Strong Hyperon-Nucleon Pairing in Neutron Stars

Xian-Rong Zhou,[1,2] H.-J. Schulze,[3] Feng Pan,[2,4] and J. P. Draayer[4]

[1]*Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China*

[2]*Department of Physics, Liaoning Normal University, Dalian 116029, People's Republic of China*

[3]*Dipartimento di Fisica, Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy*

[4]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, USA*

(Received 31 December 2004; published 26 July 2005)

We explore the possibilities of hyperon-nucleon pairing, involving Λ or Σ^- hyperons, using different Nijmegen hyperon-nucleon potentials. We find possible very large $n\Sigma^-$ gaps and estimate their relevance for neutron star physics.

DOI: 10.1103/PhysRevLett.95.051101 PACS numbers: 26.60.+c, 13.75.Ev, 21.65.+f, 24.10.Cn

The importance of nucleonic (neutron-neutron and proton-proton) pairing for the physics of neutron stars has been widely recognized in the literature [1], and numerical estimates have been given that establish the existence of neutron ${}^1S_0$ pairs in the crust of the star and of proton ${}^1S_0$ and neutron ${}^3PF_2$ pairing in the core of the star [2,3]. The main physical effects due to pairing are the glitches of neutron stars [4] and their cooling behavior [5].

In this Letter we wish to advance an "exotic" possibility for pairing, namely, that between nucleons and hyperons, which appear in the inner part of the star [6,7]. In principle, pairing can also take place between the different hyperon species (mainly Λ or Σ^-) [8]. However, currently there are no experimental constraints on the hyperon-hyperon interactions and consequently, the available hyperon-hyperon potentials are not reliable.

On the other hand, there is experimental scattering information on the nucleon-hyperon interaction, and several nucleon-hyperon potentials compatible with these data are available, most notably those of the Nijmegen group. In this Letter we use the most recent "soft-core" potentials NSC89 [9] and NSC97a-f [10] in order to estimate the eventual gaps between the different nucleon and hyperon species. It is our aim to perform exploratory calculations in order to identify the attractive hyperon-nucleon channels NY; $N = n, p$; $Y = \Lambda, \Sigma^-$ with nonvanishing pairing gaps with the different potentials and to estimate the order of magnitude of the gaps that can be expected in a neutron star. We begin by exposing briefly the relevant formalism.

We are interested in the pairing properties of a system with partial nucleon and hyperon densities ρ_N and ρ_Y, or equivalently total density $\rho = \rho_N + \rho_Y$ and asymmetry $\alpha = (\rho_N - \rho_Y)/(\rho_N + \rho_Y)$. For convenience we also introduce the notation $k_F = (3\pi^2\rho/2)^{1/3}$, which in the case of symmetric matter ($\rho_N = \rho_Y$) coincides with the Fermi momenta of nucleons and hyperons.

The BCS theory generalized to asymmetric matter [11,12] yields the basic coupled equations for the determination of the (angle-averaged) gap function Δ_k (focusing on the more general case of pairing in the coupled ${}^3SD_1$ channel involving a two-component gap function), and the chemical potentials of nucleons and hyperons μ_N and μ_Y for given densities ρ_N and ρ_Y,

$$\begin{pmatrix} \Delta_L \\ \Delta_{L'} \end{pmatrix}_{k'} = -\sum_k \frac{\theta(E_k - \delta\epsilon_k)}{2E_k} \begin{pmatrix} V_{LL} & V_{LL'} \\ V_{L'L} & V_{L'L'} \end{pmatrix}_{kk'} \begin{pmatrix} \Delta_L \\ \Delta_{L'} \end{pmatrix}_k, \tag{1}$$

$$\rho_N + \rho_Y = 2\sum_k \left[1 - \frac{\epsilon_k}{E_k}\theta(E_k - \delta\epsilon_k)\right], \tag{2}$$

$$\rho_N - \rho_Y = 2\sum_k \theta(\delta\epsilon_k - E_k), \tag{3}$$

where $L' = L + 2$,

$$E_k = \sqrt{\epsilon_k^2 + \Delta_k^2}\,, \qquad \Delta_k^2 = (\Delta_L)_k^2 + (\Delta_{L'})_k^2\,, \tag{4}$$

and

$$\epsilon_k = \frac{k^2}{2m} - \frac{\mu_N + \mu_Y}{2}, \qquad \delta\epsilon_k = \frac{\mu_N - \mu_Y}{2} - \beta\frac{k^2}{2m} \tag{5}$$

with the reduced NY mass $m = 2m_N m_Y/(m_N + m_Y)$ and $\beta = (m_Y - m_N)/(m_Y + m_N)$. In this exploratory Letter we employ only kinetic single-particle energies in the gap equation. The relevant potential matrix elements are

$$(V_{LL'})_{kk'} = \int d^3r j_{L'}(k'r) V_{LL'}^S(r) j_L(kr) \tag{6}$$

with $S = 1$; $L, L' = 0, 2$ for the ${}^3SD_1$ channel and $S = 0$; $L, L' = 0$ for the ${}^1S_0$ channel.

The physical interpretation of the above equations is as follows. The unpaired excess particles (in our case, nucleons) subject to the condition $E_k < \delta\epsilon_k$ are concentrated in the energy interval $[\mu - \delta e, \mu + \delta e]$, $\delta e = \sqrt{\delta\mu^2 - \Delta^2/(1 - \beta^2)}$ with $\mu = \frac{1}{2}[\frac{\mu_N}{1+\beta} + \frac{\mu_Y}{1-\beta}]$ and $\delta\mu = \frac{1}{2}[\frac{\mu_N}{1+\beta} - \frac{\mu_Y}{1-\beta}]$. They are Pauli blocking the gap Eq. (1). This leads to a rapid decrease of the resulting gap when increasing the size $2\delta e$ of the interval, i.e., the asymmetry $\alpha \approx 3\delta e/2\mu$.

The above equations can be analyzed analytically [12] in the weak-coupling situation, $\Delta \ll \delta e \ll \mu$, yielding the gap as a function of asymmetry:

$$\frac{\Delta}{\Delta_0} = \sqrt{1 - \frac{4\mu}{3\Delta_0}\sqrt{1-\beta^2}\alpha}, \tag{7}$$

where Δ_0 and μ are the gap and chemical potential for the symmetric system of the same total density. The gap vanishes at

$$\alpha_{\max} = \frac{3\Delta_0}{4\mu}\frac{1}{\sqrt{1-\beta^2}}. \tag{8}$$

For the application to neutron star physics we need to provide an equation of state (EOS) of hypernuclear matter in order to determine the composition (particle fractions) of the beta-stable and charge-neutral matter present inside the star. We use in this work the results of a Brueckner-Hartree-Fock (BHF) [13] approach extended to hypernuclear matter, described in detail in Ref. [7], which employs the Argonne V_{18} [14] +Urbana UIX [15] nucleon-nucleon and the NSC89 hyperon-nucleon potentials. In this sense it is compatible with the interaction used for the hyperon-nucleon gaps.

We proceed now to the presentation of the numerical results obtained by solving Eqs. (1)–(3). We begin in Fig. 1, with the existing s-wave gaps $\Delta = \Delta_{k_F}$ in the different channels involving Λ or Σ^- hyperons in symmetric hyperon-nucleon matter ($\rho_N = \rho_Y$). Results obtained with the NSC89 and the NSC97a-f potentials are compared, which in the plots are labeled with the indices 0 and 1–6, respectively.

One notes at first glance the enormous gaps in the $n\Sigma^-$ $^3SD_1$ channel, of the order of several tens of MeV, and extending to very large density. The NSC89 potential yields the highest values, followed by the NSC97f-a in that order. The physical reason for these large gaps is the existence of a quasiboundstate in this channel and the absence of a repulsive core in these potentials [9,10]. We remark that actually the potentials NSC89 and NSC97e,f appear to be favored in confrontation with experimental data on lambda hypernuclei [16]. Concerning the sigma hyperons, the NSC89 potential yields BHF single-particle depths that are weakly bound or unbound in nuclear matter [7], whereas recent experimental data seem to indicate a stronger repulsion [17].

We find also gaps of the order of 1 MeV in the $n\Sigma^-$ $^1S_0$ and $n\Lambda$ $^1S_0$ channels, but these are too small and exist at too low density in order to play a role in neutron stars. In higher partial waves no gaps appear to exist, apart from a

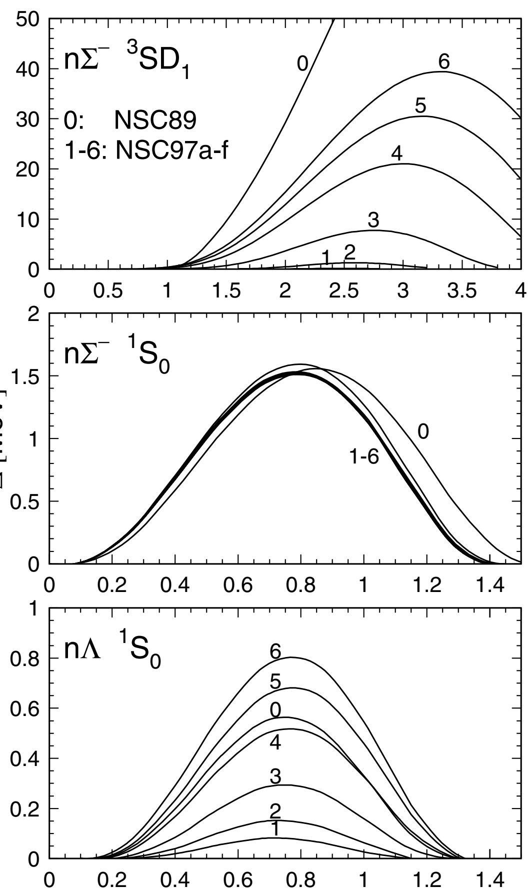

FIG. 1. The different hyperon-nucleon gaps in symmetric matter. The numbers near the curves denote the NSC89 (0) or the NSC97a-f (1–6) potentials.

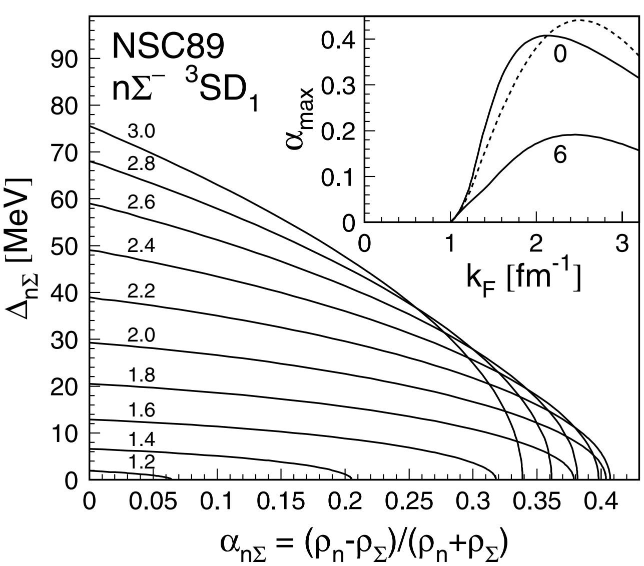

FIG. 2. The $n\Sigma^-$ $^3SD_1$ gap with the NSC89 potential in asymmetric matter as a function of asymmetry for different total densities. The numbers above the curves indicate the value of $k_F = (3\pi^2\rho_{n\Sigma}/2)^{1/3}$ (in fm^{-1}). The inset shows the maximum asymmetry as a function of k_F (solid line labeled 0) together with the estimate Eq. (8) (dashed line) for the NSC89 and the NSC97f potential (solid line labeled 6).

$n\Sigma^- \ ^3PF_2$ gap of the order of 1 MeV with the NSC89 potential only (not shown), that is, however, dominated by the $^3SD_1$ gap in the same channel. Also, we do not find any pairing between protons and Λ or Σ^- hyperons with any potential.

We therefore continue with the $n\Sigma^- \ ^3SD_1$ gap and show in Fig. 2 the gaps in asymmetric matter characterized by total density $\rho_{n\Sigma} = \rho_n + \rho_\Sigma$ and asymmetry $\alpha_{n\Sigma}$. In the following we present only results with the NSC89 potential in order to demonstrate the largest possible effect. With the other potentials one obtains analogous, smaller results. One observes the typical behavior according to the weak-coupling estimate Eq. (7). Because of the very large gap in symmetric matter the maximum asymmetry allowing for pairing reaches also very large values above 0.4, which are shown in the inset of the figure together with the estimate Eq. (8). For comparison is also shown the maximum asymmetry for the potential NSC97f, which reaches only values below 0.2.

It is then clear that even in the very asymmetric matter inside a neutron star, $n\Sigma^- \ ^3SD_1$ pairing can be expected. This is demonstrated in the last plot Fig. 3, showing as a function of total baryon density $\rho_B = \rho_n + \rho_p + \rho_\Lambda + \rho_{\Sigma^-}$ the composition of beta-stable matter according to the BHF EOS [3,7], the relevant partial density $\rho_{n\Sigma}$ and asymmetry $\alpha_{n\Sigma}$, and the finally resulting $n\Sigma^- \ ^3SD_1$ gap in that environment. One observes the onset of the gap at around $\rho_B \approx 1.0 \text{ fm}^{-3}$ when the $n\Sigma^-$ asymmetry drops below ≈ 0.4, and reaching values of the order of 10 MeV at higher baryon density. For comparison, the lowest panel of the figure shows the neutron-neutron and proton-proton $^3PF_2$ pairing gaps obtained in naïve BCS approximation with the Argonne V_{18} potential, as published in Ref. [3]. One notes that both gaps extend beyond $\rho_B = 1 \text{ fm}^{-3}$ with values of less than 1 MeV. This is due to the reduced nucleonic partial densities in the presence of hyperons.

In conclusion, in this Letter we explored the possibility of pairing in the various hyperon-nucleon channels relevant, in particular, for neutron star physics, using realistic hyperon-nucleon potentials of the Nijmegen group. With several of these potentials we found surprisingly large $n\Sigma^- \ ^3SD_1$ gaps that might persist even in the strongly asymmetric matter encountered in a neutron star. The resulting gaps are so strong that they would dominate (in fact, suppress) any direct neutron-neutron pairing [3] and could have important implications for the cooling behavior [18] of the star, as they would strongly modify the nucleonic URCA processes and more importantly block the direct hyperonic Σ^- URCA process, which could otherwise completely dominate the cooling in the core of massive neutron stars [18].

Even more drastic consequences could be due to an eventual phase separation of the superfluid and normal components [19] that might be energetically favorable in the case of very large gaps. In the most extreme situation a phase consisting only of neutron, protons, and Σ^- in equal fractions could be the preferred one at high density. These speculations open completely new possibilities for the interior structure of a neutron star and will be addressed in a future article.

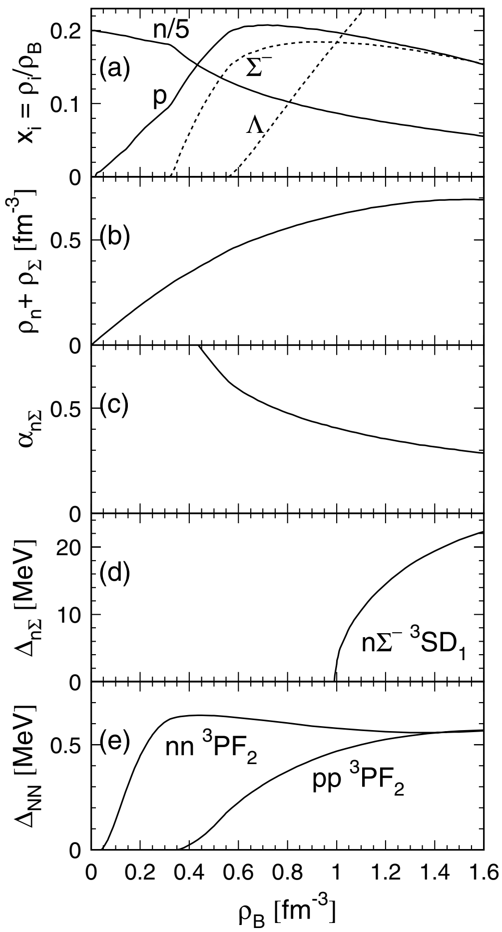

FIG. 3. Baryon fractions in beta-stable matter (a); corresponding total $n + \Sigma^-$ density (b) and asymmetry (c); resulting $n\Sigma^-$ $^3SD_1$ gap with the NSC89 potential (d); nucleonic $^3PF_2$ BCS gaps with the V_{18} potential (e).

This Letter served mainly to indicate the theoretical possibility of the presented exotic pairing scenario. We have chosen the most favorable conditions (potential NSC89) in order to obtain the maximum effect. The choice of other potentials strongly influences the final results. In fact, with the NSC97 potentials the maximum asymmetry remains below ≈ 0.2 such that $n\Sigma^-$ pairing does not appear with the EOS that we use. On the other hand, the gap inside the star depends crucially on the nucleon-hyperon asymmetry in that environment, and other hypernuclear EOS [6] might yield more favorable (lower) asymmetry values leading to pairing at even lower total baryon density, or compensating weaker potentials.

Unfortunately, more quantitative predictions cannot be made given the present state of the theory. While this is due mainly to insufficient knowledge of the hyperon-nucleon interactions, it is also a result of the simplified theoretical treatment of several many-body effects, such as neglecting self-energy terms and polarization corrections to the pairing interaction that can be essential at high density. However, even for the nucleonic pairing these are presently not under control [1]. In any case it would be highly desirable to have better constrained hyperon-nucleon potentials, not only for the present application, but also for the equation of state of high-density baryonic matter [6,7], or for the theoretical modeling of hypernuclei [16,17].

This work was supported by the National Natural Science Foundation of China under Contract No. 10347115, the U.S. National Science Foundation (Contract No. 0140300), the Southeastern Universities Research Association, the Education Department of Liaoning Province (Contract No. 202122024), and the LSU-LNNU joint research program (Contract No. C164063). H.-J. S. appreciates the kind hospitality in Liaoning Normal University.

[1] A. B. Migdal, Sov. Phys. JETP **10**, 176 (1960); U. Lombardo and H.-J. Schulze, in *Physics of Neutron Star Interiors*, edited by D. Blaschke, N. K. Glendenning, and A. Sedrakian, Lecture Notes in Physics Vol. 578 (Springer-Verlag, Berlin, 2001), pp. 30; D. J. Dean and M. Hjorth-Jensen, Rev. Mod. Phys. **75**, 607 (2003).

[2] J. Cugnon, P. Deneye, and A. Lejeune, Z. Phys. A **328**, 409 (1987); I. Bombaci and U. Lombardo, Phys. Rev. C **44**, 1892 (1991); W. Zuo, I. Bombaci, and U. Lombardo, Phys. Rev. C **60**, 024605 (1999); Ø. Elgarøy, L. Engvik, M. Hjorth-Jensen, and E. Osnes, Nucl. Phys. **A604**, 466 (1996); W. Zuo, Z. H. Li, G. C. Lu, J. Q. Li, W. Scheid, U. Lombardo, H.-J. Schulze, and C. W. Shen, Phys. Lett. B **595**, 44 (2004).

[3] Xian-Rong Zhou, H.-J. Schulze, En-Guang Zhao, Feng Pan, and J. P. Draayer, Phys. Rev. C **70**, 048802 (2004).

[4] P. W. Anderson and N. Itoh, Nature (London) **256**, 25 (1975); S. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects* (Wiley, New York, 1983); J. A. Sauls, in *Timing Neutron Stars*, edited by H. Ögelman and E. P. J. van den Heuvel (Kluwer, Dordrecht, 1989), p. 457; *Proceedings of US-Japan Joint Seminar, Kyoto, 6–10 November 1990*, The Structure and Evolution of Neutron Stars, edited by D. Pines, R. Tamagaki, and S. Tsuruta (Addison-Wesley, Reading, MA, 1992).

[5] S. Tsuruta, Phys. Rep. **292**, 1 (1998); H. Heiselberg and M. Hjorth-Jensen, Phys. Rep. **328**, 237 (2000); D. G. Yakovlev and C. J. Pethick, Annu. Rev. Astron. Astrophys. **42**, 169 (2004).

[6] S. Balberg, I. Lichtenstadt, and G. B. Cook, Astrophys. J. Suppl. Ser. **121**, 515 (1999); J. M. Lattimer and M. Prakash, Astrophys. J. **550**, 426 (2001); P. Haensel, in *Final Stages of Stellar Evolution*, edited by C. Motch and J.-M. Hameury, EAS Publication Series Vol. 7 (EDP Sciences, Les Ulis, 2003), pp. 249; N. K. Glendenning, *Compact Stars, Nuclear Physics, Particle Physics, and General Relativity* (Springer-Verlag, Berlin, 2000), 2nd ed..

[7] M. Baldo, G. F. Burgio, and H.-J. Schulze, Phys. Rev. C **58**, 3688 (1998); **61**, 055801 (2000); C. Maieron, M. Baldo, G. F. Burgio, and H.-J. Schulze, Phys. Rev. D **70**, 043010 (2004).

[8] S. Balberg and N. Barnea, Phys. Rev. C **57**, 409 (1998); T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **102**, 1043 (1999); Nucl. Phys. **A670**, 222 (2000); T. Takatsuka, S. Nishizaki, Y. Yamamoto, and R. Tamagaki, Prog. Theor. Phys. **105**, 179 (2001); T. Tanigawa, M. Matsuzaki, and S. Chiba, Phys. Rev. C **68**, 015801 (2003); I. Vidaña and L. Tolós, Phys. Rev. C **70**, 028802 (2004).

[9] P. M. M. Maessen, Th. A. Rijken, and J. J. de Swart, Phys. Rev. C **40**, 2226 (1989).

[10] V. G. J. Stoks and Th. A. Rijken, Phys. Rev. C **59**, 3009 (1999).

[11] G. Sarma, J. Phys. Chem. Solids **24**, 1029 (1963); H. T. C. Stoof, M. Houbiers, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. **76**, 10 (1996); M. Houbiers, R. Ferwerda, H. T. C. Stoof, W. I. McAlexander, C. A. Sackett, and R. G. Hulet, Phys. Rev. A **56**, 4864 (1997); A. Sedrakian, T. Alm, and U. Lombardo, Phys. Rev. C **55**, R582 (1997); A. Sedrakian and U. Lombardo, Phys. Rev. Lett. **84**, 602 (2000); A. I. Akhiezer, A. A. Isayev, S. V. Peletminsky, and A. A. Yatsenko, Phys. Rev. C **63**, 021304(R) (2001); J. Liao and P. Zhuang, Phys. Rev. D **68**, 114016 (2003).

[12] A. Sedrakian, Phys. Rev. C **63**, 025801 (2001); U. Lombardo, P. Nozières, P. Schuck, H.-J. Schulze, and A. Sedrakian, Phys. Rev. C **64**, 064314 (2001).

[13] J. P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rep. **25C**, 83 (1976); H.-J. Schulze, M. Baldo, U. Lombardo, J. Cugnon, and A. Lejeune, Phys. Rev. C **57**, 704 (1998); M. Baldo, *Nuclear Methods and the Nuclear Equation of State* (World Scientific, Singapore, 1999).

[14] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).

[15] B. S. Pudliner, V. R. Pandharipande, J. Carlson, and R. B. Wiringa, Phys. Rev. Lett. **74**, 4396 (1995); M. Baldo, I. Bombaci, and G. F. Burgio, Astron. Astrophys. **328**, 274 (1997); M. Baldo and L. S. Ferreira, Phys. Rev. C **59**, 682 (1999); X. R. Zhou, G. F. Burgio, U. Lombardo, H.-J. Schulze, and W. Zuo, Phys. Rev. C **69**, 018801 (2004).

[16] J. Cugnon, A. Lejeune, and H.-J. Schulze, Phys. Rev. C **62**, 064308 (2000); I. Vidaña, A. Polls, A. Ramos, and H.-J. Schulze, Phys. Rev. C **64**, 044301 (2001); I. Vidaña, A. Ramos, and A. Polls, Phys. Rev. C **70**, 024306 (2004).

[17] J. Mares, E. Friedman, A. Gal, and B. K. Jennings, Nucl. Phys. **A594**, 311 (1995); J. Dabrowski, Phys. Rev. C **60**, 025205 (1999); P. K. Saha *et al.*, Phys. Rev. C **70**, 044613 (2004).

[18] C. Schaab, S. Balberg, and J. Schaffner-Bielich, Astrophys. J. Lett. **504**, L99 (1998); D. Page, M. Prakash, J. M. Lattimer, and A. W. Steiner, Phys. Rev. Lett. **85**, 2048 (2000); T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **112**, 37 (2004).

[19] P. F. Bedaque, H. Caldas, and G. Rupak, Phys. Rev. Lett. **91**, 247002 (2003); H. Caldas, Phys. Rev. A **69**, 063602 (2004).