p}$$
$$\simeq 2\int_0^\infty\left[\frac{\partial V(\sqrt{z^2+b^2})}{\partial y}\right]\frac{dz}{pv}\approx\frac{2V}{mv^2}\sim\frac{V}{T}. \tag{2}$$

Hydrogen-hydrogen scattering at keV energies can be measured experimentally and calculated with high accuracy. We believe that the qualitative features of strong forward peaking and correspondingly reduced transport cross section will still be manifest. Thus the transport cross section, which is $\frac{1}{2}\langle\theta\rangle^2\sigma_{el}$, will be about 10^3 times smaller than the naive geometric value. The transport cross section for mirror hydrogen then is of the order of 10^{-22} cm^2, which is close to the required value for self-interacting dark matter. These approximations are commensurate with the data and calculations of the cross section for H-H scattering [14]. For scattering to excited states, including ionization, we would expect less forward peaking but smaller cross section at keV energies.

The above discussion implicitly assumed that the halo H′s are not ionized. This assumption is motivated by the fact that the small velocity $\beta\approx 10^{-3}\leqslant\alpha_{em}$ tends to preclude ionization in H′-H′ collisions. Also, the ordinary hydrogen in our galaxy is largely un-ionized. The H′ halo could, however, behave differently. If some ionization $\mathrm{H}'\rightarrow p'+e'$ occurs due to fluctuations, it can increase the e' energy by $e'\mathrm{H}'$ collision. The latter might thermally equilibrate after some $m_{p'}/m_{e'}\approx 2000$ collisions and have energies of order 10–20 keV. Subsequent $e'\mathrm{H}'$ collision could lead to further ionization, enhancing the e' population. We will not address this complex scenario and all its implications. However, we wish to emphasize here that, in so far as the transport cross section of dark matter particles, is concerned, the cross sections for both the neutral H′ atom and ionized $(p'\mathrm{H}', p'p')$ are in the same interesting range of 10^{-23} cm^2 or so.

To clarify this point, we note that in $p'p'$ scattering the relevant differential cross section is the Rutherford cross section:

$$\frac{d\sigma}{d\Omega}=\frac{4\alpha^2}{m'^2\beta^4(1-\cos\theta)^2}. \tag{3}$$

While this strongly peaks at $\theta\rightarrow 0$, the transport cross section (calculated using the same definition as before) diverges only logarithmically and we get

$$\sigma_{tr}=\frac{8\alpha^2}{m'^2\beta^4}\ln(\theta_{min}) \tag{4}$$

where $\theta_{min} \approx 1/b_{max}$, b_{max} being the maximum value of the impact parameter. This b_{max} increases from $a'_{Bohr} \approx \frac{1}{30} a_{Bohr} \simeq 10^{-10}$ cm in the un-ionized case to effectively the interparticle separation of $(m_{p'}/0.3\text{ GeV})^{1/3}$ cm$\approx$4 cm. This leads to σ_{tr} for the ionized case, which is about 24 times larger than the un-ionized case discussed in the previous section and compatible with the requirement in [1].

III. DISSIPATION AND SHAPE OF THE MIRROR HALO

We next examine the dissipation time scale which is important for understanding the shape of the mirror dark matter halo. Mirror symmetry implies that mirror particles like ordinary ones are dissipative, namely, that energy can be lost by γ' emission. For the baryonic matter in galaxies, it is this process of energy loss that causes the collapse to a galactic disk, which provides a lower energy configuration with same total angular momentum. However, if mirror matter is to form a realistic, roughly spherical galactic halo, such disk formation should not be allowed. The time scale for the disk formation in our galaxy has been estimated [15,16] to be equal to the dynamical free fall time $1/(G_N\rho)^{1/2} \approx 10^8$ yr (using a density of one proton per cm^3).[2] The dominant dissipative process is thermal bremstrahlung. Since the latter scales as m^{-2}, for the mirror baryons, the corresponding time scale would be longer by a factor of $(m^2/m'^2) \sim 10^{-3}$. This slows the relaxation time required to form a disk to about 100 billion years, which is way beyond the age of the universe.

Mirror star formation, as discussed in [11], does not depend on bremstrahlung, but rather on molecular cooling and is not affected by the present discussion.

In conclusion, we have pointed out that, in mirror matter models, the mirror hydrogen atom has all the right properties to be the self-interacting dark matter of the universe. In particular, we note that due to the near forward nature of the H-H scattering, the effective, relevant transport cross section is around 10^{-22} cm^2, and is adequate to damp the core density of the dark matter in galactic halos. We further note that, even if the mirror hydrogen is ionized, the relevant transport cross section is of the right order for mirror matter playing the role of self-interacting dark matter to avoid the cuspy halo problem.

[2]This accident is crucial to the formation of the disk. If the dissipation time was much larger, galaxy clusters would form prior to disks, and if it were much shorter, the galaxy would likely fragment.

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