Effect of meson mass decrease on superfluidity in nuclear matter

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$^1S_0$ pairing in symmetric nuclear matter is studied 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.

Introduction

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 study $^1S_0$ pairing in symmetric nuclear matter by means of QHD, which has been succeeded in describing not only the saturation property of nuclear matter but spherical, deformed and rotating nuclei. Therefore an 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 owing to high density which is a few times larger than the normal nuclear matter density.

In attacking this problem relativistically, we put strategies into three categories on the basis of the types of the particle-hole (p-h) and the particle-particle (p-p) channel interactions. The first is that relativistic mean field (RMF) is used for the p-h channel and one-boson-exchange (OBE) interaction derived from the same parameter set as the p-h chennel for the p-p channel. Kucharek and Ring adopted it[2)] as mentioned later. The second is that RMF is adopted for the p-h channel and a bare nucleon-nucleon force for the p-p channel. Such a study was carried out by Rummel and Ring.[3)] The third is that one takes relativistic G-matrix for the p-h channel and a bare nucleon-nucleon force for the p-p channel. According to the above, our present study comes under the second category though we introduce a medium modification other than conventional ones, namely, Brueckner correlation etc, therein.[4)] Another series of studies[5,6)] which fall under the first category are currently in progress and the talk concerning one of them was given at the symposium by M. M.

Formalism

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:

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

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 RMF theory, are also included. Deriving the p-p channel interaction in the relativistic models is one of the current topics though a practical approach, namely, the use of a non-relativistic force (the Gogny force) in the p-p channel, has been often 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 the 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 OBE interaction with RMF parameter set such as NL1 was 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 the p-p interaction and produces a consistent result with the non-relativistic studies, where the maximum pairing gap at the Fermi surface 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. The nuclear system is a strongly interacting one which should be described by the underlying theory, Quantum Chromodynamics (QCD). Up to now, however, such an attempt faces the difficulty due to its complexity in low-energy region. To overcome the situation, effective theories have been developed and some of them offer a suggestion that the hadronic properties might be modified in the medium, which is a result of a partial restoration of chiral symmetry. One of the hot issues among them is the vector meson mass decrease in the light both of theory and of experiment.

In the pioneering work done by Brown and Rho, it was pointed out that the change of hadron masses might occur in conformity with the chiral symmetry arguments.[7)] 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 masses and the density:

$$\frac{M^*}{M} = \frac{m^*_{\rho,\omega}}{m_{\rho,\omega}} = \frac{\Lambda^*_{\rho,\omega}}{\Lambda_{\rho,\omega}} = 1 - C\frac{\rho}{\rho_0}, \quad C = 0.15\,, \tag{2}$$

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 meson-nucleon 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 renowned relation is often referred to as the "Brown-Rho (BR) scaling." This scaling indirectly affects the physics of finite nuclei and neutron stars since it implies the modification of nuclear forces as a natural consequence.

Recently, Rapp et al. showed that hadron mass decrease conforming to this scaling was compatible with the saturation property of nuclear matter.[8)] They constructed the OBE potential just by adding two extra σ-bosons to the original Bonn potential with slight modifications to the Bonn-B parameter set. These bosons are parameterized so as to simulate the correlated 2π exchange processes in the medium, to which the BR scaling is actually applied. Moreover, they performed a Dirac-Brueckner-Hartree-Fock (DBHF) calculation with the potential to confirm the compatibility between the nuclear saturation and their potential. This "In-Medium Bonn potential" makes the study of the medium effects on superfluidity quite tractable. Accordingly we adopt this potential as the p-p interaction in the gap equation.

Results and discussion

The resulting pairing gap at the Fermi surface in symmetric nuclear matter 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 the BR scaling reduces the gap significantly, however, the values stay in the physically acceptable range.

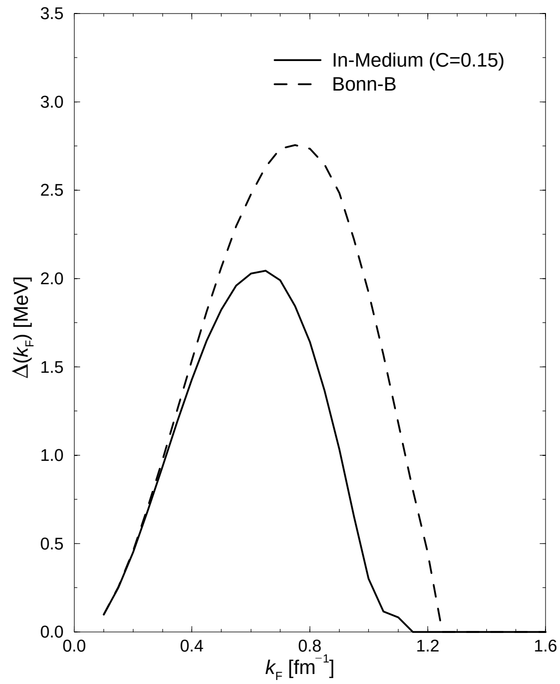

Fig. 1. The pairing gaps at the Fermi surface in symmetric nuclear matter are drawn as a function of Fermi momentum k_F. Details are in the text.

Before going into a 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, typically 1-2 fm^{-1}, where the gap and the potential have the same sign.

Next, to see the mass decrease effects on the p-p interaction, the 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.

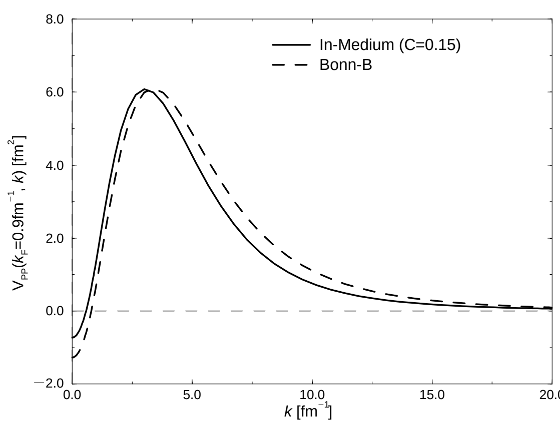

Fig. 2. The particle-particle channel interactions v_{pp} as a function of momentum, at a Fermi momentum $k_F = 0.9\ \mathrm{fm}^{-1}$. Details are in the text.

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 the 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 using the partially BR scaled p-p interaction, that is, applying the 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 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. Figure 3 ascertains that the reduction of the gap is mainly due to the meson mass decrease though the nucleonic one is responsible for it to some extent.

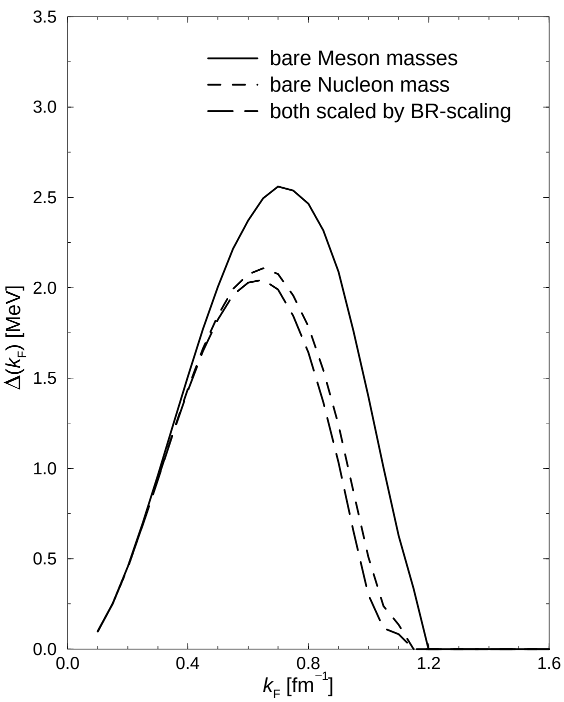

Fig. 3. The pairing gaps obtained with the partially BR scaled p-p interactions. Details are in the text.

Now it is evident that the meson mass decrease is a primary factor of the reduction as shown in Fig. 3, we explain how the shift of the interaction occurs. First of all, one of the differences between the In-Medium Bonn potential and the Bonn-B potential is whether the medium effect, that is, the decrease of hadron mass is taken into account or not. On the other hand, the vector meson takes charge of the repulsive force in the OBE picture. Therefore a range of the repulsive force is lengthened when a vector meson mass decreases, which is shown in the relation:

$$r \approx \frac{h}{mc} < \frac{h}{m^* c} \approx r^*, \tag{3}$$

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 the interaction shifts to lower-momentum region. Actually, this shift manifests itself in Fig. 2 and 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.

Having studied the p-p interactions so far in momentum space, let us here turn to the brief discussion in r-space to see the effect intuitively. Figure 4 represents the In-Medium Bonn and Bonn-B potentials with the solid and dashed line respectively; they are Fourier-transformed to r-space at $k_{\rm F} = 0.9$ fm^{-1} where the gap obtained from the former is substantially reduced. As the density increases, an attractive dip shifts outwards and gets shallower; in addition a core becomes somewhat softer though it is left unchanged near $r = 0$. These are the consequences of the lengthening of the in-medium range represented by Eq. (3).

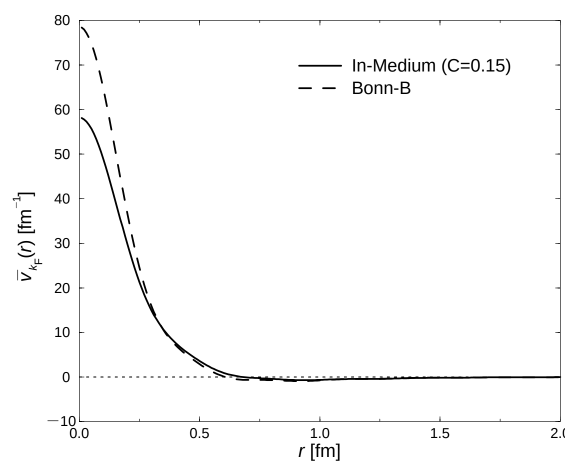

Fig. 4. The particle-particle channel interactions $v_{\rm pp}$ as a function of r, at a Fermi momentum $k_{\rm F} = 0.9$ fm^{-1}. Details are in the text.

We also note another ingredient connected with the reduction of the gap. The In-Medium Bonn potential contains the cutoff masses in its form-factors of the meson-nucleon vertices, which are also scaled according to the BR scaling. They are of the form

$$\frac{\Lambda_\alpha^{*\,2} - m_\alpha^{*\,2}}{\Lambda_\alpha^{*\,2} + \mathbf{q}^2}, \tag{4}$$

where $\mathbf{q}$ is the momentum transfer.[9] 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 due to the vector mesons in large-$|\mathbf{q}|$. Therefore, in-medium scaling of cutoff mass results in an additional reduction of the gap in the high-density region.

Finally, we mention that using σ-ω linear parameter set instead of NL1 for the p-h channel makes the results almost unchanged.[4]

Conclusions

In summary, we performed the numerical calculation of the pairing gap using the 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. Using 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.[5)]

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