Path-integral hadronization for the nucleon and its interactions

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The central problem in nuclear physics remains to understand the origin and nature of the nuclear force. In spite of the belief that we have attained the fundamental theory for the strong interactions– Quantum chromodynamics (QCD), this theory still eludes a satisfactory and complete description. The basic problem of QCD is that its natural and fundamental degrees of freedom, quarks and gluons, are not the observable baryon and meson states of the strong interaction. Thus bridging the missing link between the fundamental and observable degrees of freedom stands as one of the stark challenges of nuclear/elementary particle physics today. Although we do have an *ab initio* approach to solve this problem, that is lattice QCD, this endeavor is still miles away from achieving such a goal. This naturally motivates us to resort to non-perturbative QCD-based approaches of which this study is one.

We address this lingering missing link by deriving a chiral meson-nucleon Lagrangian from a microscopic model of quarks and diquarks using path-integral methods [1]. Chiral symmetry and its spontaneous breaking have consistently proven to be key concepts in understanding meson and baryon structure and many features of the nuclear force. The gist of our work is as following: We start from a QCD-based effective field theory to describe quark dynamics where the gluons have been integrated out. This is the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ Nambu-Jona-Lasinio (NJL) model that accommodates most of QCD symmetries. Guided by general principles, we then assume that the nucleon can be described as quark-diquark correlations and introduce diquarks as elementary fields in the problem. This assumption hinges upon the dynamical fact that two quarks can combine to form a color anti-triplet leading with the third quark to the formation of a color-singlet bound state, a baryon. Moreover, this assertion is vindicated by a mounting experimental evidence that diquarks play a dynamical role in hadrons.

We verified that only two kinds of diquarks are relevant for nucleons: the scalar isoscalar and the axial-vector isovector. By introducing composite meson and nucleon fields through the method of path-integral hadronization and then using a loop and derivative expansion of the resulting quark/diquark determinants, we arrive at an effective chiral meson-nucleon Lagrangian. The path-integral hadronization used here consists of two steps: bosonization to produce mesons as quark-antiquark correlations and what we label as "fermionization" which generates baryons as quark-diquark correlations. In our model, mass, coupling constants, electromagnetic radii, anomalous magnetic moments, and form factors of the composite nucleon are calculated in terms of at most two free parameters.

In this fashion, our treatment parallels, in the sense of calculating nucleon physical observables, the approach of using the Faddeev equation for three quark states, or the approach of using static quark exchange, the Salpeter equation or the fully relativistic Bethe-Salpeter equation for a quark-diquark system. Nonetheless, our formalism yields, in addition to nucleon observables, a Lagrangian of the quantum hadrodynamics (QHD) type that describes the rich meson-nucleon interactions in a fully covariant and chirally symmetric formalism.

While this program is applied to the case of deriving an effective Lagrangian for nucleons and mesons, it is certainly of general nature and can possibly be applied alternatively to yield prolifically other baryons and their interactions such as the Δ particle.

As of today, we have managed to calculate an extensive set of nucleon observables for the first time on the basis of the path-integral hadronization approach [1]. Indeed, many of the nucleon physical properties such as mass, coupling constants, electromagnetic radii, anomalous magnetic moments, and form factors have been determined from a model of essentially one free parameter. By taking into account the intrinsic diquark form factor, we established a remarkable agreement with the experimental data for the nucleon size and the electric form factors, while our calculations show missing strengths for the magnetic form factors and the axial-vector coupling constant. The discrepancy is likely due to the absence of the axial-vector diquark in the present numerical study. Furthermore, the Ward-Takahashi identity and the Goldberger-Treiman relation were verified.

In summary, this work is an ambitious program of using path-integral techniques and QCD-based effective field theories to study baryon structure and to derive a full-fledged nuclear force. The final goal of the program is a derivation of an effective field theory for the nuclear force, namely, quantum hydrodynamics (QHD) from quark dynamics. As for the future, we plan to attain a numerical study using both the scalar and axial-vector diquarks including their intrinsic form factors . This is a challenging and rather difficult task due to the axial-vector diquark intricate structure as a particle of one unit spin and isospin. Some of the ensuing complications are the axial-vector diquark direct coupling to the weak interaction and the electroweak scalar-axial-vector transitions. At a later stage, we hope to generalize our approach to chiral SU(3) symmetry to study the structure of the baryon octet. More details concerning our treatment can be found in Ref. [1]

References

[1] L.J. Abu-Raddad, A. Hosaka, D. Ebert, and H. Toki, Phys. Rev. C **(66)** (2002) 025206.