Some Recent Topics on Possible Chiral Restoration in Nuclear Medium

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Abstract
Some topics are introduced on possible evidences of chiral restoration in nuclei and related ones. The topics include the $\sigma$-mesonic mode in nuclei, the vector mesons in a nuclear matter, deeply bound pionic and Kaonic nuclei with a discussion on the nature of $\Lambda(1405)$. Other related topics are briefly mentioned. An emphasis is put on that phenomena even in finite nuclei with normal and sub-normal nuclear density, as will be explored in the new project in GSI and possibly in J-PARC, are interesting for physics of finite-density QCD.

§1. Introduction

According to the present understanding,\(^1\)–\(^5\) the hadronic matter at relatively low temperature might undergo various phase transitions successively or simultaneously; the new phases and the transitions include liquid-gas phase transition, the nuclear $^1S_0$-, $^3P_2$- and $^3S_1$-$^3D_1$-superconductivity, the pion condensation, Kaon condensation, H-dibaryon matter, a mixed state of hadron-quark phases, chiral restoration, color-super conducting (CSC) phases with various complications. In the present report, focusing on the chiral transition in nuclear matter, I will discuss some characteristic changes in the scalar and vector correlations associated with the (partial) restoration of chiral symmetry in the hadronic medium. Some recent topics will be also introduced, which may have a relevance to the chiral properties of finite nuclei.\(^6\)

It will be clear that phenomena in finite nuclei with normal and even sub-normal nuclear density, as will be explored in the new project in GSI and possibly in J-PARC, are interesting as a physics of finite-density QCD.

§2. Chiral Properties at Finite Density

Although there has been recently a tremendous development in the lattice-QCD simulations at finite chemical potential,\(^7\) it is fair to say that such lattice simulations are still premature to give a definite thing for the hadronic and/or quark matter, especially on a phase transition at finite density with relatively low temperatures.

A heuristic argument based on a Hellman-Feynman theorem can tell us that the chiral condensate $\langle \bar{q}q \rangle$ decreases at finite density $\rho_B$ as well as at finite $T$. For the the degenerate nucleon system $|NM\rangle$, one may start from the formula\(^8\)

$$\langle NM|\bar{q}q|NM\rangle = \frac{\partial \langle NM|\mathcal{H}_{QCD}|NM\rangle}{\partial m_q},$$

(2.1)

where the expectation value of QCD Hamiltonian may be evaluated to be $\langle NM|\mathcal{H}_{QCD}|NM\rangle = \varepsilon_{\text{vac}} + \rho_B [M_N + B(\rho_B)]$. Here, $\varepsilon_{\text{vac}}, M_N$ and $B(\rho_B)$ denote the vacuum energy, the nucleon mass and the nuclear binding energy per particle, respectively. Thus one ends up with

$$\frac{\langle NM|\bar{q}q|NM\rangle}{\langle \bar{q}q \rangle_0} = 1 - \rho_B \frac{\Sigma_{\pi N} + \hat{m}}{m_{\pi}} \frac{d}{d\rho_B} B(\rho_B),$$

(2.2)

where $\Sigma_{\pi N} = (m_u + m_d)/2, \langle N|\bar{u}u + \bar{d}d|N\rangle$ denotes the $\pi$-N sigma term with $\hat{m} = (m_u + m_d)/2$; the semi-empirical value of $\Sigma_{\pi N}$ is known to be (40 – 60) MeV.\(^9\) Notice that the correction term with finite $\rho_B$ is negative and gives a reduction of some 30 - 50% of $\langle NM|\bar{q}q|NM\rangle$ already at the normal nuclear matter density $\rho_0 = 0.17 fm^{-3}$. One may notice that the physical origin of this reduction is clear; the scalar probe given by the operator $\bar{q}q$, hits either the vacuum or a particle present in the system at $\rho_B \neq 0$, where $\bar{q}q$ picks up a positive contribution to the chiral condensate because of the positive scalar charge $\langle N|\bar{q}q|N\rangle > 0$ of a nucleon.
From the above estimate, one might suppose that the central region of heavy nuclei is dense enough to cause a partial restoration of chiral symmetry, realizing some characteristic phenomena of the chiral restoration in nuclear medium, which may be observed by experiments in the laboratories on Earth.  

§3. The \( \sigma \) mesonic mode in nuclei

It is a well-known fact in many-body or statistical physics that if a phase transition is of second order or weak first order, there may exist specific collective excitations called \textit{soft modes};\(^{10}\) they actually correspond to the quantum fluctuations of the order parameter. In the case of chiral transition, there are two kinds of fluctuations; those of the phase and the modulus of the chiral condensate. The former is the Nambu-Goldstone boson, i.e., the pion, while the latter has the quantum numbers \( I = 0 \) and \( J^{PC} = 0^{++} \), which then may be identified with the meson historically called the \( \sigma \) meson.\(^{11}\)

3.1. The scalar mesons in free space

After the establishment of the chiral perturbation theory\(^{12}\) for describing low energy hadron phenomena, people has also come to be able to describe resonances in a consistent way with chiral symmetry.\(^{13,14}\) A central problem was recognized\(^{15,16}\) to incorporate the fundamental properties of the scattering amplitude such as unitarity, analyticity and the crossing symmetry together with chiral symmetry. Recent cautious phase shift analyses for the pi-pi scattering\(^{16-19}\) and the decay processes of heavy particles such as \( D \rightarrow \pi \pi \pi \)\(^{20}\) showed a pole identified with the \( \sigma \) in the \( s \) channel together with the \( \rho \) meson pole in the \( t \) channel: The \( \sigma \) pole has the real part \( \text{Re} \ m_{\sigma} = 500-800 \text{ MeV} \) and the imaginary part \( \text{Im} \ m_{\sigma} \approx \text{Re} \ m_{\sigma} \).\(^{16,18}\)

One should notice that there are serious controversies on the nature of the scalar mesons including the \( \sigma \):\(^{19}\) The low-lying scalar mesons with \( J^{PC} = 0^{++} \) of the simple \( q\bar{q} \) nature is at odd with the conventional constituent quark model;\(^{21}\) they should be a \( P \)-wave state\(^{(3P_0)} \), which is in turn usually heavier than 1.2 GeV. Within the framework of the non-relativistic constituent quark model, the low-lying scalar mesons might be described as diquark-antidiquark states, i.e., four-quark states, which can have as large as 600 MeV binding energy due to the color-magnetic interaction as argued by Jaffe.\(^{22}\) However, it should be noticed that the pion cannot be understood within the conventional constituent quark model, either. As first shown by Nambu,\(^{23}\) the pion may be interpreted as a \textit{collective} state given as a superposition of many \( q\bar{q} \) states. Thus a natural interpretation of the \( \sigma \) as the quantum fluctuation of the chiral order parameter is also a collective state as the pion as the phase fluctuation of the chiral order parameter;\(^{11,23}\) the collectiveness of them are due to chiral symmetry and its dynamical breaking. It may possibly be the case that the \( \sigma \) pole is only dynamically generated by the chiral dynamics, implying that the \( \sigma \) is a \( \pi \pi \) molecule. One may also mention that the argument based on the “mended symmetry” of Weinberg assumes the \( \sigma \) mass below or equal to the \( \rho \) meson mass.

3.2. \( \sigma \) meson in hadronic matter

If the \( \sigma \) is really associated with the fluctuation of the chiral order parameter, the \( \sigma \) can be a \textit{soft mode} of the chiral restoration as was first argued and demonstrated in.\(^{11}\) It implies that the \( \sigma \) pole moves toward the origin of the complex energy plane in the chiral limit and the \( \sigma \) may become a sharp resonance as chiral symmetry is restored at high temperature and/or density; see also.\(^{24}\) The present author proposed some experiments\(^{25,26}\) to create the scalar mode in nuclei thereby to obtain a clearer evidence of the existence of the \( \sigma \) meson and also to examine the possible restoration of chiral symmetry in the nuclear medium.

Notice, however, that a hadron ejected into a nuclear/hadron medium might lose its identity and describing the whole system in terms of the (possibly) changed mass and width of the hadron can be inadequate. The most proper quantity to observe the behavior of a hadron in a matter is the response function or spectral function: As long as the coupling
of the hadron with the environment is relatively small, a peak corresponding to the hadron remains with a small width in the spectral function, then one can speak of the width and the shifted mass of the hadron in the matter. The spectral function in the scalar channel is obtained from the propagator. The \( \sigma \)-meson propagator at rest in the medium reads
\[
D^{-1}_\sigma(\omega) = \omega^2 - m_\sigma^2 - \Sigma_\sigma(\omega; \rho_\sigma),
\]
where \( m_\sigma \) is the mass of the \( \sigma \) in the tree-level, and \( \Sigma_\sigma(\omega; \rho_\sigma) \) represents the loop corrections in the vacuum as well as in the medium. The corresponding spectral function is given by
\[
\rho_\sigma(\omega) = -\frac{1}{\pi} \text{Im} D_\sigma(\omega) \quad (3.1)
\]
Now one can see that \( \text{Im} \Sigma_\sigma \propto \theta(\omega - 2m_\sigma)\sqrt{1 - 4m_\sigma^2/\omega^2} \) near the two-pion threshold in the one-loop order. On the other hand, the pole mass \( m_\sigma^* \) in the medium is defined by \( \text{Re} D^{-1}_\sigma(\omega = m_\sigma^*) = 0 \). Partial restoration of ChS implies that \( m_\sigma^* \) approaches to \( m_\sigma \). Thus there should exist a density \( \rho_\sigma \) at which \( \text{Re} D^{-1}_\sigma(\omega = 2m_\sigma) \) vanishes even before the complete restoration of ChS where \( \sigma-\pi \) degeneracy gets realized;
\[
\text{Re} D^{-1}_\sigma(\omega = 2m_\sigma) = [\omega^2 - m_\sigma^2 - \text{Re} \Sigma_\sigma(\omega = 2m_\sigma)] = 0 \quad (3.2)
\]
At this point, the spectral function is solely given in terms of the imaginary part of the self-energy:
\[
\rho_\sigma(\omega \approx 2m_\sigma) = -\frac{1}{\pi} \text{Im} \Sigma_\sigma \propto \frac{\theta(\omega - 2m_\sigma)}{\sqrt{1 - 4m_\sigma^2/\omega^2}} \quad (3.3)
\]
which clearly shows the near-threshold enhancement of the spectral function. This should be a general phenomenon to be realized in association with partial restoration of ChS.

To make the argument more quantitative, Hatsuda, Shimizu and the present author evaluated the spectral function \( \rho_\sigma(\omega) \) in the \( O(4) \) linear \( \sigma \)-model and showed that the spectral enhancement near the \( 2m_\pi \) threshold takes place in association with partial restoration of ChS at finite baryon density; the calculation was a simple extension of the finite \( T \) case done by Chiku and Hatsuda. An improvement of this mean-field level calculation was subsequently made by including the \( p-h \) and \( \Delta-h \) contributions to the pion propagator. In this case, the spectral strength spreads into the energy region even below \( 2m_\pi \), but the qualitative feature of the enhancement at \( 2m_\pi \) still remains.

Interestingly enough, CHAOS collaboration observed that the spectral function of the invariant mass \( M_{\pi^\pm \pi^\pm}^A \) for \( \pi^\pm \pi^\pm \) from the reaction \( A(\pi^+, \pi^\pm)A' \) near the \( 2m_\pi \) threshold with \( A \) ranging from 2 to 208. They obtained the following interesting result: When \( A = 2 \), i.e., the target is deuteron, the spectral function has only a tiny strength around the threshold, while it increases dramatically in the \( I = J = 0 \) channel with increasing \( A \). The spectral function shows no such an increase in the \( I = 2 \) channel. For the experimental confirmation of the threshold enhancement seen in measurements of \( 2\pi^0 \) and \( 2\gamma \) final states with hadron/photon beams off the heavy nuclear targets are necessary. Those channels are free from the \( \rho \) meson background inherent in the \( \pi^+\pi^- \) measurement; see also. An experiment detecting \( 2\pi^0 \) from the reaction \( A(\pi^0, \pi^0\pi^0)A' \) with \( E_\pi \approx 400 - 460 \) MeV and \( A = H, ^{12}C, Pb \) has been made by TAPS group as shown in Fig.1, a dramatrical softening of the spectral function in the \( \sigma \) channel is seen for heavier nuclei. Notice that the pions are absorbed mostly in the surface region and may be difficult to prove the interior of nuclei, while the \( \gamma \) is more easily penetrate deep into nuclei and can prove the possible density effects on the spectral function in the matter as shown in. One can also study the in-medium \( \pi-\pi \) amplitude using the same \( O(4) \) model: Jido, Hatsuda and the present author showed that a large

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\(^*\) This experiment was motivated to explore the \( \pi-\pi \) correlations in nuclear medium.\(^{31}\)

\(^{**}\) However, see a recent work\(^{35}\) in which an account is given of the downward shift of the \( \pi^0\pi^0 \) spectral function in terms of the conventional final state interactions of the pions with the nucleons. Clearly, more theoretical and experimental works are needed to settle down the issue.
enhancement of the cross section near the threshold is obtained along with the increase of the baryon density. Then one may ask whether the near-threshold enhancement obtained in the O(4) linear σ model can arise also in the non-linear models which lack in the explicit σ field. In, it was shown that it is the case and also an vertex in the non-linear chiral Lagrangian is identified which is responsible for the enhancement.

To study these problems, it is best to start with the standard polar parameterization of the chiral field, \( M = \sigma + i\vec{r} \cdot \vec{\pi} = (\langle \sigma \rangle + S)U \) with \( U = \exp(i\vec{r} \cdot \vec{\phi}/f_{\pi}) \). Here, \( \langle \sigma \rangle \) is the chiral condensate in nuclear matter as before, while \( f_{\pi}^* \) is to be the “in-medium pion decay constant”. Taking the heavy-scalar and heavy-baryon limit limit simultaneously, and integrating out the scalar field \( S \), one can obtain the following effective Lagrangian:

\[
\mathcal{L}_{\text{eff}} = \left( \frac{f_{\pi}^2}{4} - \frac{gf_{\pi}}{2m_{\pi}^2} \bar{N}N \right) \left( \text{Tr}[\partial U \partial U^\dagger] - \frac{\hbar}{f_{\pi}} \text{Tr}[U^\dagger + U] \right) + \mathcal{L}_{\pi N}^{(1)} + \cdots ,
\]

where In (3.4), \( \mathcal{L}_{\pi N}^{(1)} \) is the standard p-wave π-N coupling and \( \cdots \) denotes other higher dimensional operators which are not relevant for the present discussion. Here all the constants are taken for the vacuum: \( f_{\pi} = \langle \sigma \rangle_0 \), \( m_{\pi}^2 = \lambda \langle \sigma \rangle_0^2/3 + m_N^2 \), and \( m_N = g\langle \sigma \rangle_0 \).

\( \bar{N}N \) in eq.(3.4) may be replaced by the baryon density \( \rho \) in the mean-field approximation, leading to a reduction of the vacuum condensate:

\[
f_{\pi} = \langle \sigma \rangle_0 \rightarrow \langle \sigma \rangle = \langle \sigma \rangle_0 (1 - g\rho/f_{\pi}m_{\pi}^2) = f_{\pi}^* .
\]

This implies that the proper normalization of the pion field in the nuclear medium should be

\[
\phi' = (\phi/f_{\pi}) \cdot f_{\pi}^* \equiv Z^{1/2} \phi ,
\]
with $Z^{1/2} \equiv f_{\pi}^*/f_{\pi}$. This is the wave-function renormalization in the medium. One can now see that the origin of the near-threshold enhancement is the wave-function renormalization in the nuclear medium, ascribed to the following new vertex:

$$L_{\text{new}} = -\frac{3g}{2\lambda f_{\pi}} \bar{N}N \text{Tr}[\partial U \partial U^\dagger].$$

(3.7)

owing to the scalar nature, this vertex can affect not only the pion propagator but also the interaction among pions in the nuclear medium. In Fig. 2, $4\pi$-$N$-$N$ vertex generated by $L_{\text{new}}$ is shown.

Here it should be pointed out that the vertex eq.(3.7) has been known to be one of the next-to-leading order terms in the non-linear chiral Lagrangian in the heavy-baryon formalism; see for a recent development on the in-medium chiral perturbation theory.

3.3. Simultaneous softening of the $\sigma$ and the $\rho$ mesons associated with chiral restoration

Recently, Yokokawa et al have constructed a unitarized $\pi$-$\pi$ scattering amplitude in a hot and dense matter, and shown that the spectral functions in the $\sigma$ and the $\rho$ meson channels gives rise to a softening in tandem as the chiral symmetry is restored. They adopted the $N/D$ method a la Igi and Hikasa, in which the scattering amplitude satisfies the analyticity and approximately the crossing symmetry. The effect of the effect of chiral restoration is taken into account in the mean field level, which is tantamount to replacing $f_{\pi}$ by $f_{\pi}^*(\rho)$.

Four types of chiral models were taken to construct the scattering amplitude which is to be unitarized to check the possible model dependence: Model A; The “$\rho$ model” in which the $\pi$ and bare-$\rho$ are the basic fields, and the $\sigma$ is to be generated dynamically. Model B; The “$\sigma$ model” in which the $\pi$ and bare-$\sigma$ are the basic fields, and the $\rho$ must be be generated dynamically. Model C; The “degenerate $\sigma$-$\rho$ model” in which the $\pi$, bare-$\sigma$ and bare-$\rho$ are all the basic fields. Model D; The leading chiral Lagrangian $L_2$, which solely can generate the $\sigma$ dynamically but not the physical $\rho$.

In Fig. 3, the trajectories of the moving complex poles in $I = J = 0$ channel along with the decrease of $f_{\pi}^*$ are shown for the four models; the crosses indicate the pole positions in the vacuum. One sees that the It should be remarked that there exist two poles in the both channels (except for Model D), one of which moves toward the $2m_{\pi}$ threshold. It implies that the sigma meson which is elusive in the free space may appear as a rather sharp resonance in hot and/or dense medium where chiral symmetry is partially restored. This pole behavior was first suggested in and shown in. A remarkable point is that the softening also occurs in the $\rho$ meson channel, which leads to some interesting implications to the in-medium cross sections, which are shown in Fig. 4. The upper (lower) panels are for the case with small (large) restoration of chiral symmetry with $0.5f_{\pi} < f_{\pi}^* < f_{\pi}$ $(0.1f_{\pi} < f_{\pi}^* < 0.5f_{\pi})$, which is supposed to correspond to lower (high) densities. At low densities, one sees that a significant of the red-shift of the peak (softening) of the cross section occurs in the $\sigma$ meson channel, while a large broadening with a relatively small softening occurs in the $\rho$ meson channel, which, as will be discussed in the subsequent section, has a strong relevance to the spectral change obtained from the relativistic heavy ion collisions by CERES collaboration.

§4. Chiral restoration and vector mesonic modes in nuclei

The spectral function deduced from the lepton pairs from the heavy ion collisions such as Pb-Au collisions both at high energy (158 GeV/A) and at low energy (40 GeV/A) show a
Fig. 3. The movement of the poles in $I=J=0$ channel (left panel) and $I=J=1$ channel (right panel) along with the decrease of $f_\pi^*$. The crosses are the pole positions in the vacuum. Taken from.\(^{39}\)

Fig. 4. The in-medium $\pi-\pi$ cross sections in $I=J=0$ channel (left panel) and $I=J=1$ channel (right panel) for Model-B: Each upper (lower) panel shows the case of small (large) restoration corresponding to $0.5f_\pi < f_\pi^* < f_\pi$ ($0.1f_\pi < f_\pi^* < 0.5f_\pi$). Taken from.\(^{39}\)

sizable enhancement of the $e^+e^-$ yield below the $\rho$-meson peak.\(^{42}\) This may or may not be related to the partial chiral restoration in nuclear medium originally proposed in.\(^{43}\) It is worth mentioning that a simultaneous softening of the spectral function in the $\sigma$ meson (or $f_0(600)$) and the $\rho$ meson discussed in the last section\(^{39}\) may also account for the spectral change seen in the STAR experiment at RHIC,\(^{44}\) as argued in.\(^{45}\) In the STAR experiment,\(^{44}\) observed signals are reported for a variety of mesonic as well as baryonic resonances produced by mid-central Au-Au collisions at $\sqrt{s} = 200$ GeV, where the temperature effect should dominate the density effect.

The E325 experiment at KEK\(^{46}\) measured $e^+e^-$ pairs from the p-A collision at 12 GeV. The similar enhancement over the known source and combinatorial background as CERES is seen in the mass range of about 200 MeV below the $\rho-\omega$ peak for A=Cu.

§5. Deeply bound pionic atoms and reduction of $f_\pi^*$ in nuclei

It is interesting that there are other possible experimental evidences for partial chiral restoration in nuclear matter than the chiral fluctuations in the sigma meson channel discussed so far. The deeply bound pionic atom has proved to be a good probe of the properties of the hadronic interaction deep inside of heavy nuclei. It has been suggested\(^{47},^{48}\) that the
anomalous energy shift of the pionic atoms (pionic nuclei) owing to the strong interaction could be attributed to the decrease of the effective pion decay constant $f_{\pi}^*(\rho)$ at finite density $\rho$ which may imply that the chiral symmetry is partially restored deep inside of nuclei. This scenario has been confirmed$^{49}$ by a microscopic calculation taking into account the energy dependence of the pion optical potential. It is interesting that Kolomeitsev et al.$^{49}$ also showed that their result can be understood in terms of the in-medium renormalization of the wave function$^{49}$, as was important in the softening of the spectral function in the $\sigma$ channel.$^{36}$

§6. The nature of $\Lambda(1405)$ and possible deeply bound Kaonic nuclei

The anti-Kaon in nuclear matter show a very attractive nature. Waas and Weise$^{52}$ showed that the spectral function for the anti-Kaon in nuclear matter shows a dramatical softening, as shown in Fig.1 and 2 in their paper.$^{52}$ Akaishi and Yamazaki$^{53}$ considered seriously the attractive nature of the Kaon-nuclear interaction which may lead to the $\Lambda(1405)$ as a bound state, and showed that the attraction can manifest itself in a more dramatic way in a proton-rich matter. They demonstrated that the Kaonic nuclei could be deeply bound matter. The creation of such an abnormal state of matter has been also confirmed by Dote et al.$^{54}$ using an ab initio molecular dynamical calculation called Anti-symmetrized molecular dynamics developed by Horiuchi.$^{55}$ They showed that the created matter may have as high as 8 times of the normal nuclear density. After the workshop, a report was made of the possible evidence of such an exotic state.$^{56}$ If such a dense matter with strangeness was confirmed, it would open a new era of nuclear/hadron physics. It provides systems with high density and strangeness. It can be a laboratory on Earth for examining the dense matter expected in the interior of neutron stars and possibly in quark stars.

§7. Summary and concluding remarks

I have tried to convince you that the nuclear matter at and even below the normal nuclear density ($\rho \simeq \rho_0$) would be also interesting for physics of finite density QCD:

1. One might observe precursory phenomena of chiral restoration in various channels, i.e., the $\sigma$- and the vector meson channels and also the baryon channels$^{**}$

2. Such a research with the matter at $\rho \simeq \rho_0$ can give a sound basis for attacking and exploring high-density matter, for example, through the study on chiral dynamics at $\rho \neq 0$.

3. Most importantly, rich experimental information will be available in the near future, from the ongoing and future projects in GSI, KEK and J-PARC (former JHF).

There are several topics which are related to chiral restoration in the nuclear medium but were not covered in the present report because of the lack of time. These include:

(i) The chiral properties of baryons of positive and negative parity and their behavior along with the chiral restoration.$^{57}$
(ii) The effects of the scalar and vector correlations at $\mu_B \neq 0$, which may manifest itself in a peculiar behavior in the scalar and vector susceptibilities at $\mu \neq 0$, especially around the critical end point of the chiral transition.$^{58}$
(iii) Possible influence of the possible precedent meson condensation and H-baryon matter to the QCD phase transition at finite density.$^{59}$

In passing, I would like to emphasize that the experimental data from the facilities and theoretical works based on effective theories and lattice QCD will cultivate the field of finite density QCD together with astronomical data from neutron stars, supernovas and hopefully quark stars.

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$^*$ However, see also a recent phenomenological analysis,$^{50}$ where it is argued that the energy dependence of the on-shell pions is more essential, as in.$^{51}$

$^{**}$ I failed to give an account of it owing to the lack of time.
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References

10) See e.g., P. W. Anderson, Basic Notion of Condensed Matter Physics (Benjamin, California, 1984).