Symmetry Energy Effects on Superfluidity of Neutron Stars

T. Takatsuka
(Iwate Univ.)

*) in collaboration with R. Tamagaki and S. Nishizaki
Introduction

As a conventional picture, liquid inner core of neutron stars (NSs) is taken to be composed of $n$, $p$, $e^-$ and $\mu^-$. By a pairing correlation due to the attractive NN interaction, both of $n$ and $p$ are in the superfluid state (*);

$n \rightarrow 3P_2$-superfluid, $p \rightarrow 1S_0$-superfluid, in the density region $\rho \sim (1-4) \rho_0$ with $\rho_0$ = nuclear density.

At present, however, following two points should be taken into account;

1. Hyperon ($Y$) mixing surely occurs → So, as a standard picture, NSs are composed of $n$, $p$, $Y (= \Lambda, \Sigma^-, ---)$, $e^-$ and $\mu^-$.  
2. Uncertainty of nuclear symmetry energy ($E_{\{\text{sym}\}}$), the high light of this symposium.

In this talk, we discuss how the superfluidity of baryons (N,Y) is affected by $E_{\text{sym}}$, trying to use larger $E_{\text{sym}}$ in neutron star matter calculations.

We consider two cases

CASE-1 → without Y degrees of freedom
\[(n, p, e^-, \mu^-)\]

CASE-2 → with Y-mixing
\[(n, p, \Lambda, \Sigma^-, e^-, \mu^-)\]
Three elements in gap equations

Here, we note the 3-elements (Fermi momentum $k_{FB}$, effective mass $m^*_B$ and pairing interaction) to control the energy gap.

\[
\Delta_B(k) = -\frac{1}{\pi} \int \frac{k'}{d^3 k'} \langle k' \mid V_{BB} \mid 1\rangle \langle 1 \mid \Delta_B(k') \rangle \times \frac{\hat{\xi}_B^2(k') + \Delta_B^2(k')}{\sqrt{\hat{\xi}_B^2(k') + \Delta_B^2(k')}}
\]

\[
\hat{\xi}_B(k') \equiv \xi_B(k') - \xi_B(k_{FB}) \approx \frac{\hbar^2 (k'^2 - k_{FB}^2)}{2 m^*_B}
\]

For 3P2 NN pairing, the situation is similar, although the gap equation becomes complex due to the 3P2-3F2 tensor-coupling.
That is, $E_{\text{sym}}$ affects $y_\{B\}$ (fraction of baryon components) at a given $\rho$
\[ \rightarrow \text{affects } k_{\{FB\}}^2 = (3\pi \rho y_\{B\})^{1/3}, \text{ and also } m^*_\{B\} \]
(B=N,Y)

As for the pairing interaction for the baryon pair,
We use
OPEG-A (Tamagaki pot.) for NN
ND-soft (soft-core version of Nijmegen hard-core D-type pot.) for YY
□ Influence on NS cooling

○ Usually, direct URCA process (β-decay) is forbidden and modified URCA process becomes an efficient ν-emission process.

○ However, if \( y_p \) exceeds \( \sim 15\% \), β-decay can be possible and extremely efficient ν-emission provides a very rapid cooling scenario of NSs.

< Cooling processes due to ν-emission >

- But, if directly applied, it causes a serious problem of “too rapid cooling” incompatible with NS surface-temperature observations.

- This problem is resolved if baryon superfluidity to suppress “two rapid cooling” is realized.

  → Coexistence of direct URCA and superfluidity of associated baryons is essential for a fast cooling scenario to be compatible with observations.
CASE-1

(n, p, e⁻, μ⁻)

○ Large $E_{\text{sym}}$ → DBHF
○ Normal $E_{\text{sym}}$ → OPEG-A
Solid lines: Large $E_{sym}$
Dashed lines: Normal $E_{sym}$
Critical Temperature for Superfluids

- Large $E_{\text{sym}}$
- Normal $E_{\text{sym}}$

NS-Matter with OPEG-A Pot.

- OPEG-A pairing int.
- $m_n^*$, $m^*$ from G-Matrix cal. with OPEG-A
**CASE-2**

\[(n, p, \Lambda, \Sigma^{\text{-}}, e^{\text{-}}, \mu^{\text{-}})\]

- Large \(E_{\text{sym}}\) → 2.0 \(V_{\text{T0}}\) (RSC)
- Normal \(E_{\text{sym}}\) → 1.0 \(V_{\text{T0}}\) (RSC)

(*) Details of our approach are given by S. Nishizaki’s talk in this symposium (session V, tomorrow morning)
Summary

- For NSs composed of \((n, p, e^-, \mu^-)\), a large \(E_{\text{sym}}\) increases proton fraction and thereby the onset density for N-Durca is made lower \((\sim 3.5\rho_0)\). However, at that density-region, N-superfluidity disappears, leading to “too rapid cooling” and so N-Durca cannot be a candidate for the cooling scenario of colder class NSs.

- For NSs composed of \((n, p, e^-, \Lambda, \Sigma^-)\), a large \(E_{\text{sym}}\) increases \(y_p\) and also works for the appearance of hyperons at lower densities. The change of fractional density for baryon components \(\left(\rho_B = y_B \rho\right)\) causes the change of \(k_{FB}\) and \(m^*_B\). The net effect is the weakening of baryon superfluidities.

- N-Durca fails to coexist with N-super. In addition, \(\Lambda\)-super disappears when information from “NAGARA event” is taken into account. This situation indicates that a serious problem of “too rapid cooling” cannot be resolved even by a large \(E_{\text{sym}}\), requesting further studies on the cooling scenario consistent with observations.