Eur. Phys. J. A **13**, 213–215 (2002)

THE EUROPEAN PHYSICAL JOURNAL A

Necessity of extra repulsion in hypernuclear systems: Suggestion from neutron stars

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Received: 1 May 2001 / Revised version: 8 July 2001

Abstract. Neutron star models with hyperon-mixed core are studied by a realistic approach to use the YN and the YY interactions consistent with hypernuclear data. From the compatibility of the theoretical maximum mass with the observed neutron star mass 1.44 $M_\odot$ of PSR1913+16, the necessity of some extra repulsion in hypernuclear systems, *e.g.*, a repulsion from three-body force, is stressed. It is noted that the increase of baryon degrees of freedom to avoid the short-range repulsion effectively is an essential mechanism causing the Y-mixed phase.

PACS. 26.60.+c Nuclear matter aspects of neutron stars – 13.75.Ev Hyperon-nucleon interactions – 21.80.+a Hypernuclei – 21.65.+f Nuclear matter

1 Introduction

Study on hyperon (Y)-mixed neutron star matter is of great interest in relation to the properties of neutron stars such as the equation of state (EOS), the cooling [1–4] and the superfluidity [5–7], and is a subject renewed by recent advances in hypernuclear physics. In this paper, we concentrate on the softening effects on the EOS due to the Y-mixing and stress that some extra repulsion in YN (hyperon-nucleon) and YY interactions is demanded from the compatibility with the mass observation of neutron stars. In the investigation, we pay particular attention to our present knowledge of YN and YY interactions.

2 Outline of approach

We calculate the EOS of Y-mixed neutron star matter and the neutron star models as in the following [8]. For simplicity, we restrict ourselves to Y$\equiv \{\Lambda, \Sigma^-\}$ neglecting the Ξ^-component, since Ξ^- would hardly appear due to the higher mass.

First, we perform the G-matrix calculations for $\{\mathrm{n}+\Lambda\}$-matter with the Λ-fraction y_Λ ($y_\Lambda + y_\mathrm{n} = 1$), for several sets of the total baryon density ρ and y_Λ. Then, on the basis of the G-matrix results, we construct the local effective ΛN ($\tilde{V}_{\Lambda\mathrm{N}}$) and $\Lambda\Lambda$ ($\tilde{V}_{\Lambda\Lambda}$) interactions with ρ- and y_Λ-dependences. Quite similarly we construct $\tilde{V}_{\Sigma^-\mathrm{N}}$ and $\tilde{V}_{\Sigma^-\Sigma^-}$ from the G-matrix calculations for $\{\mathrm{n}+\Sigma^-\}$-matter. In these calculations we use the Nijmegen-D hard-core baryon-baryon interaciton model [9] (NHC-D with a slight modification in the S-state ΛN interaction) as a best choice, since NHC-D gives results most consistent with hypernuclear data [10].

As for the local effective NN interaction ($\tilde{V}_\mathrm{NN}$), we use the $\tilde{V}_\mathrm{RSC}$ [11], previously conctructed from the G-matrix results with the Reid-soft-core (RSC) potential, and the phenomenological three-body force ($\tilde{V}_\mathrm{TNI}$) supplementing the $\tilde{V}_\mathrm{RSC}$, *i.e.*, $\tilde{V}_\mathrm{NN} = \tilde{V}_\mathrm{RSC} + \tilde{V}_\mathrm{TNI}$. Our $\tilde{V}_\mathrm{TNI}$ consists of two parts [12]; the attractive ($\tilde{V}_\mathrm{TNA}$) and the repulsive ($\tilde{V}_\mathrm{TNR}$) part, ($\tilde{V}_\mathrm{TNI} = \tilde{V}_\mathrm{TNA} + \tilde{V}_\mathrm{TNR}$) and is based on the three-nucleon interaction (TNI) of a Lagaris-Pandharipande type [13] expressed effectively in a form of two-body force with ρ-dependence. Parameters inherent in $\tilde{V}_\mathrm{TNI}$ is determined in such a manner as $\tilde{V}_\mathrm{NN}$ generates the proper saturation properties of symmetric nuclear matter and the nuclear incompressibility κ. The value of κ is a measure of the stiffness of a nuclear-part EOS (N-EOS). Here we consider two cases; $\kappa = 250(300)$ MeV leading to a moderately stiff (stiff) EOS of normal (namely, without Y) neutron star matter, corresponding to the choice of TNI2 (TNI3) in $\tilde{V}_\mathrm{NN}$.

By using $\tilde{V}_\mathrm{NN}, \tilde{V}_\mathrm{YN}$ and $\tilde{V}_\mathrm{YY}$ thus obtained, we calculate respective fractions in a β-equilibrated system composed of n, p, Λ, Σ^-, e^- and μ^-, under the conditions of charge neutrality, chemical equilibrium and baryon number conservation, and obtain the EOS responsible for neutron star models with Y-mixing. Finally, by solving a so-called TOV equation, we have the neutron star models

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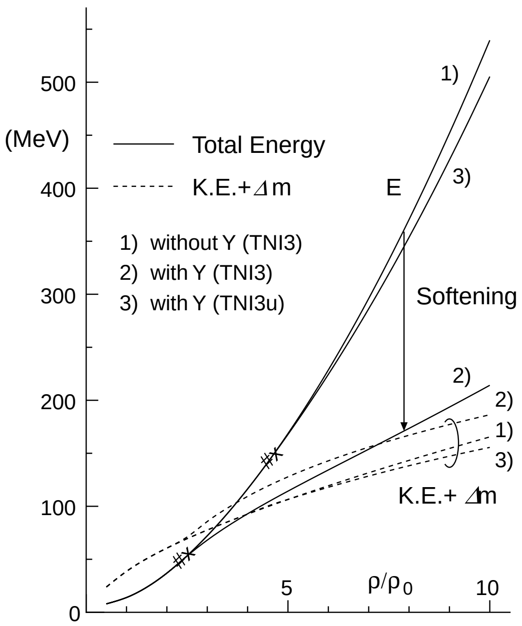

Fig. 1. Softening of EOS due to the hyperon (Y)-mixing for the case with the three-body force TNI3. Dotted curves illustrate the Fermi kinetic energy (KE) plus the difference of rest-mass energy (KE $+\Delta m$). ρ_0 is the normal nuclear density. Details are in the text.

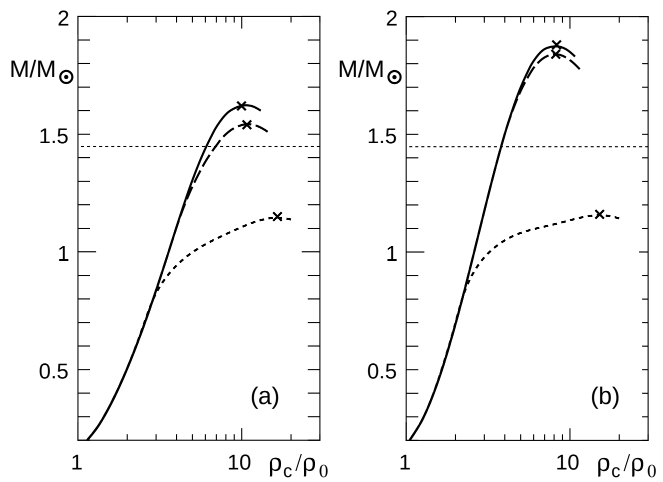

Fig. 2. Neutron star mass M *versus* the central density ρ_c for the NN interaction with (a) TNI2 and (b) TNI3. Solid, dotted and dashed curves correspond to the cases of 1), 2) and 3) in fig. 1, respectively.

with the Y-mixed core to be compared with normal models without Y-mixing.

3 Results and discussion

It is found that hyperons such as Λ and Σ^- begin to appear at around $\rho = (2.5\text{–}3.0)\rho_0$ with $\rho_0(\equiv 0.17\,\text{nucleons/fm}^3)$ being the standard nuclear density, depending on the stiffness of N-EOS, *i.e.*, the repulsive character of $\tilde{V}_{\rm NN}$. For stiffer N-EOS, the threshold density $\rho_{\rm t}(\rm Y)$ for the Y-mixing becomes lower; *e.g.*, $\rho_{\rm t}(\Lambda) \simeq 2.5\rho_0$ for stiffer N-EOS with $\kappa = 300$ MeV (*i.e.*, $\tilde{V}_{\rm NN}$-TNI3) as compared with $\rho_{\rm t}(\Lambda) \simeq 3.0\rho_0$ for less stiff N-EOS with $\kappa = 250$ MeV ($\tilde{V}_{\rm NN}$-TNI2). This is because the threshold condition $\mu_{\rm n} = \mu_\Lambda$, with $\mu_{\rm n}$ and μ_Λ being the chemical potential of n and Λ, respectively, is satisfied at lower ρ due to the increased $\mu_{\rm n}$ for stronger repulsive effects in $\tilde{V}_{\rm NN}$-TNI3.

As ρ increases, the hyperon fraction $y_{\rm Y}$ increases and in the core region of neutron stars hyperons become components comparable with nucleons. For instance, at $\rho = 6\rho_0$, the baryon population is such that $y_\Lambda \sim 20\%$, $y_{\Sigma^-} \sim 15\%$, $y_{\rm p} \sim 15\%$ and $y_{\rm n} \sim 50\%$, both for $\tilde{V}_{\rm NN}$-TNI2 and $\tilde{V}_{\rm NN}$-TNI3. This situation is very different from the usual neutron star matter where neutrons are the dominant component with $y_{\rm n} \gtrsim 90\%$ and protons admixed with $y_{\rm p} \lesssim 10\%$, and is expected to bring about new effects on neutron star properties with Y-mixing.

Of particular interest is a dramatic softening effect on the EOS which is clearly seen in fig. 1, where the case of $\tilde{V}_{\rm NN}$-TNI3 is compared between the EOS with Y and the EOS without Y. This means that the maximum mass $M_{\rm max}$ of neutron stars sustained by the EOS with Y is greatly reduced compared to the case without Y. In fact, for $\tilde{V}_{\rm NN}$-TNI2, $M_{\rm max} \simeq 1.15M_\odot$ in the former although $M_{\rm max} \simeq 1.62M_\odot$ in the latter, as shown in fig. 2 (a) by the crosses. The result $M_{\rm max} \simeq 1.15M_\odot$ is remarkably smaller than $M_{\rm obs} = 1.44M_\odot$ observed for the neutron star PSR1913+16. The inconsistency between theory and observation cannot be resolved by enhancing the stiffness in N-EOS, *i.e.*, the use of $\tilde{V}_{\rm NN}$-TNI3, as shown in fig. 2(b). In this case, $M_{\rm max} \simeq 1.16M_\odot$ with Y whereas $M_{\rm max} \simeq 1.88M_\odot$ without Y. This is because the stiffer the nuclear-part EOS, the Y-mixed phase develops from lower densities and thereby the softening effect becomes stronger. It is worth mentioning that $M_{\rm max} < M_{\rm obs}$ results even for the case with only Λ-mixing, neglecting the contribution from Σ^--mixing [8].

The crucical problem $M_{\rm max} < M_{\rm obs}$ for neutron stars with Y-mixing is not a consequence peculiar to our neutron star models. The recent works by Baldo *et al.* [14], and Vidaña *et al.* [15] encounter the same situation; $M_{\rm max} \simeq (1.22\text{–}1.26)M_\odot$ in the former where the AV18 and the Paris two nucleon potentials, supplemented by the three-body force, are used for N-EOS, and $M_{\rm max} \simeq 1.34M_\odot$ in the latter to adopt the N-EOS by Akmal-Phandaripande-Ravenhall [16]. So this too strong softening effect, incompatible with observation, is taken to be common to neutron star EOSs where the hyperon degrees of freedom is taken into account. It is worth mentioning that even in the so-called relativistic-mean-field approximation, the reduction of $M_{\rm max}$ due to the Λ-mixing is so remarkable and the reconciliation of $M_{\rm max}$ with $M_{\rm obs}$ is not easy, as far as the binding energy of Λ-hypernuclei is taken into account [17,18].

The fact that the problem $M_{\rm max} < M_{\rm obs}$ comes out for the Y-mixed neutron stars, irrespectively to the stiffness of the N-EOS, strongly suggests a necessity for some extra repulsion in hypernuclear systems. As one of the candidates, here we consider the repulsion from the three-body force, since the effects of many-body interactions should not be restricted to nuclear systems. For simplicity, we try to include quite phenomenologically the repulsion of our TNI, $\tilde{V}_{\rm TNR}$, also in the YN and the YY parts, as well as in the NN part (hereafter we call this treatment "universal inclusion of TNI" denoted as TNIu). Then we have the realization of the Y-mixed phase at higher densities; $\rho_{\rm t}({\rm Y})$ and the $y_{\rm Y}$–ρ relationship, $y_{\rm Y}(\rho)$, are pushed by about ρ_0 to a higher density side. The important point is that in this case we have a moderate softening, not a dramatic softening as before, as shown in fig. 1. Correspondingly we have a larger $M_{\rm max}$ as shown in fig. 2 by the dashed curves; $M_{\rm max} \simeq 1.54M_\odot$ for TNI2u and $M_{\rm max} \simeq 1.84M_\odot$ for TNI3u, nicely satisfying the constraint $M_{\rm max} > M_{\rm obs} = 1.44M_\odot$ from observations.

Finally we want to give a comment on the softening mechanism. In the Y-mixed phase, the number of baryon species is larger than that of normal neutron star matter composed of n and p and hence the sum of the Fermi kinetic energies (KE) is made lower at fixed ρ due to the increased degrees of freedom. The statement that the softening effect comes from this energy gain is not correct, although it is used very often. This is because the KE including the rest-mass energy (*i.e.*, KE $+\Delta m$) is almost the same in the cases with Y and without Y, as shown in fig. 1 by the dotted curves. From the figure, we can clearly see that the energy gain, *i.e.*, the softening mechanism, is brought about not by the KE part (including Δm) but by the interaction energy part. For normal neutron star matter at high densities ($\rho \gtrsim (3–4)\rho_0$), a short-range repulsion dominates in the interaction energy, especially for neutrons. On the other hand, for the Y-mixed case, the fractional density $\rho_i (= y_i \rho)$ of the respective baryon species is made lower and thereby the short-range repulsion becomes less effective, leading to the energy gain from the case without Y. This is an essential point in the mechanism of energy gain and the softening effect in the Y-mixing problem.

4 Concluding remarks

We wish to remark that the transition from normal neutron star matter to the hyperon-mixed neutron star matter can essentially be characterized by the transition to avoid effectively the short-range repulsion by increasing the baryon degrees of freedom. This transition causes a dramatic softening of the EOS, leading to a crucial problem $M_{\rm max} < M_{\rm obs} = 1.44M_\odot$ in contradiction to observations of neutron star mass.

We wish to stress that, conversely speaking, the problem $M_{\rm max} < M_{\rm obs}$ is an interesting problem to suggest the necessity for some extra repulsion in hypernuclear systems (*i.e.*, YN and YY interactions). We remark that the three-body repulsion introduced in nuclear systems, if it applies similarly to hypernuclear systems, could be one of the candidates, leading to the result $M_{\rm max} > M_{\rm obs}$, nicely compatible with observations.

Of course we can consider other candidates for such ρ-dependent extra repulsion, which include i) the repulsive corrections arising from the quenching of attraction in the $N\Delta$ configuration by the dispersion and the Pauli effects [17], ii) the repulsive contribution in the relativistic Dirac-Brueckner-Hartree-Fock approach [18] which is taken to originate from virtual pair terms with the positive- and the negative-energy states [19], and also iii) the repulsive effects coming from an in-medium hadron parameter modifications due to partial restoration of the chiral symmetry of the QCD Lagrangian [20]. Study on these cases remains as our future subject.

The authors wish to thank R. Tamagaki for his cooperative discussions. This work is financially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture (No. 11640245 and 11640286).

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