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ASTROPHYSICAL BOUNDS ON MIRROR DARK MATTER, DERIVED FROM BINARY PULSARS TIMING DATA

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Abstract: Mirror Dark Matter (MDM) has been considered as an elegant framework for a particle theory of Dark Matter (DM). It is supposed that there exists a dark sector which is mirror of the ordinary matter. Some MDM models allow particle interactions mirror and ordinary matter, in addition to the gravitational interaction. The possibility of neutron to mirror neutron transition has recently been discussed both from theoretical and experimental perspectives. This paper is based on a previous work in which we obtained stringent upper limits on the possibility of converting neutrons to mirror neutrons in the interiors of neutron stars, by using timing data of binary pulsars. Such a transition would imply mass loss in neutron stars leading to a significant change of orbital period of neutron star binary systems. The observational bounds on the period changes of such binaries, therefore put strong limits on the above transition rate and hence on the neutron – mirror-neutron mixing parameter ϵ'. Our limits are much stronger than the values required to explain the neutron decay anomaly via $n - n'$ mixing.

Keywords: dark matter, neutron stars, pulsars

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1. Introduction

The idea of mirror dark matter (MDM) has been considered by various authors [1]. In this class of models each ordinary particle p has a mirror particle p' counterpart. There is, a generic problem in that the extra mirror neutrinos (ν') and mirror photon (γ') contribute too much to the number of degrees of freedom at the Big Bang Nucleosynthesis (BBN) epoch, destroying the success of the big bang nucleosynthesis predictions. A possible way out is to assume a breaking of the Z_2 symmetry in the early universe so as to have asymmetric inflationary reheating in the two sectors (ordinary matter and MDM) resulting in a lower reheat temperature (T') of the mirror sector compared to (T) of the visible one [4]. This breaking eventually trickles down to the low energies leading in general to a splitting the mirror and visible fermion masses [5]. The above mentioned symmetric picture could however remain almost exact if the asymmetric inflation picture is carefully chosen. Cosmologies of such scenarios have been discussed in [2] and references therein.

An interesting new phenomenon is possible in almost exact mirror models, if there are interactions mixing the neutron with the mirror neutron state (denoted by $\epsilon_{n-n'} \equiv \epsilon'$). In such a case, one can expect $n \to n'$ oscillations to take place in the laboratory [7] and indeed there are ongoing and already completed searches for such oscillations [3] at various neutron facilities.

We note that $n - n'$ oscillation is similar to neutron-anti-neutron oscillation suggested very early [9] and extensively discussed in the literature. For recent reviews, see [10]. The rate governing the $n - \bar{n}$ oscillations was limited by laboratory experiments to be

$$\epsilon_{n\bar{n}} = 1/\tau_{n\bar{n}} < 10^{-8}\,\mathrm{sec}^{-1} \text{ or } 10^{-23}\,\mathrm{eV}. \tag{1}$$

We focus on the possibility that $n \to n'$ transitions can lead to mass loss of a neutron star and if the latter is a member of a binary system, then this mass loss affects the binary period. Indeed (see [12]), the mass loss of any kind of such neutron stars implies an increase of the orbital period of the binary system P_b. In the following sections we find that observational limits on $|\dot{P}_b/P_b|$ of binary pulsars yield stringent bounds on the $n - n'$ mixing parameter ϵ'.

2. Transition of a neutron star to a mixed neutron-mirror neutron star induced by $n - n'$ mixing

We note that $n \to n'$ transitions, kinematically forbidden in nuclei, can occur in neutron stars. The neutrons in neutron stars are mainly bound by gravity and *not* by nuclear forces. Let us, suppose that an $n \to n'$ conversion occurred at some point in the star. Under the pressure a neighboring neutron then will be pushed to "hole" generated by the converted neutron, gaining in the process kinetic energy which is of order of the Fermi energy E_F. Additional energy gain is obtained, since the produced n' gravitates to the center of the star and a surface neutron replaces the neutron which went into the above mentioned "hole". Therefore the net (eventually radiated via neutrino and mirror neutrino emission) energy stemming from an early, single nn' transition is:

$$m_n c^2 \left(\mathrm{e}^{\phi(R)} - \mathrm{e}^{\phi(0)}\right) + < E_F >, \tag{2}$$

where $\mathrm{e}^{\phi(r)} = g_{oo}^{1/2}(r)$, $\mathrm{e}^{\phi(R)} = (1 - 2GM/c^2)^{1/2}$ and $< E_F >$ is the average Fermi energy of the disappeared neutron. Thus the gravitational mass of the neutron star will decrease. This has led [13] to propose that ($n \to n'$) oscillations generating completely mixed nn' stars, may explain the observed mass distribution of neutron stars.

3. The rate of $n \to n'$ transition

We express the $n \to n'$ transition rate $\Gamma(n \to n')$ by

$$\Gamma(n \to n') = \Gamma(nn) P_{nn'} \,, \tag{3}$$

where Γ_{nn} is the rate of nn collisions and $P_{nn'}$ is the probability of having n' (rather than n) at the time of the collision.

Equation (3) is based on the supposition [14] in which one assumes that:

a) The coherent buildup of the $|n'>$ component in the initial purely $|n>$ state of the two component system, proceeds unimpeded by nuclear interactions during the time of flight between two consecutive collisions.

b) The coherent build-up stops upon collision and the n' part is released as outgoing mirror neutron particles.

Denoting by t_{nn} the mean free time for neutron-neutron collisions and by ϵ' the rate for n to n' oscillation, the Hamiltonian in the two dimensional $|n>$, $|n'>$ Hilbert space leads to

$$P_{nn'} = [\epsilon' \cdot t_{nn}]^2.$$

Substituting the above $P_{nn'}$ and $\Gamma_{nn} = t_{nn}^{-1}$ in equation (3), one gets

$$\Gamma_{n \to n'} = t_{nn} \epsilon'^2. \tag{4}$$

Taking $t_{nn} \approx 10^{-23}$ sec, the flight time of a neutron a $O(Fermi)$ distance at a speed $\sim \frac{1}{3}c$ yields

$$\Gamma_{n \to n'} = 6 \times 10^{-8} [\epsilon'/10^{-11} \ \text{eV}]^2 \, \text{yr}^{-1}. \tag{5}$$

In what follows we shall use astrophysical data to obtain bounds on $\Gamma_{n \to n'}$ and employ equation (5) to derive bounds on ϵ'.

4. Neutron star models and their descendant fully mixed neutron – mirror neutron stars

To obtain the resulting mass and radius decrease, we solved numerically the TOV equations with a commonly used equation of state [21]. We first solve the TOV structure equations for pure neutrons. Then for the same baryon number we solve the TOV equations for a totally mixed neutron – mirror neutron star. We employ the method used by us in [6]. In this specific case we have two fluids obeying the same nuclear equation of state where the only interaction is through the gravitational field.

We considered three different models each characterized by its total baryon number (that does not change in the transition). For each baryon mass we calculated the initial and final mass and radius. We also calculated the initial $e^{\phi(R)} - e^{\Phi(0)}$. The resulting models are:

$\underline{M_b = 1.81 M_\odot}$

$$M = 1.57 M_\odot, \quad R = 12.2\,\mathrm{km}, \quad \mathrm{e}^{\phi(R)} - \mathrm{e}^{\Phi(0)} = 0.15,$$

$$M_{nn'} = 1.43 M_\odot = 0.91 M, \quad R_{nn'} = 8.8\,\mathrm{km} = 0.72 R,$$

$\underline{M_b = 2.17 M_\odot}$

$$M = 1.82 M_\odot \quad R = 12.37\,\mathrm{km}, \quad \mathrm{e}^{\phi(R)} - \mathrm{e}^{\Phi(0)} = 0.17,$$

$$M_{nn'} = 1.62 M_\odot = 0.89 M, \quad R_{nn'} = 8.8\,\mathrm{km} = 0.71 R,$$

$\underline{M_b = 2.44 M_\odot}$

$$M = 1.97 M_\odot, \quad R = 12.4\,\mathrm{km}, \quad \mathrm{e}^{\phi(R)} - \mathrm{e}^{\Phi(0)} = 0.19,$$

$$M_{nn'} = 1.7 M_\odot = 0.86 M, \quad R_{nn'} = 8.65\,\mathrm{km} = 0.7 R.$$

5. The relation between the mixing parameter ϵ' and the mass loss rate

Returning to the main goal of the paper, namely limiting ϵ', we need to relate the rate of neutron to mirror neutron transition to the stellar $\dot{M}/M$. Since neutrons from the entire volume of the neutron star can transform to n', the resulting total mass loss of the neutron star due to this is proportional to $\Gamma_{n\to n'}$.

A great advantage is that all the different binary pulsars (with variety of masses, spin down ages and companions) should conform to a single fundamental parameter: ϵ'. Thus, we can use the youngest pulsars to set stringent limits on ϵ'. In turn, this implies that also the older pulsars are still in the process of transition. In particular, for small enough values of ϵ' even these older pulsars may be at the very initial stages of the pure to mixed star transition.

We next present two estimates of $\dot{M}/M$.

First estimate

The first estimate uses the average value $\dot{M}/M \approx \Gamma_{nn'}\Delta M/M$ during the complete transition to a mixed star where, ΔM is the total mass reduction. The $\Delta M/M = 0.09 \div 0.14$ obtained in the previous section then yields a representative value

$$\left|\frac{\dot{M}}{M}\right| \approx 0.12\,\Gamma_{nn'}. \tag{6}$$

Second Estimate

Here we use the results of the numerical solutions of the neutron stars presented in Section 4. We apply equation (2) to the very beginning of the transition process and find

$$\left|\frac{\dot{M}}{M}\right| \geq \left(e^{\phi(R)} - e^{\phi(0)}\right) \Gamma_{nn'} = (0.15 \div 0.19)\Gamma_{nn'}. \tag{7}$$

It reassuring that the estimates by the two methods agree up to a factor of 1.5. It also makes sense that at the very beginning the process is faster than that derived from the first method which represents a time average over the entire transition.

Thus we adopt

$$\left|\frac{\dot{M}}{M}\right| \geq 0.14\Gamma_{nn'} \tag{8}$$

as a representing value during the entire transition episode.

6. Limits on ϵ' derived from timing observations of binary pulsars

Jeans (1924) in [11] pointed out that the mass of the star that emits electromagnetic radiation decreases with time and therefore, the orbital elements of a binary system should evolve with time. Assuming that in the local frame of each star the radiation emission is spherically symmetric, he obtained

$$Ma = \text{ constant}, \tag{9}$$

where a is the semi-major axis and $M = m_1 + m_2$ is the total mass of the system. This and the expression for the binary period

$$P_b = 2\pi\sqrt{\frac{a^3}{GM}} \tag{10}$$

imply

$$\frac{\dot{P}_b}{P_b} = -2\frac{\dot{M}}{M}. \tag{11}$$

Since $\dot{M} < 0$, $\dot{P}_b > 0$ so that the orbital period keeps increasing.

Except for the nature of emission process this is the same as the situation addressed here. We consider next four binary pulsars and obtain the the limits on the present rate of the mass change for each system.

In general, only neutron stars which are still in the process of transiting to a mixed star will exhibit mass loss. A priori, for extremely "high" $\Gamma_{nn'}$ some of the older observed pulsars in binaries may be "too old".

PSR 1916+13

We use the data of [15]. The spin down age of the pulsar is $1.1 \times 10^8\,\mathrm{yr}$. It is commonly assumed that the pulsar companion is a neutron star, so that there is no mass transfer between the binary members. Also one neglects the mass accretion from the interstellar medium. After accounting for the expected gravitational radiation, Galactic acceleration, and further dynamical corrections there is still some limited room for a positive change of binary period that could have followed from the mass decrease,

$$\frac{\dot{P}_b}{P_b} < 1.36 \times 10^{-11}\,\mathrm{yr}^{-1} \tag{12}$$

implying

$$\left|\frac{\dot{M}}{M}\right| < 6.8 \times 10^{-12}\,\mathrm{yr}^{-1}$$

for the two neutron stars losing mass. Using equations (5) and (14) the bound

$$\epsilon' < 2.8 \times 10^{-13}\ \ \mathrm{eV}$$

follows.

PSR J1141-6545

This is a young pulsar of age about 2×10^6 yr. The companion is a massive white dwarf of mass $0.98 M_\odot$ and the neutron star has a mass $1.3 M_\odot$, see [19, 20].

This system is a superb laboratory for testing GR. Using the data from the above observational papers, one finds that the residual (subtracting from the measured value the gravitational radiation terms as well as the galactic acceleration and the kinematic effect and allowing for the uncertainties of all the above) positive possible value of the orbital period rate of change is very small

$$\frac{\dot{P}_b}{P_b} < 1.84 \times 10^{-12}\,\mathrm{yr}^{-1},$$

implying for the given masses and taking into account that only the neutron star is undergoing the mass loss

$$\left|\frac{\dot{M}}{M}\right| = \frac{M + M_c}{2M}\frac{\dot{P}_b}{P_b} < 1.6 \times 10^{-12}\,\mathrm{yr}^{-1},$$

where M_c is the mass of the white dwarf companion.

This implies a limit

$$\epsilon' < 1.4 \times 10^{-13}\ \mathrm{eV}.$$

This result is very important, as for the other three pulsars pulsars, one may have argued that the transition $n \to n'$ has already finished. This young pulsar closes the door on this argument.

PSR J0437-4715

This is a neutron star-white dwarf binary with masses of $1.76 M_\odot$ and $0.25 M_\odot$, respectively. The spin-down age is $1.6 \times 10^9\,\mathrm{yr}$. Using the data from the above observational papers, one finds that the residual (subtracting from the measured value the gravitational radiation terms as well as the galactic acceleration and the kinematic effect and allowing for the uncertainties of all the above) positive possible value of the orbital period rate of change is [20],

$$\frac{\dot{P}_b}{P_b} < 2.8 \times 10^{-11}\,\mathrm{yr}^{-1},$$

implying

$$\left|\frac{\dot{M}}{M}\right| < 1.6 \times 10^{-11}\,\mathrm{yr}^{-1}$$

and therefore,

$$\epsilon' < 4.4 \times 10^{-13}\,\mathrm{eV}.$$

PSR J1952+2630

This pulsar is in a binary orbit with a $(0.93 \div 1.4) M_\odot$ white dwarf companion [18]. Its spin down age is $7.7 \times 10^7\,\mathrm{yr}$, the orbital period is 0.39 days and during 800 days of follow-up the error on the period is 7×10^{-12} days. This leads to $\dot{P}_b/P_b < 8.2 \times 10^{-12}\ \mathrm{yr}^{-1}$.

Taking into account that only the pulsar losses mass, we get

$$\left|\frac{\dot{M}}{M}\right| = \frac{M + M_c}{2M}\frac{\dot{P}_b}{P_b} < 7 \times 10^{-12}\,\mathrm{yr}^{-1},$$

where M_c is the mass of the white dwarf companion.

Thus one finds

$$\epsilon' < 2.9 \times 10^{-13}\,\mathrm{eV}.$$

The expected period change due to gravitational radiation in this pulsar is 2 orders of magnitude smaller, and thus does not interfere with the derived limit.

7. Discussion

In this paper, used astrophysical data, notably, precision pulsar timing measurements to strongly constrain a putative $n \to n'$ transition in neutron stars.

We solved numerically the general relativistic structure equations for neutron stars with three different baryon mass. Using a realistic nuclear matter equation of stat, we first solved for a pure ordinary neutron star and then (for the same baryon mass) we obtained the solution for a fully mixed neutron-mirror neutron star. In this way, we found the average mass reduction rate over the the time span of the transition. From the solution of the ordinary neutron star we found the mass reduction at the very beginning of the process. We found that two methods yield similar relations between the rate of mass change of the star and the rate of the microscopic process.

This allows us to restrict the mixing parameter between. We find that the key parameter ϵ' responsible for $n \to n'$ transition is restricted to be below 4.4×10^{-13} eV.

All four binary pulsars considered here yield quite similar limits on ϵ'. Of particular importance is the the limits are quite the same even though systems ages vary between 2×10^6 yr and 1.6×10^9 yr. The presence of the youngest binary pulsar refutes the possibility that for the older pulsars the process has been already finished.

Our limits on ϵ' also exclude the possibility that nn' oscillations can explain the neutron decay anomaly [22].

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