QCD Fossils in Nuclei?

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Abstract

It will be a dream of many nuclear physicists, or theoretical physicists in general, to understand nuclear physics in terms of quarks and gluons using quantum chromodynamics or its low-energy effective theories. Thanks to advancement in theory, in experiments and in supercomputers, we could now dream such a happy dream. We study asymmetric dense matter and finite nuclei in the framework of an effective theory of QCD. We show that the model can reproduce nuclear matter properties reasonably well. We find that the spin-orbit interaction is sensitive to the chiral invariant nucleon mass and can be used as litmus paper to study the origin of nucleon mass in nuclei.

Keywords: *Rare isotopes; QCD; nuclear matter*

1 Introduction

It is widely believed that quantum chromodynamics (QCD) is the fundamental theory of strong interactions. As it is well-recognized, however, we are still far away from describing nuclei in terms of quarks and gluons using QCD since nucleons and mesons are the degrees of freedom at low energies relevant to nuclear physics. However, thanks to developments in theory, i. e., effective field theories and many-body methods, in experiments and in supercomputers, we have now a good chance to understand nuclear physics in terms of QCD or its low-energy effective theories. This sort of efforts is important and timely not only for scientific amusement but also for challenges and opportunities to be posed and to be offered by forthcoming rare isotope facilities.

The nucleus is an interesting and intriguing quantum finite many-body system and provides convenient laboratory to test our understanding of strong interactions and many-body techniques. Since the nucleus consists of protons and neutrons, it is natural to model the nucleus as a collection of interacting protons and neutrons. Therefore, it will be highly nontrivial to understand nuclei in the context of QCD.

Nevertheless, one may ask a question whose answer might come with the next generation rare isotope (RI) facilities and supercomputers: *are there any remnants of non-perturbative QCD in nuclei?* Since the question "*what are the QCD fossils in nuclei?*" is too broad, we narrow it down to "*what is the origin of nucleon mass and how to study it with rare isotopes?*"

As it is well-said, the Higgs particle could explain the origin of a fraction of the mass of visible matter, roughly only 2% of them. If you address a question about

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the rest 98% to particle physicists, they would say that quarks and gluons moving around inside the hadrons with high velocity will explain the rest. If you ask the same question to nuclear physicists, they will propose something interesting which is related to QCD vacuum, i. e., quark-antiquark condensates.

It is out of questions that *ab initio* approaches in nuclear physics will reveal some aspect of the origin of nucleon mass in connection with rare isotopes, but in this article, we will discuss how such a question can be addressed in nuclei based on a chiral effective approach of QCD. In Section 2, we summarize two distinctive pictures on the origin of the nucleon mass in QCD effective approaches. Also, an extended parity doublet model will be introduced and a possibility to tell different pictures in nuclei will be discussed. We then present a brief summary of our discussion in Section 3.

2 Nucleon mass in a parity doublet model

In this section we present two distinctive pictures on the origin of nucleon mass, except the one from current quark masses.

As it is well-known, the nucleon mass (in the chiral limit) in the linear sigma model is given by

$$m_N = g_\pi \sigma_0, \tag{1}$$

where g_π is a coupling constant and σ_0 is the vacuum expectation value of the sigma field. As it is manifested, the nucleon mass in the chiral limit will be zero when $\sigma_0 = 0$, i. e., in the case of chiral symmetry restoration.

In the parity doublet model [1], two nucleon fields transform in a mirror way under the chiral $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_\mathrm{R}$ transformations,

$$\begin{aligned} &\psi_{1R} \to \mathcal{R}\psi_{1R}, \quad \psi_{1L} \to \mathcal{L}\psi_{1L}, \\ &\psi_{2R} \to \mathcal{L}\psi_{2R}, \quad \psi_{2L} \to \mathcal{R}\psi_{2L}. \end{aligned} \tag{2}$$

Now, one can easily show that $m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$ is invariant under the chiral transformations; m_0 is called chiral invariant nucleon mass. Then, the nucleon part of the parity doublet model Lagrangian reads

$$\begin{aligned} \mathcal{L} = \bar{\psi}_1\, i\,\partial\!\!\!/\,\psi_1 + \bar{\psi}_2\, i\,\partial\!\!\!/\,\psi_2 + m_0(\bar{\psi}_2\,\gamma_5\,\psi_1 - \bar{\psi}_1\,\gamma_5\,\psi_2) \\ + a\,\bar{\psi}_1(\sigma + i\gamma_5\,\vec{\tau}\cdot\vec{\pi})\psi_1 + b\,\bar{\psi}_2(\sigma - i\gamma_5\,\vec{\tau}\cdot\vec{\pi})\psi_2. \end{aligned} \tag{3}$$

To obtain the mass of the nucleon $N(938)$ and its parity partner $N(1500)$, we diagonalize the kinetic and mass terms

$$m_{N\pm} = \frac{1}{2}\left(\sqrt{(a+b)^2\sigma_0^2 + 4m_0^2} \mp (a-b)\sigma_0\right). \tag{4}$$

Here, one can see that even if we assume the chiral symmetry restoration $\sigma_0 = 0$, the mass of the nucleon and its parity partner remains finite and degenerate as $m_{N\pm} = m_0$ to realize the chiral symmetry restoration. In Ref. [1] the value of the chiral invariant mass was determined as $m_0 = 270$ MeV from the decay width of $N^\star(1535) \to N + \pi$. The model is then extended by including vector mesons to study the nuclear matter [2], where $m_0 \sim 800$ MeV to account for (symmetric) nuclear matter incompressibility.

If $m_0 \sim 800$ MeV is true, then the role of spontaneous symmetry breaking characterized by the non-zero value of σ_0 is quite minor when it comes to the origin of the nucleon mass and the value is too different from the one determined in free space. To understand this discrepancy and to study asymmetric dense nuclear matter, we further extended the model by including an additional potential term of σ and by considering the hidden local symmetry [3].[1]

It was shown in Ref. [3] that the extended parity doublet model reasonably reproduces the properties of normal nuclear matter with the chiral invariant nucleon mass m_0 in the range from 500 to 900 MeV. It was also found that the first-order phase transition for the liquid-gas phase transition disappears in asymmetric matter and that the critical density for the chiral phase transition at nonzero density becomes smaller for larger asymmetry. The m_0 dependence of the slope parameter L was also investigated, where L is defined by

$$L = 3\rho_0 \left(\frac{\partial S}{\partial \rho} \right)_{\rho_0} . \tag{5}$$

Here ρ_0 denotes the saturation density and S is the nuclear symmetry energy. It was shown that the slope parameter is independent of m_0 [3].

2.1 Chiral invariant mass and nuclei

Since the nucleus is a quantum finite many-body system, physics in free space or in infinite nuclear matter can change in nuclei. For instance, the internal quark structure of a nucleon bound in nuclei differs from that of a free nucleon, see Ref. [4] for a recent review. It was observed in Ref. [5] that the confinement scale (or the intrinsic energy scale of QCD) might change from ~300 MeV in the free nucleon to ~100 MeV in a nucleus.

Now, we study the properties of nuclei in the extended parity doublet model with the relativistic Thomas–Fermi approximation to find any nuclear structure observables that are sensitive to the value of the chiral invariant mass [6]. As an example, we choose ^{40}Ca and focus on the spin-orbit interaction. The spin-orbit interaction $\alpha(r)$ is defined by

$$V_{SO}(r) = \frac{1}{2m_{N^+} r} \left(g_\omega \frac{d\omega_0}{dr} - \frac{dm_{N^+}}{dr} \right) \vec{s} \cdot \vec{L} \equiv \alpha(r)\, \vec{s} \cdot \vec{L}, \tag{6}$$

where ω_0 is the time component of the omega meson field. Referring to Ref. [6] for details, we here show a result which demonstrates m_0 dependence of the spin-orbit interaction. In Fig. 1 we plot the maximum value of the spin-orbit interaction α_{so}^{max} as a function of the chiral invariant mass with various values of the incompressibility K. Note that the empirical value of α_{so}^{max} is around 2 [7]. From Fig. 1 we can see that the spin-orbit interaction is sensitive to the value of the chiral invariant mass and prefers smaller m_0.

[1] Here, we briefly introduce the hidden local symmetry. In the non-linear sigma model, the basic building block to construct the Lagrangian is given in terms of $U = e^{2i\pi/f_\pi}$ and U transforms as $U \to \mathcal{L} U \mathcal{R}^\dagger$ under the chiral symmetry transformation. In the hidden local symmetry approach it is given by $U = \xi_L^\dagger \xi_R$, where $\xi_{L,R} = e^{i\sigma/f_\sigma} e^{\mp i\pi/f_\pi}$ and $\xi_{L,R}(x) \to h(x)\, \xi_{L,R}(x)\, (\mathcal{L}^\dagger, \mathcal{R}^\dagger)$. Here, $h(x)$ constitutes the hidden local symmetry. We can introduce vector mesons as gauge bosons associated with $h(x)$.

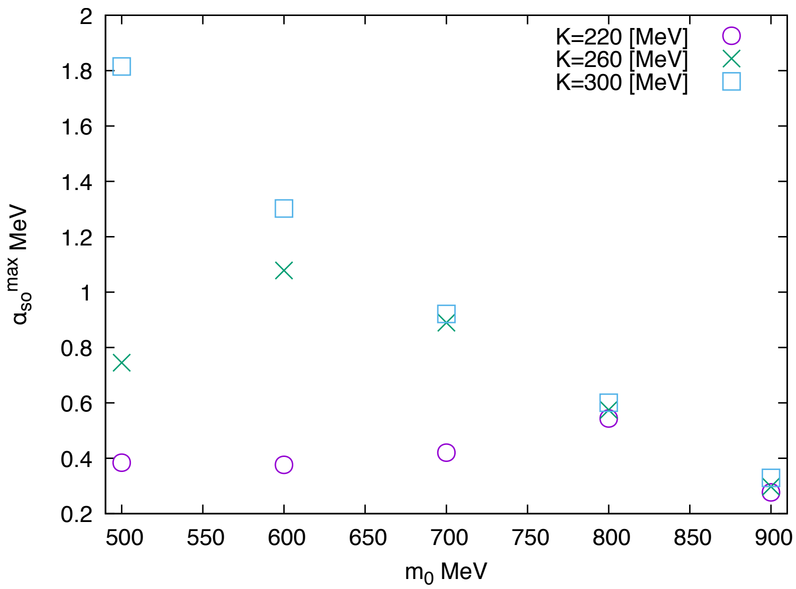

Figure 1: The maximum value of the spin-orbit interaction as a function of m_0 with various values of the incompressibility K.

3 Summary

Though it is out of questions that *ab initio* approaches in nuclear physics will reveal some aspects of the origin of nucleon mass in connection with rare isotopes, in this article we discussed how such a question can be addressed in nuclei based on the chiral effective approach of QCD. We first summarized two distinctive pictures on the origin of the nucleon mass in QCD effective approaches, the linear sigma model and the parity doublet model. We then introduced an extended parity doublet model and investigated possibility to tell the different pictures in nuclei. We found that the spin-orbit interaction is sensitive to the chiral invariant nucleon mass and can be used as litmus paper to study the origin of the nucleon mass in nuclei.

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