Neutrinos and non-perturbative nucleon structure

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There are many vital questions concerning the non-perturbative structure of the nucleon for which neutrinos are uniquely suited to give answers. We outline some of the essential issues in hadronic physics which can and should be addressed with high intensity neutrino beams.

1. INTRODUCTION

We concentrate on the most significant open questions concerning nucleon structure and the way non-perturbative QCD works. We begin with the axial form factors of the nucleon, that is the elastic form factor and the many possible inelastic transition form factors. A comparison between these and the corresponding electromagnetic form factors promises to be particularly revealing. Then we turn to some of the outstanding questions that can be probed in the deep-inelastic regime, including the flavor and spin-flavor asymmetries and what these might teach us.

2. AXIAL FORM FACTORS

Chiral symmetry plays an extremely important role in modern hadron physics – from low energy meson production to hadron form factors and the extrapolation of lattice data to the physical quark mass [1]. Through PCAC the axial form factor of the nucleon plays a special role – it is the most natural guide to the way the pion couples to a nucleon [2]. Through a series of bubble chamber experiments in the 70's and 80's (e.g. Ref. [3]) the charged current (CC) axial form factor of the nucleon appears to be reasonably well known. It seems to be well represented by a dipole with mass parameter $M_A = 1.03 \pm 0.04$ GeV [1]. However, it is clear that the statistical errors on the data are such that the sensitivity to deviations from a dipole was not great. It is unacceptable that such a fundamental property of the nucleon is not better determined.

From the point of view of building quark models of the nucleon, the axial form factor also has a special role. G-parity forbids any contribution from the pion cloud itself (unless there is some discontinuity [2,4], so in terms of a chiral quark model (such as the cloudy bag, CBM [5,6]) this form factor directly probes the quark core of the nucleon. For example, the measured axial charge radius (obtained from m_A above) corresponds to a bag radius around 1.1 fm in the MIT bag (or CBM) – where $r_A \sim 0.62R$ [2]. This interpretation is even more suggestive when it comes to the $N \to \Delta$ transition form factor. Certainly the experimental situation there is much worse than for the elastic form factor, but the best indication is that in the $N \to \Delta$ case the form factor is *much* harder [3] – typically $m_A \sim 1.3$ GeV, but with an error of 10–20%.

Although the comparison between the axial elastic and $N \to \Delta$ transition form factors is important, even more important is the comparison with the electromagnetic (M1) transition form factor. There, of course, the pion cloud does have a significant role and indeed the best dipole mass parameter for the M1 amplitude is much *smaller* than that for the elastic magnetic form factor [7] (which has a dipole mass parameter around 0.84 GeV). That is, there is almost a factor of two difference between the radius of the M1 and axial $N \to \Delta$ transition form factors! This is a fundamental difference which must be addressed by any serious model of baryon structure.

Of course, the $N \to \Delta$ transition is just the beginning. Very precise new experiments at Mainz and JLab are yielding extremely accurate information on the transition form factors for a large number of baryon resonances [8]. If this data is really to be exploited for the maximum physics content, it would be extremely helpful to have information of similar quality from neutrino experiments on the corresponding axial transition form factors. This must be a high priority for any future accelerator producing high intensity neutrino beams.

2.1. Axial form factor in medium

A great deal of effort is currently being devoted at CERN, RHIC and elsewhere to exploring the transitions between hadronic and quark and gluon phases of matter. Equally important from the point of view of any coherent approach to this problem is to map out the precursors to these phase transitions. In particular, from the point of view of QCD, it is not natural to view an atomic nucleus as built of free nucleons [9]. Rather, if one begins with some form of Born-Oppenheimer approximation, it is far more natural to see the shell model orbitals filled by quasi-particles with nucleon quantum numbers, but whose internal structure has self-consistently adjusted to the local mean scalar and vector mean-fields – the quark-meson coupling model was constructed to explore precisely this point [10,11]. In order to explore the precursors to deconfinement it then becomes crucial to map out the changes in the properties of bound "nucleons".

Although such precursor signals have proven elusive, recent experimental advances at Mainz and Jlab have led to a rather exciting hint of a deviation of the ratio G_E/G_M for a nucleon bound in ^{4}He from the free ratio [12,13]. Indeed the experimental findings, over a range of momenta up to more than 2 GeV^2, seem to be in quite good agreement with predictions from the quark meson coupling model made several years before the experiments [14]. Furthermore, the theoretical analysis of the *ratio* of polarization observables is quite insensitive to effects of distortion, exchange current corrections, and so on [12,15].

Obviously this phenomenon will be explored in much greater detail for additional nuclei and other momentum transfers over the next few years. However, it is clear that this discovery immediately suggests that one might look for similar in-medium changes in other hadron form factors, such as the axial form factor. With this in mind, Lu *et al.* recently explored the density dependence of $G_A(Q^2)$ within the same model that seems to describe the density dependence of G_E/G_M [16]. Figure 1 shows the resulting change

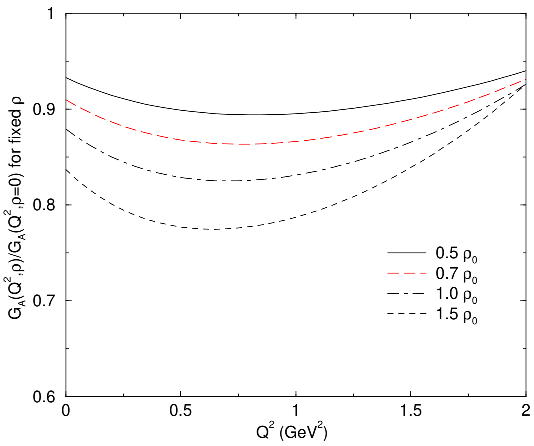

Figure 1. The nucleon axial form factor at different densities with $R_0 = 0.95$fm – from Ref. [16]. The effect of medium modification, which is more important in the small momentum transfer region, grows as the baryon density increases.

of shape of the axial form factor as the baryon density grows. Once again the verification of such a change, along with the corresponding change in the electromagnetic form factors, would be extremely valuable for our understanding of nuclear matter and its changes of phase.

3. SPIN AND FLAVOR DEPENDENCE OF PARTON DISTRIBUTION FUNCTIONS

The best known ambiguity in the unpolarised valence distribution is the asymptotic d/u ratio. For several decades this was believed to be proportional to $(1-x)$ [17]. Indeed, in spite of the fact that this behaviour is in disagreement with the expectation based perturbative QCD (pQCD) [18] that the ratio d/u should tend to $1/5$ as $x \to 1$, it is built into most standard parton distribution functions (PDF's). However, a careful relativistic treatment of binding, Fermi motion and off-shell corrections in the deuteron by Melnitchouk and Thomas in 1996 [19] suggested that the SLAC data [20] was in fact consistent with the pQCD expectation. A similar conclusion has been reached by others (e.g. Ref. [21]), but one would really like a demonstrably model independent proof for such a fundamental property of the nucleon.

One exciting possibility, which can be carried out after the Jefferson Lab 12 GeV upgrade, is to use the charge symmetry of the ^{3}H-^{3}He system to extract F_{2n}/F_{2p} and hence d/u up to $x \sim 0.85$ [22]. However, a direct measurement of the ratio of ν to $\bar{\nu}$ deep inelastic scattering at large-x on hydrogen would yield a totally unambiguous ratio. In combination with the JLab measurement in the very large-x region, this could yield quantitative information on possible new physics, such as six-quark configurations in the A=3 system.

3.1. Light sea

In an extremely important series of experiments at CERN, HERA and Fermilab [23–25], it has been clearly established that there is an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton. This was actually anticipated on the basis of chiral symmetry almost a decade before the NMC experiment [26], but only recently has the unambiguous role of chiral symmetry, in terms of a leading non-analytic (LNA) contribution to $\bar{d}-\bar{u} \sim m_\pi^2 \ln m_\pi$, been established [27]. Such behaviour cannot be cancelled by any other mechanism, unless by chance at one particular quark mass. This realization has led to important advances in connecting moments of PDF's calculated in lattice QCD to data [28,29].

On the other hand, there has been an alternative suggestion concerning the non-perturbative origins of $\bar{d}-\bar{u}$ for more than a decade [30]. Actually this explanation has its roots in the Pauli correction of Field and Feynman [31], but the modern view is far deeper. To illustrate the concept we briefly review the recent work on related problem in 1+1 dimensions by Tsushima *et al.* [32].

The problem of fermions moving in scalar and vector potentials in 1+1 dimensions has been widely studied since the work of Jackiw and Rebbi [33]. In particular, one has the fascinating possibility of fermions with fractional charge. Our concern is with a fermion moving in a purely scalar potential. In 1+1 dimensions one can explicitly examine the vacuum structure, which differs from the vacuum in the absence of the scalar potential. In particular, in terms of free fermion states, some of the higher states in the Dirac sea of the scalar potential will be unoccupied, while an equal number of positive energy states will be occupied. In the context of deep inelastic scattering, the process of normal ordering amounts to the statement that a deep inelastic probe will see the difference between the structure of the target and the free vacuum. Thus the change in the sea, even in the absence of valence quarks (of course, that would not be stable by itself but this is a thought experiment), amounts to the statement that the empty scalar potential looks like a sea of $q-\bar{q}$ pairs to an incident probe. Of course, this intrinsic sea carries no net spin or flavor.

On the other hand, if one considers a valence quark bound in this scalar potential, one needs a complete set of free positive *and* negative energy fermion levels to fully describe its wave function (unless the system is totally non-relativistic). A consequence of adding a valence quark to the interacting vacuum described above is that it will not only fill some positive energy free states but some of the vacant negative energy levels. Of course, the valence normalisation from the positive energy states alone is not complete. How do we interpret this? It is simple: the addition of the valence quark removes some of the intrinsic antiquark sea (of the same flavor), the corresponding sea quarks then make up the missing valence normalisation. The result is a system with a valence quark and some of the intrinsic sea, of the same flavor, suppressed.

If we take this result over to 3+1 and the proton, it is obvious that because we add two valence u-quarks and only one valence d, the intrinsic sea will now contain an excess of $d-\bar{d}$ pairs. It has so far proven difficult to make a quantitative estimate of the effect in models like the bag, but indications in the original work [30] suggested that the integral of $\bar{d}-\bar{u}$ should be between 0.05 and 0.20 – certainly the right order of magnitude. This leaves us with two mechanisms for the experimental observation and it is clearly very important for our understanding of hadron structure to determine how much should be attributed to each one.

The key to this separation is that the clear link between the reduction of the sea and the quantum numbers of the valence quarks provides a signature of the origin of the effect. Using an SU(6) wave function for a polarised proton, one finds that the valence u-quarks have predominantly positive polarisation, whereas the valence d's are only slightly, but negatively polarised. Hence one expects that the intrinsic sea produced by the Pauli effect should have $\Delta\bar{u}$ positive and a little larger (by a factor 5/3 - 1/3, for exact SU(6) symmetry) than the Pauli contribution to $\bar{d}-\bar{u}$, whereas $\Delta\bar{d}$ should be very small in magnitude (1/3 of the Pauli contribution to $\bar{d}-\bar{u}$, for exact SU(6) symmetry) and negative. In comparison, the sea produced by chiral symmetry is unpolarised. Thus a determination of $\Delta\bar{u}$ and $\Delta\bar{d}$, together with the existing information on $\bar{d}-\bar{u}$, should allow us to unambiguously understand the origins of the non-perturbative, light-quark sea of the nucleon. High intensity neutino beams with a polarised hydrogen target (certainly an ambitious experiment) provide a wonderful way to resolve this problem.

3.2. Strange sea

Because the strange quark is much heavier, the Pauli effect discussed above for $\Delta\bar{q}$ should be relatively small. On the other hand, considerations of chiral SU(3) show that there is an unambiguous difference between the shape of $s(x)$ and $\bar{s}(x)$ [27]. This was first pointed out by Signal and Thomas [34] and later by Brodsky and Ma [35] (although the s-wave $\bar{K}N$ coupling used there needs revision). Prompted by improvements in the determination of the strange quark PDF's in recent neutrino experiments [36], as well as the determination of the strangeness form factors of the nucleon, there has also been quite a bit of theoretical activity on the problem of $s(x)-\bar{s}(x)$ recently [37–39].

For the present, it is probably fair to say that there is no convincing experimental evidence for such an asymmetry. Nevertheless, it must be there at some level and it is again a crucial property of the nucleon that really ought to be pinned down. It is the archetype upon which we can begin to build an understanding of the role of heavier quarks in light hadrons.

4. CONCLUSION

As we have shown with just a few key examples, intense neutrino beams offer the promise of crucial new insight into the non-perturbative structure of hadronic systems. It is vital that in planning future facilities one counters the one dimensional view of physics that values speculation about physics beyond the standard model above everything else. The least understood part of the standard model is QCD in the non-perturbative regime and the physics issues outlined here need to be pursued vigorously.

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