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CHIRAL-SCALE EFFECTIVE FIELD THEORY FOR DENSE AND THERMAL SYSTEMS*

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In this contribution, I will present some properties of nuclear matter (NM) using the chiral-scale effective field theory (EFT) anchored in the chiral, scale, and hidden local flavor symmetries of QCD. We show that the sound velocity (SV) of NM can saturate the conformal limit and exhibits a peak configuration in the intermediate density. To extend the chiral-scale EFT to both dense and thermal systems, we establish a chiral-scale density counting (CSDC) rule and explore the contributions up to $\mathcal{O}(k_{\rm c}^{12})$.

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1. Introduction

Chiral EFTs have been widely and successfully used in nuclear physics [1–3]. The advantage of these approaches is that they are anchored in the chiral symmetry so are closer to QCD than phenomenological models. In conventional chiral EFTs, pions and lowest-lying vector mesons can be consistently included alongside nucleons. However, because the scalar mesons are integrated out in the nonlinear realization of chiral symmetry, the isoscalar scalar meson, σ — an important degree of freedom responsible for the attraction between nucleons — is absent. This limits the applicability of chiral EFTs in nuclear physics, particularly in the mean-field approach.

The trace anomaly of QCD provides a source for the σ meson in hadronic models [4]. In 2012, Crewther and Tunstall proposed an approach to include the σ meson in chiral EFT [5] by conjecturing that QCD has an infrared fixed point (IRFP) and that the theory is slightly away from it. In this approach, the σ meson is identified as the Nambu–Goldstone boson (NGB) of scale symmetry breaking — the dilaton — with a small mass arising from the deviation from the IRFP that explicitly breaks scale symmetry. The existence of the IRFP is supported by some literature, *e.g.*, Refs. [6, 7].

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In this contribution, I will present some properties of NM using the chiral-scale EFT systematized in Ref. [8], which, in addition to nucleons, includes the lightest scalar meson as NGB of scale symmetry breaking, pions as the NGBs of chiral symmetry breaking, and the lowest-lying vector mesons as the gauge bosons of hidden local flavor symmetry.

2. Chiral-scale effective field theory

For the present purpose, we decompose the Lagrangian into the pure meson part $\mathcal{L}_M$ and the baryon part $\mathcal{L}_B$ as

$$\mathcal{L} = \mathcal{L}_M + \mathcal{L}_B\,, \tag{1}$$

where

$$\begin{aligned}
\mathcal{L}_M ={}& f_\pi^2 \varPhi^2 \mathrm{Tr}\left(\hat{\alpha}_\perp^\mu \hat{\alpha}_{\mu\perp}\right) + \frac{m_\rho^2}{g_\rho^2}\varPhi^2 \mathrm{Tr}\left(\hat{\alpha}_\parallel^\mu \hat{\alpha}_{\mu\parallel}\right) - \frac{1}{2g_\rho^2}\mathrm{Tr}\left(V_{\mu\nu}V^{\mu\nu}\right)\\
&+ \frac{1}{2}\left(\frac{m_\omega^2}{g_\omega^2} - \frac{m_\rho^2}{g_\rho^2}\right)\varPhi^2 \mathrm{Tr}\left(\hat{\alpha}_\parallel^\mu\right)\mathrm{Tr}\left(\hat{\alpha}_{\mu\parallel}\right) - \frac{1}{2g_0^2}\mathrm{Tr}\left(V_{\mu\nu}\right)\mathrm{Tr}\left(V^{\mu\nu}\right)\\
&+ \frac{1}{2}\partial_\mu\chi\partial^\mu\chi + \frac{f_\pi^2}{4}\varPhi^2 \mathrm{Tr}\left(\mathcal{M}U^\dagger + U\mathcal{M}^\dagger\right) + h_5\varPhi^4 + h_6\varPhi^{4+\beta'}\,,
\end{aligned}\tag{2}$$

$$\begin{aligned}
\mathcal{L}_B ={}& \bar{N}i\gamma_\mu D^\mu N - m_N\varPhi\bar{N}N\\
&+ \left[g_A C_A + g_A\left(1 - C_A\right)\varPhi^{\beta'}\right]\bar{N}\hat{\alpha}_\perp^\mu\gamma_\mu\gamma_5 N\\
&+ \left[g_{V_\rho}C_{V_\rho} + g_{V_\rho}\left(1 - C_{V_\rho}\right)\varPhi^{\beta'}\right]\bar{N}\hat{\alpha}_\parallel^\mu\gamma_\mu N\\
&+ \frac{1}{2}\left[g_{V_0}C_{V_0} + g_{V_0}\left(1 - C_{V_0}\right)\varPhi^{\beta'}\right]\mathrm{Tr}\left[\hat{\alpha}_\parallel^\mu\right]\bar{N}\gamma_\mu N\,.
\end{aligned}\tag{3}$$

For the notations and conventions, we refer to Refs. [9, 10]

3. The pseudoconformal structure

The chiral-scale EFT is a framework in which chiral symmetry is realized in a nonlinearly, and the trace anomaly effect is incorporated through dilaton compensator. Therefore, it is a natural approach for considering medium effects on the parameters in the sense of Brown–Rho scaling [11]. Regarding the explicit density dependence of the medium-modified parameters, since we have no prior information from underlying QCD, we take lessons from the skyrmion crystal approach, which predicts that the medium-modified parameters, such as f_π^*, m_N^*, m_ρ^*, *etc.*, first decrease with density and then remain constant above certain density, characterized by the transition from skyrmion to half-skyrmion phase [12].

By tuning the scaling parameter with respect to the NM properties around saturation density n_0, we found that the SV can saturate the conformal limit after the topology change occurring at density $n_{1/2}$ [13], as shown in Fig. 1. Note that, although the SV saturates the conformal limit, this does not mean that the theory is scale invariant, since the trace of the energy-momentum tensor (TEMT) is a nonzero, density-independent constant (as shown in Fig. 1) that does not contribute to the SV.

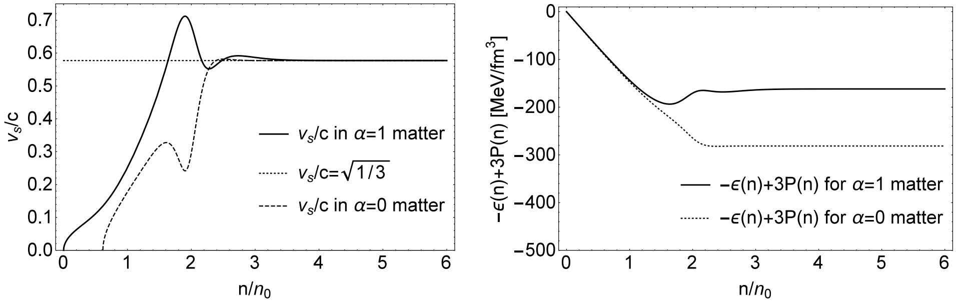

Fig. 1. Sound velocity (left panel) and TEMT (right panel) *versus* density for symmetric matter ($\alpha = 0$) and neutron matter ($\alpha = 1$) [13].

The data from nuclear physics and heavy-ion collisions constrain the transition density to $2.0n_0 \lesssim n_{1/2} \lesssim 4n_0$ [14]. Therefore, the conformal SV can appear in the cores of massive NSs. This discovery is in stark contrast to the earlier belief that the conformal SV cannot appear at densities below the regime where perturbative QCD is applicable, since otherwise a massive NS with a mass around two solar masses cannot be obtained [15]. Although this finding was novel when it was first reported, it has since been observed in various models (see, *e.g.*, Ref. [16]).

4. Peak of sound velocity

We next discuss the peak of SV, which is normally attributed to a phase or configuration transition in NM and has not been predicted in a unified hadronic model. Based on the chiral-scale EFT, and using the standard mean-field approximation, we found that the peak of SV arises naturally [9, 10]. The results are shown in Fig. 2.

Figure 2 indicates that the origin of the peak is tied to the generic property of the chiral-scale EFT that is not shared by Walecka-type models. In the former, the effective screening masses of the vector mesons are modified by the dilaton compensator χ, *e.g.*, for the omega meson $m_\omega^*/m_\omega = \langle\chi\rangle^*/f_\chi$. The quantity m_ω^* — and similarly $\langle\chi\rangle^*$ — cannot keep decreasing, since otherwise the system would become unstable owing to the infinite omega meson repulsion. This behavior is indeed numerically demonstrated in Fig. 2.

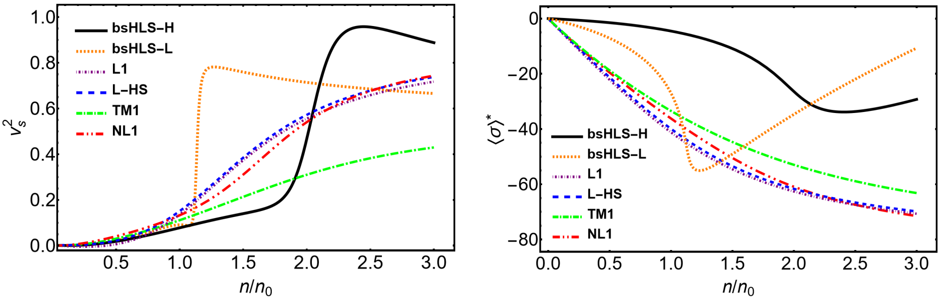

Fig. 2. Sound velocity (left panel) and VEV of sigma (right panel) *versus* density for from chiral-scale EFT (bsHLS-H and bsHLS-L) and Walecka-type models [9, 10].

5. Chiral-scale density counting rule

We finally extend the chiral-scale EFT to systems at both finite density and finite temperature. Since the dilaton compensator involves the σ meson through $\mathrm{e}^{\sigma/f_\chi}$, a Taylor expansion is required. To estimate the contribution from each order of the expansion, we establish a counting rule that is valid up to the densities of the cores of massive stars — the CSDC rule — in addition to the chiral-scale counting rule in matter-free space.

Since mesons can be treated as background fields induced by nucleons in NM, their EOMs can be solved via the Green's function method with the corresponding fermion currents. For example, for the σ meson,

$$\sigma(x) = \int\limits_V \mathrm{d}^4x' D_\sigma(x-x') \left(-g_{\sigma NN}^{\mathrm{OBE}} \bar{N}(x') N(x')\right) , \tag{4}$$

where $D_\sigma(x-x')$ is the retarded Green's function of the σ-meson field. If the density does not become very high, the baryonic bilinear currents, such as the one in Eq. (4), should be of order $n \propto k_{\mathrm{F}}^3$. For the values of k_{F} relevant to the cores of massive neutron stars, the characteristic momentum is up to $k_{\mathrm{c}} \sim 700$ MeV $\sim 10\ n_0$, which is the same order as that of chiral-scale counting rules. Furthermore, the couplings are assumed to have a consistent order, *e.g.*, the couplings between mesons and nucleons are of $\mathcal{O}(p) \sim \mathcal{O}(k_{\mathrm{c}})$ except for $g_{\pi NN}^{\mathrm{OBE}}$ due to its derivative coupling. In addition, the following assignments are made for the meson fields $\sigma, \pi, \omega_\mu, \rho_\mu^i \sim \mathcal{O}(k_{\mathrm{c}}^2)$ because of their derivative couplings to the baryons. For a detailed discussion, we refer to Ref. [17].

As an example, we show the NM properties calculated order-by-order in Table 1. One can conclude that the CSDC rule works well and that it is sufficient to include contributions up to $\mathcal{O}(k_{\mathrm{c}}^{12})$, *i.e.*, the N^{4}LO. We argued in Ref. [17] that the CSDC rule can also be applied to thermal systems up to $T \sim 100$ MeV. Here, we will not elaborate on this extension.

Table 1. Results of NM properties. $E, E_{\rm sym}, L$ and, K are, respectively, binding energy, symmetry energy (SE), SE slope, and incompressibility. $T_{\rm c}$ is the GLPT critical temperature and $n_a = 1.5n_0$. n_0 is in unit of fm^{-3} and others are in MeV.

	Empirical		$\mathcal{O}(k_{\rm c}^6)$	$\mathcal{O}(k_{\rm c}^8)$	$\mathcal{O}(k_{\rm c}^{10})$	$\mathcal{O}(k_{\rm c}^{12})$
n_0	0.155 ± 0.050	[18]	0.160	0.160	0.160	0.158
$E(n_0)$	-15.0 ± 1.0	[19]	−16.3	−15.6	−16.1	−15.4
$E(n_a)$	-13.3 ± 0.5	[20]	−6.92	−12.0	−8.99	−11.2
$K(n_0)$	230 ± 30	[21]	566	366	572	391
$E_{\rm sym}(n_0)$	30.9 ± 1.9	[22]	31.6	32.1	31.8	32.2
$L(n_0)$	52.5 ± 17.5	[22]	104	83.2	75.7	77.8
$T_{\rm c}$	20.0 ± 3.0	[23]	19.0	26.5	24.0	22.5

6. Summary and perspective

In this contribution, we presented some predictions of the NM properties using the chiral-scale EFT anchored in the chiral and scale symmetries of QCD, *i.e.*, the pseudoconformal structure, the origin of SV and CSDC rules. In the future, we plan to perform a full scan of the parameter space, include higher loop corrections to NM, and extend the approach to include strangeness.

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