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Effects of Meson Mass Decrease on Superfluidity in Nuclear Matter

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¹S₀ pairing in nuclear matter is investigated by taking the hadron mass decrease into account via the "In-Medium Bonn potential" which was recently proposed by Rapp *et al.* The resulting gap is significantly reduced in comparison with the one obtained with the original Bonn-B potential and we ascertain that the meson mass decrease is mainly responsible for this reduction.

Superfluidity in nuclear matter is one of the important issues in nuclear physics since it forms the foundation for nuclear structure theory and has close relationship to neutron-star physics. To describe a nuclear many-body system, relativistic models are attracting attention as well as non-relativistic ones. This is due to the success of Quantum Hadrodynamics (QHD) originated with the study by Chin and Walecka in 1970's [1].

We studied ¹S₀ pairing in nuclear matter by means of QHD, which has been succeeded in describing the various phenomena of nuclei, that is, not only the saturation property of nuclear matter, but spherical, deformed and rotating nuclei. Therefore improvement on the description of pairing which is essential in open shell nuclei would make QHD more reliable. To speak of neutron-star physics, relativistic effect might be important due to high density which is a few times larger than the normal nuclear matter density.

As is well known, QHD is an effective field theory of hadronic degrees of freedom. The Lagrangian density for the present model is like this:

$$\begin{aligned} \mathcal{L} = & \bar{\psi}(i\gamma_{\mu}\partial^{\mu} - M)\psi + \frac{1}{2}(\partial_{\mu}\sigma)^2 - \frac{1}{2}m_{\sigma}^2\sigma^2 \\ & - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_{\omega}^2\omega_{\mu}\omega^{\mu} - \frac{1}{4}\mathbf{R}_{\mu\nu} \cdot \mathbf{R}^{\mu\nu} + \frac{1}{2}m_{\rho}^2\rho_{\mu} \cdot \rho^{\mu} \\ & - g_{\sigma}\bar{\psi}\sigma\psi - g_{\omega}\bar{\psi}\gamma_{\mu}\omega^{\mu}\psi - g_{\rho}\bar{\psi}\gamma_{\mu}\boldsymbol{\tau} \cdot \boldsymbol{\rho}^{\mu}\psi - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4, \\ & \Omega_{\mu\nu} = \partial_{\mu}\omega_{\nu} - \partial_{\nu}\omega_{\mu}, \quad \mathbf{R}_{\mu\nu} = \partial_{\mu}\boldsymbol{\rho}_{\nu} - \partial_{\nu}\boldsymbol{\rho}_{\mu}. \end{aligned} \quad (1)$$

Here ψ is the nucleon field, σ stands for σ -boson field, ω for ω -meson field and ρ for ρ -meson field. Non-linear self-coupling terms for σ -boson, which are crucial for a realistic description of nuclear properties within Relativistic Mean Field Theory (RMFT), are also included. Deriving the particle-particle (p-p) channel interaction in the relativistic models is one of the current topics through practical approach, namely, the use of a non-relativistic force (e.g. Gogny force) in p-p channel, has been adopted in the finite nuclei calculations.

The first study of pairing by means of QHD was done by Kucharek and Ring in 1991 [2]. In order to incorporate the pairing field, meson fields must be quantized and the anomalous Green's function is defined by the Gor'kov factorization. The customary manipulation gives Relativistic-Hartree-Bogoliubov (RHB) equation. Hence a transcendental equation of effective nucleon mass for the mean field and an ordinary non-linear gap equation for the pairing field organize the non-linear system of equations.

The resulting gap obtained by adopting the one-boson-exchange (OBE) interaction with RMFT parameter set such as NL1 is too large to achieve a consensus. Aforementioned "practical approach" for finite nuclei is a remedy for this excessive gap problem. In nuclear matter, alternatively, a bare interaction in free space can be used as p-p interaction and produces a consistent result with the non-relativistic studies, where the maximum pairing gap ranges from 2 to 4 MeV [3].

A possible extension in alignment with the above policy is to take the change of the hadron properties into consideration. In the pioneering work done by Brown and Rho, it was pointed out that the change of hadron masses may occur in conformity with the chiral symmetry arguments [4]. Although there is still controversy on this subject, some experiments seem to support the vector meson mass decrease. The change is expressed by the linear relation between the mass^{*} and the density:

$$\frac{M^*}{M} = \frac{m_{\rho\omega}^*}{m_{\rho\omega}} = \frac{\Lambda_{\rho\omega}^*}{\Lambda_{\rho\omega}} = 1 - C \frac{\rho}{\rho_0}, \quad C = 0.15, \quad (2)$$

where M is the nucleon mass, $m_{\rho\omega}$ are the masses of the ρ - and ω -meson and $\Lambda_{\rho\omega}$ are the cutoff masses in the form factors applied to each nucleon-meson vertex. The scaling factor C is taken to be 0.15, which is almost in line with the one obtained from QCD sum rules. This relation is often referred to as "Brown-Rho (BR) scaling."

Then, Rapp *et al.* showed that hadron mass decrease conforming to the scaling was compatible with the saturation property of nuclear matter [5]. They constructed the OBE potential just by adding two extra σ -bosons to the original Bonn-B potential with slightly modified parameters. This "In-Medium Bonn potential" makes the investigation of the medium effects on superfluidity quite

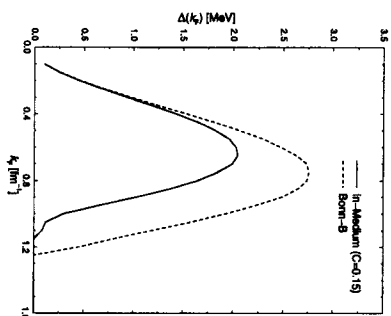


FIG. 1. The pairing gaps at the Fermi surface as a function of Fermi momentum k_F . Details are in the text.

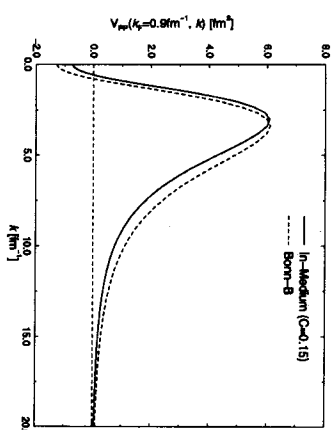


FIG. 2. The particle-particle channel interactions as a function of momentum k_F , with a Fermi momentum $k_F = 0.9 \text{ fm}^{-1}$. Details are in the text.

tractable. Accordingly we adopt this potential as the p-p interaction in the gap equation.

The resulting pairing gap at the Fermi surface is shown in Fig. 1, which is drawn as a function of Fermi momentum with the solid line. The dashed line corresponds to the gap obtained by using the original Bonn-B potential. Comparison shows that the inclusion of hadron mass decrease in concert with BR scaling reduces the gap significantly, however, the values stay in the physically acceptable range.

Before going into the detailed discussion of the gap, the structure of the gap equation has to be reviewed to clarify how the contributions come from each momentum region. As pointed out by Rummel and Ring [3], on the one hand, positive contributions come from the low- and high-momentum region where the gap has the opposite sign to the potential, which is due to the minus sign in the integrand of the gap equation. On the other hand, negative contributions come from the intermediate-momentum region where the both potentials have a repulsive peak.

Next, to see the mass decrease effects on the p-p interaction, In-Medium Bonn potential and the original Bonn-B potential are given in Fig. 2, which represents the shift of the In-Medium Bonn potential to the lower-momentum region. In other words, the hadron mass decrease leads to reduction of magnitude in the region giving the positive contributions to the gap as mentioned above. This is the main reason why reduction of the gap occurs in the case of In-Medium Bonn potential.

But a question may arise: which hadron is responsible for this reduction, nucleon or meson? In order to answer this, we also calculate the gap applying BR scaling only to either hadron. Note that such a treatment would make the potential unphysical in the sense that the saturation might not be reproduced in the Dirac-Brueckner-Hartree-Fock (DBHF) calculation. The result is shown in Fig. 3, where the solid, dashed and long-dashed lines correspond to the cases of decreasing only the nucleon mass, only the meson masses and the both, respectively. This figure ascertains that the reduction of the gap is mainly due to the meson mass decrease though the nucleon is responsible for it to some extent.

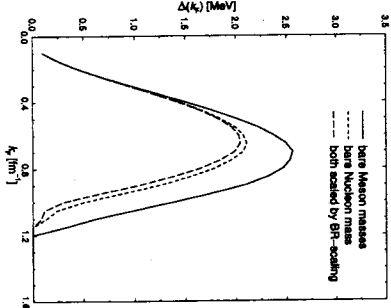


FIG. 3. The pairing gaps obtained with the partially BR scaled p-p interactions. Details are in the text.

What the shift of repulsive part brings about can be explained as follows: on the one hand, a point of difference between the In-Medium Bonn potential and the original Bonn-B potential lies in the consideration of the medium effect, that is, the decrease of hadron mass. As shown in Fig. 3, the decrease of meson mass is mainly responsible for the reduction of the gap. On the other hand, the vector meson takes charge of the repulsive force in the one-boson-exchange picture. When the mass decreases, the range of the repulsive force will be lengthened which is shown in the relation,

$$r \approx \frac{\hbar}{mc} < \frac{\hbar}{m^*c} \approx r^*, \quad (3)$$

where c is the speed of light and an asterisk stands for the quantity scaled in the medium. This lengthening means that the repulsive part of nuclear force shifts to lower-momentum region in momentum space. Actually, this shift manifests itself in Fig. 2. Consequently, the magnitude of the attractive force in low-momentum (long-range) region and of the repulsive force in high-momentum (short-range) region are weakened. As mentioned earlier, both regions give positive contributions to the pairing gap. Thus we confirm that it is the mass decrease of vector meson that largely reduces the gap.

We also note another ingredient connected with the reduction of the gap. In-Medium Bonn potential contains the cutoff mass in the form-factor of each meson-nucleon vertex, which is also scaled according to the Brown-Rho scaling,

They appear in the form

$$\frac{\Lambda_\alpha^{*2} - m_\alpha^{*2}}{\Lambda_\alpha^{*2} + q^2}, \quad (4)$$

where q is the momentum transfer [6]. Since the higher the density becomes, the more nucleons feel the high-momentum part of the p-p interaction, simultaneous reduction of Λ_α and m_α leads to a further weakening of the repulsion owing to the vector mesons in large- $|q|$. Therefore, in-medium scaling of cutoff mass results in an additional reduction of the gap in the high-density region.

In summary, we performed the numerical calculation of the pairing gap using In-Medium Bonn potential as the p-p interaction. The resulting gap is considerably reduced in comparison with the one obtained with the original Bonn-B potential and is consistent with the non-relativistic studies. The use of the meson theoretic potential reveals that the vector meson mass decrease, or lengthening the range of repulsive forces accounts for the reduction. Whether the polarization of Dirac sea as well as Fermi sea is effective for it remains a conjecture left for further investigation [7].

References

- [1] B. D. Serot and J. D. Walecka, *Adv. Nucl. Phys.* **16**, 1 (1986).
- [2] H. Kucharek and P. Ring, *Z. Phys. A* **339**, 23 (1991).
- [3] A. Rummel and P. Ring, preprint (1996).
- [4] G. E. Brown and M. Rho, *Phys. Rev. Lett.* **66**, 2720 (1991).
- [5] R. Rapp *et al.*, LANL e-Print archive nucl-th/9706006.
- [6] R. Machleidt, *Adv. Nucl. Phys.* **19**, 189 (1989).
- [7] M. Matsuzaki and P. Ring, *ibid.* nucl-th/9712060; M. Matsuzaki, *Phys. Rev. C* **58**, 3407 (1998).