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From nuclear structure to nucleon structure

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Abstract

Similarities between nuclear structure study with many-body theory approach and nucleon structure calculations with lattice QCD are pointed out. We will give an example of how to obtain the connected sea partons from a combination of the experimental data, a global fit of parton distribution functions and a lattice calculation. We also present a complete calculation of the quark and glue decomposition of the proton momentum and angular momentum in the quenched approximation. It is found that the quark orbital angular momentum constitutes about 50% of the proton spin.

Keywords: Nuclear structure; Nucleon structure; Quantum chromodynamics; Quark and glue momentum and angular momentum

1. In memoriam

This manuscript is dedicated to the memory of Gerald E. Brown who was my Ph.D. thesis advisor, a mentor in my professional career and a lifelong friend.

I first met Gerry in the Fall of 1972 when I was a graduate student in Stony Brook. He just returned from NORDITA. He summoned me to his office one day and asked me if I could do some calculation for him. The problem is calculating the spectrum of two nucleons in the orbital j with a delta function interaction. The next day, I went to show him my results. He had a look and said “The gap between the 0^+ and 2^+ states is a factor of 2 of that between 2^+ and 4^+. OK, you can work for me now.” I did not know it was a test to help him decide whether he wanted to take me on as his research assistant.

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Gerry is well known for many insightful quotations about physics. Let me relate one which is attributed to him and it may not have been recorded in a written form before. During the opening talk at one Few Body Conference, Gerry was quoted to have said "In classical physics, you cannot solve three-body problem. With quantum mechanics, you cannot solve two-body problem and with relativistic quantum mechanics, you cannot solve one-body problem. In quantum field theory, you don't know how to solve the vacuum." Following Gerry's logic, we can now append his quote by "With the advent of string theory, you no longer know where the vacuum is."

I have learned many-body theory and Landau's Fermi-liquid theory under Gerry and my Ph.D. thesis was on a self-consistent RPA calculation of nuclear giant resonances on Hartree–Fock ground states. In the later years, I have followed Gerry to work on chiral soliton model of the nucleon, particularly the skyrmion. The many intriguing properties of the nucleon both theoretically and experimentally have led me to work on lattice quantum chromodynamics (QCD) calculation since the late eighties.

From 1995 to 2009, we have been meeting in Caltech every January as part of a contingent of theory guests, courtesy of Bob KcKeown and Brad Fillipone of the Kellogg Lab. During these visits, Gerry would explain to me his work in black holes and heavy ion collisions and I would update him on the progress in lattice QCD. Over the years, I would like to think that I have inherited part of his extraordinary enthusiasm and love for physics through osmosis and I have been influenced greatly by his way of dissecting and tackling a complex problem through intuition, backed by estimation.

It is natural to extend the study from nuclear structure to nucleon structure, especially when there is an excellent tool in lattice QCD. I am indebted to Gerry for introducing me to the fascinating world of nuclear and nucleon structures. I would like take this opportunity to thank him for his encouragement and support over the years.

2. Introduction

Historically, the study of nuclear structure started out from models like the liquid-drop model, the collective models and the shell model. The modern approaches include many-body theory, Green's function Monte Carlo and lattice effective theory calculation. Similarly, the study of nucleon structure progressed from quark model, MIT bag model, chiral soliton model, QCD sum rules, instanton liquid model to the more recent lattice QCD calculation. The latter is an *ab initio* Euclidean path-integral calculation of QCD with controllable statistical and systematic errors. I will make a comparison between the many-body theory approach to nuclear structure and the lattice QCD approach to nucleon structure. I will draw some parallels of the two approaches and point out some differences.

Many-body theory is a non-relativistic quantum field theory, while QCD is a relativistic quantum field theory. As such, concepts like valence and sea degrees of freedom, collective phenomenon, and vacuum polarization are common, albeit in different contexts. In the case of nucleus, the first order of approximation is the mean-field description of the ground state of Fermi sea, such as the shell model or the Hartree–Fock approximation as depicted in Fig. 1a and the nucleon quasi-particle and -hole states around the Fermi sea interact via an effective interaction. This is analogous to the quenched approximation of lattice QCD where the partition function is approximated by the gauge action only without the fermion determinant as depicted in Fig. 1b. Nucleon properties are calculated with the multi-point correlation functions with the 3-quark interpolation field for the source and sink of the nucleon at distant time slices in the pure gauge background.