

Nuclear symmetry energy from QCD sum rules (postprint)

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Full Text

Nuclear Symmetry Energy from QCD Sum Rules

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Abstract

We calculated the nucleon self-energies in isospin asymmetric nuclear matter and obtained the nuclear symmetry energy by taking the difference between those of neutron and proton. We find that the scalar (vector) self-energy part gives a negative (positive) contribution to the nuclear symmetry energy, consistent with results from relativistic mean-field theories. Also, we found an exact four-quark operator product expansion for the nucleon sum rule. Among them, twist-4 matrix elements which can be extracted from deep inelastic scattering

experiments constitute an essential part in the origin of the nuclear symmetry energy from QCD. Our result also extends the early success of QCD sum rules in symmetric nuclear matter to asymmetric nuclear matter.

Key words: Nuclear symmetry energy, Relativistic mean field theory, QCD sum rule, Twist-4 matrix elements

2 Brief Description of Theoretical Method

Recently, the Korean government decided to build a low-energy rare isotope accelerator, RAON, which will be mainly used to study exotic properties of isospin asymmetric nuclear matter ranging from rare isotopes to neutron stars. To understand these exotic properties, one should know what causes the differences from symmetric nuclear matter.

In Dirac phenomenology, strong vector repulsion and scalar attraction in the optical potential are needed to explain phenomena in nucleon-nucleus scattering, and this tendency naturally emerges from relativistic mean field model calculations. Almost 20 years ago, this tendency was confirmed at the QCD level using finite density QCD sum rules by Cohen, Furnstahl, and Griegel [1-4]. These studies showed that nucleon bulk properties can be understood in terms of QCD degrees of freedom.

2.1 Phenomenological Approach

There was an early attempt to describe isospin asymmetry in finite nuclei using a linear potential. The well-known Bethe-Weizsäcker formula includes a term accounting for the total shifted energy due to neutron excess, where the isospin asymmetry is given by $I = (N - Z)/A$. When the nuclear symmetry energy is assumed to depend linearly on density, this term can be easily calculated as shown in equation (2). For infinite nuclear matter, the energy density per nucleon of asymmetric (neutron-rich) nuclear matter can be written as in equation (3). Motivated by these considerations and with the hope of expressing the origin of nuclear symmetry energy in QCD degrees of freedom, we have applied QCD sum rules to asymmetric nuclear matter.

In the asymmetric nuclear matter case, the averaged quasi-nucleon energy E can be obtained by density integration of the single nucleon energy E_n . If one assumes linear density dependence of E_n (and E_p), it is straightforward to obtain the averaged single nucleon energy. Using a mean-field type approximation, which provides a plausible and clear view of single nucleon energy in nuclear matter, a single nucleon in asymmetric nuclear matter can be regarded as a quasi-nucleon on the asymmetric Fermi sea with large self-energies. The nucleon symmetry energy can then be obtained from the difference between the neutron and proton self-energies.

2.2 QCD Sum Rule for Nucleon in Asymmetric Nuclear Matter

In this study, we followed the formalism in Refs. [1-4], with detailed descriptions of equations and formulas given in Ref. [5]. The brief steps are as follows. First, the QCD sum rule approach begins with calculating the correlation function, which contains states of all possible quantum numbers for the quasi-nucleon in asymmetric nuclear matter. This correlation function can be directly evaluated using operator product expansion (OPE). The OPE of the correlation function can be written as products of Wilson coefficients and localized operator expectation values (condensates). At short distances, the Wilson coefficients can be calculated using perturbative diagrammatic methods. Additionally, the correlation function is expected to have a spectral structure similar to the propagator in relativistic mean field theory (RMFT). In this ansatz, the nucleon phenomenological self-energies are located near the quasi-nucleon pole state. Since we are only interested in the self-energies near the quasi-nucleon pole, both the OPE and phenomenological sides should be weighted. After this weighting process, known as Borel transformation, the pole contribution becomes enhanced while the continuum contribution is suppressed. By equating both weighted expressions, one can relate the nucleon self-energies to the OPE terms in QCD degrees of freedom.

3 Nuclear Symmetry Energy from QCD Sum Rules

To verify the physical quantity calculated from QCD sum rules, one should set an appropriate range for the Borel mass. This requires the following criteria: (1) the contribution of the highest mass dimension condensate should not exceed 50% of the lowest mass dimension condensate contribution, and (2) the continuum contribution of each OPE term should not exceed 50% of the pole contribution.

The nuclear symmetry energy containing condensates up to mass dimension-five is shown in Fig. 1.

Fig. 1 (Color online) Nuclear symmetry energy which contains up to mass dimension-five condensates.

From Fig. 1, one can verify that the nuclear symmetry energy has a value near 40 MeV, consistent in order of magnitude with previous studies. In the following, we present the nuclear symmetry energy containing condensates up to mass dimension-six, dividing the discussion into two cases: one including twist-4 matrix elements and the other excluding them.

So far, in nucleon OPE, no exact contribution from four-quark operators has been known. In this study, we have found the exact four-quark operators. Especially, spin-2 operators (twist-4) can be extracted from DIS experiments [6], and their contribution to the nuclear symmetry energy is extremely important. Among the dimension-six operators, these twist-4 matrix elements play a crucial role.

If one accounts only for the mass dimension-six spin-1 condensates, the result is shown in the following figure.

Fig. 2 (Color online) Nuclear symmetry energy which contains up to mass dimension-six condensates (without twist-4). This result presents the same result as in Phys. Rev. C, 87: 015204.

From Fig. 2, one can find weak vector repulsion and scalar attraction consistent with RMFT results that include the isovector meson exchange channel [7].

3.2 Results with Twist-4 Operator Contribution

By including the twist-4 contribution, one can see from Fig. 3 that the mechanism of repulsion-attraction becomes more apparent. This result suggests that the reaction mechanism in isospin asymmetric nuclear matter may originate from multi-quark operators such as twist-4 operators.

In this study, we calculated the nucleon self-energy in asymmetric nuclear matter at the QCD level using finite density QCD sum rule techniques. We successfully reproduced the nuclear symmetry energy of previous studies in order of magnitude and found the exact four-quark condensates in the nucleon sum rule. From these results, we confirmed the meaningful fact that the isovector meson exchange mechanism suggested by many RMFT-type studies may have its origin in multi-quark operators such as twist-4 operators. The contribution of twist-4 matrix elements mimics RMFT results [7].

The twist-4 matrix elements currently contain some uncertainties, but the upgrade plan of Jefferson Lab may provide precise twist-4 matrix elements, allowing us to gain a deeper understanding of the role of twist-4 operators in nuclear symmetry energy. Still, the high-density behavior of nuclear symmetry energy has not been fully uncovered. Such unknown properties can be studied through experimental efforts, for example using RAON, or through theoretical investigations.

References

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Fig. 3 (Color online) Nuclear symmetry energy which contains up to mass dimension-six condensates with twist-4 matrix elements. This result presents the same result as in Phys Rev C, 87: 015204.

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