The properties of pairing correlations in symmetric nuclear matter are studied in the relativistic mean field (RMF) theory with the effective interaction PK1. Considering well-known problem that the pairing gap at Fermi surface calculated with RMF effective interactions are three times larger than that with Gogny force, an effective factor in the particle-particle channel is introduced. For the RMF calculation with PK1, an effective factor 0.76 give a maximum pairing gap 3.2 MeV at Fermi momentum 0.9 fm$^{-1}$, which are consistent with the result with Gogny force.

1. Introduction

The mean field theory, including non-relativistic mean field theory with effective nucleon-nucleon interactions such as Skyrme or Gogny, and the relativistic mean field (RMF) theory, has received wide attention due to its successful descriptions of lots of nuclear phenomena during the past years. In the framework of the RMF
theory, the nucleons interact via the exchanges of mesons and photons. The representations with large scalar and vector fields in nuclei provide simpler and more efficient descriptions than non-relativistic approaches that hide these scales. In these sense, the RMF theory is more fundamental. With a limited number of free parameters, i.e. meson masses and meson-nucleon coupling constants, the RMF theory has proved to be successful in quantitatively describing the properties of nuclear matter and neutron stars, nuclei near the valley of stability, and exotic nuclei with large neutron or proton excess with proper treatment of the pairing correlations and continuum effects. It gives naturally the spin-orbit potential, the origin of the pseudo-spin symmetry as a relativistic symmetry, and the spin symmetry in the anti-nucleon spectrum.

Since 1950's, a large number of striking experimental facts, such as the binding energy difference between even-even and odd-even nuclei and a systemic reduction of the moments of inertia of even-even nuclei compared with their neighboring odd-even nuclei in deformed nuclei, suggest the existence of the superfluid phenomena in these systems. In astrophysics, the origin of pulsar glitches, which are sudden discontinuities in the spin-down of pulsars, can also be understood via the superfluidity in the inner crust of these stars. All of these phenomena suggest that the pairing correlations play an important role in theoretical study on the properties of nuclei structure and nuclear matter.

The first relativistic study of superfluidity in infinite nuclear matter was done by Kucharek and Ring in 1991. They studied the pairing correlations in symmetric nuclear matter using the relativistic Hartree-Bogoliubov (RHB) method with an one-boson-exchange (OBE) potential in the particle-particle channel. However the resulting pairing gap at the Fermi surface are about three times larger than that with the Gogny force. Therefore, the effective pairing interaction used in RHB calculation are either the finite range Gogny force or the Skyrme type zero-range force. In particular, with the Skyrme type zero-range force, lots of achievements have been made to describe the nuclei far away from the line of $\beta$-stability with proper treatment of the pairing correlations and continuum effects.

However, it is still an open problem how the same nucleons interaction via the exchanges of mesons and photons in the Hartree channel can be used in the particle-particle channel as well. In fact, the large pairing gap in RHB calculation with an OBE potential in the particle-particle channel comes from the behavior of the pairing matrix elements at large momenta. The various effective forces in RMF models are adjusted for mean-field calculations in Hartree channel only, i.e., only for momenta below the Fermi momentum, thus a realistic particle-particle interaction can have very different behavior at high momenta. Therefore, in order to get reasonable values for the pairing gap, one can use a suitable value of cutoff in the momentum space in the relativistic mean field calculations, or consider various effects, such as the medium polarization, the in-medium meson mass decrease, and the mesons nonlinear terms to reduce the pairing gap in nuclear
In this paper, the properties of pairing correlations in symmetric nuclear matter will be studied in the RMF theory with the newly developed effective interaction PK1. In order to solve the well-known problem that the pairing gap at Fermi surface calculated with RMF effective interactions are three times larger than that with Gogny force, an effective factor in the particle-particle channel will be introduced. In section II, a brief description of the RMF theory and RHB theory for nuclear matter is presented. The results and discussions are given in the following section. Finally in the last section, a brief summary is given.

2. Theoretical Framework

2.1. Relativistic Mean Field Theory

A general review of the RMF theory and its application in nuclear physics could be found in Refs. [3, 4, 5]. Here a brief review of RMF theory for nuclear matter is given. The start point of RMF theory is an effective Lagrangian density with the nucleons interacting via the exchange of various mesons and the photon:

\[
\mathcal{L} = \bar{\psi} \left[ i\gamma^\mu \partial_\mu - m - g_\sigma \sigma - g_\omega \gamma^\mu \omega_\mu - g_\rho \gamma^\mu \vec{\tau} \cdot \vec{\rho}_\mu - e\gamma^\mu \frac{1-\tau_3}{2} A_\mu \right] \psi \\
+ \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - U(\sigma) - \frac{1}{4} \Omega^{\mu \nu} \Omega_{\mu \nu} + \frac{1}{2} m_\omega^2 \omega^{\mu \nu} \omega_{\mu \nu} + U(\omega) \\
- \frac{1}{4} \tilde{R}^{\mu \nu} \tilde{R}_{\mu \nu} + \frac{1}{2} m_\rho^2 \rho^{\mu \nu} \rho_{\mu \nu} - \frac{1}{4} A^{\mu \nu} A_{\mu \nu}. \tag{1}
\]

The Dirac spinor \( \psi \) denotes the nucleon with mass \( m \). The isoscalar scalar \( \sigma \)- and isoscalar vector \( \omega \)-mesons offer medium-range attractive and short-range repulsive interactions respectively, and the isovector vector \( \rho \)-meson provides the necessary isospin asymmetry. Their masses are denoted by \( m_\sigma, m_\omega \) and \( m_\rho \), \( g_\sigma \), \( g_\omega \) and \( g_\rho \) are the corresponding meson-nucleon coupling constants. \( \tau \) is the isospin of nucleon, and \( \tau_3 \) is its three-component. The nonlinear \( \sigma \) and \( \omega \) self-interactions \( U(\sigma) \) and \( U(\omega) \) are respectively denoted as,

\[
U(\sigma) = \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4, \quad U(\omega) = \frac{1}{4} c_3 (\omega^\mu \omega_\mu)^2, \tag{2}
\]

with the self-coupling constants \( g_2, g_3 \) and \( c_3 \). The field tensors \( \Omega_{\mu \nu}, \tilde{R}_{\mu \nu}, \) and \( A_{\mu \nu} \) are as the followings,

\[
\Omega_{\mu \nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \quad \tilde{R}_{\mu \nu} = \partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu, \quad A_{\mu \nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \tag{3}
\]

The classical variation principle gives the following equations of motion,

\[
\left[ i\gamma^\mu \partial_\mu - m - g_\sigma \sigma - g_\omega \gamma^\mu \omega_\mu - g_\rho \gamma^\mu \vec{\tau} \cdot \vec{\rho}_\mu - e\gamma^\mu \frac{1-\tau_3}{2} A_\mu \right] \psi = 0, \tag{4}
\]
for the nucleon spinors and
\[
\left( \partial^\mu \partial^\nu + m^2 \right) \sigma = -g_\sigma \bar{\psi} \psi - g_2 \sigma^2 - g_3 \sigma^3, \tag{5}
\]
\[
\partial_\mu \Omega^{\mu\nu} + m^2 \omega^{\nu} = g_\omega \bar{\psi} \gamma^\nu \psi - c_3 (\eta^\nu \omega^{\nu})^3, \tag{6}
\]
\[
\partial_\mu \bar{R}^{\mu\nu} + m^2 \rho^{\nu} = g_\rho \bar{\psi} \gamma^\nu \tilde{R} \psi + g_\rho \bar{\rho}_\mu \times \bar{R}^{\mu\nu}, \tag{7}
\]
\[
\partial_\mu A^{\mu\nu} = e \bar{\psi} (1 - \tau_3) \gamma_\mu, \tag{8}
\]
for the mesons and photon, where the sum over all the particle states in the no-sea approximation is adopted for the source term in the Eqs. (5, 6, 7, 8).

2.2. Relativistic Hartree-Bogoliubov Theory

Usually, in the RMF theory, the mesons are treated as classical fields. In order to describe the superfluidity of the nuclear many-body system, one needs to quantize not only the nucleon but also the meson fields. By using the well-known canonical quantization method and the Green’s function techniques, neglecting retardation effects and the Fock term as it is mostly done in RMF, one can get the so-called Relativistic Hartree-Bogoliubov (RHB) equation, 19
\[
\left( h - \lambda - \Delta \right) \begin{pmatrix} U_k \\ V_k \end{pmatrix} = e_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}, \tag{9}
\]
where
\[
h = \alpha \cdot p + V + \beta (M + S), \tag{10}
\]
is the Dirac Hamiltonian with the scalar potential \(S\) and vector potential \(V\),
\[
S = g_\sigma \sigma, \quad V = \beta \left( g_\omega \gamma^\mu \omega_\mu + g_\rho \gamma^\mu \tilde{R}_\mu + e \gamma^\mu \frac{1 - \tau_3}{2} A_\mu \right). \tag{11}
\]
The pairing field is
\[
\Delta_{ab} = \frac{1}{2} \sum_{cd} \bar{V}_{abcd} \kappa_{cd}, \tag{12}
\]
where \(\bar{V}_{abcd}\) is the two-body effective interaction in the particle-particle (pp) channel and the pairing tensor \(\kappa_{ab} = \sum_k V^*_{ak} U_{bk}\). The quasi-particle eigenvectors are denoted as \((U_k, V_k)\), and \(e_k\) is its corresponding quasi-particle energies.

The chemical potential \(\lambda\) in Eq. (9) is determined by the particle number with the subsidiary condition,
\[
\sum_k V_k^2 = N. \tag{13}
\]

2.3. Application to Symmetric Nuclear Matter

For the static, uniform infinite nuclear matter, the coulomb field is neglected, and the space-like components as well as the differential of the time-like components of the meson fields vanish. Furthermore, for symmetric nuclear matter, the \(\rho\) meson
has no contribution on the mean field potential. Then the scalar potential \( S \) and vector potential \( V \) are constants and have the simple form,

\[
S = g_\sigma (\sigma), \quad V = g_\omega (\omega_0).
\]

The RHB equation (9) can be decomposed into \((2 \times 2)\) matrices of BCS-type,

\[
\begin{pmatrix}
\varepsilon(k) - \lambda & \Delta(k) \\
\Delta(k) & -\varepsilon(k) + \lambda
\end{pmatrix}
\begin{pmatrix}
u(k) \\
v(k)
\end{pmatrix}
= e(k)
\begin{pmatrix}
u(k) \\
v(k)
\end{pmatrix},
\]

where the eigenvalue of the Dirac Hamiltonian for positive energies is denoted as, \(\varepsilon(k) = V + \sqrt{k^2 + (m + S)^2}\), the Fermi energy \(\lambda = \varepsilon(k_F)\), and the quasi-particle energy \(e(k) = \sqrt{(\varepsilon(k) - \lambda)^2 + \Delta^2(k)}\). The corresponding occupation numbers \(\nu^2(k)\) have the form

\[
\nu^2(k) = \frac{1}{2} \left(1 - \frac{\varepsilon(k) - \lambda}{\sqrt{(\varepsilon(k) - \lambda)^2 + \Delta^2(k)}}\right).
\]

The pairing field \(\Delta(k)\) obey the usual gap equation,

\[
\Delta(k) = -\frac{1}{8\pi^2} \int_0^\infty f : v_{pp}(k, p) \frac{\Delta(p)}{\sqrt{(\varepsilon(p) - \lambda)^2 + \Delta^2(p)}} p^2 dp.
\]

where \(f\) is an effective factor introduced to reduce the pairing potential. The effective interaction in the \(pp\) channel \(v_{pp}(k, p)\) is the one-meson exchange potential,

\[
v_{pp}(k, p) = v^\sigma_{pp}(k, p) + v^\omega_{pp}(k, p) + v^\rho_{pp}(k, p),
\]

where

\[
v^\sigma_{pp}(p, k) = \frac{g_\sigma^2}{2\varepsilon^*(k)\varepsilon^*(p)} \left\{ (\varepsilon^*(p) - \varepsilon^*(k))^2 + m_\sigma^2 - 4m^2 - 4m^2\right\} \ln \frac{(k + p)^2 + m_\sigma^2}{(k - p)^2 + m_\sigma^2} - 1,
\]

\[
v^\omega_{pp}(p, k) = \frac{g_\omega^2}{\varepsilon^*(k)\varepsilon^*(p)} 2\varepsilon^*(k)\varepsilon^*(p) - m^2 \ln \frac{(k + p)^2 + m_\omega^2}{(k - p)^2 + m_\omega^2},
\]

\[
v^\rho_{pp}(p, k) = \frac{g_\rho^2}{\varepsilon^*(k)\varepsilon^*(p)} 2\varepsilon^*(k)\varepsilon^*(p) - m^2 \ln \frac{(k + p)^2 + m_\rho^2}{(k - p)^2 + m_\rho^2},
\]

with effective mass \(m^* = m + g_\sigma\sigma\), and \(\varepsilon^*(k) = \sqrt{k^2 + m^2}\).

The meson fields are replaced by their mean values, and could be solved from the corresponding equations of motion by the various giving nucleon densities,

\[
m^2_\omega \rho_\omega = g_\omega \rho_\omega - c_3 \omega_0^3,
\]

\[
m^2_\sigma \rho_\sigma = -g_\sigma \rho_\sigma - g_2 \sigma^2 - g_3 \sigma^3,
\]

where \(\rho_\sigma\) and \(\rho_\omega\) are respectively the scalar- and baryon-density,

\[
\rho_\sigma = \overline{\psi}\psi = \frac{2}{\pi^2} \int_0^\infty \frac{m + g_\sigma \sigma}{\sqrt{k^2 + (m + g_\sigma \sigma)^2}} \nu^2(k) k^2 dk,
\]

\[
\rho_\omega = \psi^\dagger \psi = \frac{2}{\pi^2} \int_0^\infty \nu^2(k) k^2 dk.
\]
3. Results and discussions

For a given Fermi momentum $k_F$, the coupled Eqs. (14, 16, 21, 22) can be solved self-consistently by iteration. The properties of $^1S_0$ pairing correlations of symmetric nuclear matter are studied with the newly developed effective interaction PK1 which takes into account the self-interactions of $\sigma$-meson and $\omega$-meson as well as the isospin dependence of the nuclear matter. \(27\)

The momentum integration in the gap equation, in principle, should go to infinity. In actual calculations, it is necessary to have a cutoff in the momentum space and the convergence of the pairing gap on the cutoff momentum should be checked. The dependence of the pairing gap on the cutoff momentum for different Fermi momentum is given in Fig. 1. The results indicate that the cutoff momentum $K_C \geq 10$ fm$^{-1}$ will guarantee the numerical convergence. In the following, $K_C = 20$ fm$^{-1}$ will be adopted and the corresponding effective interaction in the $pp$ channel, the momentum-dependence of the pairing gap, and the influence of effective interactions on the pairing gap at the Fermi surface, etc., will be investigated.

![Fig. 1. The pairing gap $\Delta(k_F)$ at the Fermi surface as a function of the cutoff momentum $k_C$ in the momentum space for different values of Fermi momentum $k_F = 0.3, 0.6, 0.9, \text{ and } 1.2$ fm$^{-1}$ with the effective interaction PK1.](image)

3.1. The effective interaction in the $pp$ channel

The contour plot for the effective interaction in the $pp$ channel $v_{pp}(k, p)$ for different Fermi momentum with the effective interaction PK1 are shown in Fig. 2 where the contours with negative values are denoted by red dashed lines.
The interaction is attractive for small and repulsive for larger momenta \( k \) and \( p \), or equivalently, attractive for large distances and repulsive for small distances. At around 1.5 fm\(^{-1}\), the interaction will change from being attractive to being repulsive. The repulsive interaction reaches its maximum value at the momenta \( k \) and \( p \) around 4 fm\(^{-1}\). The maximum repulsive interaction increases with the Fermi momentum.

The behavior of the effective interaction in the \( pp \) channel \( v_{pp}(k,p) \) can be understood from contributions of different mesons, as shown in Fig. 3. The scalar meson \( \sigma \) provides the attractive part of the effective interaction, \( v_{\sigma pp}(p,k) \), with a peak value at zero momentum, and approaching zero with the increasing momentum. While the vector meson \( \omega \) and \( \rho \) provide the repulsive part, which extend to higher momenta than \( v_{\sigma pp}(p,k) \). The main contribution for the repulsive part comes from the \( \omega \) meson, as seen in the figures, \( v_{\omega pp}(p,k) \) is one order of magnitude larger than \( v_{\rho pp}(p,k) \).

Different mesons contributions to the effective interaction in the \( pp \) channel \( v_{pp}(k,p) \) as a function of \( p \) at \( k = k_F = 0.9 \) fm\(^{-1}\) with the effective interaction PK1 are shown in Fig. 4. The sum of all the mesons contributions has considerable repulsive contributions for momenta larger than about 1.5 fm\(^{-1}\), which is remarkably different from the one by the Gogny force calculation.\(^{19}\)
Fig. 2. Contour plots for the effective interaction in the $pp$ channel $v_{pp}(k, p)$ as a function of the momenta $p$ and $k$ for different Fermi momentum $k_F = 0.3, 0.6, 0.9, \text{ and } 1.2 \text{ fm}^{-1}$ with the effective interaction PK1. The contour lines have a distance of 1 (fm$^2$) and the negative values are denoted as red dashed lines.
Fig. 3. Contour lines of different mesons contributions for the effective interaction in the $pp$ channel $v_{pp}(k, p)$ as a function of the momenta $p$ for Fermi momentum $k_F = 0.9$ fm$^{-1}$ with the effective interaction PK1. The contour lines have unit of fm$^2$ and the negative contours are denoted as red colors.

Fig. 4. Different mesons contributions to the effective interaction in the $pp$ channel $v_{pp}(k, p)$ as a function of $p$ at $k = k_F = 0.9$ fm$^{-1}$ with the effective interaction PK1. The dashed lines corresponds to that of the $\sigma$-, $\omega$- and $\rho$-fields, the solid line represents the total contribution.
3.2. The momentum-dependence of the pairing gap

For a given $v_{pp}(k, p)$, the momentum-dependence of the pairing gap $\Delta(k)$ can be obtained from Eq. (16). The momentum-dependence of $\Delta(k)$ with different Fermi momentum is shown in Fig. 5. The pairing gap has large and positive values at small momenta, then decreases with the momentum and changes its sign around $2.5 \text{ fm}^{-1}$. It continues to decrease till $\sim 4.0 \text{ fm}^{-1}$, then slowly turns to zero. The difference of pairing gap for different Fermi momentum is revealed mainly by the behaviors at low momentum. At zero momentum, the largest pairing gap occurs at the Fermi momentum $0.9 \text{ fm}^{-1}$.

![Fig. 5. The pairing gap $\Delta(k)$ as a function of the momentum $k$ for Fermi momentum $k_F = 0.3, 0.6, 0.9, \text{ and } 1.2 \text{ fm}^{-1}$ with the effective interaction PK1.](image)

3.3. The pairing gap at the Fermi surface

One of most important properties of pairing gap is its value at the Fermi surface. In Fig. 6 the pairing gap $\Delta(k_F)$ at the Fermi surface as a function of the Fermi momentum $k_F$ with the effective interaction PK1 is shown in comparison with the
results obtained with the effective interactions NL1, NL2, NL3, NL3, TM1, and the results calculated with Gogny force and Bonn potential.

It is found that the pairing gap \( \Delta(k_F) \) is strongly dependent on the nuclear matter density, or equivalently, the Fermi momentum. The pairing gap \( \Delta(k_F) \) increases with the Fermi momentum (or density) and reaches maximum at Fermi momentum \( k_F \approx 0.9 \text{ fm}^{-1} \), then rapidly drops down to zero. Usually, the pairing gap at the Fermi surface calculated with RMF effective interactions is almost three times larger than the value calculated with Gogny force. Moreover, the pairing gap at lower Fermi momentum does not vanish in calculations with the RMF effective interactions, while it does vanish in calculations with Gogny force or Bonn potential.

These differences come from the integral in Eq. (16) for the pairing gap, which depends on the products of pairing gap parameter \( \Delta(p) \) and the effective interaction in the \( pp \) channel \( v_{pp}(k,p) \). From \( v_{pp}(k,p) \) in Fig. 2 and \( \Delta(p) \) in Fig. 3, it is found that considerable contributions to the integral in Eq. (16) may come from high momenta region. While the various effective forces in RMF models are adjusted for mean-field calculations in Hartree channel only, i.e., they are only valid for momenta below the Fermi momentum and the a realistic interaction in the \( pp \) channel \( v_{pp}(k,p) \) can have very different behavior at high momenta.

Considering that the RMF effective interactions give a too much strong pairing field, an effective factor is introduced in the particle-particle channel to reduce the pairing gap. For PK1, if a factor \( f = 0.76 \) is introduced, the resulting pairing gap is almost the same as those with Gogny force or Bonn potential, and a maximum pairing gap 3.2 MeV is obtained at Fermi momentum 0.9 fm\(^{-1} \), as shown in Fig. 6.
Fig. 6. The pairing gap $\Delta(k_F)$ at the Fermi surface as a function of the Fermi momentum $k_F$ for different effective interactions. The results of Gogny and Bonn come from the Ref. [21].
4. Summary

The pairing properties in the $^1S_0$ channel for symmetric nuclear matter have been studied in the RMF theory with the effective interaction PK1. The one-meson exchange potential is used in the particle-particle channel in consistent with the particle-hole channel. The effective interaction in the $pp$ channel is found to be attractive at small momenta with attractive range around 1.5 $\text{fm}^{-1}$ and repulsive at large momenta. The pairing gap at the Fermi surface is strongly dependent on the nuclear matter density. It grows as the Fermi momentum increases, reaching its maximum values at Fermi momentum around 0.9 $\text{fm}^{-1}$, then drops down to zero rapidly. Considering the fact that the pairing gap at Fermi momentum calculated with RMF effective interactions are three times larger than that with Gogny force, an effective factor in the particle-particle channel is introduced. For the effective interaction PK1, a factor $f = 0.76$ will produce almost the same results as those with Gogny force or with Bonn potential.

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