Hyperon-Mixed Neutron Stars

Tatsuyuki TAKATSUKA*)

Faculty of Humanities and Social Sciences, Iwate University, Morioka 020-8550, Japan

(Received)

Hyperon mixing in neutron star matter is investigated by the G-matrix-based effective interaction approach under the attention to use the YN and the YY potentials compatible with hypernuclear data and is shown to occur at densities relevant to neutron star cores, together with discussions to clarify the mechanism of hyperon contamination. It is remarked that developed Y-mixed phase causes a dramatic softening of the neutron star equation of state and leads to the serious problem that the resulting maximum mass $M_{\rm max}$ for neutron star model contradicts the observed neutron star mass ($M_{\rm max} < M_{\rm obs} = 1.44M_{\odot}$), suggesting the necessity of some "extra repulsion" in hypernuclear system. It is shown that the introduction of three-body repulsion similar to that in nuclear system can resolve the serious situation and under the consistency with observation ($M_{\rm max} > M_{\rm obs}$) the threshold densities for Λ and Σ^- are pushed to higher density side, from $\sim 2\rho_0$ to $\sim 4\rho_0$ (ρ_0 being the nuclear density). On the basis of a realistic Y-mixed neutron star model, occurence of Y-superfluidity essential for "hyperon cooling" scenario is studied and both of Λ- and Σ^--superfluids are shown to be realized with their critical temperatures 10^{8-9} K, meaning that the "hyperon cooling" is a promising candidate for a fast non-standard cooling demanded for some neutron stars with low surface temperature. A comment is given as to the consequence of less attractive $\Lambda\Lambda$ interaction suggested by the "NAGARA event" ${}^{6}_{\Lambda\Lambda}$He.

§1. Introduction

Usually a liquid core of neutron stars are taken to be a system composed of predominant neutrons and small amount of protons, coexisting with electrons and muons assuring charge neutrality. With the increase of baryon density ρ toward the central region, however, there arises a strong possibility that hyperons, such as Λ, Σ^- and Ξ^-, could appear and become important constituents comparable to nucleons. This is because the chemical potential of predominant neutrons increases with increasing ρ and eventually it becomes energetically profitable to replace neutrons at the Fermi surface by hyperons through a strangeness non-conserving weak interaction, in spite of the higher rest-mass energy of hyperons. Thus the introduction of strangeness degrees of freedom into neutron stars (NS's) provides us with an exotic hypernuclear system not realized in laboratories and has a potential to bring about new insights into the strangeness nuclear physics, not constrained as in usual hypernuclei at ordinal nuclear density $\rho_0(\equiv 0.17$ nucleons/fm$^3)$.

In this paper, we study the hyperon-mixed NS's. Our first aim is to discuss the aspect of hyperon (Y) mixing on the basis of our recent works [1)−4)]. To date, this interesting problem has been discussed in many literatures, with starting from a simple but pioneering works [5),6)] made in an early stage of neutron star physics, and afterward by applying several many-body approaches such as variational [7),8)]

*) E-mail: takatuka@iwate-u.ac.jp

and G-matrix [9),10)] calculations in the potential description, mean-field treatments in the field description to include explicitly mesons [11)–20)] and also semiphenomenological methods [21)]. Of course, to be realistic for dense baryonic matter, it is essential to take into account the short-range correlations between baryons. In this respect, the variational or the G-matrix approaches are most reliable. Unfortunately, our knowledge of hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions has been very limited and accordingly the results of Y-mixing problem have not been free from large uncertainties. In recent years, however, this situation is greatly improved by the progress both in the experimental and the theoretical sides. Valuable information is extracted from hypernuclear data; about the YN interactions through the binding properties [22)–28)] and the effective mass [29)] in medium and also about the $\Lambda\Lambda$ interaction through the bond energies in double Λ hypernuclei [30)–35)]. Theoretical studies on baryon-baryon (BB) interactions from the viewpoints of OBE and /or quark cluster models are developed by several groups; Nijmegen [36),37)], Julich [38),39)], Tokyo [40),41)], Kyoto-Niigata [42),43)], Funabashi-Gifu [44)] and Ehime [45)]. Therefore the interests in Y- mixing in NS cores are being renewed. Here we study the subject through the G-matrix-based effective interaction approach, paying particular attention to the use of realistic YN and YY interactions compatible with hypernuclear data. We discuss the transition densities $\rho_t(Y)$ for each Y species and their populations in NS cores, together with the discussion as to the mechanism of Y contamination.

Our second aim is to explore the characterisitic property of the equation of state (EOS) responsible for Y-mixed neutron stars [1)–4)]. We find that the EOS with Y-mixing is dramatically softened as compared with that without Y-mixing, i.e., usual cases, and as a result the maximum mass $M_{\rm max}$ for Y-mixed neutron stars turns out to be by far smaller than the observed mass $M_{\rm obs}$(PSR1913+16)=$1.44M_\odot$, clearly contradicting observations ($M_{\rm max} < M_{\rm obs}$). This shortcoming suggests that some extra repulsion has to work in hypernuclear system. As an attempt we introduce phenomenologically the three-body repulsion with ρ-dependence into the hypernuclear system (YN and YY part), in analogy with that in nuclear system (NN part). As a consequence we have a reasonable Y-mixed neutron star models consistent with observations.

Our last aim is to address whether hyperons admixed in NS cores could be superfluid or not. This problem has been discussed in several literatures [46)–52)] and is of special interest in association with a rapid cooling scenario needed for some neutron stars. That is , recent observations of surface temperature for some NS's (e.g., Vela X-1, Geminga and PSRJ0205+6499) suggest the fact that these NS's are too cold to be cooled by a standard cooling scenario, i.e., typically the modified URCA ν-emission process (e.g., $n + n \to n + p + e^- + \bar{\nu}_e$), and so demands more efficient ν-emission mechanism, namely, the so-called non-standard scenario for fast cooling [53)]. The direct URCA ν-emission process made possible in a Y-mixed core (the β-decay process with Y, e.g., $\Lambda \to p+e^-+\bar{\nu}_e$), called as "hyperon cooling", is one of the candidates for such fast cooling mechanism [54)]. However, the direct application of hyperon cooling leads to a serious result of "too rapid cooling" and hence needs some suppression mechanism, most naturally, the superfluidity of hyperons [55),56)],

[57]. That is, the hyperon cooling can explain observations only when the hyperons can be superfluid. Our series of examinations show that this is the case, i.e., hyperons such as Λ and Σ^- are likely to be superfluid and the hyperon cooling scenario is a promising candidate compatible with the low surface temperature observed [49), 58)].

Outline of our approach and details of Y- mixing in NS cores are explained in the next section (§2). The EOS, the necessity of extra repulsion and Y-mixed neutron star models are discussed in §3. The Y-superfluidity and also n-and p-superfluidities in Y-mixed NS's are investigated in §4, where consequences on the cooling problem is discussed and also a comment is given to the disappearance of Λ-superfluid in a context of the less attractive $\Lambda\Lambda$ interaction suggested by the "NAGARA event" ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ [32]. The last section (§5) is for concluding remarks.

§2. Aspects of hyperon mixing

2.1. *Outline of approach*

For simplicity, we restrict ourselves to $Y \equiv \{\Lambda, \Sigma^-\}$ as the hyperon components, neglecting the contamination of Ξ^- component because it would be less likely for Ξ^- to appear due to the higher mass ($m_{\Xi^-} = 1321$ MeV compared to $m_\Lambda = 1116$ MeV and $m_{\Sigma^-} = 1192$ MeV). We calculate the Y-mixed NS matter composed of n, p, Λ, Σ^-, e^- and μ^- by an affective interaction approach. In practice, we construct the YN and YY effective local potentials, $\tilde{V}_{YN}$ and $\tilde{V}_{YY}$, in a ρ- and y_Y- dependent way, from the G-matrix calculations carried out for $\{n+Y\}$ matter with the mixing ratio $y_Y (\equiv \rho_Y/\rho)$. In these calculations, we use the YN and YY interactions from the Nijmegen D-type hard core potentials [36] with a slight modification in the S-state ΛN part (NHC-Dm) [29] as a best choice, since this BB interaction model gives results most consisitent with hypernuclear data. More details for the construction of $\tilde{V}_{YN}$ and $\tilde{V}_{YY}$ are referred to Refs.1) and 4).

As for the NN effective local potential $\tilde{V}_{NN}$, we use it as $\tilde{V}_{NN} = \tilde{V}_{\mathrm{RSC}} + \tilde{V}_{\mathrm{TNI}}$, i.e., the two-nucleon effective potential $\tilde{V}_{\mathrm{RSC}}$ [59] constructed previously from the G-matrix results with the Reid- Soft-Core potential [60], supplemented by the phenomenological three-body potential $\tilde{V}_{\mathrm{TNI}}$ [61]. Our $\tilde{V}_{\mathrm{TNI}}$ is expressed in the effective two-body force with ρ-dependence and consists of two parts, the attractive ($\tilde{V}_{\mathrm{TNA}}$) and the repulsive ($\tilde{V}_{\mathrm{TNR}}$) parts ($\tilde{V}_{\mathrm{TNI}} = \tilde{V}_{\mathrm{TNA}} + \tilde{V}_{\mathrm{TNR}}$) and is based on the three-nucleon interaction (TNI) proposed by Lagaris and Pandharipande [62), 63)]. The contribution from TNA is minor at high densities and that from TNR dominates in TNI, giving the repulsion increasing with ρ. Parameters in $\tilde{V}_{\mathrm{TNI}}$ are determined so as to reproduce the empirical saturation property of symmetric nuclear matter and the nuclear incompressibility κ measuring the stiffness of a nuclear- part EOS (N-part EOS); e.g., $\kappa = 250$ MeV (TNI2), $\kappa = 300$ MeV (TNI3) and $\kappa = 280$ MeV (TNI6).

By using these effective interactions, $\tilde{V}_{NN}$, $\tilde{V}_{YN}$ and $\tilde{V}_{YY}$, we calculate the fractions y_i (mixing ratios) for respective components ($i = n$, p, Λ, Σ^-, e^- and μ^-) in β equilibrium, under the conditions of charge neutrality, chemical equilibrium and baryon number conservation, together with the EOS responsible for the Y-mixed NS's. We also obtain the effective-mass parameters $m^*_Y(\rho)$ of hyperons in medium in a ρ-dependent way, which are to be used in the discussion of Y-superfluidity.

2.2. *Mechanism of Y-mixing*

Before going to the results for full calcurations, we discuss the mechanism of Y-contamination and emphasize that the Y-mixed baryon matter is sure to be realized. Meanwhile we focus attention only to the kinetic energy part with rest-mass energy, ignoring the interaction energy part. Then the threshold condition for Λ to appear in neutron star matter ($y_n \sim 1$) is given by

$$m_\Lambda c^2 = \mu_\Lambda = \mu_n = \epsilon_{Fn} + m_n c^2, \tag{2·1}$$

where $\mu_\Lambda(\mu_n)$ is the chemical potential of $\Lambda(n)$, the rest-mass energies are as $m_\Lambda c^2 =$ 1116 MeV and $m_n c^2 = 940$ MeV, and $\epsilon_{Fn} = \hbar^2(3\pi^2 y_n \rho)^{2/3}/2m_n$ is the Fermi kinetic energy of a neutron on the Fermi surface. We see the condition (2·1) is satisfied at $\rho \simeq 5\rho_0$ for $y_n = 1$, namely, Λ can participate for $\rho \gtrsim \rho_t(\Lambda) \simeq 5\rho_0$ even for the case without interactions. This density regime is well realized in the central cores of NS's, teaching us the importance to include the hyperon degrees of freedom.

When the interactions are switched on, the condition (2·1) becomes as

$$m_\Lambda c^2 + U_\Lambda(0) = \mu_\Lambda = \mu_n = \epsilon_{Fn} + U_n(k_{Fn}) + m_n c^2, \tag{2·2}$$

where k_{Fn} is the Fermi momentum of neutrons, $U_\Lambda(k)$ $(U_n(k))$ is a single-particle potential dependent on the momentum k and $k = 0$ $(k = k_{Fn})$ for the particle $\Lambda(n)$ at the threshold. Since the existence of Λ hypernuclei means the net attractive contribution from ΛN interaction, we expect that $U_\Lambda(0)$ would be negative. On the contrary, $U_n(k_{Fn})$ may well be repulsive in dense matter with $\rho \gtrsim 2\rho_0$. Then the comparison of Eq.(2·2) with Eq.(2·1) clearly shows that Λ is able to appear at lower densities than $5\rho_0$.

Next we discuss the case of Σ^-- mixing. In this case, the threshold condition is given by

$$m_{\Sigma^-} c^2 = \mu_{\Sigma^-} = \mu_n + \mu_e = \epsilon_{Fn} + m_n c^2 + \mu_e \tag{2·3}$$

for non-interacting case and

$$m_{\Sigma^-} c^2 + U_{\Sigma^-}(0) = \mu_{\Sigma^-} = \mu_n + \mu_e = \epsilon_{Fn} + U_n(k_{Fn}) + m_n c^2 + \mu_e \tag{2·4}$$

for the case with interactions, where μ_{Σ^-} (μ_e) is the chemical potential of Σ^- (e^-). Since electrons are highly relativistic and $\mu_e = \sqrt{k_{Fe}^2 + (m_e c^2)^2}$ amounts to (100-200) MeV depending on y_e and ρ, and also the mass difference between Σ^- and Λ is about 80 MeV, the condition (2·3) can be satisfied at lower density compared to the case of Λ-mixing (Eq.(2·1)). The condition (2·4) shows that the difference between $U_{\Sigma^-}(0)$ and $U_\Lambda(0)$ also affects which of Λ and Σ^- is the first to appear.

To summarize, we want to stress the following points:
(i) Both of Λ- and Σ^-- mixings depend not only on the YN interaction but also on the NN interaction. The threshold density $\rho_t(Y)$ gets lower and the mixing ratio $y_Y(\rho)$ becomes larger as the attraction (the repulsion) of YN (NN) interactions become stronger. Generally, $\rho_t(Y)$ is lower for stiffer N-part EOS.
(ii) In addition, the nuclear symmetry energy $E_{\rm sym}(\rho)$ plays an important role. Larger $E_{\rm sym}(\rho)$ realizes lower $\rho_t(\Sigma^-)$ because larger $E_{\rm sym}(\rho)$ means higher y_p (hence higher y_e) and thereby larger μ_e leading to the lower $\rho_t(\Sigma^-)$ to satisfy the condition (2·4). That is, Σ^- is more likely to appear for the N-part EOS with larger $E_{\rm sym}(\rho)$.
(iii) It should be noted that $E_{\rm sym}$ also affects $\rho_t(Y)$ through $U_n(k_{Fn})$ in Eqs.(2·2) and (2·4), since larger $E_{\rm sym}$ means lower $y_n(= 1 - y_p)$ and hence lower k_{Fn}, suppressing the increase of repulsion from $U_n(k_{Fn})$. In Λ- or Σ^--mixing, this acts for higher $\rho_t(Y)$.

2.3. *Numerical results for Y-mixing*

As mentioned in the previous section, Λ begins to appear at $\rho \simeq 5\rho_0$ even for the non-interacting case. To see transparently how the interactions affect $\rho_t(\Lambda)$, we treat a simplified system composed of n, p, Λ, e^- and μ^-. Results are shown in Table I. The effects of interactions causes a downward shifts of $\rho_t(\Lambda)$ as $\rho_t(\Lambda) \simeq 5.07\rho_0$ $\rightarrow 3.98\rho_0 \rightarrow 2.94\rho_0$ according to the non-interacting $\rightarrow$ only with $U_\Lambda(0) \rightarrow$ both with $U_\Lambda(0)$ and $U_n(k_{Fn})$, for $\tilde{V}_{\Lambda N}$ from NHC-Dm and $\tilde{V}_{NN}$ with TNI2. The effect of $U_\Lambda(0)$ depends on the YN interaction, to the extent that $\rho_t(\Lambda) \simeq 4.99\rho_0$ for NHC-F (Nijmegen F-type) [36] in comparison with $\rho_t(\Lambda) \simeq 3.98\rho_0$ for NHC-Dm. This comes from the difference, which grows with ρ, in the partial-wave contributions between NHC-F and NHC-Dm, although they equally reproduce $U_\Lambda(0) \simeq -30$ MeV from hypernuclear data. Also more repulsive $U_n(k_{Fn})$ works for lower $\rho_t(\Lambda)$; $\rho_t(\Lambda) \simeq$ $3.98\rho_0 \rightarrow 2.94\rho_0 \rightarrow 2.39\rho_0$ as no TNI ($\kappa = 153$ MeV) $\rightarrow$ TNI2 ($\kappa = 250$ MeV) $\rightarrow$ TNI3 ($\kappa = 300$ MeV), showing lower $\rho_t(\Lambda)$ for stiffer N-part EOS.

Results for the full system composed of n, p, Λ, Σ^-, e^- and μ^- are illustrated

Table I. Dependence of the threshold density $\rho_t(\Lambda)$ for Λ-mixing on the effects of YN and YY interactions. κ is the nuclear incompressibility and ρ denotes the nuclear density.

$\rho_t(\Lambda)/\rho_0$	for YN, YY	and NN=RSC+TNI (κ in MeV)
5.07		non-interacting case
3.98	NHC-Dm	RSC (153)
4.99	NHC-F	RSC (153)
2.94	NHC-Dm	RSC+TNI2 (250)
2.39	NHC-Dm	RSC+TNI3 (300)

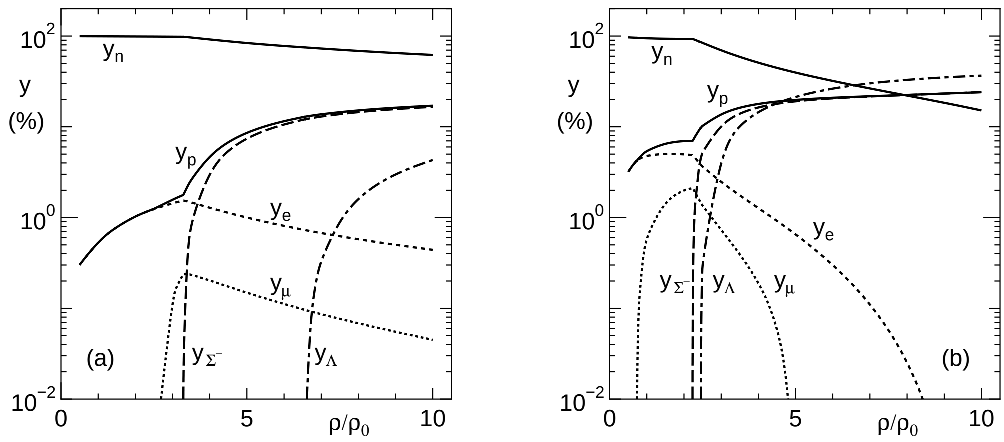

Fig. 1. Fractions $y_i(\equiv \rho_i/\rho)$ of respective component ($i = n, p, \Lambda, \Sigma^-, e^-, \nu^-$) for Y-mixed neutron star matter as a function of total baryon density ρ in the unit of nuclear density ρ_0 ($\equiv 0.17$ nucleons/fm^3); (a) non-interacting case and (b) interacting case through YN, YY (NHC-Dm) and NN (RSC+TNI3) potentials (denoted by TNI3 in short). TNI3 case generates the nuclear-part EOS with incompressibility $\kappa = 300$ MeV.

in Figs.1 for (a) non-interacting case and (b) interacting case through YN, YY (NHC-Dm) and NN (RSC+TNI3) potentials. In the non-interacting case, $\rho_t(\Sigma^-)(\simeq 3.28\rho_0)$ is much smaller than $\rho_t(\Lambda)(\simeq 5.07$ for Eq.(2·1)) due to large μ_e overwhelming $\Delta mc^2 = (m_{\Sigma^-} - m_\Lambda)c^2$, as explained in 2.2. In other words, the Σ^--mixing precedes the Λ- mixing, owing to the fact that Σ^- with negative charge, in different from charge neutral Λ, can subsititute for electrons with high energy and thereby can reduce the total energy of the system. Fig.1(a) also shows that $\rho_t(\Lambda)$ is pushed to higher density side, i.e., $\rho_t(\Lambda) \simeq 6.57\rho_0$ compared to $\rho_t(\Lambda) \simeq 5.07\rho_0$ in the case only with Λ. This upward shift is due to the reduction of y_n caused by the preceding mixing of Σ^- and the constraint from baryon number conservation, since smaller y_n means higher $\rho_t(\Lambda)$ in Eq.(2·1).

Comparison of Fig.1(a) with Fig.1(b) shows that interactions shift the threshold densities down to the values $\rho_t(\Sigma^-) \simeq 2.23\rho_0$ and $\rho_t(\Lambda) \simeq 2.45\rho_0$ through the effects of $U_Y(0)$ and $U_n(k_{Fn})$ in Eqs.(2·2) and (2·4), respectively. It is remarked that Λ and Σ^- start to appear at almost the same density, in contrast with $\rho_t(\Sigma^-) << \rho_t(\Lambda)$ for non-interacting case. This is because the $\Sigma^- n$ interaction with total isospin $\frac{3}{2}$ state dominating in NS matter is repulsive [26), 27)] in contrast with the attractive Λn interaction. As to the dependence on $U_n(k_{Fn})$ closely related to the NN repulsion, the changes of $\rho_t(Y)$ are such that $\rho_t(\Sigma^-) \simeq 2.23\rho_0 \to 2.83\rho_0$ and $\rho_t(\Lambda) \simeq 2.45\rho_0 \to 2.95\rho_0$ for RSC+TNI3 ($\kappa = 300$ MeV) $\to$ RSC + TNI2($\kappa = 250$MeV), namely, for less repulsive NN interaction (softer N-part EOS).

Once the hyperons start to appear, the fraction $y_Y(\rho)$ increases monotonusly with ρ and amounts to $y_{\Sigma^-} \simeq 22\%$ and $y_\Lambda \simeq 30\%$ at $\rho \simeq 6\rho_0$, for instance. Accordingly, a notable change of y_n and y_p take place; y_n of neutrons predominated before Y-mixing decreases with ρ and also y_p of protons compensating the negative charge of Σ^- increases with ρ, accompanying the decrease of y_e and y_μ substituted by y_{Σ^-}; $y_n \simeq 36\%$, $y_p \simeq 22\%$, $y_e < 1\%$, and $y_\mu < 1\%$ at $\rho = 6\rho_0$. Thus, in the core region of NS's, hyperons becom components comparable with nucleons. This aspect is very different from the usual NS matter, where neutrons dominate with $y_n \gtrsim 90\%$ and protons are admixed with $y_p \lesssim 10\%$, and is expected to bring about new effects on NS properties. In the next section, we discuss the EOS with Y-mixing.

§3. Necessity of Extra Repulsion

In Fig.2, EOS's expressed by the total energy per baryon versusu ρ, are compared between the cases with Y and without Y, for the use of $\tilde{V}_{BB}$ (RSC+TNI3, NHC-Dm; hereafter denoted simply by TNI3). A notable feature is a dramatic softening of the EOS due to the Y-mixing, which means that the maximum mass $M_{\rm max}$ of NS's sustained by the EOS with Y is greatly reduced compared to the case without Y. For the cases TNI2 ($\kappa = 250$ MeV) and TNI6 ($\kappa = 280$ MeV) this situation is quite similar. In fact, $M_{\rm max} \simeq 1.08 M_\odot$ with Y compared to $M_{\rm max} \simeq 1.62 M_\odot$ without Y as shown in Fig.3(a) for TNI2 case. The results $M_{\rm max} \simeq 1.08 M_\odot$ is remarkabley smaller than $M_{\rm obs} = 1.44 M_\odot$ observed for the neutron star PSR1913+16. This inconsistency between theory and observation cannot be resolved by enhancing the stiffness in N-part EOS, i.e., the use of TNI3 ($\kappa = 300$ MeV), as shown in Fig.3(b). In this case, $M_{\rm max} \simeq 1.10 M_\odot$ with Y, whereas $M_{\rm max} \simeq 1.88 M_\odot$ without Y. This is because the stiffer the N-part EOS, the Y-mixed phase developes from lower densities as discussed in 2.2 and thereby the softening effect become all the more stronger.

Of course, the the problem $M_{\rm max} < M_{\rm obs}$ could occur also by a strongly softened EOS relevant to pion or kaon condensates. But in these cases, $M_{\rm max} > M_{\rm obs}$ can be ensured by choosing a stiffer N-part EOS within the present uncertainties in the

Fig. 2. EOS's expressed by the total energy per baryon versus ρ for cases with Y and without Y by the use of $\tilde{V}_{BB}$ (RSC+TNI3, NHC-Dm). TNI3u denotes the case where TNR3 is included universally, i.e., also for YN- and YY-parts. Dotted lines are the contributions from kinetic energy plus rest-mass energy.

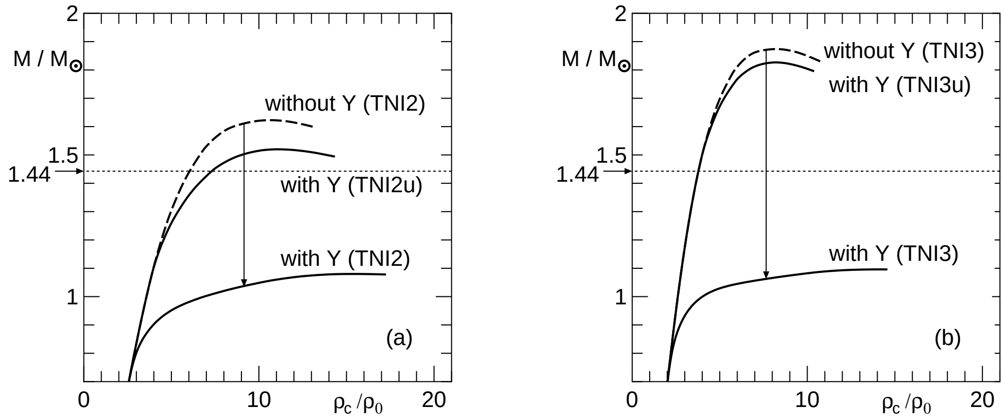

Fig. 3. Mass M versus central density ρ_c for neutron star models with Y and without Y; (a) TNI2 and TNI2u cases ($\kappa = 250$ MeV) and (b) TNI3 and TNI3u cases ($\kappa = 300$ MeV). Notations are the same as those in Fig.2.

short-range NN repulsion. In the Y-mixed case, however, this problem cannot be solved by such a choice, as just mentioned above, and so serious. In addition, this serious problem is not a consequence peculiar to our way of approach, i.e., our weaker NN repulsion from the Reid-Soft-Core potential ($\tilde{V}_{\rm RSC}$) supplemented by TNI or our many-body approach using G-matrix method. Baldo et al [9]. used the N-part EOS from G-matrix approach where a modern NN potential with a stronger repulsive core, such as the AV14 potential [64] or Paris potential [65], is adopted together with a three-body repulsion, but they obtained $M_{\rm max} \simeq (1.22 - 1.26)M_\odot$. Vida$\tilde{n}$a et al. [10] obtained $M_{\rm max} \simeq 1.34M_\odot$ even in the case of a stiffer N-part EOS, in particular, the EOS by Akmal et al. [66] based on a variational calculations. Therefore the result $M_{\rm max} < M_{\rm obs}$ is taken to be common to NS models with Y-mixing, as far as a realistic treatment of NN interactions and short-range correlations are duely taken into account.

Here we wish to stress that conversely speaking, the problem $M_{\rm max} < M_{\rm obs}$ is an interesting problem suggesting a necessity of some “extra repulsion” in hypernuclear systems. As one of the candidates, we try to introduce the repulsion from the three-body force since the importance of the three-body interaction is well recognized for nuclear system [67] and should not be restricted to nuclear system. For simplicity, we try to include universally the repulsion of our TNI, $\tilde{V}_{\rm TNR}$, also into the YN and the YY parts, as well as in the NN part (hereafter called “universal inclusion of TNI” and denoted in short by TNIu). Then, we have a moderate softening, not a dramatic softening as before, as shown in Fig.2. Correspondingly we have a larger $M_{\rm max}$, as shown in Fig.3; $M_{\rm max} \simeq 1.54M_\odot$ for TNI2u and $M_{\rm max} \simeq 1.84M_\odot$ for TNI3u, nicely satisfying the condition $M_{\rm max} > M_{\rm obs} = 1.44M_\odot$ from observations. As to the aspect of Y-mixing, we illustrate in Fig.4 the fractions $y_i(\rho)$ for respective components by making comparison between TNI6 (Fig.4(a)) and TNI6u (Fig.4(b)) cases. It is noted that the realization of a Y-mixed phase is pushed to higher density side; $\rho_t(\Lambda) \simeq (2.60 \to 4.02)\rho_0$ and $\rho_t(\Sigma^-) \simeq (2.43 \to 4.06)\rho_0$ for TNI6$\to$ TNI6u.

Table II. Typical quantities relevant to Y-mixed neutron stars. $M_{\max}$, R and ρ_c are respectively the mass, the radius and the central density for a maximum mass neutron star with Y-mixing, and $\rho_t(\Lambda)$ ($\rho_t(\Sigma^-)$) denotes the threshold density for $\Lambda(\Sigma^-)$-mixing.

EOS	$\rho_t(\Lambda)/\rho_0$	$\rho_t(\Sigma^-)/\rho_0$	$M_{\max}/M_\odot$	R/km	ρ_c/ρ_0
TNI2	2.95	2.83	1.08	7.70	16.10
TNI6	2.60	2.43	1.09	8.07	14.67
TNI3	2.45	2.23	1.10	8.28	13.90
TNI2u	4.01	4.06	1.52	8.43	11.08
TNI6u	4.02	4.06	1.71	9.16	9.07
TNI3u	4.01	4.01	1.83	9.55	8.26

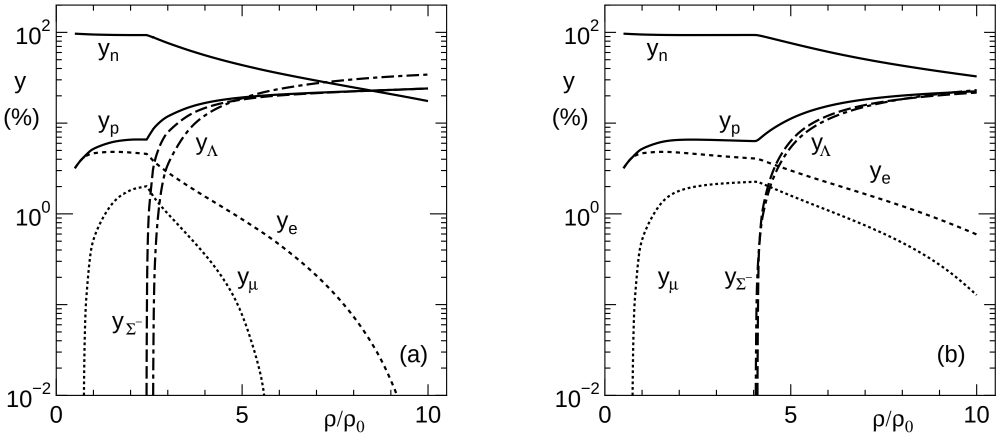

Fig. 4. Fractions y_i versus ρ; (a) TNI6 and (b) TNI6u cases. TNI6 and TNI6u cases generate the nuclear-part EOS with incompressibility $\kappa = 280$ MeV. Notations are the same as those in Fig.1.

Results for TNI2u and TNI3u cases are quite similar, and typical quantities relevant to neutron star models with Y-mixing are summarized in Table II.

It is worth while to give a comment on the mechanism of a dramatic softening of the EOS encountered here[3), 4)]. In the Y-mixed phase, the number of baryon species is larger than that in normal NS matter composed of n and p and hence the sum of the Fermi kinetic energies (KE) is made lower at a fixed ρ due to the increased degrees of freedom. The statement that the softening effect comes from this energy gain is not correct, because the KE including the rest-mass energy (i.e., KE+Δmc^2) is almost the same between the cases with Y and without Y, as shown in Fig.2 by the dotted curves. From the figure, we can see that the energy gain, i.e., the softening effect, is brought about not by the KE part (including Δmc^2) but by the interaction energy part. For NS matter without Y, short- range repulsions dominate in the interaction energies at high densities ($\rho \gtrsim (3-4)\rho_0$), especially for neutrons. On the other hand, for NS matter with Y, the fractional density $\rho_i (= y_i \rho)$ of respective baryon species ($i = n, p, \Lambda, \Sigma^-$) is made lower and thereby the short-range repulsions become less effective, leading to a remarkable energy gain from the case without Y. This is an essential point in the softening mechanism.

§4. Superfluidity of Hyperons and Consequences on Neutron Star Cooling

In this section, we discuss whether hyperons could be in the superfluid state or not, on the basis of the Y-mixed NS models obtained in the previous section. The aspect of Y-mixed NS models (TNI2u, TNI3u, TNI6u) are very similar and here we concentrate on the TNI6u case.

4.1. *Realization of Hyperon Superfluids*

Hyperons participate in a high-density region ($\rho \gtrsim \rho_t(Y) \simeq 4\rho_0$) of neutron star cores, but their fractional densities ρ_Y ($= y_Y\rho$; $Y \equiv \Lambda$, Σ^-) are relatively low (Fig.4(b)). Then the pairing interaction V_{YY} responsible for the Y-superfluidity should be the YY interaction in the ${}^1S_0$ state ($V_{YY}({}^1S_0)$) which is most attractive at low scattering energies corresponding to low Fermi energies $\epsilon_{FY} (= \hbar^2(3\pi^2\rho_Y)^{2/3}$ $/2m_Y)$. Therefore the energy gap equation to be treated here is a well-known ${}^1S_0$-type [68]:

$$\Delta_Y(q) = -\frac{1}{\pi}\int_0^\infty q'^2 dq' < q' \mid V_{YY}({}^1S_0) \mid q > \Delta(q')/\sqrt{\tilde{\varepsilon}_Y^2(q') + \Delta_Y^2(q')}, \quad (4\cdot1)$$

$$\tilde{\varepsilon}_Y(q) \equiv \varepsilon_Y(q) - \varepsilon_{FY} \simeq (q^2 - q_{FY}^2)/2m_Y^*, \quad (4\cdot2)$$

$$< q' \mid V_{\ YY}({}^1S_0) \mid q > \equiv \int_0^\infty r^2 dr j_0(q'r) V_{YY}(r;{}^1S_0) j_0(qr), \quad (4\cdot3)$$

where $\Delta_Y(q)$ is the energy gap function, q_F ($= (3\pi^2\rho y_Y)^{1/3}$) is the Fermi momentum and m_Y^* denotes the effective mass of Y in medium. As in Eq.(4·2), we take the effective-mass approximation for the single-particle energy $\varepsilon_Y(q)$. We use a bare $V_{YY}({}^1S_0)$ and do not introduce the effective interaction $\tilde{V}_{YY}({}^1S_0)$ instead of $V_{YY}({}^1S_0)$, as adopted in Ref. 51), since the use of $\tilde{V}_{YY}$ in the gap equation leads to an incorrect result due to the double counting of the short-range correlation effect. When $V_{YY}({}^1S_0)$, y_Y and m_Y^* are given, the ${}^1S_0$-gap equation (Eq.(4·1) with Eqs.(4·2) and (4·3)) can be solved exactly by a numerical method and the energy gap $\Delta_Y (\equiv \Delta_Y(q_{FY}))$ is obtained.

Since the YY pairing interaction is not so certain as NN case, we consider three OBE-type potentials, ND-Soft [33), 47)], Ehime [45)] and FG-A [44)], expecting to cover the present uncertainties, which are based on the SU(3) symmetry hypothesis with the framework of the octet baryons and the nonet mesons. The main difference are in the meson species introduced and the treatment of the short-range interaction: ND-Soft is a soft-core version of the original Nijmegen D-type hard-core potential (NHC-D) [36)], constructed so as to fit the t-matrix from NHC-D, and is expressed simply by a superposition of three-range Gausian functions. Ehime is a potential from the Ehime group, characterized by an application of the OBE scheme throughout all

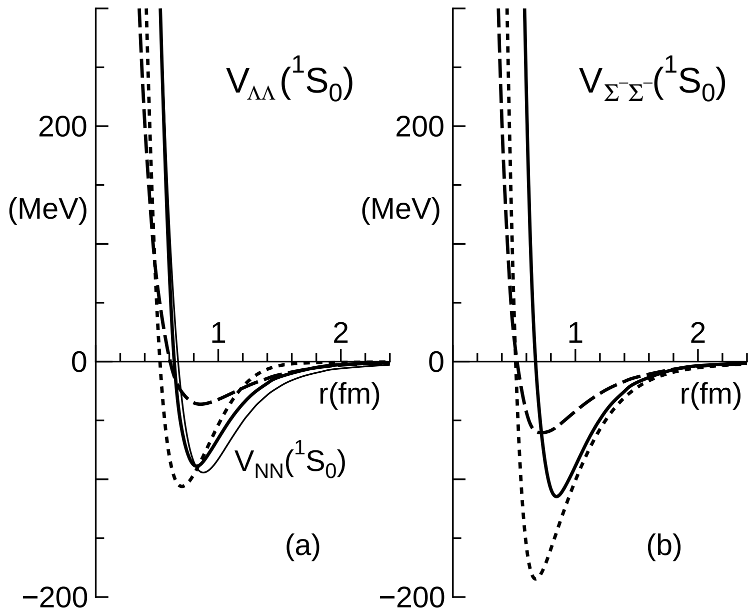

Fig. 5. YY interaction in the $^1S_0$ state; (a) for $\Lambda\Lambda$ and (b) for $\Sigma^-\Sigma^-$. Solid, dashed and dotted lines correspond to the baryon-baryon potential from ND-Soft, Ehime and FG-A and the thin solid line is for the $^1S_0$ NN potential from OPEG-A. Notations are explained in the text.

the interaction ranges and by the phenomenological introduction of a neutral scalar meson to take the 2π-correlation effects into account, in addition to nonet scalar mesons. FG-A is the potential type-A from the Funabashi-Gifu group, where the σ-meson is introduced in the nonet scheme and a phenomenological repulsive core is introduced with the strengths constrained by the SU(3) representation of two-baryons. Ehime includes the velocity dependent terms and FG-A includes both of the velocity-dependence and the retardation effects.

The attractive effect coming from the $\Lambda\Lambda-\Sigma\Sigma-\Xi N$ channel coupling is significant for the $V_{\Lambda\Lambda}(^1S_0)$. In FG-A, this effect is taken into account by adding an extra term $\Delta V_{\rm sim}$ to the direct- channel part $V^D_{\Lambda\Lambda}(^1S_0)$ so that $V^{(\rm eff)}_{\Lambda\Lambda}(^1S_0) \equiv V^D_{\Lambda\Lambda}(^1S_0) + \Delta V_{\rm sim}$ can simulale the $^1S_0$ $\Lambda\Lambda$ phase shifts including the channel coupling effect. We use this $V^{(\rm eff)}_{\Lambda\Lambda}(^1S_0)$ as $V_{\Lambda\Lambda}(^1S_0)$, by taking $\Delta V_{\rm sim} = 93e^{-(r/r_1)^2} - 1000e^{-(r/r_2)^2}$ MeV with $r_1 = 1.0$ fm and $r_2 = 0.6$ fm [48]. For ND-Soft, the channel coupling effect is already included in the original t-matrix to be fitted, and for Ehime, this effect has no relevance since it is constructed in a single-channel approximation. Three potentials are shown in Fig.5 for $\Lambda\Lambda$ and $\Sigma^-\Sigma^-$ cases, where $V_{NN}(^1S_0)$ from OPEG ^{1}E-A potential [69] is also shown for comparison. $V_{\Lambda\Lambda}(^1S_0)$ is observed to be less attractive but not so different from $V_{NN}(^1S_0)$ and suggests a possible occurence of Λ-superfluidity depending on m^*_Λ and y_Λ. $V_{\Sigma^-\Sigma^-}$ is more attractive than $V_{\Lambda\Lambda}(^1S_0)$, which means that Σ^--superfluidity is more likely to occur than Λ-superfluidity as far as the pairing interaction is concerned. Three potentials differ considerably both in the short-range repulsion and in the intermediate-range attraction; e.g., ND-Soft

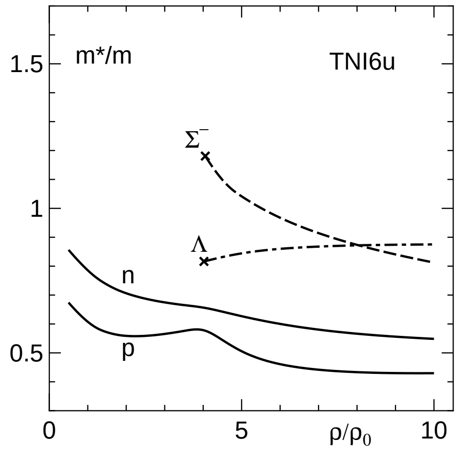

Fig. 6. Effective-mass parameter $\tilde{m}^*_B (\equiv m^*_B/m_B)$ of baryons versus ρ in Y- mixed neutron star matter for the TNI6u case where Λ and Σ^- start to appear at around $4\rho_0$.

has a stronger repulsion and a deeper attraction than Ehime, and FG with less repulsive core (smaller core radius) is expected to generate more attractive effects than ND-Soft and Ehime at higher densities.

As for the Y-mixing ratio y_Y and the effective mass m^*_Y, we use those from TNI6u model. y_Y are already shown in Fig.4(b). m^*_Y are plotted in Fig.6 in terms of the effective-mass parameter $\tilde{m}^*_Y$ defined by $\tilde{m}^*_Y = m^*_Y/m_Y$, where $\tilde{m}^*_N$ are also shown for comparison. It is noted that at the densities $\rho \simeq (4-6)\rho_0$ of interest, $\tilde{m}^*_\Lambda \simeq (0.82-0.86)$ and $\tilde{m}^*_{\Sigma^-} \simeq (1.18-0.97)$ are remarkabley larger than $\tilde{m}^*_n \sim (0.66-0.60)$ and $\tilde{m}^*_p \sim (0.59-0.46)$. This feature means that Y- superfluidities, especially Σ^- -superfluidity, are more likely to occur than N-superfluidities, as far as the effective masses are concerned.

Calculated results are shown in Fig.7(a) in terms of the critical temperature $T_c(Y)$ defined by $k_B T_c(Y) \simeq 0.57\Delta_Y$ with k_B the Boltzmann constant. Following points are to be noted [49), 58)].

(i) Both of Λ and Σ^- are likely to be in a superfluid state, since their $T_c(Y)$, although depending on $V_{YY}(^1S_0)$ and ρ, are well above the internal temperature $T \simeq 10^8$ K of ordinal neutron stars.

(ii) Λ and Σ^- become superfluids as soon as they appear in neutron star cores. Λ-superfluid is realized in a limited density region ($\rho \sim (4-6)\rho_0$) while Σ^-- superfluid exists up to higher densities.

(iii) $T_c(\Sigma^-) \sim 10^{10-11}$ K for Σ^--superfluid is larger than $T_c(\Lambda) \sim 10^9$ K by more than one order of magnitude, which comes mainly from extremely large $\tilde{m}^*_{\Sigma^-}(\sim 1)$ compared to $\tilde{m}_\Lambda(\sim 0.8)$. This means that Σ^--superfluidity is already realized even at an early stage of thermal evolution where T is as high as 10^{10} K.

4.2. *Hyperon Cooling Scenario*

As mentioned in §1, the existence of Y- superfluids shown here supports the idea of hyperon cooling scenario for neutron stars with low surface temerature. In the

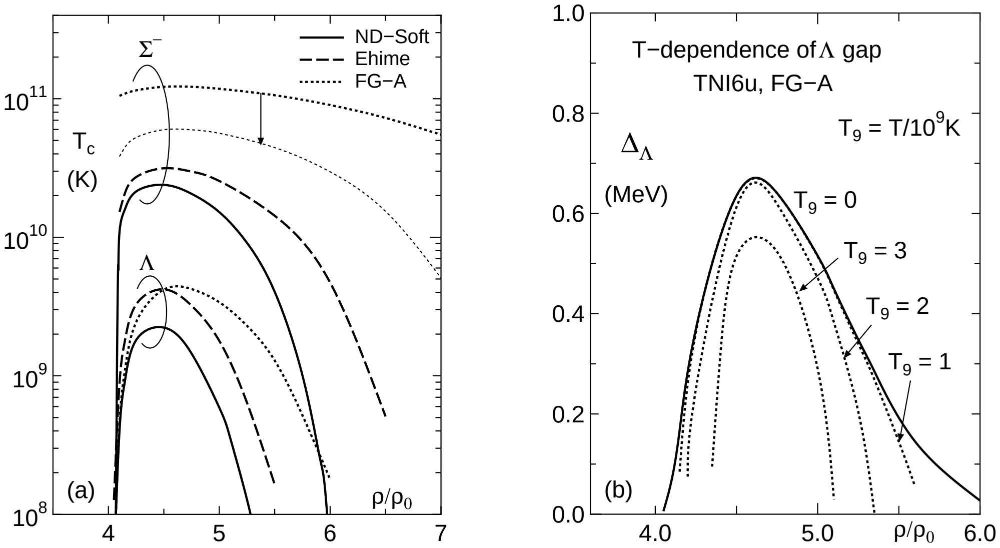

Fig. 7. (a) Critical temperatures $T_c(Y)$ of hyperon superfluids as a function of ρ, defined by $\kappa_B T_c(Y) = 0.57\Delta_Y$ with Δ_Y being the $^1S_0$ energy gap at zero temperature ($T = 0$) and κ_B the Boltzmann constant, calculated for y_Y and $\tilde{m}^*_Y$ from TNI6u case and for the $^1S_0$ pairing interactions corresponding to those in Fig.5. The arrow attached to the FG-A case indicates the decrease of T_c due to a less attractive $\Lambda\Lambda$ interaction suggested by the "NAGARA event". (b) Temperature (T) dependence of Λ energy gap Δ_Λ for TNI6u parameters and FG-A $\Lambda\Lambda$ potential.

cooling calculations, we need ν-emissibities for various ν-emission processes for which n- and p-superfluidities as well as Y- superfluidities play important roles through the influences on heat capacity and suppression effects for the rate of ν- emission. In Fig.8, we show the superfluid results for all the baryon componets in the case of the TNI6u Y-mixed neutron star model [58)], where $T_c(n)$ and $T_c(p)$ are calculated for OPEG-A NN potentials [69)], and $T_c(\Lambda)$ and $T_c(\Sigma^-)$ are for ND-Soft YY potential. We see that superfluidities of nucleon components are also realized ($T_c(N) \gtrsim 10^8$ K); p-superfluid is of the $^1S_0$-type corresponding to low ρ_p like ρ_Y, whereas n-superfluid is of the $^3P_2$-type corresponding to high ρ_n because at high densities the pairing interaction $V_{NN}(^3P_2)$ in the $^3P_2$ state, instead of $V_{NN}(^1S_0)$, becomes most attractive (details are referred to Ref.68)). $T_c(N)$ decreases gradually with ρ and is smaller than $T_c(Y)$. This comes mainly from the fact that $\tilde{m}^*_N$ is remarkably smaller than $\tilde{m}^*_Y$ (Fig.6). A sharp drop of $T_c(p)$ just beyond the $\rho_t(\Sigma^-)(\simeq 4\rho_0)$ is caused by the rapid increase of y_p (hence k_{Fp}) making stronger the repulsive core effect.

The results in Fig.8 are from the energy gap of baryons at zero temperature ($T = 0$). In Fig.7(b), we show how the energy gap is affected by the effect of finite temperature T, taking Δ_Λ for ND-Soft and TNI6u as an example [50)]. A remarkable T- dependence of energy gap is observed, which indicates the importance of using the T- dependent Δ_i ($i = n, p, \Lambda, \Sigma^-$) in the calculation for thermal evolution of neutron stars, since Δ_i, not $T_c(i)$, enters in the physical inputs associated. In fact, we derive the ν-emissibities by taking account of the T-dependence of Δ_i, as well as the ρ-

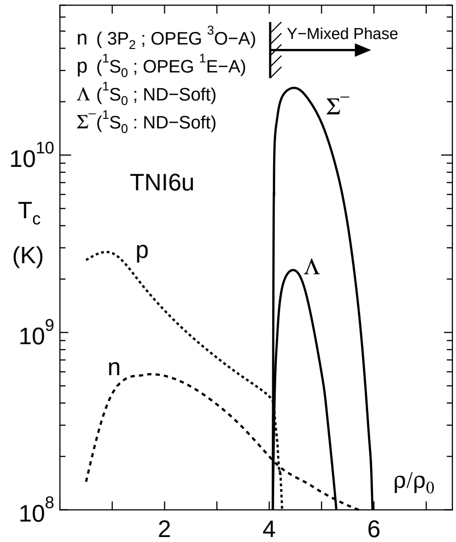

Fig. 8. Critical temperature T_c versus ρ for baryon superfluids in Y-mixed neutron star matter calculated for TNI6u parameters and for pairing interactions taken as ${}^1S_0$ YY interaction from ND-Soft, ${}^1S_0$ pp interaction from OPEG ^{1}E-A and ${}^3P_2$ nn interaction from OPEG ^{3}O-A potentials.

dependence[70]. At low and intermediate densities ($0.5\rho_0 \lesssim \rho \lesssim 4\rho_0$) where hyperons are absent, the Cooper-pair process ($\nu\bar{\nu}$-pair emission when thermally excited two quasi-particles recombine into the Cooper-pair in the BCS state)[71), 72)] in the n ${}^3P_2$-superfluid dominates by (1-2) order of magnitude compared to the standard process of modified Urca in most cases. At higher densities ($4\rho_0 \lesssim \rho \lesssim 6\rho_0$), the direct URCA process of Λ ($\Lambda \to p + e^- + \bar{\nu}_e$, $p + e^- \to \Lambda + \nu_e$) dominates when $T_c(\Lambda) \lesssim 1 \times 10^9$ K, while it is completely suppressed if $T_c >> 1 \times 10^9$ K. The direct URCA process of Y ($\Sigma^- \to \Lambda + e^- + \bar{\nu}_e$, $\Lambda + e^- \to \Sigma^- + \nu_e$) is completely suppressed at $\rho \simeq (4-5.5)\rho_0$ due to very large Δ_{Σ^-} and become active only for $\rho > 5.5\rho_0$. The direct URCA process of Σ^- ($\Sigma^- \to n + e^- + \bar{\nu}_e$, $n + e^- \to \Sigma^- + \nu_e$) is forbidden because a so-called triangle condition for Fermi momenta does not hold ($k_{Fn} > k_{F\Sigma^-} + k_{Fe^-}$). Also, this momentum conservation condition forbids the nucleon direct URCA process ($n \to p + e^- + \bar{\nu}_e$, $p + e^- \to n + \nu_e$) up to $\sim 6.5\rho_0$.

To summarize simply the cooling picture for Y-mixed NS's[70)], the principal agent for ν-emission is the Cooper-pair cooling from ${}^3P_2$ n-superfluid for $\rho < \rho_t(Y)$ and is the hyperon cooling from the direct URCA process of Λ for $\rho > \rho_t(Y)$. The latter brings about an extremely enhanced ν-emission responsible for a rapid nonstandard cooling, in contrast with a moderate cooling from the former. Thus, from a view of Y-mixed neutron stars, we have the hyperon cooling scenario as follows; less massive stars, whose central density ρ_c is below $\rho_t(Y)$, in other words, the mass $M \lesssim 1.4M_\odot$ for TNI6u-EOS (see Fig.9), cools moderately through the Cooper-pair cooling, and on the contrary, more massive stars with $M > 1.4M_\odot$ cools very rapidly through the hyperon cooling. Very recently, on the basis of our results, Tsuruta and her coworkers[73)] carried out the numerical calculation for the thermal

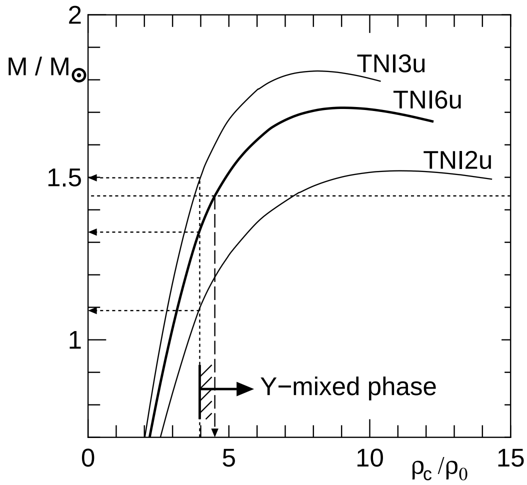

Fig. 9. Mass M versus central density ρ_c for Y-mixed neutron star models with TNI3u-, TNI6u- and TNI2u- EOS's. In every cases, Y-mixed phase starts at around $4\rho_0$. Arrows indicate the minimum mass beyond which neutron stars contain a Y-mixed core.

evolution of neutron stars. By adopting the TNI3u-EOS, they have shown that the colder class NS data (Vela X-1, Geminga, PSRJ0205+6499) are well reproduced by taking a neutron star mass $M \sim (1.5-1.6)M_\odot$ with a Y-mixed core and the hotter class NS data can be reproduced by $M \lesssim 1.4M_\odot$ without Y-mixed core. This shows that the hyperon cooling scenario is a promissing candidate for nonstandard fast cooling for neutron stars.

4.3. *"NAGARA event"* ${}^{6}_{\Lambda\Lambda}$He *and* Λ*-superfluidity*

Here we wish to give a comment on the Y-superfluidity in relation to the information from hypernuclear data. In 4.1, we have chosen ND-Soft, Ehime and FG-A potentials for the ${}^1S_0$ YY pairing interaction. One of the reason for such a choice is in the fact that these three potentials well reproduce the binding energy $\Delta B_{\Lambda\Lambda}$ of $\Lambda\Lambda$ pair in double Λ hypernuclei (${}^{10}_{\Lambda\Lambda}$Be, ${}^{13}_{\Lambda\Lambda}$B) [30),31),33)–35)]. This data provides an important information to the property of $\Lambda\Lambda$ interaction and constrain its ambiguity. In fact, the $T_c(\Lambda)$ calculated from three potentials are well bunched in contrast with $T_c(\Sigma^-)$ (see Fig.7(a)), giving a confidence to our Λ-superfluid results. Recently, however, the NAGARA group [32)] observed a new event of double Λ hypernucleus ${}^{6}_{\Lambda\Lambda}$He in the emulsion experiment, called "NAGARA event", and extracted new result $\Delta B_{\Lambda\Lambda} \sim 1$ MeV, compared to old $\Delta B_{\Lambda\Lambda} \simeq (4-5)$ MeV [30),31)]. If this less attractive $\Lambda\Lambda$ interaction is confirmed, the consequence on the Λ-superfluidity is serious.

By performing the energy calculations for $\alpha + \Lambda + \Lambda$ system, Hiyama et al [74)]. found that new $\Delta B_{\Lambda\Lambda} \sim 1$ MeV is almost equivalent to take $V'_{\Lambda\Lambda}({}^1S_0) \simeq 0.5V_{\Lambda\Lambda}({}^1S_0)$ from ND-Soft (precisely, the potential strength is multiplied by a factor 0.45 at short-distance and by a factor 0.5 at intermediate- and long-distances). So we have tried the energy gap calculation for $\Lambda\Lambda$ pairing by using this $V'_{\Lambda\Lambda}({}^1S_0)$ and have

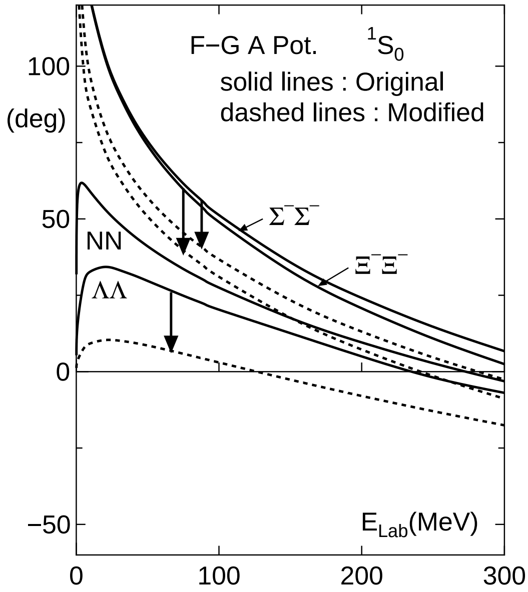

Fig. 10. $^1S_0$ phase shifts from FG-A YY potentials as functions of scattering energy in laboratory frame $E_{\rm Lab}$; solid lines for original potentials and dashed lines for modified ones taking into account the effect of "NAGARA event" explained in the text. $^1S_0$ NN phase shifts from OPEG ^{1}E-A are also shown for reference.

found that the Λ-superfluidity disappears for realistic $\tilde{m}^*_\Lambda$ ($T_c(\Lambda) << T_{in}$). Then there arises a question how about the Σ^--superfluidity. To see this, we reconstruct the BB interaction model of OBE-type so as to reproduce the phase shifts from $V'_{\Lambda\Lambda}(^1S_0)$, by weakening the attractive contribution form σ-meson exchange. We do this modification for FG-A potential, by paying our attention to the condition not to influence the NN interaction sector since it is well determined. This can be done as follows [75].

In the framework of octet baryons plus nonet mesons with SU(3) symmetry, the coupling constant $\tilde{g}_{BBm}$ for the BB interactions through one meson (m) exchange is expressed in terms of 4 parameters; singlet coupling $\tilde{g}^{(1)}$, octet coupling $\tilde{g}^{(8)}$, parameter α relevant to a so-called F-D ratio, mixing angle θ. Conversely speaking, this means that a set of these 4 parameters are uniquely determined if 4 coupling constants are given. For the scalar meson case ($m \equiv \sigma$, a_0, f_0), we use $\tilde{g}_{NN\sigma}$, $\tilde{g}_{NNa_0}$, $\tilde{g}_{NNf_0}$ and $\tilde{g}_{\Lambda\Lambda\sigma}$, keeping $\tilde{g}_{NNm}$ unchanged and adjusting $\tilde{g}_{\Lambda\Lambda\sigma}$ so as to reproduce the phase shifts from $V'_{\Lambda\Lambda}(^1S_0)$. Actually, a reduction of $\tilde{g}_{\Lambda\Lambda\sigma}$ by about 10% is satisfactory for this reproduction. Then, from a new set of $\{\tilde{g}^{(1)}, \tilde{g}^{(2)}, \alpha, \theta\}$, new $\tilde{g}_{\Sigma^-\Sigma^-m}$ responsible for the modified $V_{\Sigma^-\Sigma^-}(^1S_0)$ are obtained. Results are shown in Fig.10, where the $^1S_0$ NN phase shifts from OPEG ^{1}E-A potential is also shown for reference. It is observed that the "NAGARA event" effect causes downward shifts of $(15-20)$ degrees for every cases, but the phase shifts for modified $V_{\Sigma^-\Sigma^-}$ is positive and still higher than those for $V_{NN}(^1S_0)$ at low scattering energies, suggesting the survival of the Σ^-- superfluidity. In fact, the energy gap calculations lead to the results that $T_c(\Sigma^-) \sim 10^9$ K $> T_{in}$ (a thin dashed line in Fig.7(a)), in contrast with $T_c(\Lambda) << T_{in}$. That is, the Λ-superfluidity can not be expected but the Σ^--superfluidity persists, if the "NAGARA event" information is taken into account.

Finally we add a word to the "NAGARA event" effects on the Y-mixed NS models. In conclusion, the effects are almost negligible because the energy contribution from $\Lambda\Lambda$ interaction between small components is very small [4]. The influence on bulk properties of NS's is estimated by taking $\tilde{V}_{\Lambda\Lambda} \to \frac{1}{5}\tilde{V}_{\Lambda\Lambda}$ corresponding to $\Delta B_{\Lambda\Lambda} \sim (4-5)$ MeV $\to \ \sim 1$ MeV. Minor changes are found: both of $\rho_t(\Lambda)$ and $\rho_t(\Sigma^-)$ are unaffected, $y_\Lambda(y_{\Sigma^-})$ is affected to the extent that $y_\Lambda = 11.3\% \to 8.3\%$ ($y_{\Sigma^-} = 12.5\% \to 12.4\%$) at $\rho = 6\rho_0$ and TNI3u case, for instance, and also $M_{\max} = (1.83 \to 1.84)M_\odot$, $\rho_c = (8.26 \to 8.19)\rho_0$ and $R = (9.55 \to 9.56)$ km.

§5. Concluding Remarks

We have investigated the problem of Y-mixing in NS matter and characteristics of the EOS by the G-matrix-based effective interaction approach, paying attention to the use of YN and YY interactions compatible with hypernuclear data. On the basis of a Y-mixed NS model, we have discussed the possible occurence of Y- superfluidity and consequences on the cooling problem of NS's. We present main points with some remarks.

(i) In NS cores, the mixing of hyperons such as Λ and Σ^- does indeed take place with a monotonus increase of respective mixing ratio with increasing density and hyperons become components of importance comparable with nucleons. Thus the inclusion of strangeness degrees of freedom into theories of NS's allows us to predict new properties of NS's. It is remarked that the Y-mixing depends not only on the YN interaction but also on the stiffness and the symmetry energy of N-part EOS.

(ii) According to the growth of the Y-mixed phase, the EOS is dramatically softened and leads to the crucial problem that the predicted $M_{\max}$ fails to satisfy the condition $M_{\max} > M_{\rm obs} = 1.44 M_\odot$, in a model independent way, suggesting that we need some extra repulsion in hypernuclear system, i.e., in the NY and the YY interaction parts. This necessity can be taken a return call from NS physics to hypernuclear physics.

(iii) It is remarked that introducing a repulsion similar to the three-body repulsion in nuclear system is one possible way to obtain a results $M_{\max} > M_{\rm obs}$ consistent with observations. In this case with such an "extra repulsion", Y-mixing occurs at higher densities ($\gtrsim 4\rho_0$), not at lower densities ($\gtrsim 2\rho_0$) found in many works, and with smaller values of y_Y, leading to a moderately softened EOS.

(iv) Our "extra repulsion" is introduced at a phenomenological level. As one of the origins, obviously it includes the two-pion exchange three-body force with an isobar $\Delta(1232)$ excitation, which has been shown to generate a strong ρ-dependent repulsion for nuclear matter [76]. It is primarily important to study how this process provides the "extra repulsion" for the Y-mixed NS matter by paying attention to the change of coupling constants and the fractional density of respective baryons. Of course, it is of interest to study other possible candidates for such "extra repulsion", which includes the quenching of attraction in the $N\Delta$ configuration [77], the repulsive contribution in relativistic approaches [78] , [79] and also the repulsive effects coming

from an in- medium hadron parameter modifications [80].
(v) For a realistic NS model compatible with observations, it is shown that both of Λ- and Σ^--superfluids are realized with the critical temperature $T_c(Y) \sim 10^{8-9}$ K in NS cores. The occurence of Y-superfluidity means that a rapid cooling scenario of NS's, a so-called "hyperon cooling" combined with the Y- superfluidity, could be one of the candidates to explain an unusually low surface temperature observed for some NS's. We stress that the superfluidity of baryons relevant to the direct URCA ν-emission processes is vital to non-standard cooling scenarios avoiding a "too-rapid cooling", and so the existence or non-existence of the superfluids is a unique tool to discriminate a real candidate among many possible ones so far proposed [81), 56]. Since so-called "kaon cooling" and "nucleon direct URCA cooling" are unlikely due to the non-existence of baryon superfluids associated [81) − 83], the "hyperon cooling" here remains as a promising candidate.
(vi) Information from hypernuclear data is closely related to neutron star physics. The small $\Lambda\Lambda$-bond energy extracted from "NAGARA event" ${}^{6}_{\Lambda\Lambda}$He suggests a less attractive $\Lambda\Lambda$ pairing interaction. If this is true, the existence of Λ superfluidity becomes very unlikely and the "hyperon cooling" scenario breaks down. In this connection, it is important to study the possibility that the small $\Lambda\Lambda$- bond energy is explained without reduction of the $\Lambda\Lambda$ attraction, e.g., by introducing a repulsive ΛNN three-body interaction and some many-body effect not explored yet [70]. In the context of NS cooling scenarios, it is also important to study the "pion cooling", another promising candidate, by making a thorough examination for the superfluidity of quasi-baryons relevant to pion condensates [84].

Acknowledgements

This paper is based on the works made in collaboration with S. Nishizaki, Y. Yamamoto and R. Tamagaki. The author would like to thank them, especially R. Tamagaki for his helpful discussion about the baryon-baryon interaction models. He also thanks S. Tsuruta, T. Tatsumi and T. Muto for their cooperative discussions about the cooling problem of neutron stars and M. Wada for his useful discussion to use the Funabashi-Gifu potential. This work is financially suported by Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Culture, Sports, Science and Technology (13640252).

References

1) S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog. Theor. Phys. **105** (2001), 607.
2) Y. Yamamoto, S. Nishizaki and T. Takatsuka, *Proc. 7th Int. Cont. on Hypernuclear and Strange Particle Physics* (HYP2000), Torino, Italy, Oct.23-27, 2000, ed. E. Botta, T. Bressani and A. Feliciello; Nucl. Phys. **A691** (2001), 432c.
3) T. Takatsuka, S. Nishizaki and Y. Yamamoto, *Proc. 16th Int. Symp. on Perspectives in Physics with Radioactive Isotope Beams* (RIB2000), Hayama, Kanagawa, Japan, Nov.13-16, 2000; Eur. Phys. J. **A13** (2002), 213.
4) S. Nishizaki, Y. Yamamoto and T. Takatsuka, Prog. Theor. Phys. **108** (2002), 703.
5) S. Tsuruta and A.G.W. Cameron, Can. J. Phys. **44** (1966), 1895.
6) W.D. Langer and L. Rosen, Astrophys. Space Sci. **6** (1970), 217.
7) V.R. Pandharipande, Nucl. Phys. **A178** (1971), 123.

8) H.A. Bethe and M.B. Johnson, Nucl. Phys. **A230** (1974), 1.
9) M. Baldo, G.F. Burgio and H.-J. Schulze, Phys. Rev. **C61** (2000), 055801.
10) I. Vidaña, A. Polls, A. Ramos, L. Engvik and M. Hjorth-Jensen, Phys. Rev. **C62** (2000), 035801.
11) N.K. Glendenning, Phys. Lett. **B114** (1982), 392; Nucl. Phys. **A493** (1989), 521; Phys. Rev. **C64** (2001), 025801.
12) F. Weber and M.K. Weigel, Nucl. Phys. **A505** (1989), 779.
13) Y. Sugahara and H. Toki, Prog. Theor. Phys. **92** (1994), 803.
14) F. Schaffner and I.N. Mishustin, Phys. Rev. **C53** (1996), 1416.
15) S. Pal, M. Hanauske, I. Zakout, H. Stöcker and W. Greiner, Phys. Rev. **C60** (1999), 015802.
16) M. Hanauske, D. Zschiesche, S. Pal, S. Schramm, H. Stöcker and W. Greiner, Astrophys. J. **537** (2000), 958.
17) P.K. Sahu and A. Ohnishi, Nucl. Phys. **A691** (2001), 439c.
18) T. Muto, Nucl. Phys. **A691** (2001), 447c.
19) Z.X. Ma, Z.G. Dai, and T. Lu, Astron. & Astrophys. **366** (2001), 532.
20) J.S. -Bielich, M. Hanauske, H. Stöcker and W. Greiner, Phys. Rev. Lett. **89** (2002), 171101.
21) S. Balberg and A. Gal, Nucl. Phys. **A625** (1997), 435.
22) T. Nagae et al., Phys. Rev. Lett. **80** (1998), 1605.
23) T. Fukuda et al., Phys. Rev. **C58** (1998), 1306.
24) Y. Yamamoto and H. Bando, Prog. Theor. Phys. Suppl. No.81 (1985), 9.
25) C.B. Dover and A. Gal, Prog. in Particle and Nucl. Phys. **12** (1984), 171.
26) T. Harada, S. Shinmura, Y. Akaishi, and H. Tanaka, Nucl. Phys. **A507** (1990), 715.
27) T. Harada, Phys. Rev. Lett. **81** (1998), 5257.
28) C.J. Batty, E. Friedman and A. Gal, Prog. Theor. Phys. Suppl. No.117 (1994), 227.
29) Y. Yamamoto, S. Nishizaki and T. Takatsuka, Prog. Theor. Phys. **103** (2000), 981.
30) M. Danysz et al., Nucl. Phys. **49** (1963), 121.
31) S. Aoki et al., Prog. Theor. Phys. **85** (1991), 1287.
32) H. Takahashi et al., Phys. Rev. Lett. **87** (2001), 212502.
33) Y. Yamamoto, T. Motoba, H. Himeno, K. Ikeda and S. Nagata, Prog. Theor. Suppl. No.117 (1994), 361.
34) T. Yamada and C. Nakamoto, Phys. Rev. **C62** (2000), 034319.
35) C.B. Dover, D.J. Millener, A. Gal and D.H. Davis, Phys. Rev. **C44** (1991), 1905.
36) M.M. Nagels, T.A. Rijken and J.J. de Swart, Phys. Rev. **D15** (1977), 2547; **D20** (1979), 1633.
37) T.A. Rijken, V.G.J. Stoks and Y. Yamamoto, Phys. Rev. **C59** (1999), 21.
38) B. Holzenkamp, K. Holinde and J. Speth, Nucl. Phys. **A500** (1989), 485.
39) A. Reuber, K. Holinde and J. Speth, Nucl. Phys. **A570** (1994), 543.
40) M. Oka, K. Shimizu and K. Yazaki, Prog. Theor. Phys. Suppl. No.137 (2000), 1.
41) K. Shimizu, S. Takeuchi and A.J. Buchmann, Prog. Theor. Phys. Suppl. No.137 (2000), 43.
42) Y. Fujiwara, C. Nakamoto and Y. Suzuki, Phys. Rev. Lett. **76** (1996), 2242; Phys. Rev. **C54** (1996), 2180.
43) Y. Fujiwara, M. Kono, C. Nakamoto and Y. Suzuki, Phys. Rev. **C64** (2001), 054001.
44) I. Arisawa, K Nakagawa, S. Shinmura and M. Wada, Prog. Theor. Phys.. **104** (2000), 995.
45) T. Ueda, K. Tominaga, M. Yamaguchi, N. Kijima, D. Okamoto, K. Miyagawa and T. Yamada, Prog. Theor. Phys. **99** (1998), 891; Nucl. Phys. **A642** (2000), 995.
46) T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **102** (1999), 1043; Nucl. Phys. **A670** (2000), 222c.
47) T. Takatsuka, S. Nishizaki, Y. Yamamoto and R. Tamagaki, Feq-Body Systems Suppl. **12** (2000), 108.
48) T. Takatsuka, S. Nishizaki, Y. Yamamoto and R. Tamagaki, Prog. Phys. **105** (2001), 179.
49) T. Takatsuka, S. Nishizaki, Y. Yamamoto and R. Tamagaki, Nucl. Phys. **A691** (2001), 254c; Prog. Theor. Phys. Suppl. No.146 (2002), 279.
50) T. Takatsuka and R. Tamagaki, Proc. 16th Int. Conf. on Particles and Nuclei, Osaka, Japan, Sep.30-Oct., 2002; ed. H. Toki, K. Imai and T. Kishimoto; Nucl. Phys. **A721** (2003), 1003c.
51) S. Balberg and N. Barnea, Phys. Rev. **C57** (1998), 409.

52) T. Tanigawa, M. Matsuzaki and S. Chiba, Phys. Rev. **C68** (2002), 015801.
53) S. Tsuruta, Comments Astrophys. **11** (1986), 151.
54) C.J. Pethick, Rev. Mod. Phys. **64** (1992), 1133.
55) S. Tsuruta, Proc. US-Japan Joint Seminar on *The Structure and Evolution of Neutron Stars*, kyoto, Japan, Nov.6-10, 1990, ed. D. Pines, T. Tamagaki and S. Tsuruta (Addison-Wesley, 1992), p.371.
56) S. Tsuruta, Phys. Reports **292** (1998), 1.
57) D. Page and J.H. Applegate, Astrophys. J. **394** (1992), L17.
58) T. Takatsuka, S. Nishizaki, Y. Yamamoto and R. Tamagaki, in preparation.
59) S. Nishizaki, T. Takatsuka, N. Yahagi and J. Hiura, Prog. Theor. Phys.. **86** (1991), 853.
60) R.V. Reid, Ann. of Phys. **50** (1968), 411.
61) S. Nishizaki, T. Takatsuka and J. Hiura, Prog. Theor. Phys. **92** (1994), 93.
62) I.E. Lagaris and V.R. Pandharipande, Nucl. Phys. **A369** (1981), 470.
63) B. Friedman and V.R. Pandharipande, Nucl. Phys. **A361** (1981), 502.
64) R.B. Wiringa, R.A. Smith and T.L. Ainsworth, Phys. Rev. **C29** (1984), 1207.
65) M. Lacombe, B. Loiseau, J.M. Richard R. Vinh Mau, J. Côtê, P. Pirès and R. de Tourreil, Phys. Rev. **C21** (1980), 861.
66) A. Akmal, V.R. Pandharipande and D.G. Ravenhall, Phys. Rev. **C58** (1998), 1804.
67) R.B. Wiringa, Rev. Mod. Phys. **65** (1993), 231.
68) T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. Suppl. No.112 (1993), 27.
69) R. Tamagaki and T. Takatsuka, Prog. Theor. Phys. **105** (2001), 1059; R. Tamagaki, Prog. Theor. Phys. **39** (1968), 91.
70) T. Takatsuka and R. Tamagaki, submitted to Prog. Theor. Phys.
71) E. Flowers, M. Runderman and P. Sutherland, Astrophys. J. **205** (1976), 541.
72) D.G. Yakovlev, A.D. Kaminker, O.Y. Gnedin and P. Haensel, Phys. Reports **351** (2001), 1.
73) S. Tsuruta, review paper presented at IAU Symposium, Sydney, Australia, July 2003.
74) E. Hiyama, M. Kamimura, T. Motoba, T. Yamada and Y. Yamamoto, Phys. Rev. **C66** (2002), 024007.
75) R. Tamagaki and T. Takatsuka, Soryushiron kenkyu (Kyoto), **106** (2002), B85.
76) K. Kasahara, Y. Akaishi and H. Tanaka, Prog. Theor. Phys. Suppl. No.56 (1974), 96.
77) A.M. Green and P. Haapakoski, Nucl. Phys. **A221** (1974), 429.
78) R. Brockmann and R. Machleidt, Phys. Rev. **C42** (1990), 1965.
79) G.E. Brown, W. Weise, G. Baym and J. Speth, Comments Nucl. Part. Phys. **17** (1987), 39.
80) A.B. Santra and U. Lombardo, Phys. Rev. **C62** (2000), 018202.
81) T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **97** (1997), 345.
82) T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **94** (1995), 457.
83) S. Tsuruta, M.A. Tefer, T. Takatsuka, T. Tatsumi and R. Tamagaki, Astrophys. J. **571** (2002), L143.
84) T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **101** (1999), 1043.