Hyperon Mixing and Two Serious Problems in Neutron Stars *

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- Characteristic properties of hyperon-mixed NSs
  ------ too-soft EOS and too-rapid Cooling
- Toward solving the problem of too-soft EOS
- Hyperon Superfluidity under the EOS compatible with 2-solar-mass NSs
- Concluding remarks

Characteristic properties of hyperon-mixed NSs

Hyperon(Y) mixing in neutron stars (NSs) has gathered much attention and has been investigated in many literatures. Nowadays, it is well known that, primarily Y-mixed phase sets on at around the density $\rho \sim (2-4)$ times nuclear density below the central density of NSs.

Then what happens for Y-mixed NSs? Here I emphasize two points:

① **Too-softened EOS**  
A most striking aspect is a dramatic softening of the EOS, being unable to sustain even $1.44$ solar-mass known as a canonical mass. This too-soft EOS problem is necessarily highlighted by recent observation of massive NSs with $2$ solar-mass and the contradiction between theory and observation is sometimes called "hyperon puzzle" ("hyperon crisis"). By the way, long before the $2$ solar-mass observations, the significance of the problem had been claimed in our works[*], remarking a particular softening mechanism and introducing the "universal 3-body force",

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Another serious problem is in the difficulties to explain the thermal evolution of NSs. Y-mixed NSs have extremely high neutrino-emissibility through $\beta$-decay processes including Y (Y-Durca; Y-cooling), which is larger by (6-7) orders of magnitudes than that of modified URCA (Murca; standard cooling). As a result, it leads to a problem that all the NSs from which thermal X-ray are detected should have very light mass, $M < M_{\odot}$ in reference to $M(Y\text{-mixed})$ discussed in ①. This is very unlikely by considering a population of observed NS masses, $M(\text{obs}) > M_{\odot}$.

Therefore we need some suppression mechanism for Y-cooling. One of the candidates is a realization of Y-superfluids, whose possibility is discussed later on.

Here we stress that these two serious problems(①, ②) should be solved simultaneously.

In the following slides, I show the situations closely related to ① and ②.
G-matrix-based Effective Interaction Approach

Nishizaki-Yamamoto-Takatsuka (2002)
$M_{max} < M_{obs}$ (Softened EOS by Y)

After 2M\_sun observations

Strong Softening of the EOS

Hyperon Crisis
(by T. Hatsuda)
Even Λ-only mixing, situation is the same!
Brueckner-Hartree-Fock

L-Vidana et al, P.R. C62 (2000) 035801
M. Baldo et al, P.R. C61 (2000) 055801
Hyperons are always present
→ profound consequence for NS-mass

G-matrix with nucleonic 3-body force

Chiral SU(3) RMF


Short summary

1) Y-mixing is sure to occur (\(\Lambda,\) at least)
2) Even if only the \(\Lambda\)-mixing could occur, the softening situation is unchanged.
3) We have a dilemma i.e., enhancing NN repulsion leads to more developed Y-mixing at lower densities and stronger softening effects which compensates the enhanced NN repulsive contribution.

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Serious Something are missing!
Toward solving the problem of too-soft EOS

So many works have been done for solving the problem of too-soft EOS of Y-mixed NSs. As examples:

1) In pure hadron matter framework:
   • Universal 3-body force repulsion in potential description approach,
   • $\delta$-meson effects, Fock term contribution, extended parameter-space, etc. in field description approach such as RMF,

2) In hadron matter plus quark matter framework:
   • H-Q crossover transition, and H-Q first-order transition.

3) Under a circumstance of ultra strong magnetic field.
In our earlier works*, we have found that possible candidate to solve the problem is

**Universal 3-body force**

: an extended use of the phenomenological 3-body force of Illinois’s type (Friedman-Pandharipande**): 

\[ \text{NNN} \rightarrow \text{BBB} \]


Dramatic softening of EOS $\rightarrow$ Necessity of “Extra Repulsion”

(a) 2B come in short distance
(b) Deformation (resistance)
(c) Fusion into 6-quark state

(by R. Tamagaki)

Energy barrier ($\sim 2\text{GeV}$) corresponds to repulsive core of BB interactions
BBB interactions

Additionally 2GeV excitation

Height of 3-body pot.

Fig. 7. Pictorial view of the exotic tribaryon and its preformation stage; (left) string-junction net of the tribaryon $T^7_9$, (right) $BBB(\bar{B}B)(\bar{B}B)$ states arising from the fission of the interjunction strings, and (bottom) an example illustrating one of many possible configurations for full overlap of $BBB$, where the dotted area indicates the formation region of a string-junction net. Such view is the unfolded-sheet drawing of the tribaryon having three-dimensional spread.
Universal 3-body Force

SJM  BBB

Pom.-exch.BBB


\[ M/M_\odot \]

\[ 2\pi\Delta + SJM2 \]

\[ + SJM1 \]

\[ TNI6u \]

\[ 2\pi\Delta \]

\[ R \text{ [km]} \]

\[ \rho_c/\rho_0 \text{ [g cm}^{-3}] \]

\[ R \text{ [km]} \]

\[ \text{[M sol]} \]

Universal 3-body Force


First-order H-Q transition
($\sigma$-$\omega$-$\rho$-$\delta$-$\phi$ model)
Horvath-Souza(2017)
Effects of $\Sigma$ -pot. , $\phi$

Dep. on Many-body Approach , cutt-off

Interpolation by 3-window approach

○ From a view of “H-Q Crossover” due to percolation

\[
\varepsilon(\rho)_H = \varepsilon_H(\rho)f_-(\rho) + \varepsilon_Q(\rho)f_+(\rho),
\]
\[
f_{\pm}(\rho) = \frac{1}{2}\{1 + \tanh(\frac{\rho - \bar{\rho}}{\Gamma})\}
\]

○ Pressure \(P(\rho)\) is derived from

\[
P(\rho) = \rho^2 \partial (\varepsilon(\rho)/\rho)/\partial \rho
\]

H-Q crossover model
Kojo-Powell-Song-Baym (2015)

Blasche-Castilo-Benic-Contrera-Lastowiecki (2013)
Under strong magnetic field

Lopes-Menezes (2012)

Sotani-Tatsumi (2017)
Here we reconsider the existence or nonexistence problem of $\Lambda$-superfluid in NSs under the conditions:

1. Y-mixed NS EOS with universal 3-body force from the SJM, which is compatible with 2-solar-mass NSs.

2. Pauli-blocking effects in $\Lambda\Lambda-\Xi N$ coupling channel giving rise to the additional attraction in the $\Lambda\Lambda$ pairing interaction.
ΛΛ—ΞN coupling

In free space: $V_{ΛΛ}^{\text{(free)}}$ is more attractive than $\tilde{V}_{ΛΛ}^{\text{(medium)}}$ in medium.
With NAGARA
ND-Soft original
ND-Soft with Pauli-Blocking (VF3 in [3])


ΛΛ Pot.

13.4 GeV core
4.4 GeV
2.0 GeV

(MeV)

-100
-50
0
50
100

2 r(fm)

200
400
600
800
1000
Mixing ratio ($y$) and effective-mas parameter ($m^*$) ; SJM2 + TNA

<table>
<thead>
<tr>
<th>$\rho/\rho_0$</th>
<th>$y(\Lambda)$ in%</th>
<th>$m^*(\Lambda)$</th>
<th>$Y(n)$ in %</th>
<th>$m^*(n)$</th>
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<tr>
<td>4.5</td>
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<td>0.828</td>
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<td>0.93</td>
<td>0.847</td>
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<td>5.0</td>
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<td><strong>0.586</strong></td>
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<tr>
<td>5.6</td>
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<td>0.870</td>
<td></td>
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<tr>
<td>5.8</td>
<td>6.55</td>
<td>0.866</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>7.93</td>
<td>0.860</td>
<td>76.6</td>
<td>0.568</td>
</tr>
</tbody>
</table>

Larger $m^*$ for $\Lambda$ works for a realization of $\Lambda$-super
Present
EOS: SJM2+TNA
Pairing int.
$\Sigma\Sigma \rightarrow ND$-Sof including Pauli-blocking effects

Previous
EOS: TNI6u
Pairing int.
ND-Soft, (phase-shift-equivalent to ND)
Without Pauli Blocking.

Previous

Present
EOS: SJM2+TNA
Pairing int.:
$\Sigma\Sigma \rightarrow ND$-Sof
$\Lambda\Lambda \rightarrow VF2,3$ including Pauli-blocking effects
Cooling scenario depending on NS mass

(A) Lighter NSs (Murca; warm)

(B) Medium-mass NSs (suppressed Y-Durca; cool)

(C) Massive NSs (Y-Durca; very cold)
Concluding remarks

1. Due to the Y-mixing in NS cores, we are faced to two serious problems; too-soft EOS and too-rapid cooling. These two problems have to be solved simultaneously.

2. In the case of pure hadronic framework, the universal 3-body force is a solution for the problem of too-soft EOS. In the framework of hadron matter plus quark matter, the H-Q crossover transition model is a promising candidate.

3. $\Lambda$-superfluidity can be revived by taking into account the Pauli-blocking effects in $\Lambda \Lambda - \Xi N$ channel coupling, keeping less attractive $\Lambda \Lambda$ interaction suggested by the “NAGARA event”. This leads to a cooling scenario of NSs consistent with surface-temperature observations.

Finally we wish to stress that recent observation of massive NSs has opened a new paradigm for dense matter physics, and anyway needs more investigations.