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Exclusive processes at Jefferson Lab

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Abstract. Mapping the transition from strongly interacting, non-perturbative quantum chromodynamics, where nucleon–meson degrees of freedom are effective to perturbative QCD of quark and gluon degrees of freedom, is one of the most fundamental, challenging tasks in nuclear and particle physics. Exclusive processes such as proton–proton elastic scattering, meson photoproduction, and deuteron photodisintegration have been pursued extensively at many laboratories over the years in the search for such a transition, particularly at Jefferson Lab in recent years, taking the advantage of the high luminosity capability of the CEBAF facility. In this talk, I review recent results from Jefferson Lab on deuteron photodisintegration and photopion production processes and the future 12 GeV program.

Keywords. Exclusive processes; quantum chromodynamics; perturbative quantum chromodynamics.

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1. Introduction

The hadron to parton transition region in nuclear physics is especially interesting and extremely important. Low energy nuclear physics has been described successfully with effective meson-exchange models [1]. However, it is believed that quantum chromodynamics (QCD) describes the strong interaction. At sufficiently high energy, perturbative QCD (pQCD) describes hadronic reactions in terms of quark and gluon degrees of freedom. Thus far, only fleeting evidence has been discovered for a transition between a completely hadronic description of nuclear reactions and a description based on quarks and gluons. Although in principle hadronic theories can be formulated for very high energy and momentum transfer, one expects a transition region between the low energy hadronic picture and the high energy perturbative QCD picture. In this region, it will become increasingly difficult to formulate hadronic theories, but increasingly simple to understand observables from pQCD. There is no clear guidance from theory as to the limits of the transition region; it must instead be determined by experiments.

Exclusive processes are essential for studies of transitions from the non-perturbative to the perturbative regime of quantum chromodynamics. The differential cross-section for many exclusive reactions [2] at high energy and large momentum transfer appear to obey the quark counting rule [3]. The quark counting rule was originally obtained based on dimensional analysis of typical renormalizable theories. The same rule was later obtained in a short-distance perturbative QCD approach by Lepage and Brodsky [4]. Despite many successes, a model-independent test of the approach, called the hadron helicity conservation rule, tends not to agree with data in the similar energy and momentum region. Hadron helicity conservation arises from the vector coupling nature of the quark–gluon interaction, quark helicity conservation at high energies, and the neglect of the non-zero quark orbital angular momentum state in the hadron. The presence of helicity-violating amplitudes indicates that the short-distance expansion is not the whole story. In addition some of the cross-section data can also be explained in terms of non-perturbative calculations [5]. The parton orbital angular momentum was considered for the first time by Chernyak and Zhitnitsky [6] for form factors. Recently, Ji *et al* [7] derived a generalized counting rule for exclusive processes at fixed angles involving parton orbital angular momentum and hadron helicity flip. This generalized counting rule opens a new window for probing the quark orbital angular momentum inside the hadron. A natural connection between the study of the parton–hadron transition through exclusive processes and generalized parton distributions probed through deeply virtual processes is therefore established.

2. Quark counting rule and oscillations

The quark counting rule predicts the energy dependence of the differential cross-section at fixed center-of-mass angles for an exclusive two-body reaction at high energy and large momentum transfer as follows:

$$d\sigma/dt = h(\theta_{\mathrm{c.m.}})/s^{n-2}, \tag{1}$$

where s and t are the Mandelstam variables, s is the square of the total energy in the center-of-mass frame and t is the momentum transfer squared in the s channel. The quantity n is the total number of elementary fields in the initial and final states, while $h(\theta_{\mathrm{c.m.}})$ depends on details of the dynamics of the process. The quark counting rule predicts a $1/s^7$ scaling for $d\sigma/dt$ for photopion production from a nucleon target at a fixed center-of-mass angle, and a $1/s^{11}$ scaling for deuteron photodisintegration process. The quark counting rule was originally obtained based on dimensional analysis under the assumptions that the only scales in the system are momenta and that composite hadrons can be replaced by point-like constituents. Implicit in these assumptions is the approximation that the class of diagrams, which represent on-shell independent scattering of pairs of constituent quarks (Landshoff diagrams) [8], can be neglected. This counting rule was also confirmed within the framework of perturbative QCD analysis up to a logarithmic factor of α_s and are believed to be valid at high energy, in the perturbative QCD region. Such analysis relies on the factorization of the exclusive process into a hard scattering amplitude and a soft quark amplitude inside the hadron.

The entire subject is very controversial. Isgur and Llewellyn-Smith [5] argue that if the nucleon wave function has significant strength at low transverse quark momenta ($k_\perp$), then the hard gluon exchange (essential to the perturbative approach) which redistributes the transferred momentum among the quarks, is no longer required. The applicability of perturbative techniques at these low momentum transfers is in serious question. There are no definitive answers to the question ‘what is the energy threshold at which pQCD can be applied?’ Indeed the exact mechanism governing the observed quark counting rule behavior remains a mystery.

Apart from the early onset of scaling and the disagreement with hadron helicity conservation rule, several other striking phenomena have been observed in pp scattering. One such phenomenon is the oscillation of the differential cross-section about the scaling behavior predicted by the quark counting rule (s^{-10} for pp scattering), first pointed out by Hendry [9] in 1973. Secondly, the spin correlation experiment in pp scattering first carried out at Argonne by Crabb *et al* [10] shows striking behavior: it is approximately four times more likely for protons to scatter when their spins are both parallel and normal to the scattering plane than when they are anti-parallel, at the largest momentum transfers ($p_{\mathrm{T}}^2 = 5.09$ (GeV/c)^2, $\theta_{\mathrm{c.m.}} = 90°$). Later, spin-correlation experiments [11] confirm the early observation by Crabb *et al* [10]. Theoretical interpretation for such an oscillatory behavior ($s^{10}\mathrm{d}\sigma/\mathrm{d}t$) and the striking spin-correlation in pp scattering was attempted by Brodsky *et al* [12] within the framework of quantum chromodynamic quark and gluon interactions, where interference between hard pQCD short-distance and long-distance (Landshoff) amplitudes was discussed for the first time. The Landshoff amplitude arises due to multiple independent scattering between quark pairs in different hadrons. Moreover, gluonic radiative corrections give rise to a phase to this amplitude which is calculable in pQCD [13]. This effect is believed to be analogous to the Coulomb-nuclear interference that is observed in low-energy charged-particle scattering. It was also shown that at medium energies this phase (and thus the oscillation) is energy dependent [14], while becoming energy independent at asymptotically high energies [14,15].

Lastly, Carroll *et al* [16] reported the anomalous energy dependence of nuclear transparency from the quasi-elastic $A(p,2p)$ process: the nuclear transparency first increases followed by a decrease. This intriguing result was confirmed recently at Brookhaven [17] with improved experimental technique in which the final state was completely reconstructed. Ralston and Pire [18] explained the free pp oscillatory behavior in the scaled differential cross-section and the $A(p,2p)$ nuclear transparency results using the ideas of interference between the short-distance and long-distance amplitudes and the QCD nuclear filtering effect. Carlson *et al* [19] have also applied such an interference concept to the pp scattering and have explained the pp polarization data.

It was previously thought that the oscillatory $(s^{10}\mathrm{d}\sigma/\mathrm{d}t)$ feature is unique to pp scattering or to hadron-induced exclusive processes. However, it has been suggested that similar oscillations should occur in deuteron photodisintegration [20], and photopion productions at large angles [21]. The QCD re-scattering calculation of the deuteron photodisintegration process by Frankfurt *et al* [20] predicts that the energy dependence of the differential cross-section, $(s^{11}\mathrm{d}\sigma/\mathrm{d}t)$ arises primarily from the n–p scattering in the final state. If these predictions are correct, such oscillatory behavior may be a general feature of high energy exclusive photoreactions.

Farrar *et al* [22] have shown that the Landshoff contributions are suppressed at leading-order in large-angle photoproduction but they can contribute at subleading order in $1/Q$ as pointed out by the same authors. In principle, the fluctuation of a photon into a $q\bar{q}$ in the initial state can contribute to independent scattering amplitude at sub-leading order. However, the vector–meson dominance diffractive mechanism is suppressed in vector–meson photoproduction at large values of t [23]. On the other hand, such independent scattering amplitude can contribute in the final state if more than one hadron exist in the final state, which is the case for both the deuteron photodisintegration and nucleon photopion production reactions. Thus, an unambiguous observation of such an oscillatory behavior in exclusive photoreactions with hadrons in the final state at large t may provide a signature of QCD final state interaction. The most recent data on $d(\gamma,p)n$ reaction [24] show that the oscillations, if present, are very weak in this process. The rapid decrease of the cross-section with energy ($\frac{d\sigma}{dt} \propto \frac{1}{s^{11}}$) makes it impractical to investigate such oscillatory behavior. Given that the nucleon photopion production has a much larger cross-section at high energies ($\frac{d\sigma}{dt} \propto \frac{1}{s^{7}}$), it is very desirable to use these reactions to verify the existence of such oscillations.

3. Nuclear filtering and color transparency

Nuclear filtering refers to the suppression of the long distance amplitude (Landshoff amplitude) in the strongly interacting nuclear environment. Large quark separations tend not to propagate in the nuclear medium while small quark separations propagate with small attenuation. This leads to suppression of the oscillation phenomena arising from the interference of the long distance amplitude with the short distance amplitude. Nuclear transparency measurements from $A(p,2p)$ experiments carried out at Brookhaven [16] have shown a rise in transparency for $Q^2 \approx$ 3–8 (GeV/c)^2, and a decrease in the transparency at higher momentum transfers. A more recent experiment [17], completely reconstructing the final state of the $A(p,2p)$ reaction, confirms the validity of the earlier Brookhaven experiment. If the oscillatory behavior of the cross-section is suppressed in nuclei one would expect to see oscillations in the transparency, which are 180° out of phase with the oscillations in the free pp cross-section. On the other hand, Brodsky and de Teramond [25] believed that the structure seen in $(s^{10}\mathrm{d}\sigma/\mathrm{d}t)(pp \to pp)$, the A_{NN} spin correlation at $\sqrt{s} \sim 5$ GeV (around center-of-mass angle of 90°) [10,11], and the $A(p,2p)$ transparency result can be attributed to $c\bar{c}uuduud$ new resonant states. The opening of this channel gives rise to an amplitude with a phase shift similar to that predicted for gluonic radiative corrections.

While interpretations of the elastic $pp \to pp$ cross-section, the analysing power A_{NN} and the transparency data remain controversial, the ideas of nuclear filtering effect and the interference between the hard pQCD short-distance and the long-distance Landshoff amplitudes by Ralston and Pire [18] are able to explain both the $(s^{10}\mathrm{d}\sigma/\mathrm{d}t)(pp \to pp)$ oscillatory behavior and the Brookhaven $A(p,2p)$ transparency data. Carlson *et al* [19] have also applied such an interference concept to explain the pp polarization data.

Recently, a first complete calculation of 'color transparency' and 'nuclear filtering' in perturbative QCD has been carried out for electro-production experiments [26]. These calculations show that the nuclear filtering effect is complementary to color transparency (CT) effect. Color transparency, first conjectured by Brodsky and Mueller [27] refers to the suppression of final (and initial) state interactions of hadrons with the nuclear medium in exclusive processes at large momentum transfers. The phenomenon of CT occurs when exclusive processes proceed via the selection of hadrons in the so-called point-like-configuration (PLC) states. Furthermore, this small configuration should be 'color screened' outside its small radius and the compact size should be maintained while it traverses the nuclear medium. While nuclear filtering uses the nuclear medium actively, in CT large momentum transfers select out the short distance amplitude which are then free to propagate through the passive nuclear medium. The expansion time relative to the time to traverse the nucleus is an essential factor for the observation of the CT effect, based on the quantum diffusion model by Farrar *et al* [28]. Thus, while one expects to observe the onset of CT effect sooner in light nuclei compared to heavier nuclei, the large A limit provides a perturbatively calculable limit for the nuclear filtering effect. The experimental verification of the nuclear filtering effect would be a very interesting confirmation of this QCD based approach in the transition region. For a detailed discussion on the nuclear filtering effect and related subjects, we refer to a review article on the subject [29].

4. Deuteron photodisintegration

The deuteron photodisintegration reaction, $\gamma d \to pn$, is one of the simplest reactions for studying explicit quark effects in nuclei. In recent years, extensive studies of deuteron photodisintegration have been carried out at SLAC and JLab [24,30]. Figure 1 shows the scaled differential cross-section ($s^{11}\mathrm{d}\sigma/\mathrm{d}t$) from deuteron photodisintegration as a function of photon energy. The data seem to show scaling at 70° and 90°, and suggest the onset of scaling at higher photon energies at 52° and 36°. The threshold for this scaling behavior corresponds to a transverse momentum slightly over 1 GeV/c. Also shown in figure 1 are the QCD rescattering calculation [20,31] (shaded region), the quark gluon string model calculation (dashed line) [32,33], and an estimate from Radyushkin [34] (dash–dotted line) based on a quark-exchange picture. While none of the theories agree with all the data as well as one would like, they do indicate that quark models can approximately reproduce the cross-section data, therefore establishing the importance of deuteron photodisintegration process in the study of the transition region.

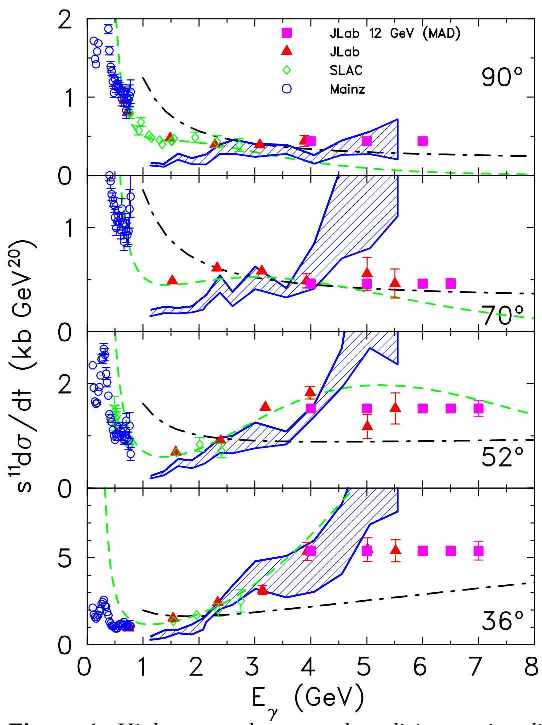

Figure 1. High energy deuteron photodisintegration differential cross-sections scaled by s^{11}. The projected results with MAD are shown as purple solid squares.

A recent polarization measurement on deuteron photodisintegration [35] disagrees with hadron helicity conservation at kinematics where quark counting behavior is observed in the differential cross-section. This is also supported by $^{1}H(\vec{\gamma},\vec{p})\pi^0$ [36], $d(e,e'\vec{d})$ deuteron tensor polarization T_{20} measurement [37], and the $p(\vec{e},e'\vec{p})$ measurement of the proton electric to magnetic form factor ratio [38]. At this point, it is extremely difficult to extend either the cross-section or the polarization measurements to higher energies at JLab with existing equipment. The planned medium acceptance detector (MAD) system in Hall A at Jefferson Lab for the 12 GeV energy upgrade will allow cross-section measurements to photon energies near 8 GeV (figure 1), and polarization measurements to about 4 GeV.

5. Nucleon photopion production

Nucleon photopion production processes ($\gamma n \to \pi^- p$, $\gamma p \to \pi^+ n$, $\gamma p \to \pi^0 p$) are essential probes of the transition from meson–nucleon degrees of freedom to quark–gluon degrees of freedom because of the simple valence quark structure of the pion. The cross-sections of these processes are also advantageous for the investigation of the so-called QCD oscillation because they decrease relatively slowly as energy increases compared with other photon-induced processes (quark counting rule predicts a s^{-7}-dependence for the differential cross-section). The relatively large cross-section at high energies will also allow the investigation of the t and p_{T} dependence of the scaling behavior in addition to the s dependence. Recent results from deuteron photodisintegration (E96-003) [24] have shown for the first time an angular dependent scaling onset in photoreactions and p_{T} seems to be the physical observable governing this onset. Therefore, it is important to test whether such angular dependent scaling onset exists in other photoprocesses. Moreover, photoreactions in nuclei allow the search for QCD nuclear filtering and color transparency.

The oscillatory scaling behavior, the anomalous spin-correlation coefficients from pp elastic scattering, and the unusual energy dependence of the nuclear transparency from the $A(p,2p)$ reaction have been discussed previously. An experiment studying whether there are similar phenomena in pion photoproduction (E94-104) was completed recently at Jefferson Lab. The results from E94-104 at 90° c.m. angle (figures 2 and 3), suggest an onset of scaling behavior around a center-of-mass energy of 2.5 GeV and show very interesting hints of possible oscillation in the scaled differential cross-section for the $\gamma n \to \pi^- p$ and $\gamma p \to \pi^+ n$ channels. While there is enormous interest in confirming whether the oscillatory scaling behavior observed in pp elastic scattering is a general feature of QCD in exclusive processes, there have also been efforts recently in understanding the precocious scaling observed in deuteron photodisintegration in terms of the parton–hadron duality (E94-110, E00-116) picture. Deviations (oscillations) from the pQCD counting rule above the resonance region can be shown in a model of a composite system with two spinless charged constituents [39], employing the so-called concept of ‘restricted locality’ of quark–hadron duality [40]. Therefore, precision measurements of these fundamental cross-sections would be a timely guide for theoretical efforts on this subject and would help understand the exact mechanism behind the scaling behavior observed in exclusive processes. An experiment (E02-010) [41] to perform a fine scan of the region between 2.3 GeV$< \sqrt{s} <$ 3.4 GeV with photopion production from nucleons was recently approved. With the upgrade of JLab energy to 12 GeV, these measurements can be extended up to $\sqrt{s}$ = 4.6 GeV, above the charm production threshold. Therefore, it is essential to test the interpretation that the observed oscillatory scaling behavior and the spin-correlation anomaly in pp elastic scattering arise from new charm resonance states.

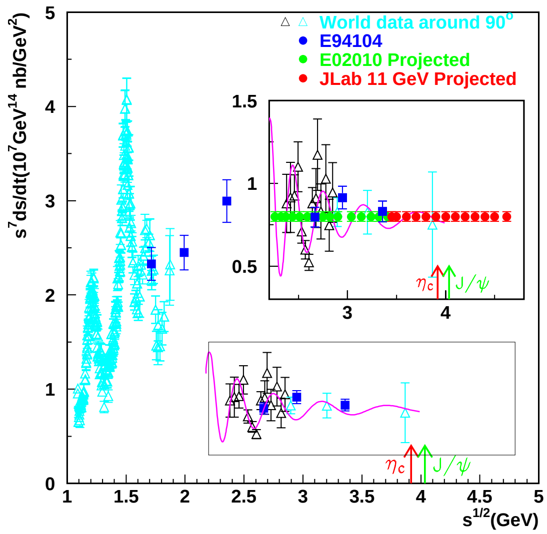

Figure 2. The scaled differential cross-section for the $p(\gamma,\pi^+)n$ process at a c.m. angle of 90°, as a function of c.m. energy, $\sqrt{s}$ in GeV. Projections for a 11 GeV beam are shown as red solid circles. The green solid circles are the projected results from E02-010 and the blue solid squares show the completed E94-104 data points. The purple solid line is a fit of the E94-104 data by Jain [42].

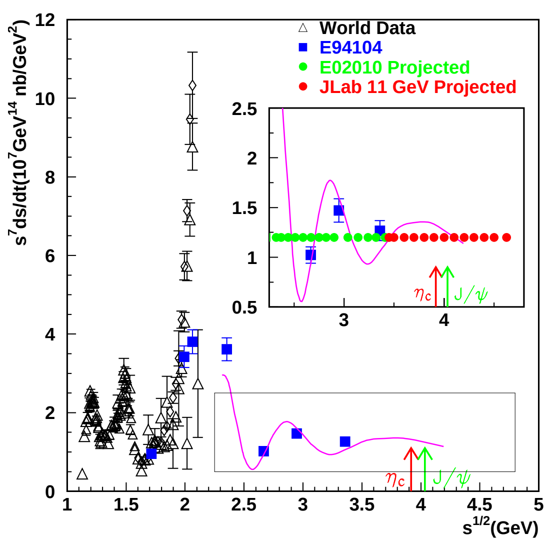

Figure 3. The scaled differential cross-section for the $n(\gamma,\pi^-)p$ process at a c.m. angle of 90°, as a function of c.m. energy, $\sqrt{s}$ in GeV. Projections for a 11 GeV beam are shown as red solid circles. The green solid circles are the projected results from E02-010 and the blue solid squares show the completed E94-104 data points. The purple solid line is a fit of the E94-104 data by Jain [42].

6. Pion photoproduction in the nuclear medium

Pion photoproduction in the nuclear medium is an integral part of the effort to map the transition from the strongly interacting, non-perturbative regime where the nucleon–meson degrees of freedom are relevant to the perturbative regime of QCD where quarks and gluons are the appropriate degrees of freedom. Photoproduction of pions in the nuclear medium is a natural extension of the program on pion photoproduction from nucleons, one of the important physics programs with a 12 GeV CEBAF. The observed global agreement with quark counting rules and the possible oscillatory scaling behavior will be investigated thoroughly with 11 GeV using photopion production processes from nucleons.

In the nuclear medium it has been suggested that long distance amplitudes are suppressed (nuclear filtering) by the strongly interacting nuclear environment [18,26]. This leads to the suppression of the oscillation phenomena arising from the interference of the long distance amplitude with the short distance amplitude (as seen in pp scattering, mentioned earlier) in nuclear medium. The experimental manifestation of this effect is predicted to be in the form of oscillations in nuclear transparency, which are 180° out of phase with oscillations in the scaled free differential cross-section. The experimental support for nuclear filtering comes from the nuclear transparency measurements using $A(p,2p)$ carried out at Brookhaven [16,17]. While nuclear filtering can explain the observed behavior [18,26], an alternative explanation put forward by Brodsky and de Teramond [25] involves new $c\bar{c}uuduud$ resonant states. Therefore, the experimental verification of the nuclear filtering effect would be a very interesting confirmation of this QCD-based approach in the transition region. The nuclear filtering effect can be studied with photopion production from nuclei such as ^{12}C. The preliminary results from the exploratory data taken on a ^{4}He target during E94-104 demonstrated the experimental technique. With JLab at 12 GeV these measurements in search of nuclear filtering can be extended beyond the charm threshold.

Color transparency (CT), discussed previously, is another phenomenon which can be studied with pion photoproduction in the nuclear medium. The expansion time relative to the time for hadron to traverse the nucleus is an essential factor for the observation of the CT effect, based on the quantum diffusion model [28]. Thus, while the large A limit provides a perturbatively calculable limit for the nuclear filtering effect, one expects to observe the onset of CT sooner in light nuclei compared to heavier nuclei. The preliminary E94-104 ^{4}He nuclear transparency results from the $\gamma n \to \pi^- p$ process at a 90° center-of-mass angle up to a center-of-mass energy of 3.0 GeV show a very intriguing momentum transfer dependence of the nuclear transparency. With a 12 GeV CEBAF and the upgraded detection system, the nuclear transparency of the $\gamma n \to \pi^- p$ process from ^{4}He can be extended to a $|t|$ value of $\sim$10 (GeV/c)^2. Such an extension allows detailed investigation of the onset of color transparency.

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