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# Photodisintegration of Light Nuclei

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**Abstract** Recent results of photodisintegration of deuteron and $^3$He measured with the CLAS at Jefferson Lab are reported. The onset of dimensional scaling is investigated in the two-body photodisintegration of $^3$He, with the results indicating a scaling onset at remarkably low energy and momentum transfer. Results on the beam-spin asymmetry of deuteron photodisintegration are expected to aid in understanding the dominant mechanisms of deuteron photodisintegration and the underlying dynamics in the medium-energy region. In this region, both effective field theories and pQCD cannot be used to describe the reaction, and understanding the underlying dynamics is based on phenomenological quark models.

**Keywords** Dimensional scaling · Constituent Counting Rules · Beam-spin Asymmetry

## 1 Introduction

Understanding the fundamental properties of the transition from the hadronic, which is well understood in the low-energy regime, to the partonic picture of nuclear interactions, has been a long standing problem of nuclear physics. Specifically, significant theoretical and experimental effort on describing nuclear structure in terms of the QCD degrees of freedom has been made. The transition region is typically identified and studied by searching for experimentally accessible phenomena that are predicted by QCD. One such phenomenon is dimensional scaling.

Dimensional scaling laws have been first derived in the framework of perturbative QCD (pQCD) and relate the energy dependence, $s$, at a high-momentum transfer of the invariant cross section to the number of elementary fields, $n$, that are involved in the interaction, $d\sigma/dt \propto s^{-n+2}$ [1]. The fundamental origin of the scaling is the scale invariance of the elementary interactions amongst hadron constituents, and therefore naturally reflects the property of asymptotic freedom of QCD at small distances.

A vast number of processes for a wide range of energies have been used to experimentally test the dimensional scalings laws. Even though dimensional scaling was justified only in the high-energy limit, $t \sim s \gg m^2$, there exists overwhelming evidence for the onset of scaling at energies much lower than those expected. Specifically, the majority of experimental data are consistent with dimensional scaling predictions at energies as low as 1 GeV. More recent theoretical efforts have shown that the scaling laws can also be derived non-perturbatively using the AdS/CFT correspondence between string theories in Anti-de-Sitter space-time and conformal field theories in physical space-time [2]. This derivation uses

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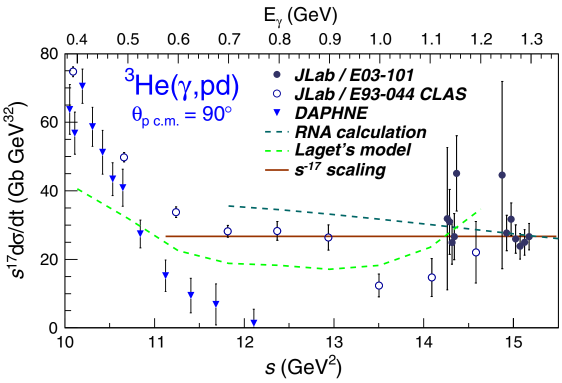


**Fig. 1** Differential cross section of the reaction $\gamma\ ^3\mathrm{He} \to pd$, at c.m. proton angle of 90°. The data are scaled by $s^{-17}$ to test predictions of dimensional scaling laws. Data shown are from CLAS E93-044 [6] (solid circles), Hall-A E03-101 [6] (open circles), and DAPHNE [7] (open triangles). The solid line corresponds to a linear fit to the data at $E_\gamma > 0.7GeV$, the dashed green line is a hadronic-model calculation [8], and the dashed blue line is calculations from pQCD inspired model [9].

the scale invariance of the interaction among hadron constituents at very large distance scales, in the so-called regime of *conformal window*, where the effective coupling is large but constant. Identifying the onset of quark-gluon dynamics in nuclei through some experimentally accessible phenomena aids in building a comprehensive picture of nuclei using the fundamental degrees of freedom of QCD.

Here we report measurements of the differential cross sections of two-body photodisintegration of $^3$He, $\gamma^3He \to pd$, and and of the beam-spin asymmetry of deuteron photodisintegration, $\vec{\gamma} d \to pn$. The data were collected at Jefferson Lab using the CEBAF Large Acceptance Spectrometer (CLAS) [3]. Experiment E93-044 [4] collected data using a circularly polarized photon beam incident on a 18-cm long cryogenic liquid $^3$He target. Data collected using a linearly polarized photon beam incident on a 40-cm long liquid deuterium target during the E06-103 [5] experiment were used for determining the beam-spin asymmetry. CLAS provided an efficient detection of the final state charged particles and allowed the determination of observables over a large fraction of the full solid angle. The sections below summarize the results from the two experiments.

## 2 Two-body photodisintegration of $^3$He

Predictions of dimensional scaling for the three-bound nucleon system were tested by studying the energy dependence of the reaction $\gamma\ ^3\mathrm{He} \to pd$. Cross sections for proton center-of-mass (c.m.) angles between 40° and 140° and photon beam energies between 0.4 and 1.5 GeV were determined. Initially, the study was focused on the 90° data, since onset of dimensional scaling is expected at reasonably large momentum transfers to both final state particles. CLAS data at proton c.m. angle 90° were recently published along with Hall-A data [6]. Figure 1 shows the energy dependence of the 90° scaled invariant cross section determined using the CLAS data along with data from experiments done at Jefferson Lab Hall-A and DAPHNE. The scaled invariant differential cross section decreases with energy up to $\sim 0.7$ GeV and seems to level out at higher energies, which is consistent with dimensional scaling laws. These laws were tested by fitting the $s$ dependence of the invariant differential cross section $d\sigma/dt$ to the function $d\sigma/dt = As^{-N}$, extracting in this way the scaling power $N$. Data from both CLAS and Hall-A experiments [6] were included in these fits. The analysis determined a scaling power of $N = 17 \pm 1$, which is well in agreement with the predictions of the dimensional scaling. The CLAS also allowed the determination of the invariant cross section at other c.m. angles, where no other measurements exist. Studies that aimed in identifying the energies at which dimensional scaling sets in were performed, showing that the threshold value of $s$ is mostly energy independent for this reaction and it sets in at photon energies between 0.6 and 0.8 GeV for all angles.

The onset of dimensional scaling at a proton c.m. angle 90° is observed at momentum transfer squared to the deuteron, $t = 0.64$ (GeV/$c$)$^2$, and proton transverse momentum of $p_\perp = 0.95$ GeV/$c$. These values are actually lower than the minimum values observed in other processes. The results on the onset of dimensional scaling of the reaction $\gamma\,^3\mathrm{He} \to pd$ qualitatively support the conformal window hypothesis, in which dimensional scaling is predicted due to the near constancy of the QCD coupling at very low momentum transfers.

Additional studies, using polarization observables can be performed to better understand the origin of dimensional scaling and the role of quarks and gluon in nuclear reactions in the GeV energy region. Deuteron photodisintegration has been the flagship process to investigate the role of quarks and gluons in nuclear reactions, since the deuteron is the simplest nucleus.

## 3 Deuteron photodisintegration

The transition region from the mesonic picture to the quark-gluon picture of nuclear interactions has been extensively studied in deuteron photodisintegration in the past 20 years by studying the onset of dimensional scaling of the differential cross section [12; 13; 14; 15; 16; 17; 18; 10]. There have been many attempts to theoretically describe the cross-section data of deuteron photodisintegration. The low-energy data are typically described using a conventional meson-baryon framework, whereas higher-energy data are expected to be described in the QCD framework. Data on the induced polarization, $p_y$, and polarization transfers, $C_x$ and $C_z$ [19; 20], indicate that pQCD alone does not provide a valid description of the reaction below 2.4 GeV. Therefore, theoretical studies have been focused on non-perturbative phenomenological models. The main models developed for deuteron photodisintegration are the reduced nuclear amplitudes model (RNA) [21; 22], the hard rescattering mechanism model (HRM) [23; 24; 25], and the quark-gluon string model (QGSM) [26; 27]. The HRM and QGSM are the only models that predict spin-dependent observables. On one hand, the HRM model can be characterized as a phenomenological extension of pQCD, whereas the QGSM is a purely non-perturbative partonic model.

The available models, and specifically the HRM and QGSM, are able to predict the dimensional scaling and describe the available differential cross-section data of deuteron photodisintegration with about the same degree of success. For this reason, additional constraints are needed to test the models under consideration. However, measurements on $p_y$, $C_x$, and $C_z$ did not allow detailed investigation of the underlying dynamics of deuteron photodisintgeration, and efforts were focused on the beam spin asymmetry, $\Sigma$ [28], which is more sensitive to reaction mechanisms. This is manifested in the differences between theoretical predictions of the QGSM [29] and HRM [30] which differ by about 40%.

An earlier measurement of the beam-spin asymmetry was carried out at Yerevan [31; 32] at incident photon energies between 0.8 and 1.6 GeV and proton c.m. angle restricted to 90°. Unfortunately, the higher photon-energy data are characterized by large uncertainties and therefore do not allow stringent tests of the mechanism of deuteron photodisintegration. Data collected using the CLAS improve sig-

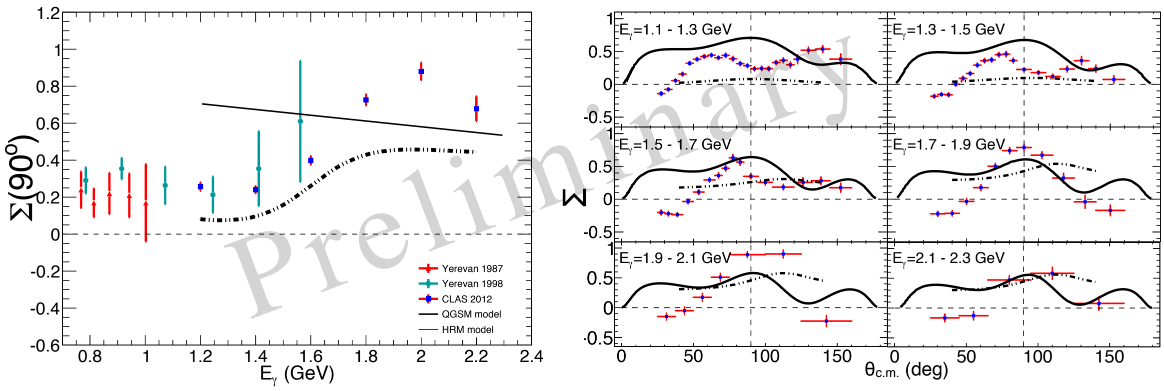


**Fig. 2** Energy (left) and angular (right) dependence of the beam-spin asymmetry of deuteron photodisintegration. Data shown are from CLAS [33] (blue), and Yerevan [31; 32] (red and cyan). Theoretical predictions of the QGSM and HRM are shown in solid and dashed lines respectively.

nificantly the kinematical coverage to proton c.m. angles between 35° and 145° and to photon energies up to 2.3 GeV [33]. Specifically, the beam-spin asymmetry was determined for six photon-energy bins between 1.1 and 2.3 GeV using a binned method. Data using linearly polarized photon beam were collected for two orientations of the photon polarization which enabled us to simplify the determination of the observable by reducing acceptance effects and associated systematic uncertainties. Figure 2 shows the energy dependence of the beam-spin asymmetry at a proton c.m. angle 90° (left), and the angular dependence for the six photon-energy bins (right). The blue points are the CLAS data. Red and cyan points are the Yerevan data [31; 32], whereas the solid and dotted-dashed line show the predictions of the QGSM and HRM respectively.

The energy dependence of $\Sigma$ suggests a transition from lower to higher values at photon energies between 1.6 and 2.0 GeV, which is predicted by the HRM model. Neither model predicts, however, the magnitude of $\Sigma$. The angular dependence of $\Sigma$ shows rich structure in the lower photon-energy bins. The high-energy photon data have simplified structures with single maxima at 90°. Overall, none of the two models is able to describe well the angular dependence of the CLAS data. The QGSM, however, seems to describe better the shape of the angular distributions. The CLAS results for $\Sigma$ extend significantly the existing database to broader kinematic range, improving at the same time the data precision. These data will be used to constraint the available theoretical models in an attempt to gain insight in the underlying dynamics of this process in the transition region.

## 4 Acknowledgments

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