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Novel effects of electromagnetic interaction on the correlation of nucleons in nuclear matter

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Abstract

The electromagnetic (EM) interactions between charged protons on the correlations of nucleons are discussed by introducing the Anderson–Higgs mechanism of broken $U(1)$ EM symmetry into the relativistic nuclear theory with a parametric photon mass. The non-saturating Coulomb force contribution is emphasized on the equation of state of nuclear matter with charge symmetry breaking (CSB) at finite temperature and the breached $^1S_0$ pairing correlations of proton–proton and neutron–neutron. The universal properties given by an order parameter field with a non-zero vacuum expectation value (VEV) nearby phase transition are explored within the mean field theory (MFT) level. This mechanism can be extended to the charged or charge neutralized strongly coupling multi-components system for the discussion of binding or pairing issues.

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Understanding the properties of nuclear matter under both normal and extreme conditions is of great importance in relativistic heavy ion collisions and explaining the appearance of compact objects such as the neutron stars and neutron-rich matter or nuclei. The determination of the properties of nuclear matter as functions of density/temperature, the ratio of protons to neutrons, and the pairing correlations—superfluidity or superconductivity is a fundamental problem in contemporary physics [1,2]. The discussion about the property of nuclear ground state-binding energy and pairing correlations at low temperature is substantial.

The in-medium behavior associated with the many-body characteristic is the key, while a non-perturbative approach is crucial. The theoretical difficulty of making low energy calculation directly with the fundamental quantum chromodynamics (QCD) makes effective theories still desirable. As accepted widely, the relativistic nuclear theory can successfully describe the saturation at normal nuclear density and the spin–orbit splitting [3,4]. The further developments [5] of

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σ–ω theory of quantum hadrodynamics model (QHD) make it possible to determine the model parameters analytically from a specified set of zero-temperature nuclear properties and allow us to study the hot nuclear properties and study variations of these results to nuclear compressibility or pairing correlation, and even the symmetry energy coefficient according to baryon density [6], which are not well known. Furthermore, the in-medium hadronic property has attracted much attention with this kind of models and there are many existed works although the relation between QCD and QHD has not been well established [7,8]. In recent years, with the refinement of nuclear theory study, the σ–ω theory has been placed in the context of effective theory and it is argued that the *vacuum* physics has been explored in part by this kind of models [9,10]. In physics, with the obvious non-vanishing fermion nucleon mass in relevant Lagrangian, the hidden chiral symmetry is explicitly broken.

The theoretical S-wave pairing correlation issue is a long-standing problem. The fundamental $^1S_0$ pairing in infinite nuclear matter within the frame of relativistic nuclear field theory was first discussed by Kucharek and Ring [11], and it was found that the gaps are always larger for three times than the non-relativistic results [12,13]. Especially, the very uncomfortable non-zero gaps of $^1S_0$ pairing correlation at zero baryon density obtained with frozen meson propagators in relativistic field theory, as recently pointed out by us [14], remind us that the realistic nuclear ground state with MFT approach might not be EM empty. On the other hand, the well established low temperature superconductivity theory tells us that it would be very interesting to discuss the broken local EM symmetry effects on the properties of the nucleons system. Although the in-medium nucleon–nucleon interaction potential induced by polarization can give a significantly improved description for EOS and superfluidity [8,14,15], the pairing difference of PP (proton–proton) from NP (neutron–proton) or NN (neutron–neutron) has been discarded. Other approaches also recently found that polarization effects suppress the S-wave gaps by a factor of 3–4 [16]. The numerical magnitude of $^1S_0$ gaps is not sensitive to a special parameters set and integral momentum cutoff when the polarization effect is taken into account [14].

The pure neutron matter cannot exist in nature, and the realistic nuclear matter is subject to the long range EM interaction. The changes of symmetry properties associated with possible phase transition realized on some conditions attract physicists very much. In nuclear physics, charge symmetry breaking explored by the quite different empirical negative scattering lengths $a_{\mathrm{NN(P)}}$ and a_{PP} is a fundamental fact [17] and there are existed works to address its theoretical origin [18]. Coulomb correlation effects are a fundamental problem in nuclear physics and play an important role for the property of nuclear matter [19,20], which may lead to rich phase structures in the low temperature occasion. For example, in Ref. [21] the influence of the non-saturating Coulomb interaction is recently incorporated in the multi-canonical formalism attempting to explain the reported experimental signatures of thermodynamic anomalies and the possible liquid–gas (LG) phase transitions of charged atomic clusters and nuclei [22]. One may naturally worry about the important role of the Coulomb repulsion force on the properties of charged system and the thermodynamics of charged/neutral nuclear matter to be reflected by relativistic nuclear theory and corresponding approaches. Within the models based on σ–ω field theory and usual adopted approaches such as MFT or relativistic Hartree approximation (RHA), one can *suppose* the similar interactions between PP and NP or NNs, with the *weak* EM interaction being neglected compared to the residual strong interaction between nucleons. Theoretically, the direct (Hartree) Coulomb contribution of charged protons to the EOS cannot be included due to the Furry theorem's limit. Although the exchange (Fock) contribution can be included in principle from the point of view of field theory, the involved calculation and radioactive corrections caused by relevant infrared singularity of photon propagator still remain to be done even in the relatively simpler zero-temperature occasion in nuclear physics. If one asks what the difference between PP and NP or NN pairing correlation is, the original version of QHD with MFT or RHA approaches cannot tell us anything. Although one can expect that the isospin breaking coupling terms such as ρNN, etc., might reflect the Coulomb repulsion contribution on the thermodynamics of isospin asymmetric system to some extent, the pairing differences between PP and NN, NP exist even for symmetric nuclear matter incorporated with the quite different empirical negative scattering lengths $a_{\mathrm{NN(P)}}$ and a_{PP}. How to incorporate the important role of EM interaction with CSB on the thermodynamics of charged/neutral system or the property of nuclear ground state on a microscopic level (continuum field theory) remains an intriguing task even in an oversimplified way (MFT or RHA) but with thermodynamics self-consistency.

In this Letter, we propose a systematic way to perform the link between the bulk and pairing correlation many-body properties of charged/neutral two-components nucleon systems through a relativistic nuclear field theory involving the interaction of Dirac nucleons with massive photons as well as the well-known scalar/vector mesons. Inspired by the continuum field theory of phase transition and based on QHD-II, the constructed phenomenological Proca-like Lagrangian through Anderson–Higgs mechanism is [3,4,23,24]

$$\begin{aligned}\mathcal{L} = \bar{\psi}\bigg[& i\gamma_\mu\partial^\mu - M - g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu \\ & - \frac{1}{2}g_\rho\gamma_\mu\vec{\tau}\cdot\vec{\rho}^{\,\mu} - e\gamma_\mu\frac{1+\tau_3}{2}A^\mu\bigg]\psi \\ & + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}H_{\mu\nu}H^{\mu\nu} \\ & + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^{\,\mu} \\ & - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma^2 A_\mu A^\mu \\ & + \delta\mathcal{L}_{\text{Higgs\&counterterm}},\end{aligned} \tag{1}$$

where σ, ω^μ, $\vec{\rho}^{\,\mu}$ and A^μ are the scalar–isoscalar, vector–isoscalar, vector–isovector meson fields, EM field with the field stresses

$$\begin{aligned} H_{\mu\nu} &= \partial_\mu\omega_\nu - \partial_\nu\omega_\mu, \\ \vec{R}_{\mu\nu} &= \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu - g_\rho(\vec{\rho}_\mu\times\vec{\rho}_\nu), \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \end{aligned}$$

for ω, $\vec{\rho}$ and A_μ's, respectively. The M, m_σ, m_ω, m_ρ and m_γ are the nucleon, meson and photon masses, while g_σ, g_ω, g_ρ and e are the coupling constants for corresponding Yukawa-like effective interaction, respectively.

Here the Lagrangian with CSB does not respect the local $U_{\mathrm{EM}}(1)$ gauge symmetry which is broken by the ground state with non-zero local electric charge of protons (although the system can be globally neutralized by the surrounding such as electrons to maintain the stability for compact object through β-equilibrium). Also, the quartic–cubic terms of σ non-linear interaction potential $U(\sigma) = b\sigma^3 + c\sigma^4$ with the additional phenomenologically determined parameters b and c have not been obviously preferred in order to discuss in a more general way although a specific assumption in $U(\sigma)$ can give a reasonable bulk compressibility for nuclear matter.

The mean field approximation can be used to discuss the thermodynamics of charged nuclear matter, from which the effective potential is derived in terms of finite temperature field theory [3,4,25]

$$\begin{aligned}\frac{\Omega}{V} = {}& \frac{1}{2}m_\sigma^2\phi_0^2 - \frac{1}{2}m_\omega^2\omega_0^2 - \frac{1}{2}m_\rho^2\rho_{03}^2 - \frac{1}{2}m_\gamma^2 A_0^2 \\ & - T\frac{2}{(2\pi)^3}\sum_i\int d^3\mathbf{k}\,\Big\{\ln\big(1+e^{-\beta(E_i^*-\mu_i^*)}\big) \\ & + \ln\big(1+e^{-\beta(E_i^*+\mu_i^*)}\big)\Big\},\end{aligned} \tag{2}$$

where $i = P, N$ represents the index of proton (P) and neutron (N), respectively, and V is the volume of the system. With the thermodynamics relation

$$\epsilon = \frac{1}{V}\frac{\partial(\beta\Omega)}{\partial\beta} + \sum_i \mu_i\rho_i,$$

one can obtain the energy density

$$\begin{aligned}\epsilon = {}& \frac{m_\sigma^2}{2g_\sigma^2}(M-M^*)^2 + \frac{g_\omega^2}{2m_\omega^2}\rho_B^2 \\ & + \frac{g_\rho^2}{8m_\rho^2}(\rho_P-\rho_N)^2 + \frac{e^2}{2m_\gamma^2}\rho_P^2 \\ & + \frac{2}{(2\pi)^3}\sum_i\int d^3\mathbf{k}\,E_i^*\big[n_i(\mu_i^*,T) + \bar{n}_i(\mu_i^*,T)\big]\end{aligned} \tag{3}$$

and pressure $p = -\Omega/V$. The baryon density is

$$\rho_B = \langle\bar{\psi}\psi\rangle_B = \sum_i \rho_i,$$

$$\rho_i = \frac{2}{(2\pi)^3}\int d^3\mathbf{k}\,(n_i - \bar{n}_i). \tag{4}$$

In above expressions, $n_i(\mu_i^*, T)$, $\bar{n}_i(\mu_i^*, T)$ are the distribution functions for (anti-)particles with $E_i^* = \sqrt{\mathbf{k}^2 + M^{*2}}$. The effective nucleon mass M^*, chemical potentials $\mu_{P(N)}^*$ are introduced by the tadpole diagrams of the sigma, omega, rho mesons and photon self-energies, respectively:

$$M^* = M - \frac{2}{(2\pi)^3}\frac{g_\sigma^2}{m_\sigma^2}\sum_i \int d^3\mathbf{k}\,\frac{M^*}{E^*}(n_i + \bar{n}_i); \quad (5)$$

$$\mu_P^* = \mu_P - \frac{g_\omega^2}{m_\omega^2}\rho_B - \frac{1}{4}\frac{g_\rho^2}{m_\rho^2}(\rho_P - \rho_N) - \frac{e^2}{m_\gamma^2}\rho_P,$$

$$\mu_N^* = \mu_N - \frac{g_\omega^2}{m_\omega^2}\rho_B + \frac{1}{4}\frac{g_\rho^2}{m_\rho^2}(\rho_P - \rho_N), \quad (6)$$

where $\mu_{P(N)}$ is the proton (neutron) chemical potential.

The photon mass m_γ appears as a free parameter which is closely related to the Coulomb energy (reflecting the binding energy contributed by adding a proton *to* or removing a neutron *from* the system) and correspondingly to Coulomb compression modulus K_C. It is worthy noting that the Coulomb energy can be discussed by the conventional many-body approaches such as the Thomas–Fermi theory with variational principle [26]. Within relativistic MFT, the K_C has been analyzed in the literature such as in Ref. [27] with the scaling model [28] phenomenologically. The bulk compression modulus K and K_C are defined by

$$K = 9\rho_0^2 \frac{\partial^2 e_b}{\partial \rho_B^2}\bigg|_{\rho_B=\rho_0},$$

$$K_C = -\frac{3\alpha}{5R_0}\left(\frac{9K'}{K} + 8\right). \quad (7)$$

Here, ρ_B, ρ_0, e_b are the baryon density, the normal baryon density and the binding energy per nucleon with

$$R_0 = \left[\frac{3}{4\pi\rho_0}\right]^{1/3}, \qquad K' = 3\rho_0^3 \frac{d^3 e_b}{d\rho_B^3}\bigg|_{\rho_B=\rho_0}.$$

The repulsive Coulomb force will modify the EOS significantly for the realistic charged system produced in heavy ion collisions. Especially, it can make the critical temperature T_c of the LG phase transition decreased to a smaller value. With careful numerical study, it is found that the softness of bulk EOS (characterized by K) is not sensitive to the Coulomb interaction but the critical temperature T_c as well as K_C is very sensitive to this repulsive force. The additional Coulomb energy term in pressure and energy density Eq. (3) contributes to removing the theoretical instability in the high baryon density region caused by a negative parameters set of b and c in the non-linear self-interaction term $U(\sigma)$ (for obtaining a reasonable compressibility modulus of bulk EOS). One can *estimate* the parameter m_γ is about 20–30 MeV for a reasonable critical temperature $T_c \sim 16$ MeV accessible in heavy ion collisions. In Fig. 1, we give the curves of pressure versus baryon density and the Coulomb compression modulus K_C according to the interaction strength characterized by m_γ with frozen parameters g_σ and g_ω which are determined by fitting the binding energy $e_b^0 = -15.75$ MeV and the bulk symmetry energy coefficient $a_{\mathrm{sym}} = 35$ MeV (for *symmetric* nuclear matter at the empirical saturation density $\rho_0 = 0.1484\ \mathrm{fm}^{-3}$ with $T = 0$) [4]. The qualitative Coulomb effect on the deformation of phase space distribution functions resulting from Eq. (4) and Eq. (6) can be reflected by the proton fraction ratio:

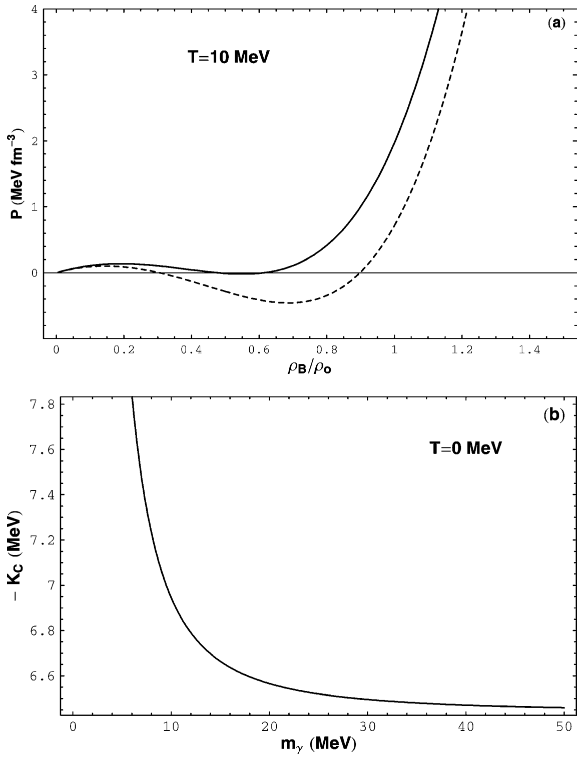

Fig. 1. For charged nuclear matter without considering the charge neutral condition with the set (a) of Table 1: (a) Pressure versus rescaled density ρ_B/ρ_0 with (solid) and without (dashed) the Coulomb repulsion interaction, (b) K_C versus the order parameter m_γ describing to what extent the EM symmetry is broken.

Table 1
The parameters are with $M = 939$, $m_\rho = 770$, $m_\omega = 783$, $m_\sigma = 520$ MeV(s) and m_γ is in (MeV). $C_i^2 = g_i^2 M^2/m_i^2$

Set	g_σ^2	g_ω^2	g_ρ^2 (C_ρ^2)	m_γ (C_γ^2)	$\frac{M^*}{M}\big\vert_{\rho_0}$
MFT					
a	91.64	191.05	6.91 (10.28)	30.44 (87.27)	0.540
b			0	28.79 (97.55)	
c			65.58 (97.55)	∞ or $e = 0$ (0)	
RHA					
d	69.98	102.76	6.91 (10.28)	26.636 (113.96)	0.731
e			0	25.51 (124.24)	
f			83.54 (124.24)	∞ or $e = 0$ (0)	

$Y_P = \rho_P/\rho_B$. It is found that this ratio changes significantly according to temperature T and total baryon density ρ_B.

Therefore, the electric repulsive force plays an isospin violating role for the many-body property. Indeed, there is some kind competition between the ρ and photon's isospin breaking effect on the phase space distribution function *deformation*. The Coulomb force makes the proton fraction decreased while the ρ meson plays a weak inverse role. Furthermore, one can readily derive the symmetry energy coefficient formula at $T = 0$,

$$
\begin{aligned}
a_{\text{sym}} &= \frac{1}{2}\frac{\partial^2(\epsilon/\rho)}{\partial t^2}\bigg|_{t=0} \\
&= \frac{k_f^3}{12\pi^2}\left(\frac{g_\rho^2}{m_\rho^2} + \frac{e^2}{m_\gamma^2}\right) + \frac{k_f^2}{6\sqrt{k_f^2 + M^{*2}}}, \\
t &= \frac{\rho_N - \rho_P}{\rho_B}.
\end{aligned}
\tag{8}
$$

In fact, if without taking into account the repulsive Coulomb contribution, one must introduce a *very large* coupling constant g_ρ to approach the empirical symmetric coefficient a_{sym} which is very far from the empirical coupling constant $g_{\rho\text{NN}}$ extracted experimentally. From Eq. (8), if taking $g_\rho = 2.63$ [7] and $a_{\text{sym}} = 35$ MeV, the free parameter m_γ can be fixed accordingly. With close study, the numerical magnitude of m_γ is more sensitive to M^* (and hence the softness of bulk EOS) than to g_ρ. The relevant parameters are listed in Table 1 corresponding to the L2 set of Ref. [4] except of taking $g_\rho = 2.63$. Further exact fitting to finite nuclei data such as charge density radii distribution, etc. [4,29], and addressing the spin–orbit splitting issue with the mirror-symmetry topic can contribute to giving a solid limit for fixing m_γ and g_ρ. The large tensor and spin–orbit forces are also crucial for understanding finite nuclei and neutron star structure which can be explored through the study for mirror-nuclei. Let us mention that the hitherto overlooked but important EM interaction role on the spin–orbit splitting for some mirror-nuclei is recently found in Ref. [30].

To study its effect on the electric neutral nuclear matter such as compact proto-neutron star would also be interesting. For the simplest $\text{NP} + e + \nu_e$ system stabilized through β-equilibrium, charge neutrality condition makes the proton fraction ratio very small. It is found that the Coulomb force does not modify this picture as indicated by Fig. 2. This is consistent with above result that the Coulomb interaction does not change the softness of bulk EOS significantly.

Correlations not only do manifest themselves in the bulk properties but also modify the quasi-particle properties of nucleons in a substantial way. Conceptually, the PP and NN(P) pairing correlations should be quite different from each other. The former has additional superconductivity contribution due to the electric charge of protons in addition to the attractive residual strong interaction compared with the scenario of NN correlation. For the fundamental $^1\text{S}_0$ pairing, the energy gap equation of nucleon–nucleon pairing in the frame of relativistic nuclear theory can be reduced to [11,13,14]

$$
\Delta(p) = -\frac{1}{8\pi^2}\int \bar{v}_{pp}(p,k)\frac{\Delta(k)}{\sqrt{\epsilon(k)^2 + \Delta^2(k)}}k^2\,dk,
\tag{9}
$$

and the coupled effective mass gap equation has been neglected here for brevity.

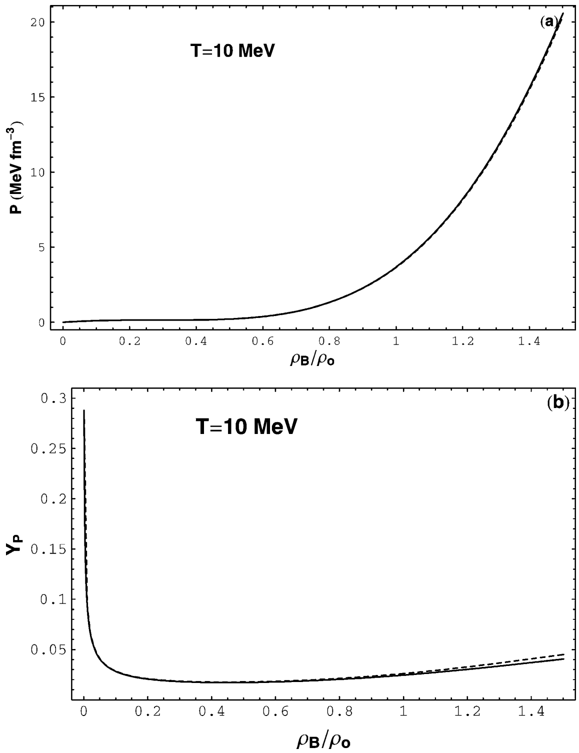

Fig. 2. For electric neutral nuclear matter stabilized through β-equilibrium: (a) Pressure versus rescaled density. (b) Proton fraction ratio Y_P. Line-styles are similar to Fig. 1.

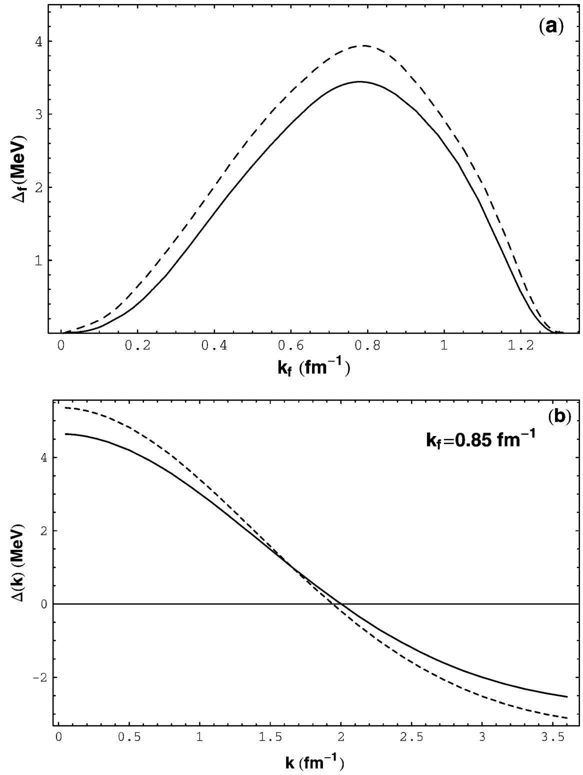

Fig. 3. (a) Pairing gap Δ_f at the Fermi surface versus Fermi momentum k_f. (b) Gap function $\Delta(k)$ versus momentum k for fixed Fermi momentum. The solid line corresponds to the result of proton–proton pairing correlation and dashed line to that of neutron–neutron.

In Eq. (9), the asymmetrized matrix elements $\bar{v}_{pp}(p,k)$ is obtained through the integration of $\bar{v}(\mathbf{p},\mathbf{k})$ over the angle θ between the three-momentums $\mathbf{p}$ and $\mathbf{k}$ with $\bar{v}(\mathbf{p},\mathbf{k})$ being the particle–particle interaction potential

$$\bar{v}(\mathbf{p},\mathbf{k}) = \mp \frac{{M^*}^2}{2E^*(k)E^*(p)} \times \frac{\mathrm{Tr}[\Lambda_+(\mathbf{k})\Gamma_+(\mathbf{p})\gamma^0\mathcal{T}^+\Gamma^+\mathcal{T}\gamma^0]}{(\mathbf{k}-\mathbf{p})^2 + m_D^2},$$

where $\Lambda_+(\mathbf{k}) = \frac{k+M^*}{2M^*}$ is the projection operator of the positive energy solution and $\mathcal{T} = i\gamma^1\gamma^3$ is the time reversal operator. The Γ is the corresponding interaction vertex of σ/ω, $\rho(\gamma)$ with nucleons while m_γ is the *photon mass*. This static electric contribution to the gap has been indicated in Fig. 3 as a curve of gap versus density with a integral momentum cutoff $\Lambda_k = 3.6\ \mathrm{fm}^{-1}$ and the set (a) in Table 1 to numerically solve the integral gap equation. The difference between PP and NN pairing correlations reflects that virtual photons proceeding in the space-like momentum transfer regime carry a unique information on the EM properties of nucleon interaction responsible for the nucleon structure. As indicated by Fig. 3, the long range but screened Coulomb interaction affects the correlation function of proton–proton pairing significantly, especially in the low momentum regime.

The physical reason for the parametric description of the EM interaction in this approach is that at first one can note the existence of locally charged system/cluster, i.e., the electro-magnetic field condensation $\sim \langle\bar{\psi}_P\gamma^\mu\psi_P\rangle$ (corresponding to the spontaneously breaking of local gauge symmetry while the gauge field obtains mass) in the low energy scale although the stable system should be globally neutral with surrounding such as electrons through β-equilibrium. This is very much similar to the chiral condensation $\sim \langle\bar{\psi}\psi\rangle$ at low energy scale. Second, from the point of view of continuum field theory with symmetry changes, the physics background of well-known low temperature LG phase transition still remains to be explored. Especially, how to reflect the CSB characteristic in relevant effective theory and approaches remains to be performed. Third, in the multi-components Fermi/Bose systems the CSB would lead to more rich phenomena, e.g., compared with the metal electric superconductivity occasion (the ions fixed as lattice).

From the point of view of Maxwell QED, because photons are massless, photon-mediated interactions are long range in contrast with a point-like meson–nucleon interaction in the existed QHD-like Lagrangian. The long range nature of photon-exchange manifests itself in the infrared singular behavior of the photon propagator. This characteristic enhances the contribution of very soft, collinear photons to the correlation energy for the EOS or the pairing problem by noting that this divergence should be avoided by the resummation approach as done in QCD or QED. Essentially, different from the QCD occasion (with the magnetic mass cutoff due to the *non-Abelian* self-interaction of gluons) [31], there is no magnetic screening in QED, which makes it very involved to discuss the superconductive behaviors in strong magnetic field occasion such as in compact star environment with conventional QHD-like Lagrangian. This approach makes it possible to further study Meissner as well as Debye screening effects in such as astrophysics [32]. The premise of this approach as a nonlocal effective theory nearby a phase transition with CSB through one-meson (photon) exchange picture would be very powerful in addressing nuclear matter (either symmetric or asymmetric) many-body properties and even those of finite nuclei.

In summary, the long range non-saturating Coulomb interaction plays an important role in the property of charged/neutral nuclear matter, which can be incorporated simultaneously with the residual strong interaction within MFT of relativistic nuclear theory through an effective Proca-like Lagrangian. The deformation of phase-space distribution function of nucleons attributed to the static electric interaction can manifest itself on the thermodynamics or the property of ground state of charged nuclear matter and the quasiparticle spectrum while the photon mass m_γ controls the strength. Especially, the repulsive Coulomb force makes the critical temperature lower than the existed theoretical anticipation and contributes to interpreting the accessible experimental results. Furthermore, the breached PP and NN pairing correlation strengths open a new window for the study of nuclear matter EM property/nuclei structure and would lead to rich physical phenomena. From the view of point of many-body physics, the low-temperature LG phase transition found in heavy ion collisions and the different correlation strengths for PP and NN(P) bound-state can be seen as the fingerprint of broken EM symmetry within MFT to some extent. Our discussion based on assuming the spontaneously broken EM gauge symmetry highlights that the $U(1)$ electric charge symmetry violating effects should be taken into account simultaneously with the $SU(2)$ isospin breaking effects played by such as ρNN coupling. The weak coupling interaction is mixed with other stronger ones and plays an important role for the many-body effects. Especially, the overlooked EM interaction contribution on the many-body properties such as thermodynamics, binding, pairing mechanism, etc., of nucleons in nuclear matter should be carefully considered from the point of view of continuum field theory.

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