# Transition to Perturbative QCD

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**Abstract.** We review the Jefferson Lab program concerning the interplay between hadronic and underlying quark degrees of freedom in exclusive reactions. Much of the program was initially based on predictions from perturbative QCD (pQCD) concerning scaling of reaction cross sections, helicity conservation, and asymptotic behavior of form factors. Although much of the data do not follow simple pQCD expectations, some observables scale better than expected. Generally, the underlying dynamics are best understood with nonperturbative quark models, but the elastic deuteron form factors provide an example of the success of hadronic models to high momentum transfer.

# 1. Introduction

Determining the kinematic regime for transition from hadronic degrees of freedom to quarkgluon degrees of freedom has been a central goal of nuclear physics for the past several decades. More than 10 years ago, it was widely believed that observing cross sections that followed the constituent counting rules or measuring polarization observables consistent with hadron helicity conservation was sufficient to signal the transition region. The constituent counting rules, developed before quantum chromodynamics (QCD), are consistent with perturbative QCD (pQCD), but do not rely on being in the pQCD regime. In fact, it is now believed that the constituent counting rules could be a consequence of the Anti-deSitter Space/Conformal Field Theory (AdS/CFT) conjecture.

A number of observables are at least approximately consistent with constituent counting rules (CCR): the elastic form factor  $G_{Mp}$ , and cross sections for exclusive photopion production from the proton and neutron, two-body photodisintegration of the deuteron, and proton-proton elastic scattering. High- $Q^2$  electron-deuteron elastic scattering is consistent with an extension of the CCR, called reduced nuclear amplitudes (RNA) – but is also very well predicted by modern relativistic hadronic calculations. It is especially striking that reactions in simple nuclei obey the CCR for two reasons: (1) the nucleons in the deuteron are for the most part relatively far apart, whereas pQCD is a short-range process, and (2) there are a relatively large number of quarks in a simple nucleus, in principle requiring a large momentum transfer to each quark.

This agreement is likely misleading, since pQCD calculations have generally been unable to reproduce the magnitude of experimental cross sections or form factors. It appears that there are significant contributions of soft physics that increase cross sections while having little effect on the CCR behavior, although for nuclear reactions it has also been suggested that there are significant unaccounted contributions from hidden-color configurations in the wave function.<sup>1</sup>



Figure 1. Dyson-Schwinger equation calculations of quark mass as a function of momentum compared to lattice QCD data [1].

Another way to think about the transition from hadronic degrees of freedom to partonic degrees of freedom is from the value of the quark momentum where the mass of the constituent quark becomes comparable with the mass of the current quark. The quark mass as a function of quark momentum has been calculated both from lattice gauge and Dyson-Schwinger approaches [2, 3]. The results are illustrated in Fig. 1. The curves represent three current quark masses, while the lattice calculations, of course, are performed for more massive quarks. From this figure, it appears that the quark momentum must be larger than about 2 GeV to begin to be in the perturbative regime, or more than 4 GeV<sup>2</sup> momentum transfer per quark. For the case of elastic scattering from the pion, one might expect perturbative QCD to become important at more than 16 GeV<sup>2</sup>, well above the range of present data. One would require the 12 GeV upgrade at Jefferson Lab to perform this experiment up to a momentum transfer of only 6 GeV<sup>2</sup>.

Furthermore, it now seems unlikely that hadron helicity conservation will be observed since it relies on quark helicity conservation and vanishing quark orbital angular momentum. We now know from a number of recent measurements, including proton form factors, the Sivers effect and Boer-Mulders asymmetries, that quark orbital angular momentum is ubiquitous. Studies of polarization in exclusive meson photoproduction and deuteron photodisintegration are also inconsistent with hadron-helicity conservation, supporting this idea, even though the cross sections in these reactions are consistent with the CCR.

Thus, as the approximate agreement of various processes with the constituent counting rules appears to be fortuitous, it remains a mystery why such good fortune is found in so many reactions. In the asymptotic pQCD limit, only the minimum *Fock state* valence quarks, exchanging the minimum number of gluons, participate in the reaction. The relative gluon-quark momenta are required to be high in all interaction vertexes so that the strong coupling constant  $\alpha_S$  is relatively small. It seems instead that in the Jefferson Lab kinematic regime one in general has significant contributions from soft physics, but it also often appears that processes can be separated into soft and hard pQCD parts. For example, it has recently been shown for some reactions that the counting rule behavior is approximately reproduced in the generalized parton

<sup>&</sup>lt;sup>1</sup> In hidden-color configurations, the deuteron is made up of two colored objects. These configurations can occur in the intermediate state in NN scattering, so theories with input from the measured NN force presumably already incorporate hidden-color effects.

distribution (GPD) / handbag picture, in which there is a hard perturbative scattering from a single quark in a hadron, with the momentum shared with other quarks through soft processes. The following sections summarize results of several of the more-studied reactions.

### 2. Hadron form factors

For mesons and baryons the leading pQCD form factor amplitudes are proportional to  $1/Q^2$ and  $1/Q^4$ , respectively. In the following sections, we describe the pion, nucleon, and  $N \to \Delta$ transition form factors.

2.1. Pion form factor



**Figure 2.** Left panel: Charged pion form factor. The dark and light filled squares are the result of the Hall C experiments [9, 10]. Right panel: Diagrams of lowest order pQCD and higher order hard processes which also contribute to the curves in the left panel.

Since the pion's valence quark structure consists of a single quark and antiquark, the lowest order pQCD mechanism requires only the exchange of a single gluon, with a high enough momentum relative to each of the quarks so that both quark-gluon vertices can be treated pertubatively. After the development of the SVZ QCD sum rules [4] there was considerable theoretical activity to obtain valence quark distributions and, from them, the leading order hadron form factors using pQCD [5]. Enthusiasm was kindled by the apparent agreement obtained with earlier measurements of the  $\pi^+$  form factor at CESR in Cornell. However, this immediately became controversial. On the theoretical side it was pointed out that the  $q\bar{q}$  valence quark distribution obtained by the sum rule method has peaks near the two physical limits of x = 1 and 0, implying that the active struck quark has either nearly all or none of the meson momentum. This situation leads to a large contribution from nonperturbative processes. The more physically reasonable asymptotic distribution, which peaks at x = 1/2, yields a much smaller  $F_{\pi^+}$  than experiment. On the experimental side several difficulties were pointed out. Since a free pion target does not exist, attempts to obtain  $F_{\pi^+}$  rely on the assumption that the proton sometimes consists of a neutron plus  $\pi^+$ , both of which are off-shell. Thus, experiments must measure cross sections at momentum transfer t < 0, separate out the longitudinal part of the cross section, to isolate the part of the cross section corresponding to directly knocking out the pion, and then extrapolate the results to the free pion pole,  $t = m_{\pi}^2$ , the kinematic point corresponding to the physical  $\pi$  mass, with an unbound  $n\pi^+$  system. Model uncertainties and the very limited quality of the early  $\pi^+$  data did not permit this.

Jefferson Lab undertook a major program in Hall C to obtain  $F_{\pi^+}$ . High quality data enabled clean extractions of the longitudinal cross sections using the Rosenbluth technique.

New Insights into the Structure of Matter: The First Decade of Science	e at Jefferson Lab	IOP Publishing
Journal of Physics: Conference Series <b>299</b> (2011) 012009	doi:10.1088/174	2-6596/299/1/012009

Improved models allowed the determination of the t-channel and non-t-channel contributions, and the magnitude of the pion form factor. Very precise measurements of  $F_{\pi^+}$  have been obtained for  $Q^2$  up to 2 GeV<sup>2</sup>, as shown in Fig. 2, along with the results of several calculations. The lowest order pQCD calculation using the asymptotic distribution function underestimates the result, but still contributes a significant fraction. Incrementally adding next-to-leadingorder contributions involving more than the minimal gluon exchanges, and also  $k_{\perp}$  components, incrementally reaches the experimental  $F_{\pi^+}$ . One may conclude [6] that although leading order pQCD cannot account for the form factor, it can be mostly accounted for by hard processes.<sup>2</sup> This is an important collateral finding for the eventual application of meson production for the study of GPDs, which requires hard perturbative treatments at the "handles" of the handbag. Also, dominance of the longitudinal cross section is essential for treating pion production in the framework of GPDs.

#### 2.2. Nucleon elastic form factors

The hadronic current for nucleon elastic scattering is

$$J_{\mu} = \bar{u}(p_2) \left[ \gamma_{\mu} F_1 + i \frac{\sigma_{\mu\nu} q^{\nu}}{2m} F_2 \right] u(p_1) \tag{1}$$

where the Dirac form factor  $F_1$  is the helicity conserving current distribution and the Pauli form factor  $F_2$  is the helicity non-conserving current distribution. A linear combination of these form factors, the electric and magnetic form factors  $G_E$  and  $G_M$ , leads to simpler expressions for the cross section and polarization observables. The major finding of Jefferson Lab, discussed more elsewhere in this volume, is that the ratio  $G_E/G_M$  falls about linearly with  $Q^2$ , rather than being about constant.



**Figure 3.** Left panel: Elastic proton helicity conserving form factor  $F_{1P}$ . Right panel: Valence quark distribution function  $\Phi_{CZ}(x)$  obtained by Ref. [5] using SVZ sum rules.

2.2.1. Proton helicity conserving form factor  $F_{1p}$  By far the highest  $Q^2$  exclusive data comes from the measurement at SLAC [11] of elastic ep scattering up to 36 GeV<sup>2</sup>. Very high  $Q^2$  is accessible by single arm electron scattering because elastic scattering is isolated in W. However,

<sup>&</sup>lt;sup>2</sup> Of related interest is the  $\pi^0 \gamma^* \gamma$  form factor. It was long believed that this form factor was basically perturbative over the measured range, until this was called into question by recent BABAR data [7] that greatly exceed the perturbative prediction for  $Q^2 > 15 \text{ GeV}^2$ . Objections exist to the correctness of this result [8], and the matter remains to be sorted out.

a single ep elastic cross section measurement cannot separate  $F_{1p}$  and  $F_{2p}$ . Figure 3 shows the result for  $F_{1p}$  assuming  $G_{Ep} = G_{Mp}/\mu_p$ ,<sup>3</sup> and the results of a lowest order pQCD calculation [12], with a valence quark distribution  $\Phi_{CZ}(x)$  obtained by the method of Ref. [5] using the SVZ sum rule, and a "running" strong coupling constant  $\alpha_S$ . As in the case of the  $\pi^+$  calculation, this distribution peaks where there is a large probability for the struck quark to have most of the proton momentum. If one repeats the calculation with the asymptotic distribution function, which peaks at values of x where all three quarks have an equal momentum fraction, the resulting curve accounts for a small fraction of the form factor. A more sophisticated formalism has been developed to include higher-order perturbative QCD resummation, or Sudakov form factor [13], which attempts to account for "strong radiative" effects.



**Figure 4.** The Jefferson Lab Pauli form factor, plotted as  $Q^2 \log^2(Q^2/\Lambda^2) (F_{2P}/F_{1p})$  [15].

2.2.2. Proton helicity non conserving form factor  $F_{2p}$  The Pauli form factor  $F_{2p}$  is intrinsically helicity non-conserving and therefore would seem to violate one of the tenets of pQCD. More precisely, neglecting orbital angular momentum, pQCD predicts  $F_{2p}/F_{1p} \propto 1/Q^2$ . A major experimental finding of the Jefferson Lab program is that  $F_{2p}/F_{1p} \propto 1/Q$  instead [14]. Reference [15] has pointed out that a pQCD framework can be valid in the case where overall helicity is not conserved but a spin flip comes from the inclusion of orbital angular momentum in the treatment of the form factor, in such a way that the helicity conservation can be retained at each vertex, while the orbital angular momentum of the initial and final state nucleons changes from  $l = 1 \rightarrow l = 0$ , or vice-versa. Indeed, a generalized power counting law can then be derived which agrees with the experimentally observed scaling. The assumption that the quarks have one unit of angular momentum in the initial state introduces a transverse term into the transition amplitude, schematically  $T(x, y) \to T(x, k_{x\perp}, y)$ , as well as to the quark distribution amplitude for the initial state, schematically  $\Psi(x) \to \Psi(x, k_{x\perp})$ . Each  $k_{\perp}$  adds a factor of 1/Qto the overall form factor compared to the leading order form factor. Finally, in order to avoid singularities coming from the regions of very small x, the Sudakov resummation is applied which basically cuts of the integral at  $x \sim \Lambda^2/Q^2$ , and adds a logarithmic factor to the form factor,

<sup>&</sup>lt;sup>3</sup> The well known data obtained by Jefferson Lab during the past several years shows that this is not the case. Instead  $G_E^p/G_M^p$  decreases about linearly with  $Q^2$ , up to  $Q^2 = 8.5 \text{ GeV}^2$ . The overall effect of a continued linear fall of  $G_E^p/G_M^p$  on the extraction of  $F_1^p$  is rather small at higher  $Q^2$  and does not materially affect the conclusion of Fig. 3.



Figure 5. Results of Jefferson Lab measurements of the  $p \to \Delta(1232)$  amplitudes. Left panel:  $G_M^*/G_D$ , from Ref. [17]. Right panel:  $R_{EM}$ . The open circles and dark solid points are Hall C data [16, 17]. The rest of the points are from Hall B [18, 19].

*i.e.*  $F_{2p} \propto \log(\Lambda^2/Q^2)/Q^6$ . A very good fit to the recent Jefferson Lab data is obtained with  $\Lambda \sim 400$  MeV.

#### 2.3. Nucleon resonances

The lowest lying nucleon excited state is the  $\Delta(1232)$ , which has both spin and isospin quantum numbers 3/2. The  $\Delta$  decays almost exclusively into a *p*-wave  $N - \pi$  final state. It is relatively isolated from other resonances. It is also very strongly excited, and almost completely saturates the unitary circle in a pion scattering Argand plot. The  $N \rightarrow \Delta$  transition has three electromagnetic multipoles — M1, E2 and S1, which are denoted magnetic dipole, electric quadrupole and scalar dipole, respectively. These are directly related to the CGLN [23] multipoles  $M_{1+}$ ,  $E_{1+}$ , and  $S_{1+}$ , where the subscript 1+ denotes that the decay meson has an orbital angular momentum l = 1 and the total spin is J = 1 + 1/2 = 3/2.

For real photons  $(Q^2=0)$  the  $\Delta$  is nearly a pure M1 excitation, and  $R_{EM} \equiv E_{1+}/M_{1+}$  is very small ( $\approx$ -2.5%). Early on this was explained in the framework of the SU6 CQM as a magnetic spin-flip excitation of one of the nucleon's quarks. At the asymptotic limit,  $Q^2 \to \infty$ , pQCD predicts the leading form factors should scale, just as in the elastic case, as  $1/Q^4$ . In addition, helicity conservation should be respected. For the  $N \to \Delta$  the helicity amplitudes are related to the multipoles as  $A_{1+} = 3E_{1+} + M_{1+}$  and  $B_{l+} = 2(E_{1+} - M_{1+})$  where  $A_{1+}$  and  $B_{l+}$ are helicity conserving ( $\Delta\Lambda=0$ ) and helicity non-conserving ( $\Delta\Lambda=2$ ) amplitudes, respectively. Thus, near threshold, with  $R_{EM} \sim 0$  one has  $B_{l+} \sim -2A_{1+}$ . However, for helicity to be conserved  $B_{l+}/A_{l+} = 0$ , so  $E_{1+} = M_{1+}$  and  $R_{EM} = +1$ . Thus, the experimental result indicates that the helicity non-conserving amplitude is comparable to the helicity conserving amplitude, contradicting the requirements of pQCD.

The  $N \to \Delta$  helicity conserving form factor can be defined in terms of hadronic currents as in Eq. (1). Since the  $\Delta$  has spin 3/2 there are three form factors  $G_M^*$ ,  $G_E^*$  and  $G_S^*$ .  $G_M^*$ , which is analogous to  $F_1$ , should also scale as  $1/Q^4$ . Earlier analysis of inclusive electron scattering data at SLAC [20, 21] suggested that the  $p \to \Delta$  form factor is decreasing with  $Q^2$  at a slope steeper than  $1/Q^4$ .

A major program was undertaken at Jefferson Lab to measure the details of the  $p \to \Delta$ resonance over as large a range of  $Q^2$  as possible to determine the evolution of the amplitudes from what is expected for a CQM toward what is expected from pQCD. Among the specific physics questions were whether  $G_M^*$  continues to fall anomalously fast as a function of  $Q^2$ , or begins to approach the scaling behavior, and whether  $R_{EM}$  remains very small and negative, or begins to turn positive, and asymptotically begins to approach +1. In addition to measurements of a few observables spanning a wide range of  $Q^2$ , one Hall A experiment [22] measured a complete set of recoil polarization observables to thoroughly determine amplitudes at a single  $Q^2 = 1 \text{ GeV}^2$ .

Figure 5 indicates that neither  $G_M^*$  nor  $R_{EM}$  in the measured  $Q^2$  region show indications of the behavior expected form pQCD. In the measured range,  $R_{EM} \sim 0$  and  $G_M^*$  falls faster than the scaling prediction. Thus, the two primary signatures of the approach to pQCD are violated, up to  $Q^2 \approx 8 \text{ GeV}^2$ , corresponding to a virtual photon wavelength that varies from near 1 fm down to about 1/20 fm.

Some theoretical arguments have been put forth to explain the fast falloff of  $G_M^*$ . Using the QCD sum rule approach, Ref. [24] argued that the leading  $N \to \Delta$  form factor should be suppressed. The nucleon has a mixed symmetry valence quark distribution,  $\Phi_{pS} + \Phi_{pA}$ , while that of the  $\Delta$  is purely symmetric  $\Phi_{\Delta S}$ . It was then found using the QCD sum rule technique that in the  $P \to \Delta$  form factor  $\langle \Phi_{pS} | T | \Phi_{\Delta S} \rangle$  and  $\langle \Phi_{pA} | T | \Phi_{\Delta S} \rangle$  have opposite signs, and tend to cancel. Thus the  $G_M^*$  would be dominated by the sub-leading helicity non-conserving contribution, which should then decrease relative to the helicity conserving form factor, as observed. At some value in  $Q^2$  the helicity non-conserving contribution would become small, and  $G_M^* \to 1/Q^4$ .

In another interesting case the transition amplitudes to the  $S_{11}(1535)$ , which has  $J^{\pi} = 1/2^{-}$ , were also measured in Hall B [25, 26] and Hall C [27] by observing the  $p\eta$  decay channel. Since J = 1/2, there is an antisymmetric as well as symmetric distribution function (as for the proton). Ref. [24] finds no cancellation of various terms in the amplitude. Experimentally the helicity conserving  $N \to S_{11}$  transition remains very strongly excited, at all  $Q^2$ , and shows signs of beginning to approach  $1/Q^4$  at the highest  $Q^2$  regions [20, 27].

# 3. Real compton scattering

Real Compton Scattering (RCS) probes the nucleon with incoming and outgoing real photons. As compared to pion photoproduction, there is a simpler final state, making it more likely that the GPD handbag mechanism describes RCS, and a slower expected energy dependence from the CCR,  $ds/dt \sim s^{-6} vs. s^{-7}$ . But the cross sections are smaller and the experiment more difficult, as one must isolate the final-state photon from a much larger background of  $\pi^0$  decay photons.

Cornell [33] found that cross sections at large c.m. angles approximately followed the CCR, for beam energies above about 3 GeV, though with poor statistical precision. The Jefferson Lab Hall A RCS experiment dramatically improved the quality of cross section data in the few GeV energy region, and also provided the first polarization point.<sup>4</sup> The cross section [34] shows that  $ds/dt \sim s^{-8}$ , a faster fall off than predicted by the CCR, even somewhat faster than predicted by Radyushkin [35] in a GPD approach. The longitudinal polarization transfer [28] shown in Fig. 6 indicates that the dynamics are consistent with predictions using the handbag approach, rather than pQCD.<sup>5</sup> Thus, RCS results to date support the handbag picture of underlying quark dynamics rather than the pQCD picture.

# 4. Pion photoproduction

Pion photoproduction would appear to be an ideal experiment to investigate the onset of perturbative physics, since it is known at low energies to be strongly influced by resonance

 $<sup>^4\,</sup>$  A follow up experiment, 07-002, has taken additional polarization data in Hall C.

 $<sup>^{5}</sup>$  It remains an unexplained oddity why, when polarization transfer on a quark is expected to follow the KN formula, the sum over all possible diagrams in the pQCD approach tends to give a result of opposite sign.



Figure 6. Longitudinal polarization transfer in RCS for  $E_{\gamma} = 3.23 \text{ GeV} [28]$ . The Klein-Nishina (polarization transfer to a point-like object) prediction is indicated by "KN". The gray band indicates the handbag approach using GPDs [29]. A constituent quark model calculation [30] in the handbag approach is labelled "CQM". A Regge-exchange calculation [31] is indicated by "Regge". The labels "COZ" and "ASY" are for pQCD calculations [32] using the asymptotic (ASY) or Chernyak-Ogloblin-Zhitnitsky (COZ) distribution amplitudes.

production, but at high energies to show cross section scaling. Jefferson Lab has obtained precise cross sections [36] at beam energies significantly above 1 GeV; a small sample of the data, shown in Fig. 7, indicate that even in the scaling region the cross section does not exactly follow the scaling rules, but appears to oscillate. In the more studied case of pp elastic scattering, such oscillations have been attributed to either resonance (charm) thresholds, or to interference between long (Landshoff) and short (pQCD) range mechanisms. Similarly, recoil polarizations in  $\gamma p \to p\pi^0$  show strong energy and angle dependences even above the resonance region [37]. In contrast to this, the  $\gamma p \to K^+\Lambda^0$  reactions produces  $\Lambda$ 's polarized in the direction of the photon spin [38], a simple behavior but one that is inconsistent with helicity conservation.

#### 5. Few-body nuclei

Studies of the deuteron, particularly elastic scattering and photodisintegration, have been a primary source of information on the transition to pQCD in nuclei [39]. Ideally, as one probes the nucleus with increasing energy and momentum transfer, cross sections and polarization observables undergo a transition in their behavior, akin to a phase transition, that clearly signals the transition from a low energy, low momentum transfer hadronic regime to a high energy, high momentum transfer quark-gluon regime. Even with no clear signal in the data, one expects a transition in the ability to formulate a description in quark vs. hadronic degrees of freedom.

Observing the transition in exclusive reactions has been more problematic. Reactions such as quasi-free d,<sup>3</sup> He(e, e'p) and ed elastic scattering, measured to large momentum transfers, are generally well understood with hadronic theories [40, 41, 42, 47, 48, 49]. In inclusive reactions, one needs both large energy - more specifically large center of mass energy W - and large momentum transfer  $Q^2$  to reach the deep inelastic regime. Thus, it makes sense that quasi-free scattering, with  $W_{\gamma^*p} \approx m_p$ , and elastic scattering, with  $W_{\gamma^*p} = m_d$  for the deuteron as a whole, but  $W_{\gamma^*p}^2 < m_p^2$  for the struck nucleon, show little if any indication of quark behavior. Whatever the quark effects are, they are already largely incorporated into the hadronic theory.

To obtain high energy and momentum transfer, we turn to photodisintegration of the



Figure 7. Comparison, taken from [36], of charged pion photoproduction from the nucleon,  $\gamma p \to \pi^+ n$  and  $\gamma n \to \pi^- p$ , at  $\theta_{c.m.} = 90^{\circ}$ .

deuteron. Above  $E_{\gamma} = 1$  GeV, with  $W^2 = s = 2E_{\gamma}m_d + m_d^2$ , W is always above 2.7 GeV – for a proton target, the 1 GeV photon leads to W > 1.66 GeV. Also, at  $\theta_{c.m.} = 90^{\circ}$ , we have a four momentum transfer -t > 1 GeV<sup>2</sup>; -t in real photo-reactions corresponds to  $Q^2$  in virtual photon transfer. Thus, the kinematics for photodisintegration above 1 GeV roughly correspond to the kinematics for inclusive deep inelastic scattering.

## 5.1. Few-body nuclear form factors

Knowledge of *ed* elastic scattering has been vastly improved by experiments at Jefferson Lab [41, 42]; data have also been taken for the <sup>3,4</sup>He form factors. [50] The deuteron form factor should fall as  $Q^{10}$  at high momentum transfer, while the A = 3 (A = 4) form factors should fall as  $Q^{16}$  ( $Q^{22}$ ). The cross section data [41] allow determination of the structure function  $A(Q^2)$ , a combination of the three form factors, which shows hints of possible scaling at the highest momentum transfers, as shown in Fig. 8.

The most complete study of the deuteron uses forward-angle cross sections for  $A(Q^2)$ , backward angle cross sections to determine the magnetic structure function  $B(Q^2)$ , and



**Figure 8.** Top panel: Deuteron form factor times  $Q^{10}$ . The expected scaling behavior leads to  $Q^{10}F_d$  being constant. Bottom panel: Deuteron form factor divided by nucleon form factor squared. The reduced nuclear amplitudes extension of pQCD predicts that the reduced form factor follows the dash line, which it does for  $Q^2 \ge 2 \text{ GeV}^2$  (taken from [41]).



**Figure 9.** Relativistic hadronic calculations compared to *ed* scattering data for the structure functions *A* and *B*. Curves are from [43] (green dot dash), [44] (black solid), [45] (blue dash), and [46] (brown dot). Updated from [39].



Figure 10. Relativistic hadronic calculations compared to ed scattering data for the tensor polarization  $t_{20}$  and the charge form factor  $G_C$ , extracted from A, B and  $t_{20}$ . More precisely, B only depends on the magnetic form factor, which is needed to extract  $G_C$  from A and  $t_{20}$ . Curves are from [43] (green dot dash), [44] (black solid), [45] (blue dash), and [46] (brown dot). Updated from [39].

polarization data [42] – or the individual form factors  $G_E$ ,  $G_M$ , and  $G_Q$  extracted from the observables – as these are independent functions with differing sensitivity to the ingredients of the theory. Figures 9 and 10 show the results from four models selected because they all give a good account of the data for A and  $T_{20}$  (and hence also for  $G_C$ ) up to  $Q^2 \simeq 3 \text{ GeV}^2$ . One of these is an early calculation based on the quark compound bag model which uses hadronic degrees of freedom to describe the long-range physics [46]; the other three are models using only hadronic degrees of freedom. Two of these [44, 45] provide an excellent description of A to the highest  $Q^2$ , and illustrate the success of modern relativistic hadronic calculations at providing a good account of the data across the entire  $Q^2$  range. It is the magnetic structure function B that is most difficult for theory to predict, but the minimum in B is also poorly determined by a few low statistics points, and most in need of an improved experiment. The essential ingredients in the best calculations are a complete treatment of relativistic effects along with an NN force based on data.

The hadronic calculations, particularly [44, 45], have superior predictive power, and are the preferred explanation in view of the fact that the pQCD estimates fail to predict the strength of the form factors by a huge factor, or the minimum in B. It seems that the hints of possible scaling shown in Fig. 8 are perhaps misleading and fortuitous, or reflect some important physics as yet not understood about the pQCD calculations. It is known that at the lowest momentum transfers measured, chiral perturbation theory, based on solving QCD with nucleons and pions, provides an excellent description of the data [51].

#### 5.2. High-energy deuteron photodisintegration

Experiments [53, 54, 55, 56, 57, 58] at SLAC and Jefferson Lab have shown that the photodisintegration cross section for  $E_{\gamma} > 1$  GeV and  $p_T > 1.3$  GeV roughly follow the constituent counting prediction [59],  $d\sigma/dt \propto s^{-11}$  at constant center of mass angle, with s the square of the center of mass energy; see Fig. 11. The behavior is amazingly good [60]; the



Figure 11. Scaling of the deuteron photodisintegration cross section is indicated by the flattening of the cross section at high energies. The extensive CLAS data set [58] is not shown (taken from [39]).

cross section has been measured to fall about a factor of  $\approx 30,000$  with an  $s^{-11}$  dependence, from 1 to 4 GeV at  $\theta_{c.m.} = 90^{\circ}$ . This can be taken as an indication that quarks might be the appropriate underlying degrees of freedom, but it is not conclusive; simple models with hadronic degrees of freedom can lead to roughly the same behavior.

There is no satisfactory hadronic theory nor is there a prospect of a good conventional hadronic theory above 1 GeV photon energy [39]. There are too many possible resonance channels with poorly known amplitudes to have a reliable prediction. But there are no clean indications of any resonances in the data, and quark models, which automatically average over the resonances, are possible. Most existing quark models are based on the idea that the incoming photon is absorbed on a pair of quarks being exchanged between the two nucleons in the deuteron. Some models do approximate evaluations of this diagram [61, 62]; others evaluate it by relating the photodisintegration to nucleon-nucleon scattering [63, 64]. Finally, the quark-gluon string model [65] is based on the idea that the dominance of planar diagrams in QCD leads to the dominance of 3-quark exchange in photodisintegration, and evaluates the reaction using Regge phenomenology.

These models, and the underlying reaction dynamics, can be tested further with polarization observables. Only three high-energy experiments have been done. The linearly polarized photon asymmetry,  $\Sigma$ , was measured at Yerevan [66], up to 1.6 GeV at  $\theta_{c.m.} = 90^{\circ}$ . The data show that above 1 GeV  $\Sigma$  is moderately sized, 0.2 or 0.3, and positive; the highest energy point indicates  $\Sigma$  might be increasing towards 1, but it is also only  $1\sigma$  above 0.3. While it was previously believed that perturbative QCD leads to hadron helicity conservation [67], which leads to  $\Sigma \to -1$ , it is

New Insights into the Structure of Matter: The First I	Decade of Science at Jefferson Lab	IOP Publishing
Journal of Physics: Conference Series 299 (2011) 012	2009 doi:10.1088/	1742-6596/299/1/012009

now understood that both chains of this argument have problems. Orbital angular momentum can lead to interesting spin effects, preventing hadron helicity conservation [68]. The limit of -1 relies on the photo-coupling being isoscalar;  $\Sigma \to 1$  if the photo-coupling is isovector [69]. The data and its interpretation can be dramatically and easily improved by a more extensive measurement of the  $\Sigma$  asymmetry in Jefferson Lab Hall B.

Recoil proton polarizations have been measured in two high-energy experiments in Jefferson Lab Hall A. E89-019 [70] found that at  $\theta_{c.m.} = 90^{\circ}$  the induced polarization steadily decreases in magnitude, going from near -1 at 500 MeV to essentially 0 by 1 GeV. This contradicts the expected hadronic behavior, in which resonances lead to large, strongly energy-dependent induced polarizations. The transferred polarizations are moderate in size near 1 GeV, but appear to steadily decrease with energy at higher energies. The ensuing experiment, E00-007 [71], measured a 5-point angular distribution for  $E_{\gamma} \approx 2$  GeV, from 37° to 110°. The polarizations have a smooth dependence with angle. The induced polarization  $p_y$  and transferred polarization  $C_{x'}$  (transverse in the reaction plane) start out negative and moderately sized, but cross zero near  $\theta_{c.m.} = 90^{\circ}$  and are positive, decreasing to be zero near  $\theta_{c.m.} = 110^{\circ}$ . From the hard rescattering model [72], if isovector photon coupling dominates, then the NN amplitude  $\phi_5$  dominates, which drives  $p_y$  and  $C_{x'}$  to zero at 90° – these are each proportional to  $\phi_5$  multiplied by a sum of other amplitudes. It is interesting that the polarization observables  $\Sigma$ ,  $p_y$ , and  $C_{x'}$  all seem to indicate a dominantly isovector coupling.

#### 5.3. Low-energy deuteron photodisintegration

Hadronic models have been much improved over the last several years, particularly due to the work of Schwamb and Arenhövel [73]. While various problems have been resolved, there remain some prominent disagreements, most notably as the energy increases above 300 MeV, the  $\Delta$  resonance region, in the induced polarization  $p_y$ , which led to much discussion of exotic dibaryons in deuteron photodisintegration back in the 1970s and 1980s.<sup>6</sup> Two recent experiments have probed this region in more detail, to perhaps provide clues why the best hadronic calculations start to fail.

A Novosibirsk experiment [74] measured tensor polarizations for energies from 25 to 440 MeV. Generally, below pion production threshold there is little model dependence to the calculations, and there is an excellent prediction of the data. At energies near the  $\Delta$  resonance, the most modern calculations of Schamb and Arenhövel improve the description of  $T_{20}$  and  $T_{22}$ , but hurt the description of  $T_{21}$ ; it is not clear whether the discrepancy arises from uncertainties in the calculation or missing underlying dynamics.

Experiment 05-103 in Jefferson Lab Hall A [75] measured the recoil proton polarizations for energies from 280 – 360 MeV and angles from 20° – 110°. This is the energy region in which  $p_y$  starts to grow in magnitude, contradicting calculations; even the modern Schwamb and Arenhövel calculations show that the induced polarization tends to be small near  $\theta_{c.m.} \approx$ 90°.<sup>7</sup> The aim of the experiment was to provide a systematic set of polarization data to try to help identify the missing reaction dynamics. The experimental results clearly show the growth of the induced polarization with energy at 90°. For the polarization transfer observables, there is qualitative agreement but subtle quantitative differences between the data and the modern theory calculations. Generally, the older more phenomenological calculations of Schwamb and Arenhövel are in slightly better agreement with the data than the newer less phenomenological

 $<sup>^{6}</sup>$  Another still unresolved notable problem from the same period is the induced neutron polarization at low energy.

<sup>&</sup>lt;sup>7</sup> In the 1970s and early 1980s, this difference led to much consideration of dibaryons in deuteron photodisintegration, leading to much of the existing polarization data; while this explanation was eventually discarded, the missing reaction dynamics has yet to be identified.

calculations of Schwamb.

# 5.4. High-energy photodisintegration of ${}^{3}He$

The underlying mechanisms of pn or deuteron photodisintegration can be illuminated by comparison with pp photodisintegration. Since there is no pp bound state, it is most natural to use <sup>3</sup>He, as with only one undetected neutron the reaction kinematics can be completely reconstructed and final state interactions are minimized. At low energies, pp disintegration is known to be small, which is understood to result from the two protons being largely in an l = 0 s state, coupled to total spin 0, with no net magnetic moment. At high energies, different ideas about the underlying reaction dynamics lead to a range of predictions for the pp disintegration cross section, from much larger than deuteron photodisintegration to much smaller [76, 77].

One important point in the photodisintegration of <sup>3</sup>He is that one can calculate the light cone momentum fraction of the undetected neutron. In general,  $\alpha = (E - p_z)/m$ ; since  $\alpha$  is a conserved quantity, we calculate  $\alpha_n = \alpha_\gamma + \alpha_{^3He} - \alpha_{p_1} - \alpha_{p_2} = 0 + 3 - \alpha_{p_1} - \alpha_{p_2}$ . The interesting thing is that  $\alpha_n$  provides an independent check of whether the pp photodisintegration is long or short range; a short range process leads to a broader, flatter distribution centered near  $\alpha_n = 1$ . In addition, the asymmetry of this  $\alpha_n$  distribution reflects how fast the cross section is falling with *s*. Thus, pp photodisintegration potentially has more information about the underlying dynamics than does deuteron photodisintegration.

An additional observation is that pp elastic scattering has prominent oscillations about the scaling prediction of energy dependence; in pn elastic scattering, oscillations are not so apparent. Thus, models which relate photodisintegration to NN scattering predict oscillations in the photodisintegration, compared to the scaling energy dependence.

An initial study of the disintegration of <sup>3</sup>He into a pp pair and n spectator [77] from Hall A at  $\theta_{c.m.} = 90^{\circ}$  and  $E_{\gamma} = 0.8 - 4.6$  GeV shows that the cross section does approximately scale as expected, as  $s^{-11}$ , for photon energies above 2 GeV, but the scaled cross section is small, about 20 times smaller than the deuteron photodisintegration cross section. The small cross section results from cancellation in the pp amplitudes [78]. The decreased statistics resulting from the small cross section makes it difficult to determine if there are indeed oscillations as predicted, or to study the  $\alpha_n$  distribution. More extensive data will soon be available from CLAS [79] at all angles, but only up to  $\approx 1.5$  GeV beam energy. A new experiment is needed to investigate the oscillations and  $\alpha_n$  distribution.

These initial studies of <sup>3</sup>He photodisintegration are also yielding results for hard disintegration into a pd final state, data which are unpublished to date. Preliminary indications are that these cross sections scale as  $s^{-17}$  above about 1 GeV beam energy.

Thus, we have seen that several high-energy photoreactions exhibit cross section scaling behavior, though the onset of scaling occurs at very different kinematics for the different reactions. The limited spin measurements do not support helicity conservation. The underlying dynamics appear to be best explained as based on the quark-interchange mechanism, or evaluated using Regge theory techniques. At present we do not understand why different reaction channels appear to exhibit scaling starting at very different kinematics.

# 6. Summary

At the start of experiments at Jefferson Lab, a broad program of exclusive reactions was planned to understand the transition from hadronic to partonic degrees of freedom. Initially, it was anticipated that new high-energy data would be explained by perturbative QCD, with large momentum transferred to every quark in the nucleons in the reaction. The Jefferson Lab experimental program has allowed high-precision cross section data and polarization data to be obtained at large momentum transfer. These data along with other experimental and theoretical developments do not in general support a purely perturbative picture as had been expected. It appears that purely perturbative hard scattering is rarely the case. Instead, we have seen the role of orbital angular momentum of partons in hadrons, and the importance and separability of hard and soft physics in the handbag mechanism in intermediate energy reactions. The underlying dynamics typically involve one quark in the nucleon carrying much of the momentum transfer, sharing it with the other quarks through the wave function, rather than through hard momentum transfers. This is reflected in the cross sections and polarizations seen in reactions on the nucleon such as elastic scattering, real Compton scattering, and meson photoproduction. For systems with more than one nucleon, the handbag dominance leads to a related underlying picture of the dominance of quark-interchange mechanism, and the importance of quark orbital angular momentum obscures the phenomenon of color transparency.

# Acknowledgments

The author acknowledges the support of the U.S. National Science Foundation grant PHY 06-52713 to Rutgers University, the U.S. Department of Energy, Office of Nuclear Physics, contract no. DE-AC02-06CH11357 to Argonne National Lab, and the U.S. Department of Energy contract No. DE-AC05-06OR23177 to Jefferson Science Associates, LLC. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.

The authors thank S. Brodsky, G. Miller, M. Schwamb, and M. Strikman for many helpful discussions, and F. Gross and M. Sargsian for helpful discussions and a review of the manuscript.

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New Insights into the Structure of Matter: The First Decade of Science at Jefferson Lab **IOP** Publishing

- Journal of Physics: Conference Series 299 (2011) 012009
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