Proton pairing in neutron stars

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We studied the influence of dispersive self-energy effects, three-body forces, and polarization contributions to the interaction kernel on the $^1S_0$ proton pairing in neutron star matter. We found that a strong suppression of the gap by self-energy effects and three-body forces is at low density compensated by the attractive polarization interaction, shifting the domain of pairing to below $\rho_B \approx 0.3$ fm^{-3}.

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The quantitative knowledge of the different neutron and proton pairing gaps in neutron stars (NS) is of vital importance for the understanding and modeling of the various phenomena that are related to them, namely the occurrence of glitches [1] and the cooling behavior [2] of the star. At the moment, the only pairing channel that seems to be theoretically under control is the $^1S_0$ neutron pairing occurring in the crust of the star, for which several calculations agree on predicting a suppression by about a factor of 4 relative to the BCS value, leading to gaps of the order of not more than 1 MeV, even if the precise density dependence is still not accurately known [3,4]. This suppression is mainly due to polarization corrections to the interaction kernel, which even in the "low-density" subnuclear domain are substantial. However, corrections to the neutron self-energy play a minor role in this regime. The $^3PF_2$ pairing of neutrons and protons in the core of the star is still burdened with too many theoretical uncertainties even on the pure BCS level [3,5] and will not be discussed here.

The focus of this article is on the remaining important $^1S_0$ proton pairing extending through the inner crust and outer core of the star. Even if the relevant partial proton densities in this environment are evidently the same as the neutron densities for $^1S_0$ neutron pairing, the presence of a much larger background neutron density leads to important modifications of the proton self-energy as well as to strong in-medium corrections to the proton-proton (pp) interaction kernel that both might strongly influence the pairing. The quantitative investigation of these effects is the purpose of this article. More precisely, we study the change of the proton gap due to (a) the influence of the momentum and energy dependence of the self-energy in Brueckner-Hartree-Fock (BHF) approximation, (b) the addition of nuclear three-body forces (3BF) to the two-body potential (2BF), and (c) polarization contributions to the interaction kernel caused by neutrons and protons in the environment.

For all calculations presented in the following we use as basic nucleon-nucleon interaction the Argonne V_{18} potential [6], which is supplemented by the Urbana UIX three-body forces [7] to ensure a realistic saturation point of nuclear matter within the BHF approach. This interaction is used for the interaction kernel of the gap equation (comprising direct and medium-induced contribution) as well as as input to the BHF calculations of the neutron and proton single-particle (s.p.) potentials that appear in the gap equation and also determine the equation of state of nuclear matter and thus the composition (proton fraction) of beta-stable NS matter [8], relevant for our calculations. All ingredients of our approach are thus consistently based on the same realistic interaction.

The microscopic theory of pairing involves in principle a four-dimensional gap equation incorporating the momentum- and energy-dependent interaction kernel $\Gamma(k,\omega;k',\omega')$ and self-energy $\Sigma(k,\omega)$, which reads [3,9–11]

$$\Delta(k,\omega) = -\int \frac{d^3k'}{(2\pi)^3}\int \frac{d\omega'}{2\pi i}\Gamma(k,\omega;k',\omega')\frac{\Delta(k',\omega')}{D(k',\omega')} \quad (1)$$

with

$$D(k,\omega) = [M(k,+\omega)-\omega-i0] \times [M(k,-\omega)+\omega-i0]+\Delta(k,\omega)^2 \quad (2)$$

and

$$M(k,\omega) = \frac{k^2}{2m}+\Sigma(k,\mu+\omega)-\mu, \quad (3)$$

where we define for convenience the energy ω relative to the chemical potential μ. For realistic systems, Γ and Σ cannot be specified in general and significant approximations have to be performed. The usual BCS approximation amounts to replacing the interaction kernel by the (energy independent) bare nucleon-nucleon potential V, and the nucleon self-energy by some realistic s.p. spectrum, e.g., the BHF values

$$U(k) = \Sigma_{\rm BHF}(k,\mu+e_k), \quad e_k = M(k,e_k). \quad (4)$$

In our case the proton chemical potential is to a very good approximation given by $\mu = k_F^2/2m + U^{(p)}(k_F)$, where $k_F = (3\pi^2\rho_p)^{1/3}$ is the proton Fermi momentum.

As shown in detail in Ref. [10], taking into account the energy dependence of the self-energy while still remaining with a static interaction kernel, $\Gamma(k,\omega;k',\omega') = V(k,k')$, leads to the gap equation

$$\Delta(k) = -\sum_{k'}\frac{V(k,k')Z(k')}{2\sqrt{M_s(k')^2+\Delta(k')^2}}\Delta(k'), \quad (5)$$

with the "symmetrized" s.p. energy

$$M_s(k) \equiv {\rm Re}\left[\frac{M(k,+e_k)+M(k,-e_k)}{2}\right] \quad (6)$$

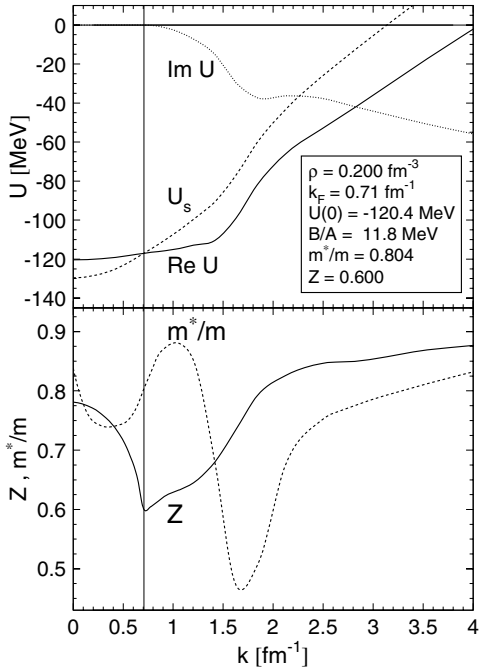

FIG. 1. Momentum dependence of the BHF proton self-energies U and U_s (upper panel) and effective mass m^*/m and spectral factor Z (lower panel) for $\rho_B = 0.2$ fm^{-3}. The vertical line shows the position of the proton Fermi momentum.

appearing in the denominator and an interaction kernel modified by the spectral factor

$$Z(k) \equiv \sqrt{M_s(k)^2 + \Delta(k)^2}\,\frac{2}{\pi}\int_0^\infty d\omega\,\mathrm{Im}\left(\frac{1}{D(k,\omega)}\right). \quad (7)$$

In principle $Z(k)$ should be calculated self-consistently with the gap function [11]. However, it is a good approximation to use the normal spectral function instead of the full one. No quasiparticle approximation is used.

We consider now the self-energy effects on the *pp* pairing under the physical conditions present in NS. The knowledge of the BHF self-energy allows the computation of the relevant s.p. energy e_k, Eq. (4), and $M_s(k)$, Eq. (6), as well as the spectral factor $Z(k)$, Eq. (7), and then the solution of the gap equation (5). To illustrate, Fig. 1 shows for a typical baryon density $\rho_B = 0.2$ fm^{-3} (the proton fraction here is $x \approx 0.06$) the BHF proton s.p. spectrum $U(k)$ and the symmetrized quantity $U_s(k)$, as well as the momentum-dependent proton effective mass $m^*(k)/m = [1 + (m/k)(dU(k)/dk)]^{-1}$ and the Z factor, Eq. (7). One notes typical values close to the Fermi surface of $Z \approx 0.6$ and $m^*/m \approx 0.8$, which hint already at a strong reduction of the gap.

In Fig. 2 we summarize the key results of our calculations in beta-stable matter as a function of total baryon density, namely (a) the Fermi momenta of neutrons and protons, (b) their effective masses $m^* \equiv m^*(k_F)$, and (c) their quasiparticle factors $Z \equiv Z(k_F)$. Panel (d) compares the gap resulting from Eq. (5) within the simplest approximation using a kinetic s.p. spectrum ($m^*/m = Z = 1$) with the one including the BHF s.p. spectrum but neglecting the energy dependence, i.e., setting $Z(k) = 1$. One notes a strong reduction from about 3

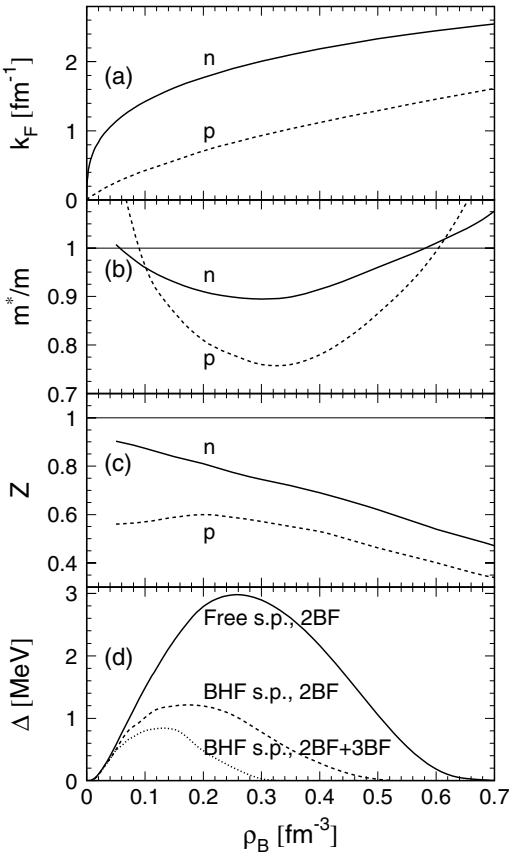

FIG. 2. Neutron and proton Fermi momenta (a), effective masses (b), and Z factors (c) in beta-stable matter. (d) Proton $^1S_0$ gap with kinetic (solid curve) and BHF s.p. spectrum (dashed curve) using only 2BF in the interaction kernel and including 3BF (dotted curve).

to 1 MeV at maximum in the latter case, because the proton effective mass is small due to strong *pn* correlations. Adding also 3BF to the interaction kernel leads to a further reduction of the gap, increasing with density, since 3BF are repulsive in the $^1S_0$ channel [12]. Attempting to include also the energy dependence via the calculated value of the quasiparticle factor $Z(k)$, Eq. (7), no solution of the gap equation is found anymore with or without 3BF.

For comparison, in pure neutron matter superfluidity is also suppressed by self-energy effects [10], but the reduction is not so strong (less than 50%) because it occurs at a lower baryon density, where both the effective mass and Z factor are close to unity. In addition, screening by polarization of the medium further reduces the gap, but superfluidity still survives with a gap value around 1 MeV [3,4]. If for proton pairing under NS conditions screening would be repulsive, no *pp* pairing could be present. However, it turns out that screening in this case is strongly attractive due to strong *pn* correlations [13] such that it can counterbalance the suppression due to self-energy effects.

Concerning the quantitative evaluation of polarization effects on the pairing interaction, unfortunately at present an accurate solution cannot be given. We therefore present in the following a simplified treatment involving several

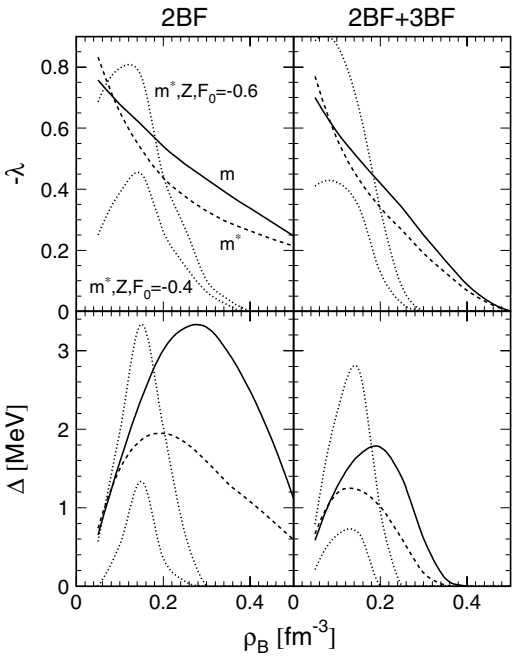

FIG. 3. Weak-coupling parameter λ (top panels) and gap Δ (bottom panels), Eq. (8), in several approximations (see text). The solid curves show BCS results without any in-medium effects, the dashed curves include the modification of the effective mass m^*, and the dotted curves take account of Z-factor and polarization corrections in addition. The left panels show results with only 2BF in the interaction kernel, and the right panels include 3BF.

approximations but that we think is reliable enough to allow our main conclusion that the *pp* polarization interaction is attractive due to the strong *pn* coupling.

As a first step, we introduce the weak-coupling approximation, where the effective particle-particle interaction at the Fermi momentum, $V_{\rm eff}(k_F, k_F)$, determines the gap value according to the well-known exponential formula [3,9,14,15]

$$\Delta = c\mu \exp\left(\frac{1}{\lambda}\right), \quad \lambda = V_{\rm eff} k_F m^* Z^2. \tag{8}$$

Notice that we define the interaction matrix element including the usual prefactor of the density of states, $N = m^* k_F/2\pi^2$. To show the degree of accuracy of this approximation, we report in Fig. 3 (left plots, solid curves) the values of the parameter λ and the gap calculated with a free s.p. spectrum ($m^*/m = Z = 1$) using Eq. (8). For $V_{\rm eff}$ we use a suitable low-momentum effective interaction, $\widetilde{V}(k, k')$ [4,14,16], with k, k' being the relative initial and final momenta of the two particles. This potential is obtained by projecting out the momenta larger than a cutoff k_c,

$$\widetilde{V}(k, k') = V(k, k') - \sum_{k''>k_c} \frac{V(k, k'')\widetilde{V}(k'', k')}{2E_{k''}}. \tag{9}$$

The gap equation, restricted to momenta $k < k_c$ and with the original interaction V replaced by $\widetilde{V}$ is exactly equivalent to the original gap equation. The discrepancy of the results with the full calculations is then solely due to the weak-coupling approximation, which is justified by the smoothness of $\widetilde{V}$ and due to the replacement $E_{k''} \to e_{k''} - \mu$ that we perform in Eq. (9). We use a cutoff value $k_c = \sqrt{2}k_F$, which is compatible with the constant $c = 8\exp(\sqrt{2}-2)/(\sqrt{2}+1) \approx 1.845$ in the weak-coupling formula. Other values of k_c do not change the results in an appreciable way. One observes that this procedure leads to deviations of less than 10% relative to the solution of the full gap equation [solid curve in Fig. 2(d)].

If the calculated effective mass m^* is introduced, the gap is suppressed and the weak-coupling formula predicts a 50% overestimate with respect to the full calculations [cf. dashed curves in Fig. 2(d) and Fig. 3 (left plot)], due to the extreme sensitivity of the gap to the inadequacy of the effective mass approximation. The same is true including 3BF [dotted curve in Fig. 2(d) and dashed curve in Fig. 3 (right plot)]. If the Z factor is also used in Eq. (8), the gap is further suppressed to an extremely small value, in agreement with the full calculations. The weak-coupling formula can thus be used in first approximation as an (over-)estimate of the gap.

We will now use the same $\widetilde{V}$ to estimate the effect of screening at the Fermi surface. In addition to the direct term the polarization of the medium introduces the so-called induced interaction, $V_{\rm eff} = \widetilde{V} + W$, with

$$W_{ik}(\boldsymbol{k}', \boldsymbol{k}) = \sum_{j,l} \sum_{\boldsymbol{p}} \langle \boldsymbol{k}', \boldsymbol{p}|\widetilde{F}_{ij}|\boldsymbol{k}, \boldsymbol{p}+\boldsymbol{q}\rangle \Pi_{jl}(\boldsymbol{p}, \boldsymbol{q}) \times \langle \boldsymbol{p}+\boldsymbol{q}, -\boldsymbol{k}'|\widetilde{F}_{lk}|\boldsymbol{p}, -\boldsymbol{k}\rangle, \tag{10}$$

where the indices i, j, k, l stand for neutron (n) or proton (p). Here $\widetilde{F}_{ij}$ are the effective scattering amplitudes, including exchange, and $\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$ is the momentum transfer. The polarization propagator Π_{jl} satisfies an RPA-type equation, which can be schematically written as

$$\Pi = \Pi^0 + \Pi^0 \begin{pmatrix} F_{nn} & F_{np} \\ F_{pn} & F_{pp} \end{pmatrix} \Pi, \tag{11}$$

and yields

$$\Pi_{nn} = \frac{\left(1 - F_{pp}\Pi_p^0\right)\Pi_n^0}{D}, \tag{12}$$

$$\Pi_{np} = \frac{F_{np}\Pi_n^0\Pi_p^0}{D}, \tag{13}$$

with

$$D = 1 - F_{nn}\Pi_n^0 - F_{pp}\Pi_p^0 + (F_{nn}F_{pp} - F_{np}F_{pn})\Pi_n^0\Pi_p^0, \tag{14}$$

where Π_i^0 are the free gas polarizations (in the static limit) and F_{ij} are the effective particle-hole interactions.

The key quantity in the weak-coupling formula is the effective particle-particle interaction at the proton Fermi momentum $k_p \equiv k_F^{(p)}$. The induced interaction will therefore be estimated at k_p. We first consider the dominant *pn* coupling in Eq. (10). Because in the relevant density range the proton fraction is only a few percentages, we neglect k_p with respect to k_n, i.e., the initial and final (relative) momenta can be identified with $k_n/2$. The interaction vertex $\widetilde{F}_{pn}$ is then just the forward scattering amplitude and will be estimated by $\widetilde{V}_{pn}(k_n/2, k_n/2)$. The *pp* coupling gives only a small correction, justifying the

following approximation: The involved momenta are all of the order of k_p, small enough to restrict the interaction vertex $\widetilde{F}_{pp}$ to s-wave scattering and to perform an average over the momenta k, k' between 0 and $2k_p$, which turns out to be very close to $\widetilde{V}_{pp}(k_p, k_p)$. The loop integral $\sum_{\boldsymbol{p}}$ in Eq. (10) is then factorized.

After projection on the $^1S_0$ proton pairing channel the final expression for the pp polarization interaction reads

$$W_{pp} = \sum_{i,j=n,p} W_{pp}^{ij},$$
$$W_{pp}^{ij} = \sum_{s=0,1} (-1)^s (2s+1) \widetilde{F}_{pi}^{(s)} \Pi_{ij}^{(s)} \widetilde{F}_{jp}^{(s)}, \tag{15}$$

which gives the well-known combination of density exchange ($s = 0$) and spin-density exchange ($s = 1$), with

$$\widetilde{F}_{pn}^{(s)} = \sum_{S,T,L,J} \frac{(2J+1)}{8\pi} \begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & S \\ \frac{1}{2} & \frac{1}{2} & s \end{Bmatrix} \widetilde{V}^{STLJ}\left(\frac{k_n}{2}, \frac{k_n}{2}\right), \tag{16}$$

where the effective interaction has been expanded in the two-body channels (partial waves) with spin S, isospin T, orbital angular momentum L, and total angular momentum J. It has to be noticed that the tensor component of the NN force is included in calculating $\widetilde{V}$ from the integral equation (9). However, in the calculation of $\widetilde{F}_{pn}^{(s)}$ only the matrix elements diagonal in the total spin projection are considered, in agreement with Eq. (16). A similar expression holds for $\widetilde{F}_{pp}^{(s)}$, with the restriction to $L = 0$ only. The inclusion in the expansion of the exchange gives simply a factor of 2.

Finally, the polarization propagators Π_{ij} are evaluated in the Landau limit, neglecting Landau parameters higher than the $L = 0$ component. The Landau parameters F_0 and G_0 representing the particle-hole interactions F_{ij} in Eqs. (11)–(14) are evaluated from $\widetilde{V}$ as effective particle-hole interaction, including in-medium modifications of the effective mass and Z factor. The off-diagonal np Landau parameters are defined by multiplying the effective forces with $\sqrt{N_n N_p}$, with N_n and N_p being the neutron and proton densities of state [17]. In the free neutron polarization function $\Pi_n^0(q)$ the Landau limit is well justified, because the momentum transfer q is proportional to $k_p \ll k_n$. In $\Pi_p^0(q)$ the dependence on q is still weak, and we take an average over $0 < q < 2k_p$.

Two observations are in order: (i) The full polarization Π is used instead of, e.g., the free polarization Π^0 (one bubble), to take into account the complete response of the medium. The use of Π^0 would seriously underestimate medium effects. (ii) In principle, a well-defined relationship should hold between particle-particle and particle-hole interactions [18,19] and we will check to which extent it could affect the present estimate.

In Fig. 4 we report the neutron Landau parameters F_0 (density response) and G_0 (spin-density response) in pure neutron matter in the domain of interest for the proton pairing calculated from our $\widetilde{V}$, appropriately including the effective masses and the Z factors. We compare with various

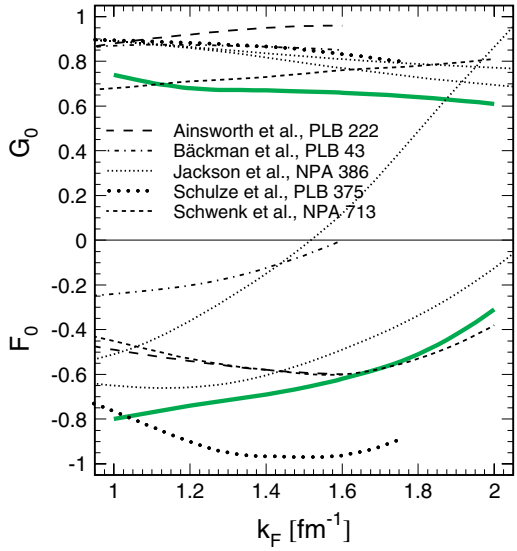

FIG. 4. (Color online) Neutron matter Landau parameters F_0 and G_0 (solid green curves) in comparison with the results of Refs. [4,20] (broken curves).

previously published results [4,20] using different many-body schemes.

Given the scarse agreement of the different results in particular for the Landau parameter F_0, we proceed for the calculation of beta-stable matter in the following way: In the neutron polarization propagator we use constant values of the Landau parameters, $G_{0_{nn}} = 0.7$ and either $F_{0_{nn}} = -0.6$ or $F_{0_{nn}} = -0.4$, where the last value serves to establish a lower bound on the pairing gap. This also implies that we neglect the influence of the small proton fraction on the neutron Landau parameter. For the proton Landau parameters $F_{0_{pp}}$ and $G_{0_{pp}}$ we find small values in the relevant proton density range, due to the strong reduction of the proton effective mass and Z factor. For simplicity we neglect them together with higher-order Landau parameters.

The resulting induced pp interaction at the Fermi momentum is strongly attractive and the corresponding weak-coupling parameters and gap values are shown in Fig. 3, where the upper dotted curves represent the results with $F_0 = -0.6$ and the lower dotted curves those with $F_0 = -0.4$, for calculations both with (right plots) and without (left plots) 3BF. The values of the gaps are also listed in Table I. One observes that in all cases the attractive polarization interaction is strong enough to

TABLE I. Values of the gaps (in MeV) including all medium effects, corresponding to the dashed curves in Fig. 3.

ρ_B(fm^{-3})	2BF		2BF+3BF	
	$F_0 = -0.4$	$F_0 = -0.6$	$F_0 = -0.4$	$F_0 = -0.6$
0.05	0.05	0.57	0.21	0.79
0.10	0.53	1.97	0.65	2.20
0.15	1.33	3.38	0.68	2.76
0.20	0.41	2.03	0.01	0.95
0.25	0.03	0.68	0	0

TABLE II. Contributions (in MeV fm^3) to the effective polarization interaction W_{pp}, Eq. (15), at $\rho_B = 0.2$ fm^{-3}. The upper part corresponds to the full calculation and the lower part to the one without tensor force. The Landau parameter $F_{0_{nn}} = -0.4$ and no 3BF were used. At this density, $\widetilde{V} = -31.6$ MeV fm^3.

	W_{pp}^{nn}	W_{pp}^{pp}	W_{pp}^{np+pn}	Total
$s = 0$	−78.5	−15.1	+32.8	−60.7
$s = 1$	−3.0	−10.0	−1.2	−14.2
Total	−69.4	+14.8	+36.3	−18.3
$s = 0$	−8.7	−12.5	+3.4	−17.8
$s = 1$	−0.1	−11.5	−0.1	−11.7
Total	−8.3	+22.1	+3.6	+17.4

overcome the complete suppression of the gaps due to the Z factor discussed before.

To clarify the origin of the attractive polarization interaction, we list in Table II the different contributions $W_{pp}^{nn}, W_{pp}^{pp}, W_{pp}^{np} + W_{pp}^{pn}$ appearing in Eq. (15), at $\rho_B = 0.2$ fm^{-3}, $F_{0_{nn}} = -0.4$, and without 3BF. One notes that the major part of the attraction arises from the *nn* polarization, which couples to the protons via two *np* interactions $\widetilde{F}_{np}$. The strong medium polarizability can be expected on physical grounds, because NS matter at neutron Fermi momenta below $\sim$1.2 fm^{-1} is known to be unstable for density fluctuations, i.e., the compressibility is negative [21]. Repulsive contributions arise both from the *pp* polarization (due to the dominance of exchange diagrams [22]) and the *np* polarization (which is of second order in Π^0).

The *np* interaction is dominated by the tensor force. Therefore, neglecting it in the calculation, the *nn* (and *np*) polarization contributions become much weaker, and the total interaction is dominated by the repulsive *pp* polarization, which is only weakly affected by the tensor force. Thus the attractive overall effect of the full calculations is inverted to repulsion, as in pure proton matter. This is in line with Ref. [19], where the screening effect in *pp* pairing was calculated with an effective force without tensor interaction, and indeed repulsion was found.

In conclusion, we studied proton $^1S_0$ pairing in asymmetric NS matter, taking into account a rather complete set of many-body effects, although in an approximate manner. We found that the strong (actually complete) suppression of the proton gap due to the energy dependence of the self-energy (Z factor) and 3BF is at low density compensated by the attractive screening caused by the polarizability of the neutron component and mediated by the strong *pn* interaction. This is at variance with *nn* pairing in pure neutron matter (and likely in NS matter), where both self-energy and screening tend to reduce the gap. The resulting domain of pairing is reduced to below $\rho_B \approx 0.3$ fm^{-3} compared to the BCS pairing obtained without medium effects extending up to $\rho_B \gtrsim 0.5$ fm^{-3}.

The maximum value of the gap must be considered uncertain due to the strong sensitivity mainly to the value of the neutron Landau parameter F_0 but also to the various other approximations made in our approach. Our estimate of the induced interaction is not self-consistent; however, the adopted approximate scheme is able to produce values of the Landau parameters in pure neutron (or proton) matter that are consistent with other calculations based on more refined many-body theory. Only drastically different absolute values of the neutron Landau parameter F_0 would modify the main conclusions, but look unlikely.

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