Bounds on Neutron- Mirror Neutron Mixing from Pulsar Timings and Gravitational Waves Detections

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Abstract

The mass loss in putative neutron star to mixed neutron - mirror neutron star transition implies a significant change of orbital period. The precise constancy of the latter can restrict scenarios recently suggested where neutron to mirror neutron mixing occurring in neutron stars, transforms them into mixed stars helping explain the narrow mass distribution observed for pulsars in binary systems. The observation of a very old millisecond pulsar with a mass of 2 solar masses is an additional strong constraint on the above transition. We also note that the observed gravitational waves signals from neutron-neutron stars merger constrain the neutron to mirror neutron transitions inside neutron stars. These considerations exclude a large region in the $\epsilon', \delta m'$ plane of the neutron-mirror neutron mixing and mass difference.
I. INTRODUCTION

The possibility that there may be a mirror sector of the standard model with identical particle content and gauge symmetry as the standard model [1] has received a great deal of attention. In particular, the dark matter of the universe as well as any sterile neutrinos may be the lightest baryon (or atom) and the light neutrinos of the mirror sector respectively. Prior to symmetry breaking, these models assume the existence of $Z_2$ (mirror) symmetry between the two sectors which keeps the same number of parameters even though the number of particles is doubled making this a very economical scenario of beyond the standard model physics. Two realizations of these theories have been extensively discussed: one where mirror symmetry is respected by the electroweak vacuum expectation values (vevs) [2] and another where the mirror symmetry is broken via different electroweak scales in the two sectors [3].

In this paper, we will focus on the first class of models where $v_{wk} = v'_{wk}$ (where $v_{wk}$ and $v'_{wk}$ denote the vev of the standard model Higgs field and the mirror SM Higgs field; we will use prime to denote the entities in the mirror sector) and we have identical microphysics and the same fermion masses on both sides. There is, however, a generic problem with both these scenarios in that the extra neutrinos ($\nu'$) and photon ($\gamma'$) from the mirror sector contribute too much to the number of degrees of freedom at the BBN epoch, destroying the success of the big bang nucleosynthesis predictions. A cure for this 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 resulting in a lower reheat temperature ($T'$) of the mirror sector compared to that ($T$) 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 [5]. Cosmology of such scenarios have been discussed in [6, 7].

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 $\epsilon_{n-n'} \equiv \epsilon'$), then one can expect $n \rightarrow n'$ oscillation to take place in the laboratory [8] and indeed there are ongoing and already completed searches for such oscillations [9, 10] at various neutron facilities. We note that $n-n'$ oscillation is very similar to neutron-anti-neutron oscillation suggested very early [11] and also discussed extensively in literature [12]. For
$n - \bar{n}$ oscillation to occur, one needs a $\Delta B = 2$ interaction that leads to a mixing mass $\epsilon_{n - \bar{n}}$ between the $n$ and $\bar{n}$ similar to $\epsilon_{n - n'}$. There is however a major difference between these two oscillations. Whereas the desired mass equality of neutron and anti-neutron is guaranteed by the CPT theorem, known to be an exact consequence of local, Lorentz invariant Quantum Field Theories, the mass degeneracy between $n$ and $n'$ oscillation requires an almost exact $Z_2$ symmetry, which as discussed above, needs to be a weakly broken symmetry to satisfy BBN constraints. Stringent upper bounds on $\epsilon_{n\bar{n}}$, the neutron anti-neutron mixings have been obtained by searching for $n\bar{n}$ conversion in magnetically shielded neutron beams [13] and in nuclei [14]. The subsequent annihilation of the generated $\bar{n}$ can be readily identified in both cases. The $(n \rightarrow \bar{n})$ transitions in nuclei are highly suppressed by the ratio: $\epsilon_{n\bar{n}}^2/(E - \bar{E})^2$ with $\epsilon_{n\bar{n}} = 1/\tau_{n\bar{n}}$ the off diagonal $\Delta B = 2$ element of the $2 \times 2$ energy -mass matrix for the $n\bar{n}$ system and $E - \bar{E}$ the large difference between the diagonal elements - the energies of the neutron and anti-neutron in the nucleus. Still the large number of neutrons in the underground detectors compensates this enormous suppression and quite remarkably the same upper limit:

$$\epsilon_{n\bar{n}} = 1/\tau_{n\bar{n}} < 10^{-8} \text{ Sec}^{-1} \text{ or } 10^{-23} \text{ eV} \quad (1)$$

is obtained both by direct oscillation searches as well as by nuclear decay searches.

The upper bounds on $n \rightarrow n'$, the analog transitions are far weaker. The $n'$ generated in neutron beams or bottles simply leave the system manifesting only in a deficiency of neutrons beyond what is expected from the neutron decay only [9].

$$\epsilon_{nn'} = \epsilon' \leq 10^{-16} \text{ eV.} \quad (2)$$

The analysis is further complicated by the possible presence of mirror magnetic fields which can suppress the transition rate and, unlike ordinary B fields, cannot be shielded. That allows for $\epsilon'$ values which are significantly higher. Also unlike for $n \rightarrow \bar{n}$, $n \rightarrow n'$ transitions inside nuclei are energetically forbidden as the neutrons are bound (typically by $\sim 8$ MeV) and the equal mass mirror neutrons with no (ordinary) nuclear interactions are unbound.

Here we focus on the recent suggestion [15] that there may be another manifestation of neutron to mirror neutron $(n \rightarrow n')$ transition with important implications i.e. it can occur
in neutron stars [16] and can convert neutron stars to mixed neutron + mirror neutron stars. This may help explain some peculiarities of the mass distribution of pulsars. The key to the new suggestion of [15] which we briefly elaborate in the next section, is that such transitions are allowed in neutron stars even though they are forbidden in nuclei. Furthermore, an analog of the remarkable coincidence between the nuclear and beam method bounds obtained in the case of $n \rightarrow \bar{n}$ transitions repeats here with the neutron stars playing the role of “giant nuclei”. Specifically sufficiently large, yet still allowed values of $\epsilon'$ which are probed in beam experiments can convert an initial neutron star to a maximally mixed-lower mass star on relevant time scales of $T \sim 10^6 - 10^{10}$ years.

It has been argued [15] that this will modify the mass distribution of the pulsars which has been measured with precision for pulsars in binaries. The effective softening of the combined equations of states leading to smaller size and increased gravitational binding, shifts the pulsar masses towards lower values over the above time scale $T$ making for a better agreement with the observed mass distribution.

Our main message, presented in sec.III below, is that this ingenious and intriguing suggestion is strongly constrained in a model independent way by precision measurements of the orbital periods of pulsars which are members of binary systems. We also discuss the possible implications for the above scenario of the recent observation of gravity waves emission in a binary neutron star merger.

It is well known [17] that mass loss implies an increase of the orbital period of the binary systems. Our claim is that if the rates of conversion of neutron stars to mixed stars are those required in the above scenario (or even a thousand times slower) the resulting period increase exceed the maximum allowed by the observations.

In section IV, we turn the argument around and use the putative neutron star→ mixed neutron–mirror neutron star transitions to exclude a large range of $\epsilon'$. This is particularly relevant when the $n - n'$ mass differences $\delta m'$ are significantly higher than $\epsilon'$ and the energy difference due to magnetic fields. The (almost) free $n \rightarrow n'$ oscillations in neutron beams or bottles are than strongly suppressed and the astrophysical limits considered here are the only way to restrict $\epsilon'$.

In Sec V, we present some further speculative comments and in sec. VI, we conclude with a summary of our results. In Appendix A, we give our estimate of the $n \rightarrow n'$ transition
rate inside a neutron star.

II. TRANSITION OF NEUTRON STAR TO MIXED NEUTRON–MIRROR NEUTRON STARS INDUCED BY N-N’ MIXINGS

The suggestion that certain stars and neutron like stars in particular, may be "mixed"–consisting of ordinary baryons and dark matter particles– has been made some time ago [18, 19]. The present authors together with Doris Rosenbaum and the late Vic Tepliz considered [18] such stars and solving the coupled TOV equations derived allowed masses of stable mixed stars. While we found, like the authors of [15], that admixing dark matter particles of equal or heavier mass than neutrons pushes down the maximal allowed stellar mass, having lighter - say $m_{n'} = \frac{m_n}{2}$ - DM particles allows exceeding the maximal neutron star mass of $\sim 2.3M_\odot$ suggested by most equations of states (EoS) of ordinary nuclear/quark matter[20, 21].

Two conceptual issues were encountered in previous mixed star discussions.

(i) There was no obvious mechanism for bringing together at some stage the required roughly equal amounts of ordinary and dark matter into the star.

(ii) The EoS of the (self interacting) DM are unknown. In the broken mirror models underlying our above mentioned work [18], we used scaling with $m(n')$ to guess the latter from the EoS of ordinary matter.

The new mixed star scenario suggested in [15] circumvents both issues.

(i) The $n \rightarrow n'$ oscillations can generate (starting with a pure ordinary neutron star) a mixed $n - n'$ star and (ii) the exact mirror model used therein implies identical EoS of mirror and ordinary matter.

The key to the arguments of ref.[15] is that $n \rightarrow n'$ transitions, kinematically forbidden in nuclei, do occur in neutron stars, causing conversion of neutron stars to mixed $(n - n')$ stars. Furthermore these transitions take relatively short astrophysically relevant times of $\sim 10 \div 100$ Myr for values of the microscopic mixing $\epsilon'$ which are allowed by all other terrestrial and cosmological limits. For completeness we will briefly recap below some of the main aspects of this argument.

The reason why $n \rightarrow n'$ transitions do occur in neutron stars is that the neutrons therein are mainly bound by gravity and not by nuclear forces which at the large densities in the
central regions of the star may become repulsive. Thus, suppose that an \( n \rightarrow n' \) conversion occurred at some point in the star. Under the pressure which is proportional roughly to the energy density, a neighboring neutron then rushes into the ”hole” generated by the converted neutron, gaining in the process kinetic energy which is of order of the Fermi energy \( E_F \). Further energy is gained when the produced \( n' \) gravitates to the center of the star and a surface neutron replaces the neutron which went into the above ”hole”. In reality we have continuous inward drifting of both mirror neutrons (\( n' \)) and neutrons (\( n \)) due to the ongoing \( n \rightarrow n' \) transitions over the whole volume of the star. This also causes the star to shrink which further significantly increases the gravitational binding. Altogether this decreases the stellar mass by about 20%. Thus the transitions do occur, albeit with suppressed rates, similar to \( n \rightarrow \bar{n} \) in nuclei. The estimate of the neutron to mirror neutron transition rate done in ref.[15] proceeds in two steps:

A) It is assumed that in each \( n - n \) collision the fraction of \( n' \)

\[
P_{nn'} = \epsilon'^2 / [E_F - E'_F]^2
\]  

in the neutrons wave-function will materialize as mirror neutrons . and next

B) The \( nn \) collisions rate \( \Gamma_{nn} \) is independently given by:

\[
\Gamma_{nn} = \sigma_{nn} vN
\]  

where \( \sigma_{nn}, v, N \) are the \( nn \) collision cross-section, the neutrons velocity and number density of neutrons in neutron star respectively . This rate was estimated to be

\[
\Gamma_{nn}(neutron\ star) = \Gamma_{nn}(nuc)[N/N_{nuc}]^{4/3} \sim 10^{24}[N/N_{nuc}]^{4/3} sec^{-1} \sim 3.5 \times 10^{24} sec^{-1}
\]  

finally leading to

\[
\Gamma(n \rightarrow n') = \Gamma_{nn} P_{nn'} \approx 10^{-6} \left( \frac{\epsilon}{10^{-11} eV} \right)^2 yr^{-1}
\]  

The actual calculations of the evolution towards the mixed star undertaken in Ref.[15] are rather complicated and far more elaborate. One has to use the spatially varying density \( n(r) \) and \( n'(r) \) of the neutrons and the mirror neutrons in the coupled TOV equations describing the instantaneous hydrostatic equilibrium states of the system. These equation
and corresponding equilibrium states keep changing in time as more and more neutrons are being converted to mirror neutrons. These mirror neutrons keep drifting to the central region of the star generating a region of a lowest energy completely mixed star. The equally mixed spherical region gradually expands and eventually overtakes the whole star. Furthermore the calculations have to be done for various equations of states relating the energy density and pressure of the ordinary nuclear matter (and of the mirror nuclear matter) in the star. The scope of the present paper is much more limited and we will not delve into these issues rather we use the final results obtained in Ref.[15]:

a) Over times of order 1 – 100 Million years the neutron to mixed star transition can be largely completed for $\epsilon' = 10^{-11} - 10^{-12}$ eV and

b) The original neutron star shrinks and if it was too massive to start with, will collapse to a black hole. Otherwise it will wind up at present when being observed as a partially or almost completely mixed star with a mass loss of 0.25-0.35 solar masses.

Such collapses and mass decrease in the above described transitions to a mixed star will then appreciably shift down and narrow the mass distribution of pulsars in binaries making for a better agreement with the observed distribution [15].

III. ASTROPHYSICAL CONSTRAINTS ON THE NEUTRON STAR TO MIXED STAR TRANSITIONS

A. limits From orbital period measurement in binary pulsars

We now describe our main result - limiting in a model independent way the above scenario by the precise measurement of the orbital period time derivative of pulsars in binary systems. Such period decrease, expected whenever the mass of either member of the binaries decreases, was first noted in 1925 by Jeans [22]. Using the constancy of the product $Ma$ with $M = M_1 + M_2$, the total mass and $a$, the semi-major axis appearing in Kepler’s law for the orbital period $P_b = 2\pi \left(\frac{a^3}{G_N M}\right)^{1/2}$, he obtained the simple expression for the change of the period of the orbital binary motion $P_b$ as a function of the mass change:

$$\frac{dP_b}{dt} = -2 \frac{dM/dt}{M}.$$  (7)
$P_b$ is the period of binary orbital motion, as distinct from $P$ which denotes the period for individual pulsar.\(^1\)

While Jeans envisioned mass loss due to the electromagnetic radiation emitted by the stars, the above relation holds for *any* form of “radiation” e.g. via neutrinos, axions, mirror photons and mass loss incurred - so long as the emission from either member of the binary is symmetric in its rest frame. As noted however in ref. [17], if some fraction of the energy in the case of interest is emitted electromagnetically - most likely as X rays in the case considered below- the extra signatures would be very remarkable and more stringent limits would obtain.

As $\frac{dM/dt}{M}$ is negative for mass loss, the period increases and the average angular velocity $\Omega_{\text{orbital}} = \frac{2\pi}{P_b}$ decreases. This is not the case for gravitational radiation which is emitted from the rotating system as a whole, decreasing the orbit and *increasing* the $\Omega_{\text{orbital}}$.

This was used in the famous inference of gravitational wave emission measurements from the period slowing down of PSR 1913+16 - the binary Hulse Taylor pulsar (age $1.1 \times 10^8$ yrs). Two of us (I.G and S.N.) in ref [17] suggested that the same precise measurements can be used to constrain also the energy loss due to continuous neutrino emission which might occur in models where neutron stars undergo internal changes over long times. Using the measured period slow-down, a total mass $M$ of about $3M_{\odot}$ and accounting for the gravitational wave mass loss which can be very accurately predicted, it was found that [17]:

\[
\Delta M \ yr^{-1} < 3 \times 10^{-12} M_{\odot} yr^{-1}. \tag{8}
\]

A somewhat stronger limit $\Delta M \ yr^{-1} < (0.96 - 1.2) \times 10^{-12} M_{\odot} yr^{-1}$ can be derived from observations on PSRJ1952+2630. This is in a binary orbit with a $0.93 - 1.4M_{\odot}$ white dwarf [25]. Its spin down age is $7.7 \times 10^7$ yr, the orbital period is 0.39 days and during 800 days of follow-up the error on the period is $7 \times 10^{-13}$ days. Thus

\(^1\) The rate of change of the latter presumably due to magnetic breaking, defines the estimated age of the pulsar via $P/\dot{P}$. The conversion of the original neutron star to a lower mass mixed star also decreases the radius of the stars leading to faster pulsar rotations and shorter periods. Indeed In the framework of the ambitious nano gravity project [28] a remarkably accurate pulsar timing has been achieved. One example is the ”millisecond” pulsar PSR J1024-0719 for which a period change of $dP/dt = (1.8551 \pm 0.0001) \times 10^{-20}$ was measured. Unfortunately since here unlike for the binary systems we cannot predict the rate of change due to ”conventional” sources, the *full* $(dP/dt)/P$ and *not* just the fractional error in it can be attributed to new physics and the ensuing bound does not improve.
\[ \left| \frac{\dot{P}_b}{P_b} \right| < (7 \times 10^{-13}/800 \text{ days}) \times (365/0.39) = 8 \times 10^{-13} \text{yr}^{-1} \]  
(9)

We next proceed to compare these bound with the expectations of the neutron\(\rightarrow\) mixed star scenario.

The pulsars are observed while they are in the electro-magnetically active , “Beaming”, phase. It is precisely the fact that the \(\epsilon' \sim 10^{-11} - 10^{-13} \text{eV} \) values needed in order to achieve this while remaining consistent with all other bounds on the \(n \rightarrow n'\) mixing, is the main motivation for the work of ref.[15].

The authors of ref.[15] start with an initial relatively broad pulsar mass distribution with an average mass of \(1.6M_\odot\). The final mass distribution obtained is also broad and has an average of \(1.25M_\odot\). However, at intermediate times when the heavier pulsars have collapsed to black holes they obtain a much narrower distribution with an average of \(1.35M_\odot\), if the conversion of the lighter pulsars is still ongoing. Thus the best fit in [15] is obtained if the typical conversion times are not just shorter than but comparable to the pulsar lifetime in the range of \(10^6 - 10^{10} \text{ years}\). The corresponding mass loss rate in the Hulse-Taylor is

\[ \sim (0.3 \times 10^{-6} - 0.3 \times 10^{-10})M_\odot \text{ yr}^{-1} \]  
(10)

which exceeds the upper bound in Eq.8 by a factor of \(10 - 10^5\). The particular limit from the above two pulsars can be evaded, if the neutron star to mixed star transition are shorter than their ages.

This last possibility is however largely negated by observation of limits from a particularly young star PSR J1755-2550. This is a young radio pulsar [24]. Discovered in 2015 and observed for 2.5 years, it is a member of a binary with orbital period of \(9.6963342(6) \text{ days}\). The spin down age is about \(2.5 \times 10^6 \text{ years}\). The uncertainty in the measured orbital period over the 2.5 years time span of the observations implies a bound \(\left| \frac{\dot{P}_b}{P_b} \right| \leq 2.1 \times 10^{-12} \text{ per year}\). This is a young pulsar so that unlike PSR1913+16 one cannot argue that the conversion process was terminated long before the present epoch. This limit is 4 orders of magnitude smaller than the rate implied by the proposed conversion.

In general, even much less sensitive measurements of period change of all other pulsars in the approximately thirty binary systems known, would exclude them from being candidates
for the scenario of ref.[15]. Clearly conversions of neutron stars to mixed stars can proceed at rates much lower than those required to impact the pulsar mass distribution. This would still manifest in the orbital period change and may allow us to exclude $\epsilon'$ values all the way down to $10^{-15} e.V$. Indeed in this case all pulsars would still be in the process of conversion to a mixed star with increasing orbital period at the time of observation.

An important feature is that while ages, periods and period stabilities greatly vary between the different pulsars, this is NOT the case for the roughly constant length of the stellar conversion: neutron star $\rightarrow$ mixed star, which makes it increasingly difficult for the conversion scenario to confront more and more binary pulsars. An example is the pulsar PSR J1614-2230 [23] which is a millisecond pulsar whose mass is $1.97 M_\odot$, in a binary system with a white dwarf companion of mass $0.5 M_\odot$. The pulse spin down age is 5.2 Gyr. Yet the pulsar has such a large mass. If the conversion did occur in the past it must have started with an very large mass of $\sim 2.6 M_\odot$. Most likely it would have collapsed to a black hole.

Two other pulsars which also allow us to set comparable constraints as above are:

(i) PSR J1141-6545 [26] which is a young pulsar with age 2 Myr with total mass $2.29 M_\odot (M_{PSR} = 1.27 M_\odot$ and $M_c = 1.02 M_\odot$. The residual rate of change of the binary orbital period (after taking care of the effect of ecceleration in the Galaxy as well as the kinematic effect and the expected gravitational radiation term) is $\dot{P}/P_b = -7.8 \times 10^{-11} yr^{-1}$. It is a young pulsar so one cannot argue that the $nn'$ process has been already terminated. Moreover the sign is opposite from the predicted by the $nn'$ conversion.

(ii) PSR J0437-4715 (age 1.6 Gyr) [27]. The residual rate of change of the binary orbital period (after taking care of the effect of ecceleration in the Galaxy as well as the kinematic effect) is $|\dot{P}/P_b| = 8.2 \times 10^{-11} yr^{-1}$. Then only caveat about (ii) is that it is a relatively old pulsar where $n-n'$ transition could have completed, although for the kind of limits on $\epsilon'$ we derive from other pulsars listed, it would have taken longer than its age and we could still use this to get a limit.

B. Gravitational Waves Observations

The recent observation (in gravitational waves and in much of the electromagnetic spectrum) of a neutron star merger is most relevant to our discussion. In the scenario of Ref.[15],
such mergers are likely to involve stars which are already mixed. In this case the radii of the stars should be considerably smaller than the 10Km usually assumed. This then causes the pattern of the emitted gravity waves to be different. To appreciate the sensitivity to even moderate changes of radius - let us consider the expected rate of GW emission. For approximately circular orbits, it is given by:

\[ \frac{dW}{dt} = \frac{32G_N}{5c^5} \mu^2 \Omega_{orb}^6 a^4 \]

where \( \mu \) is the reduced mass: \( \mu = \frac{M_1 M_2}{M_1 + M_2} \). Shrinking by the factor \( f \) the radii of both stars \( R_1 \) and \( R_2 \) will decrease the orbit size at the time of merging \( a = R_1 + R_2 \) by a same factor \( f \). Using Kepler’s law \( \Omega_{orb} \sim a^{-3/2} \), we find that \( dW/dt \) will increase by a factor of \( f^{-5} \). There will also be reduction in \( \mu \) which will tend to reduce this increase. All these would lead to a considerable enhancement of the instantaneous gravity wave luminosity. For example for a reduction of radii \( f \sim 0.7 \), the enhancement will be about four. In particular changes should occur in the predicted template that was fitted to the detailed observed temporal GW signal and was consistent with the merging neutron stars being standard neutron stars.

The great advantage of this approach is that unlike the one relying on changing periodicities - the observation need not be made while the transition from the original neutron star to the mixed star is ongoing. Indeed typically such mergers are expected to occur very late, during the cosmologically long period after the individual pulsars have died. \textit{Furthermore the effect considered is maximal if the binary pulsar in question is old enough so that the transition has terminated ( or largely did so ) at the time of observation and we have completely mixed stars with the minimal radii possible.} Another constraint on the possible decrease of the neutron star radius has been obtained [29] from gravitational wave observations of the binary neutron star merger GW170817. The authors obtained that the radius should be be in the range 8.9 ÷ 13.2R⊙ with a mean value of 10.8R⊙.

Thus this approach is somewhat complementary to the previous one and jointly the two approaches tend to much more strongly restrict the scenario of ref.[15]. Clearly one cannot, at the present with such limited statistics effectively use it to constrain the scenario of ref.[15] but this may change in the future.
IV. BOUNDS ON $\epsilon'$ FROM PULSAR PERIOD INCREASE MEASUREMENTS

We next discuss the bound on $\epsilon'$ which precision measurements of pulsar periods can provide. We note that the above estimate (see Eq. (5)) in ref.[15] of, the rate of $n \rightarrow n'$ transitions in a neutron star described in [15] [6] of $10^{-6}[\epsilon'/10^{-11}eV]^2 \text{yr}^{-1}$ may be somewhat optimistic. This has no bearing on our main result- namely that the rate of neutron star to mixed star transitions required for having an impact on the pulsar mass distribution tend to conflict with upper bounds on the period increase of the orbital motion pulsars in the binary system. It is however relevant if we wish to use this approach to limit $\epsilon'$. In Appendix A, we derive our estimate of $\Gamma_{nn'}$, which is somewhat lower:

$$\Gamma_{n\rightarrow n'} = 0.6 \times 10^{-7}[\epsilon'/10^{-11}eV]^2 \text{yr}^{-1}$$  \hspace{1cm} (12)

Using Eq. 8 and two estimates (optimistic and conservative), we find a bound on $\epsilon' \leq 10^{-15} \text{eV}$ or $10^{-13} \text{eV}$ respectively. We summarize our results in the following Table I using the estimate Eq. 12 (column 4) and that from Eq.6 (column (5))

| Pulsar name       | Age in yrs | Upper limit on $|\dot{M}/M|$ in yr$^{-1}$ | Upper limit on $\epsilon'$ in eV (using Eq. 12) | Upper limit on $\epsilon'$ in eV (using Eq. 6) |
|-------------------|------------|---------------------------------|---------------------------------|---------------------------------|
| PSR 1913+16       | $1.1 \times 10^8$ | $3 \times 10^{-12}$          | $7 \times 10^{-14}$            | $1.7 \times 10^{-14}$          |
| PSR J1755+2550    | $2.1 \times 10^6$  | $2.1 \times 10^{-12}$        | $5.5 \times 10^{-14}$          | $10^{-14}$                     |
| PSRJ1952+2630     | $7.7 \times 10^7$  | $8 \times 10^{-13}$          | $3.5 \times 10^{-14}$          | $\sim 10^{-14}$               |
| PSR J1141-6545    | $2 \times 10^6$    | $3.4 \times 10^{-11}$        | $2.2 \times 10^{-13}$          | $0.58 \times 10^{-13}$         |
| PSR J0437-4715    | $1.6 \times 10^9$  | $4.1 \times 10^{-11}$        | $3.2 \times 10^{-13}$          | $1.2 \times 10^{-13}$          |

TABLE I: Limits on $\epsilon'$ from several pulsar data using both the numbers of ref.Eq. 6 and our Eq. 12. We assume that the $n- n'$ conversion has not completed in these pulsars, in the spirit of ref.[15] where the best fit is obtained if the conversion is still ongoing. This is particularly unlikely for PSR J1755+2550, whose age is only 2.1 Myr and for PSR J1141-6545 whose age is 2 Myr.

It is important to note that almost all discussions of $nn'$ oscillations and in particular the limits on $\epsilon'$ implied by searches for such oscillations in neutron beams, assume tiny $\delta m' = m_n - m_{n'} = m - m'$ mass difference so that $\delta m' \leq \epsilon'$ and $\delta m' \leq E_{\text{magnetic}} = \mu_n B (or \mu_{n'} B')$ with $B(B')$ the ordinary and mirror magnetic fields. If however the $\delta m'$ is (much) larger than both $\epsilon'$ and the magnetic energies, then $nn'$ oscillations would be suppressed
beyond detection. However the $nn'$ transitions inside neutron stars (which are suppressed by much larger $\Delta E$ of order 20 $MeV$) are insensitive to $\delta m'$ so long as $\delta m'$ is smaller than $\Delta E$ and the bounds obtained in our analysis would extend to such large $\delta m'$ values.

In passing we note that larger values of $\delta m'$ would be in line with the comment made by two of us [5]. We pointed out that the mirror symmetry breaking at some high scale, which is required for consistency with big bang nucleosynthesis with temperatures $T' = (0.2 – 0.4)T$ tends to a "trickle down" effect via loop diagrams, barring some fine tuning, generates $\delta m'$ values much bigger than what is usually assumed.

We further note that the proposal to understand the neutron decay anomaly by using neutron-mirror neutron oscillation requires $\epsilon' \approx 10^{-10}$ eV [30] which is much larger than our upper bounds above. Our results would therefore rule out this explanation of neutron decay anomaly.

V. SOME FURTHER COMMENTS AND SPECULATIONS

It has been suggested that all (or most) of the (super) heavy, trans-lanthanide elements are produced by ejecting neutron rich fragments into the host galaxy in binary neutron star mergers. If this happens in completely mixed stars which contains equal amount of neutron and mirror neutrons, this would then imply similar abundance of ordinary and mirror trans-Lantanide elements. More generally, the microscopically exact mirror framework may also lead to proximity of mirror and ordinary atoms. Some such proximity may be required if mirror matter is seeding the formation of galaxies.

This brings up the more general question which we will briefly touch upon, of how much mirror matter is expected in the galaxy, the solar system and in earth? The different $\Omega'$ and $T'$ in the mirror and ordinary sector causes a much more abundant mirror helium $He'$ production at nucleosynthesis in the mirror sector [6]. This in turn leads to a very different pattern of star formation, supernovae and element abundance which generally is expected to be shifted to heavier elements in the mirror sector. At least 80 percent of the mirror baryonic mass should be in the form of massive stars in elliptical galaxies as otherwise the large $He' – He'$ scattering cross-sections -identical to those of $He – He$ of $\approx 10^{-16} cm^2$ -would dramatically violate the upper bounds suggested by the bullet cluster. Still since the mirror
matter is dissipative we expect that it will tend to co-cluster with ordinary matter due to their mutual gravity. Thus, it can be searched for in earth, on the lunar surface, and in meteorites. Conversely aggregates of mirror matter such as micro-haloes and mirror matter stars should include some small amount of ordinary matter - which in turn may dramatically change their properties in an observable manner.

VI. SUMMARY AND CONCLUSION

In conclusion, in this paper, we have noted that astrophysical data pertinent to precision pulsar timing and binary neutron star merger can be used to restrict the scenario of ref.[15] where $n - n'$ mixing causes transition from a pure neutron star to mixed neutron stars. In turn, this allows us to restrict particle physics parameters such as the mixing between neutron and mirror neutron ($n \rightarrow n'$) which possible in an almost exact mirror symmetric dark sector. Our conclusion is based on the recently proposed scenario [15] of neutron star to mixed neutron star transition which can arise due to $n \rightarrow n'$ transition. We find that the key parameter responsible for $n \rightarrow n'$ transition $\epsilon'$ is restricted to be below $10^{-13}$ eV to $10^{-14}$ eV by current pulsar timing data. While the constraints from the binary pulsars of age $\sim 100$ Myr could be evaded by assuming that the transition has already been completed, it is much more difficult to do so for the two pulsars with age of $\sim 2$ Myr. Also the case of the old massive (2 solar masses) pulsar casts doubt on the scenario of mass reduction. The observations of the gravitational waves from the the binary neutron star merger GW170817 constrains a reduction of the neutron stars radii which is implied by the $nn'$ process. Additionally, the constraint from the merger of 2 neutron stars detected by LIGO and VIRGO as well as by gamma ray observation is not sensitive to the time scale of the transition as these stars are likely old ones.

An interesting contrast between the current pulsar timing limits and the limits that can be obtained from laboratory searches is that our limit is valid for $n - n'$ mass differences $\delta m'$ as large as 20 MeV whereas the latter limits are valid only for much smaller splittings such as those caused by the local magnetic field difference between the visible and the mirror world.
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Appendix A

Two factors enter the above estimate \( \Gamma(n \rightarrow n') = \Gamma(nn)P_{nn'} \): the probability of having an \( n' \) at the time of \( nn \) collision \( P_{nn'} \), and the rate of such collisions \( \Gamma_{nn} \). This reflects a simple, physically motivated picture [31] in which one assumes that: a) The coherent build up of \( |n'\rangle \) in the initial purely \( |n\rangle \) 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 out-going mirror neutron particles.

We note that the high \( nn \) collision rate in Eq. 5 implies a very short flight time

\[
t_{nn} = 1/\Gamma_{nn} \approx (3 - 4) \times 10^{-25} \text{sec.}
\]  

(A1)

separating consecutive collisions.

A key point is that during flight times \( t_{nn} \) shorter than \( \Delta E^{-1} \), the admixture of the mirror neutron \( |n'\rangle \) does not build up to its asymptotic value of \( \epsilon'/\Delta(E) \) which was implicitly used in reference [15] to estimate \( P_{nn'} = [\epsilon'/\Delta(E)]^2 \).

The free evolution of the initial pure neutron state during the short time of flight starting with \( \psi(0) = |n\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) yields \( \psi(t) = e^{iHt}|\psi(0)\rangle \approx (1 + iHt)|\psi(0)\rangle \approx \begin{pmatrix} 1 \\ \epsilon't \end{pmatrix} \)

where \( H = \Delta(E)\sigma_z + \epsilon'\sigma_x \) is the Hamiltonian in the two dimensional \( |n\rangle, |n'\rangle \) Hilbert space. This then yields a probability of generating a mirror neutron \( n' \) between two consecutive collisions of \( P_{nn'} = [\epsilon',t_{nn}]^2 \).

Substituting the new \( P_{nn'} \) and \( \Gamma_{nn} = t_{nn}^{-1} \) in \( \Gamma_{n \rightarrow (n')} = \Gamma_{nn}.P \) we find an alternative
expression (appropriate for short $t_{nn}$)

$$\Gamma_{n \rightarrow n'} = t_{nn} \epsilon'^2 \quad (A2)$$

Using $t_{nn} \approx 10^{-23} \text{sec}$ - the time required to travel the $O(\text{Fermi})$ distance between neighboring neutrons at 1/3 of the speed of light then leads to a new estimate of the conversion rate:

$$\Gamma_{n \rightarrow n'} = 0.6 \times 10^{-7} [\epsilon' / 10^{-11} \text{eV}]^2 \text{yr}^{-1}\quad (A3)$$

Which is about 20 times smaller than the estimate of ref.[15]. Clearly this is a very rough estimate. In particular having the nuclear medium manifest just as a series of frequent collisions is very crude. The conversion is ongoing all the time and the proper treatment should use the Schrodinger equation in the medium as in the careful treatment of $n \rightarrow \bar{n}$ nuclear transitions by [32]. The latter works yield transition rates somewhat faster than those in [31]. In mapping out the upper limits on $\epsilon'$ in the Table I, we use both this estimate and the original estimate of ref.[15]) in Eq.6.

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