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Implications of the nuclear EMC effect

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Abstract. The discovery more than twenty years ago, by the EMC Collaboration, that the deep-inelastic-scattering DIS structure functions are influenced by the nuclear environment stunned the nuclear physics community and brought quarks and gluons into the field with great impact. A great length of time has passed, but despite a semi-infinite number of papers on the subject, there is no explanation that is universally accepted. Many models (related in one way or another to QCD) have been successful in reproducing data for deep inelastic scattering on nuclear targets, but fewer have described both the DIS and nuclear Drell-Yan experiments. Although there are some positive indications, no model has been used to predict correctly and unambiguously new independent phenomena. We review the history and discuss the best experimental prospects for future discovery.

PACS. 12.39.-x Phenomenological quark models – 21.30.Fe Forces in hadronic systems and effective interactions – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.30.Mr Muon scattering (including the EMC effect)

1 Introduction

I begin by discussing the nuclear EMC effect and the related Drell-Yan (DY) reaction with the aim of defining these terms and showing that Conventional nuclear dynamics using only hadronic physics fails. This means that the structure of a nucleon is modified when it is placed inside nucleus. I will discuss three popular models of this modification may occur and the resulting implications for new experiments. Then I will close by discussing a favorite topic–the shape of the nucleon.

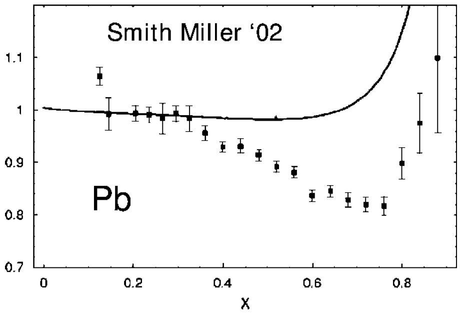

Fig. 1. EMC effect.

2 Nuclear EMC effect and related Drell-Yan process

The European Muon Collaboration (EMC) effect in which the structure function of a nucleus, measured in deep inelastic scattering at values of Bjorken $x \geq 0.4$ corresponding to the valence quark regime, was found to be reduced compared with that of a free nucleon was discovered almost twenty years ago [1]. Figure 1 shows the SLAC E139 data [1] for the ratio of the nuclear (per nucleon) to free nucleon structure function. This, contary to the expectations of many, is not unity. Despite much experimental and theoretical progress [2,3], no unique and universally accepted explanation of the depletion has emerged. The immediate parton model interpretation that the nucleon bound in a nucleus carries less momentum than in free space seems uncontested, but determining the underlying origin remains an elusive goal. I intend to discuss some extant explanations, but will not discuss the issue of A-dependence. This is because Chen and Detmold [4] used the reasonable assumption that the EMC effect is dominated by two-nucleon effect to show in a model-independent manner that the A- and x-dependence factorizes. Thus, understanding the EMC effect for one heavy nucleus is a great start to understanding the entire effect.

The publication of the EMC data and the SLAC data led to the origination of a great number models that could account for the data. This caused me to write in 1985 that "EMC means Everyone's Model is Cool".

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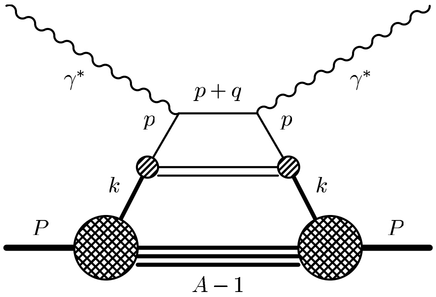

Fig. 2. Deep-inelastic-scattering diagram.

2.1 Nucleons only

It is important to rule out the possibility that the simple kinematic effects of binding energy and Fermi motion do not account for the EMC effect. If one starts with the assumption that the structure function is not modified and is the same on and off the energy shell (nucleon-only hypothesis) then evaluation of the diagram of fig. 2 leads to the simple formula

$$\frac{F_{2A}(x_A)}{A} = \int_{x_A}^{A} \mathrm{d}y f_N(y) F_{2N}(x_A/y), \qquad (1)$$

where P is the total four momentum of the nucleus, and

$$x_A \equiv Q^2 A/2P\cdot q = xAM/M_A\,, \qquad (2)$$

with M as the free nucleon mass. The variable $y = Ap^+/P^+$ is the fraction of the nuclear momentum (per nucleon) carried by a single nucleon, and $f_N(y)$ is the corresponding probability distribution. The formula (1) and simple reasoning leads to the result that the nucleon-only hypothesis does not explain the EMC effect. Under the Hugenholz van Hove theorem nuclear stability (pressure balance) implies (in the rest frame) the $P^P = P^- = M_A$. But to an excellent approximation $P^+ = A(M_N - 8\,\mathrm{MeV})$. Thus an average nucleon has $p^+ = M_N - 8\,\mathrm{MeV}$. The function $f_N(y)$ is narrowly peaked because the Fermi momentum is much smaller than the nucleon mass. This means that the value of y in the integral of (1) is contrained to be very near unity. Thus F_{2A}/A is well approximated by F_{2N} and one gets no EMC effect this way [5,6]. This is shown as the solid curve in fig. 1.

2.2 Nucleons and pions

The next thing to try is to assert that the nuclear pion cloud is enhanced, and that pions carry an excess of plus-momentum. In this case, $P^+ = P^+_N + P^+_\pi = M_A$. Many authors [2,3] found that using $P^+_\pi/M_A = 0.04$ is sufficient to account for the EMC effect. However, an excess of nuclear pions implies that the nuclear sea is enhanced and that enhancement should be observable in a nuclear Drell-Yan experiment [7]. The idea, see fig. 3, is that a quark from an incident proton (defined by large value of x_1) annihilates an anti-quark from the target nucleus defined by a smaller value of x_2. A significant enhancement of pions would enhance the anti-quarks and enhance the nuclear Drell-Yan reaction. But no such enhancement was observed [8] as shown in fig. 4. This caused Bertsch *et al.* [9] to announce "a crisis in nuclear theory", because conventional theory does not work.

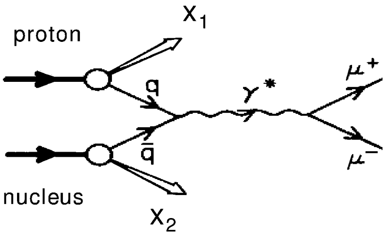

Fig. 3. DY effect.

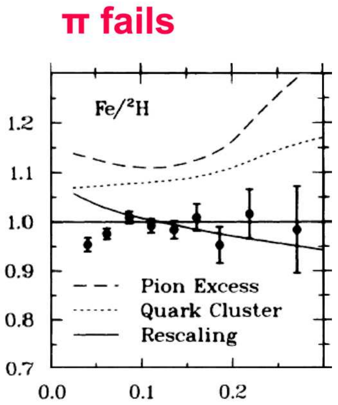

Fig. 4. DY data [8] and theory [7].

3 Nucleon modification by nuclei

We now consider the modification of the structure of a single nucleon caused by its presence in the nuclear medium. The root cause of any such modification is the interaction between nucleons, so that one needs to consider whether or not the entire concept of single-nucleon modification makes any sense at all. Our belief is that if the kinematics of a given experiment selects single-nucleon properties, such as in quasi-elastic scattering, it does make sense to consider how a single nucleon is modified.

Actually, there is a well-known example of the nuclear modification of nucleon properties. It is an experimental fact that a single bound neutron is different than a free one. In particular, the lifetime is changed from about fifteen minutes to forever. This is because binding effects modify the propagator (energy denominator) that relates the $|pe^-\nu\rangle$ component of the neutron to its dominant $|n\rangle$ one. The increase in the energy denominator suppresses the component induced by the weak interaction. Changing the energy denominator changes the wave function.

Here we shall be mainly concerned with changes in a nucleon wave function induced by external strong fields supplied by other nucleons. These strong fields polarize nucleons and are an analog of the Stark effect in which an electric field induces a dipole moment of an atom. In nuclei

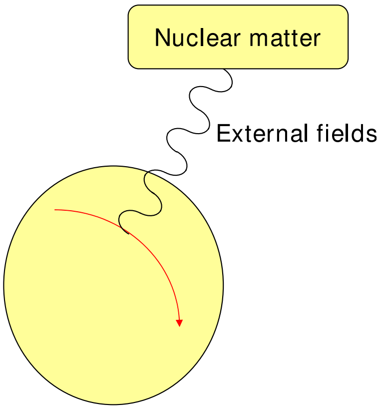

Fig. 5. Nuclear modification of nucleon properties through external fields.

there is no preferred spatial direction so we are examing phenomena related to monopole polarization.

3.1 Requirements and goals

Models aimed at explaining the EMC effect and Drell Yan experiment are subject to meeting a severe set of requirements. One needs to be able to model the free distributions for both the valence and sea quark components, satisfying the problem of maintaining good support. That is many models do not handle the requirements of momentum conservation exactly and using them can lead to obtaining structure functions that do not vanish for Bjorken x values greater than unity or less than zero. One must model the nuclear modifications in a manner that is consistent with known nuclear properties, and be able to describe the deep inelastic and di-muon production data. Finally, given all of this, one needs to predict new independent phenomena.

3.2 Three models

I discuss a set of three models, each built upon the common theme that in nuclei the quark wave functions of a single nucleon are modified by external fields provided by the surrounding nucleons, fig. 5.

In the quark meson coupling model [10] quarks in nucleons confined in an MIT bag exchange scalar and vector mesons with the nuclear medium. Later work [11] replaces the MIT bag with the NJL model. One may also immerse the chiral quark soliton model nucleon [12] in the medium [13]. In this case, the quarks exchange infinite pairs of pions as well as vector mesons with the surroundings. In both of these models the attraction needed to produce a bound state is generated by the exchange of scalar quantum numbers and the repulsion necessary to obtain nuclear saturation is caused by exchange of vector mesons. A third model involves the suppression of point-like configurations of the nucleon [14,15].

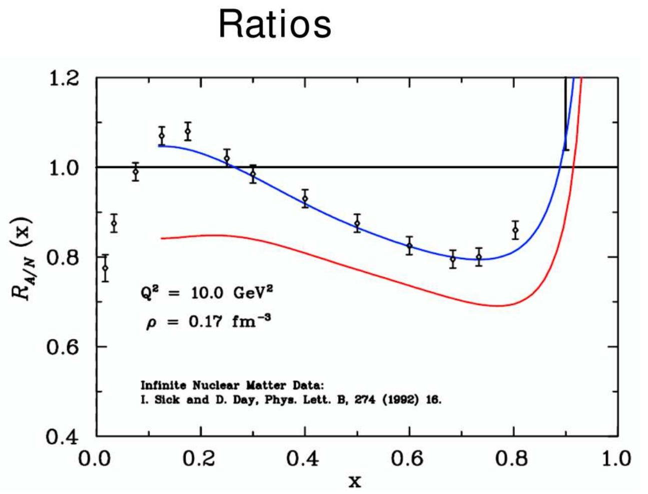

Fig. 6. (Color online) Ratio of spin-independent (blue and near data) and spin-dependent g_1 structure function (red). (I thank I. Cloet for this figure.)

3.2.1 QMC

The specific dynamical mechanism of interest is that the external scalar field enhances the lower component of the quark's Dirac wave function. This effect is exploited in a variety of interesting applications. The nuclear enhancement of the spin structure function [11] is of particular interest and is shown as fig. 6. The EMC effect of spin-dependent structure functions is significantly larger than that for the usual F_2 structure function.

3.2.2 CQSM

This model is based on the instanton-dominated nature of the vacuum [16]. The coupling of quarks couple to vacuum instantons generates spontaneously a constituent-quark mass of about 400 MeV. These quarks interact with pions through the effective Lagrangian The CQSM model Lagrangian with (anti)quark fields $\overline{\psi}, \psi$, and profile function $\Theta(r)$ representing the pion field is given by

$$\mathcal{L} = \overline{\psi}(i\partial\!\!\!/ - M e^{i\gamma_5 \boldsymbol{n}\cdot\boldsymbol{\tau}\Theta(r)})\psi, \qquad (3)$$

where $\Theta(r \to \infty) = 0$ and $\Theta(0) = -\pi$ to produce a soliton with unit winding number. The nucleon is made of three such quarks. This model is known to reproduce good nucleon properties, as well as reasonable structure functions with excellent support properties [12]. One special feature worth noting is that this model nucleon contains an intrinsic sea (at a low momentum transfer scale) generated by the modification of the infinite Dirac sea by the quark interactions with the pionic field.

This model is applied to nuclear physics [13] by allowing collections of such nucleons to exchange scalar and vector mesons as cartooned in fig. 7. Obtaining the wave function for infinite nuclear matter involves solving a double self-consistency relation. The mass and internal wave

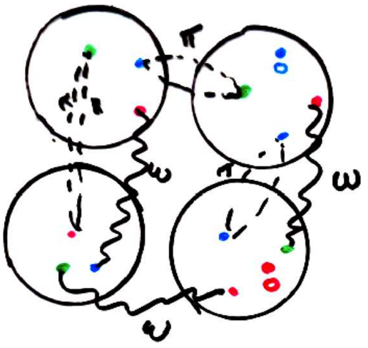

Fig. 7. Schematic display of the model [13]. The exchange of pairs of pions and of omega mesons leads to saturation of infinite nuclear matter.

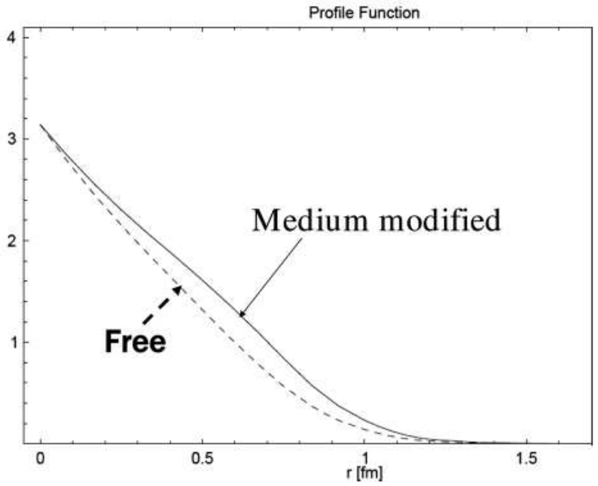

Fig. 8. Nuclear modification of the profile function.

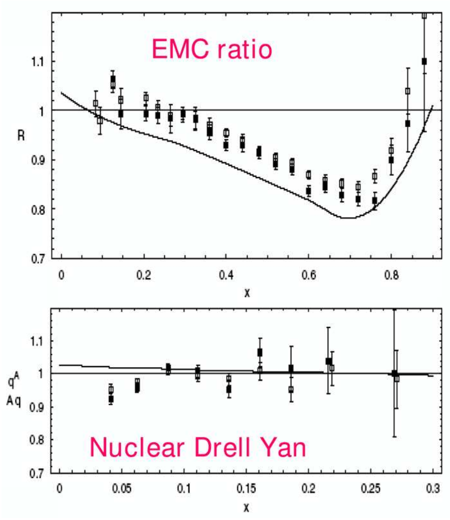

Fig. 9. Nuclear ratios of deep inelastic and Drell-Yan scattering. Nuclear matter data from Day and Sick. Drell-Yan data from [8].

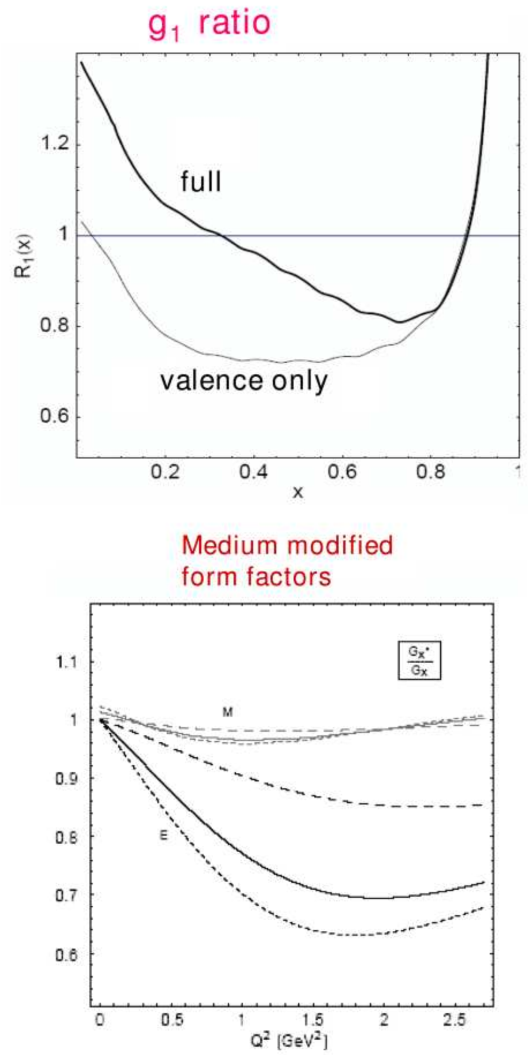

Fig. 10. Top panel: ratio of nuclear to nucleon spin-dependent g_1 structure function. The heavy curve is full calculation, the light curve is valence only. Bottom panel: medium modified electric (isoscalar) and magnetic (isovector) form factors. The three different sets of curves represent the effect of using three different nuclear densities.

function of a bound nucleon depends on the Fermi momentum. For a given set of parameters (the strength of the ωN coupling and the magnitude of the quark condensate) one minimizes the energy of the nucleus (per nucleon). We obtain excellent saturation properties. The resulting change in the profile function shown in fig. 8 is vey small, but corresponds to a slight broadening if the effective potential that binds the quarks in the nucleon. The use of the medium modified wave function to compute structure functions leads to the results shown in fig. 9. We are able to account for the EMC effect, and produce results that are in agreement with the Drell-Yan data. This indicates that the sea is not very much modified, and this can be seen by looking at the details of the results.

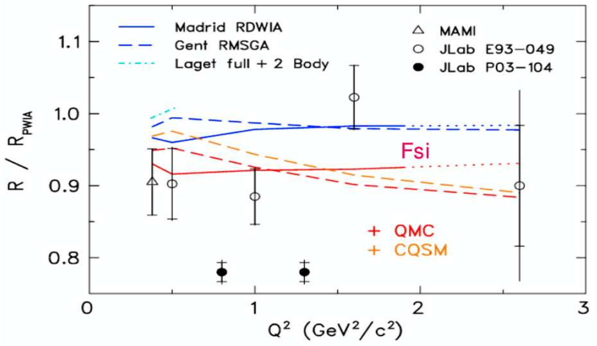

Fig. 11. Medium to free ratio of ratios G_E/G_M. Data for various measurements are compared with various theories. (I thank S. Strauch for preparing this figure.)

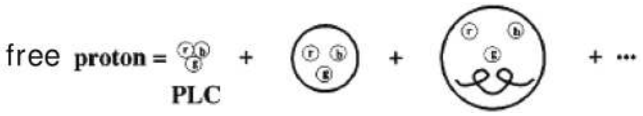

Fig. 12. Configurations of the nucleon.

The interesting extension is to the computation of other observables. The medium modified structure function is displayed in fig. 10. If one includes the effects of the valence quark only, the results are similar to those of Cloet *et al.*, but the full calculation including the effects of the sea quarks shows that the nuclear modification of g_1 is rather similar to the nuclear modification of F_2 of the usual EMC effect. This arises because the nucleon sea is not modified much. The modification of the nucleon electromagnetic form factors is shown as the bottom panel of fig. 10. The electric form factor is modified much more than the magnetic one. This effect can be studied using polarization transfer in the $^4\mathrm{He}(e,e'p)$ reactions [17]. These have the potential to measure the ratio of free to medium modified ratios of the ratio G_E/G_M. Some results are shown in fig. 11. Three calculuations that do include medium modifications line generally above the data. Both the QMC and CQSM calculations are closer to the data. The effects of a newer calculation [18] can reproduce the trend of the data without medium modifications. But the combination of medium modifications and this new final state interaction calculation would also agree with the data, within the large error bars. The crucial charge-exchange part of the final-state interaction used by [18] has not been constrained by data. This is a very exciting subject that needs to be pursued with further, more accurate experiments.

3.2.3 Supression of point-like configurations

The nucleon comes in a variety of configurations, which can be defined by the quark-gluon content of each Fock state component. See fig. 12. Suppose such a system is placed in the medium. Those of normal size feel the nuclear attraction and their energy goes down. The point-like-configurations PLC of very small size are prevented from feeling the attraction by the effects of color screening. The energy difference between the configurations of normal size and the PLCs increases. Then quantum mechanics tells us that the magnitude of the PLC is reduced and the PLC is suppressed. One consequence is that quarks in the medium have reduced momentum, in agreement with the EMC effect.

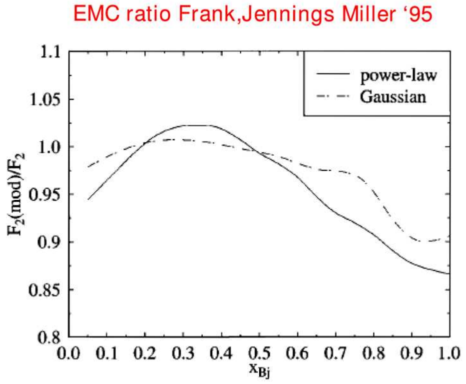

Fig. 13. EMC ratio due to PLC suppression. Only the curve labelled "power law" has meaning.

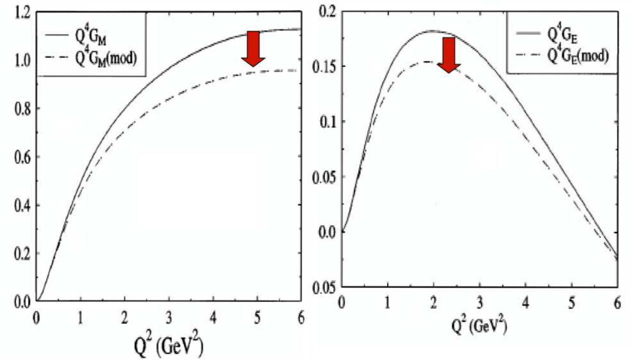

Fig. 14. Medium modifications of electric and magnetic form factors.

To make calculations, one needs a free nucleon wave function. Ours is of the relativistic constituent quark model. It is a three-quark antisymmetric wave function, that is frame independent and an eigenstate of the spin operator [19,15,20]. The wave function includes a product of three quark Dirac spinors, each evaluated at a relative momentum.

One places this wave function in the medium subject to a mean field that vanishes for configurations in which the three quarks are close together [15]. The resulting medium modifications of the structure function are shown in fig. 13. This calculation is made for a nucleon at rest, so there is no rise at large x. However, the suppression of the valence quark momentum distribution is seen.

The same model predicts medium modifications of the nucleon form factor as shown in fig. 14. The important modifications shown by the red arrow occur at larger values of momentum transfer than currently accessible experimentally. The result here show a more spectacular effect than medium modifications. The famous decrease in the

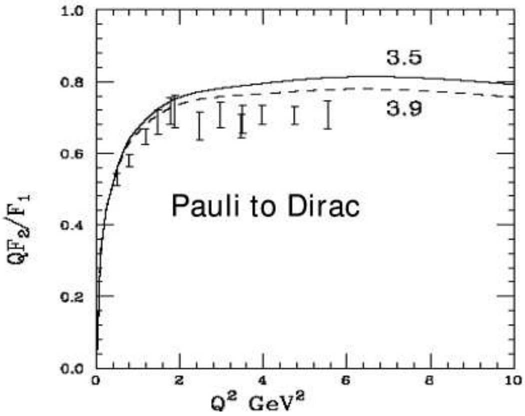

Fig. 15. QF_2/F_1, data from [21]. Theory from [20].

ratio G_E/G_M with increasing values of Q^2 was our prediction in 1995 [15]. Another view the interesting nature of the proton electromagnetic form factor is to plot the ratio QF_2/F_1 where F_2 is the Pauli form factor and F_1 is the Dirac form factor, fig. 15. In our calculation this turns out to be roughly a constant for values of Q^2 between 2 and 20 GeV^2 [20]. There is a simple explanation in terms of the lower component of the quark Dirac spinor [20]. Quarks within the proton move relativistically.

4 Shapes of the nucleon

At one point I was asked to discuss the implications of the new Jlab data for the shape of the nucleon. Relativistically moving objects have a pancake shape when viewed from a frame at rest. This is not related to the intrinsic nature of the wave function. I defined the spin-dependent density [22] to probe the relativistic nature of the quark motion within the nucleon and to reveal the shape of the nucleon. One can compute the spin-dependent density which is the probability that a quark has a given momentum **K** and spin in a direction **n**. This operator is given by the expression

$$\widehat{\rho}(\mathbf{K},\mathbf{n}) = \int \frac{\mathrm{d}^3 r}{(2\pi)^3} e^{i\mathbf{K}\cdot\mathbf{r}} \bar{\psi}(\mathbf{r}) \frac{\widehat{Q}}{e} \left(\gamma^0 + \boldsymbol{\gamma}\cdot\mathbf{n}\gamma_5\right) \psi(0). \quad (4)$$

Taking matrix elements of this operator using model nucleon wave functions reveals that sometimes the proton is shaped like a bagel and sometimes like a pretzel [22]. See fig. 16. It now also seems possible to go beyond model calculations and use the lattice to determine whether or not the proton is always spherical. It is amusing to make a final speculation. We have found that lower components account for the flatness of the ratio QF_2/F_1 and also for the non-spherical shapes of the proton. We also known, through the EMC effect that effects of the medium modify the nucleon wave function. If the medium modifies the lower components, we might then expect that the medim will also modify the shape. A possible result is shown in fig. 17. At present, it remains a challenge to experiment to measure either shape.

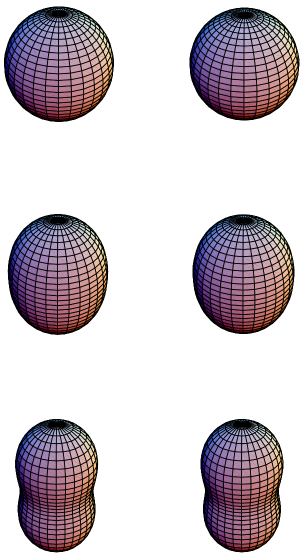

Fig. 16. Shapes of the matter distribution (eq. (4)) without the charge operator. First row: $K = 250\,\mathrm{MeV}/c$, second row: $K = 1\,\mathrm{GeV}$, third row: $K \to \infty$. Left column: **n** parallel to the proton angular momentum, right column: anti-parallel.

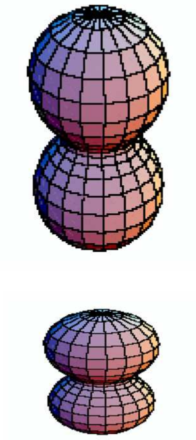

Fig. 17. Shapes of the charge distribution. Top: extreme shape of a rare configuration, bottom: possible medium modification of the same shape.

5 Summary

The predominance of the experimental evidence points to the conclusion that the structure of a nucleon is modified by immersing it in a nucleus. At the moment the use of models is the only way to address this physics. There are a set of minimum requirements for any model. The model should account for or be consistent with nuclear saturation as well as explaining the existing EMC and DY data. After this is achieved, the model should predict independent new phenomena. At the moment, the best hopes for measuring such phenomena lies with measurements of how the electromagnetic form factor is modified by the presence of the medium and in using spectator nucleon tagging in $eA \to e'XN$ experiments. Other possibilities involve trying to constrain the nuclear gluon distribution and measurements of how the nucleus might modify the Callan-Gross relation. There are a variety of possibilities for how new experiments, performed at Jefferson Laboratory, might reveal how quarks work inside the nucleus.

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