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Hard Two-body Photodisintegration of ^{3}He

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We have measured cross sections for the $\gamma^3\text{He} \to pd$ reaction at photon energies of 0.4–1.4 GeV and a center-of-mass angle of 90°. We observe dimensional scaling above 0.7 GeV at this center-of-mass angle. This is the first observation of dimensional scaling in the photodisintegration of a nucleus heavier than the deuteron.

Dimensional scaling laws directly relate the energy dependence of the high-t invariant cross sections to the number of constituents of the hadrons involved in the process. The origin of dimensional scaling is the scale invariance of the interactions among hadron constituents, and, thus, it naturally reflects the property of asymptotic freedom of QCD at small distance scales. These laws state that at fixed center-of-mass (c.m.) angle, the cross section of an exclusive two-body-to-two-body nuclear reaction at large s (the total c.m. energy squared) and t (the four-momentum transfer squared) is

$$\frac{d\sigma}{dt} \propto s^{2-n_i-n_f} = s^{-n} \quad (1)$$

where n_i and n_f are the total number of elementary fields in the initial and final states that carry a finite fraction of particle momentum; *e.g.*, 3 for a nucleon. Table I presents the experimental evidence for the success of these scaling laws.

Reaction	s GeV^2	$\theta_{c.m.}$ deg.	n Predicted	n Measured	Reference
$pp \to pp$	15-60	38-90	10	9.7±0.5	[1]
$p\pi^- \to p\pi^-$	14-19	90	8	8.3±0.3	[2]
$\gamma p \to \gamma p$	7-12	70-120	6	8.2±0.5	[3]
$\gamma p \to \rho^0 p$	6-10	80-120	7	7.9±0.3	[4]
$\gamma p \to p\pi^0$	8-10	90	7	7.6±0.7	[5]
$\gamma p \to n\pi^+$	1-16	90	7	7.3±0.4	[6]
$\gamma p \to K^+\Lambda$	5-8	84-120	7	7.1±0.1	[7]
$\gamma d \to pn$	1-4	50-90	11	11.1±0.3	[8–15]
$\gamma pp \to pp$	2-5	90	11	11.1±0.1	[16]
$\gamma^3 He \to pd$	11-15.5	90	17	17.0± 0.6	(this work)

TABLE I. Selected hard exclusive hadronic and nuclear reactions that have been previously measured.

Dimensional scaling is well founded and expected at asymptotic energies, where the available energy in the c.m. is much higher than the mass of the system. Under these circumstances, the only scale available is the energy and the s dependence arises from the norm of the active fields. However, for some reactions, the data show evidence for dimensional scaling even when s is roughly equal to the squared mass of the system, as is the case reported here.

To date there is no common model or theory that can describe all the data listed in Table I in a consistent manner. For processes on nuclear targets, phenomenological extensions of pQCD based on factorization [17–19] have been developed and have shown limited success. A common feature of model interpretations of dimensional scaling, such as [20–22], is the dominance of a hard scattering mechanism in the reaction dynamics. It was, however, also discussed that soft QCD processes [23] or destructive interference among resonances [24] can mimic scaling at medium energies.

From the standpoint of a non-perturbative approach, the scaling laws have been reviewed and derived using the AdS/CFT correspondence between string theories in Anti-de Sitter space-time and conformal field theories in physical space-time [25]. Within this approach, the interactions between hadron constituents are scale-invariant at very short but also at very large distances in the so-called "conformal window" where the effective strong coupling is large but constant, *i.e.*, scale independent. Thus, dimensional scaling laws may be probing in fact the limits of two very different dynamical regimes of asymptotically large t and s, and of small t. In order to understand better the origin of scaling, we would need to also probe rigorously exclusive nuclear processes at very small t.

For reactions that are dominated by resonances, the study of scaling at smaller t is difficult since the resonances make it hard to determine whether scaling is being observed. We chose to probe dimensional scaling in the reaction $\gamma^3\text{He} \to pd$ in the photon energy range $0.4 - 1.4$ GeV. In this energy range, photoreactions on the proton and deuteron have shown signatures of scaling [6, 8–15], but their interpretation is unclear. This reaction has the advantage that resonance mechanisms are suppressed (as shown by low-energy studies) [26]. In addition, there is evidence that two- and three-body mechanisms are important at large c.m. angles, *i.e.*, the momentum transfer is shared among two or three nucleons so that the average momentum transfer to each quark constituent would be small (maybe in the range of the "conformal window"). No other study of dimensional scaling in an $A = 3$ system has been done before. Moreover, our measurement is the first of this reaction in the GeV energy region. As previous measurements of lepton-induced reactions have only involved $A = 1$ or 2, the expected quark-counting scaling power of $d\sigma/dt \propto s^{-17}$ is higher than any previous observation in photo- or hadronic reactions.

The data presented here were taken as part of Jefferson lab (JLab) Experiments 03-101 and 93-044, which ran at the continuous electron beam accelerator facility (CEBAF) in Hall A [27] and in Hall B [28], respectively.

E03-101 was a measurement of the $\theta_{c.m.} = 90^\circ$ energy dependence of the $^3\text{He}(\gamma, pp)n_{spectator}$ reaction [16]. At an incident electron energy of 1.656 GeV we also took data at two kinematical settings which did not match the $\theta_{c.m.} = 90^\circ$ condition for that reaction. In these two kinematics we could identify two-body photodisintegration of the ^{3}He into a proton and a deuteron at angles corresponding to $\theta_{p\ c.m.} = 85^\circ$.

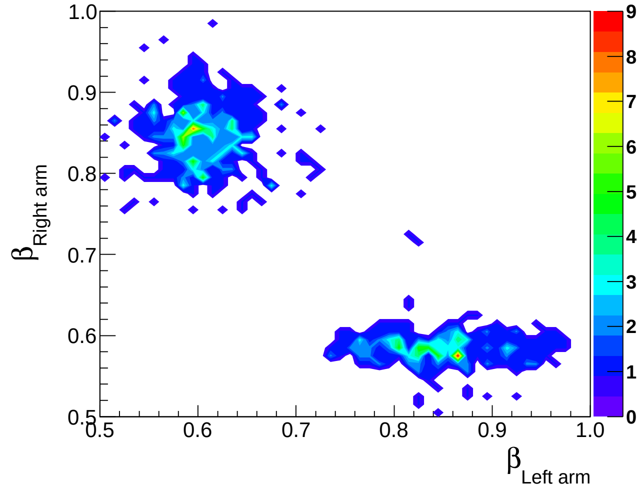

FIG. 1. (Color online) The β distribution of particles detected in coincidence by the two High Resolution Spectrometers in Hall A/E03-101. The widths of the peaks result from the calibration and time resolution of the scintillators, from the momentum acceptance of the spectrometers ($\Delta p \sim \pm 3.5\%$), and the uncertainty of the path-length correction. The different scintillators in the two spectrometers lead to different widths of the distributions.

In this experiment, untagged bremsstrahlung photons were generated when the electron beam of 1.656 GeV impinged on a copper radiator. The 6%-radiation-length radiator was located in the scattering chamber 38 cm upstream of the center of a 20-cm long cylindrical 0.079 g/cm^3 ^{3}He gas target. The size of the photon beam spot on the target, ∼2 mm, results from electron beam rastering intended to distribute the heat load across the target. The size of the target is much smaller than the ∼1-cm size of the target windows and apertures. Protons and deuterons from the target were detected in coincidence with the Hall-A high-resolution spectrometers (HRSs) [27]. The two spectrometers were set symmetrically on the two sides of the beam line in two kinematical settings corresponding to central momenta of 1.421 GeV/c at a scattering angle of 63.16° and 1.389 GeV/c at a scattering angle of 65.82°.

For each spectrometer, the scattering angles, momenta, and interaction positions at the target were reconstructed from trajectories measured with vertical drift chambers (VDCs) located in the focal plane. Two planes of plastic scintillators provided triggering and time-of-flight information for particle identification. Figure 1 shows the speed, β, of the two particles detected in coincidence. One clearly sees protons and deuterons in coincidence, with no visible backgrounds, such as pp and dd coincidences, or pions.

In analyzing the data from E03-101, the incident photon energy of the untagged beam was reconstructed event by event from the momentum and angles of the scattered particles under the assumption of two-body *pd* final-state kinematics. In order to assure the validity of this assumption and reduce backgrounds, the analysis is limited to events that fulfill two energy and momentum constraints:

1. $p_{T\,missing} \equiv p_{T(p)} + p_{T(d)} < 5$ MeV/c, and
2. $\alpha_{missing} \equiv \alpha_d + \alpha_p - \alpha_{^3He} - \alpha_\gamma < 5 \cdot 10^{-3}$.

where α is the light cone variable for each particle participating in the reaction:

$$\alpha_X = A\frac{E^X - p_z^X}{E^A - p_z^A} \approx \frac{E_X - p_z^X}{m_A/A}, \qquad (2)$$

where $A = 3$ is the mass number, E^X and p^X are respectively the energy and momentum of the particle, m_A, E^A and p^A are the nucleus mass, energy and momentum respectively, and the z direction is the direction of the incident photon beam. With the above definitions, α_γ is zero, while $\alpha_{^3\mathrm{He}}$ is 3.

Simulation of pion production with this process shows that with these cuts the contamination of non 2-body events is negligible.

The detected proton-deuteron pairs can result from either a photon or an electron disintegrating the ^{3}He nucleus. We took data with the radiator in and out of the beam, to extract the number of events resulting from photons produced in the bremsstrahlung radiator [12, 16]. Event selection cuts on the target vertex and coincidence between the two spectrometers were applied using the same techniques as [16]. The finite acceptance correction was determined using the standard Hall-A Monte-Carlo simulation software MCEEP [29].

The sources for the systematic uncertainties for E03-101 are described in [16]; for this analysis they are dominated by the finite acceptance correction, which is at the 4% – 11% level.

Experiment E93-044 used the CEBAF large acceptance spectrometer (CLAS) to measure various photoproduction reactions on ^{3}He and ^{4}He targets. A collimated, tagged, real-photon beam was produced using the bremsstrahlung tagging facility in Hall B [30]. Photons with energies between 0.35 and 1.55 GeV were incident on a 18-cm long cryogenic liquid ^{3}He target positioned in the center of the CLAS. The outgoing protons and deuterons were tracked in the six toroidal magnetic spectrometers (sectors) of the CLAS. Their trajectories were measured by three layers of drift chambers surrounding the target. Particle time of flight was measured by 6×57 scintillators (TOF) enclosing the CLAS outside of the magnetic field. The CLAS covers a polar angular range from 8° to 142° and an azimuthal angular range from 0° to 360°, excluding the angles where the torus coils are located. More details about the CLAS and experiment E93-044 can be found in [31] and [32], respectively.

In the analysis of data from E93-044, protons and deuterons were identified from momentum and time-of-flight measurements. Only events with one proton and one deuteron originating from the target were used for further analysis. Accidental and physics backgrounds were reduced by applying kinematic cuts making use of the constraints provided by two-body kinematics when both final-state particles are detected. A detailed discussion of the selection cuts can be found in [33].

Figure 2 demonstrates the effect of the kinematic cuts on the proton missing-mass-squared, MM_p^2, distribution at a proton c.m. angle of 90°. The proton missing-mass-squared is calculated as $MM_p^2 = (\tilde{p}_\gamma + \tilde{p}_{^3\mathrm{He}} - \tilde{p}_p)^2$, where $\tilde{p}_\gamma$, $\tilde{p}_{^3\mathrm{He}}$, and $\tilde{p}_p$ are the four-momentum vectors of the beam, target, and detected final-state proton, respectively. The initial event distribution, before our kinematic cuts are applied, shows a well pronounced peak at around 3.5 (GeV/c^2)^2 (which corresponds to the square of the deuteron mass), followed by a broader structure above 3.8 (GeV/c^2)^2. While the peak contains predominantly the *pd* events of interest, the broader structure contains background events produced in the reaction $\gamma^3\mathrm{He} \to pdX$, where X could be one or more missing particles. One could see that the low-mass tail of the background events extends under the *pd* peak. Our kinematic cuts select the good *pd* events from the initial sample and reject background events. For simplicity, in Fig. 2 we show the events rejected by our kinematic cuts overlaid with the initial distribution. These background events exhibit smooth behavior under the deuteron peak and reproduce the background shape outside of the peak, as expected. The uncertainty of the yield extraction due to the remaining background events is (2.30 ± 0.63)%.

The CLAS acceptance for the reaction $\gamma^3\mathrm{He} \to pd$ was evaluated by generating 2×10^7 phase-space events and processing them through GSIM [34], a GEANT-3 program that simulates the CLAS. The CLAS acceptance for *pd* events at a c.m. angle of 90° is ~ 71%. The systematic uncertainty of the acceptance is < 10%. The photon flux was calculated using the standard CLAS software [35] and has an uncertainty of 4.5% [36]. The uncertainty of the target length and density was 2% [32]. The total systematic uncertainty of the CLAS cross sections is < 11.4%, with the CLAS acceptance being the dominant source. The statistical uncertainties range from 2% to 40% depending on the energy bin. Full details about the analysis of the CLAS data can be found in [33].

Figure 3 shows the resulting cross sections from CLAS and Hall A compared to previously published data [37] for $s >$10 GeV^2. In the range of $s = 11.5 - 15$ GeV^2, the cross section falls by two orders of magnitude. The falloff of our Hall-A and CLAS data is fit as $s^{-17\pm0.6}$, which is consistent with the expected scaling degree of $n = 17$. This is the first observation of high-energy cross-section

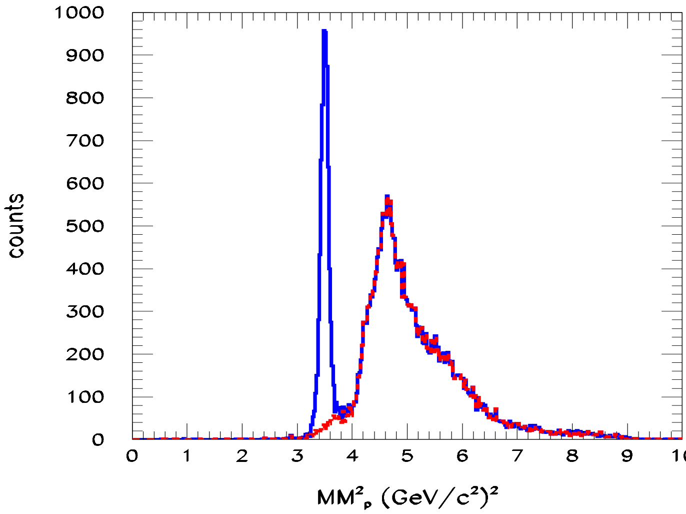

FIG. 2. (Color online) Event distributions measured by CLAS, of the missing-mass of the proton, MM_p^2 for proton c.m. angle of 90°, with (dashed red line) and without (blue solid line) the kinematic cuts, are shown. Events from the pd final state are clearly identified in the peak. Accidental and multipion events give rise to the background. The background distribution (events rejected by the kinematic cuts) exhibits smooth behavior under the deuteron peak and reproduces nicely the background shape outside of the peak.

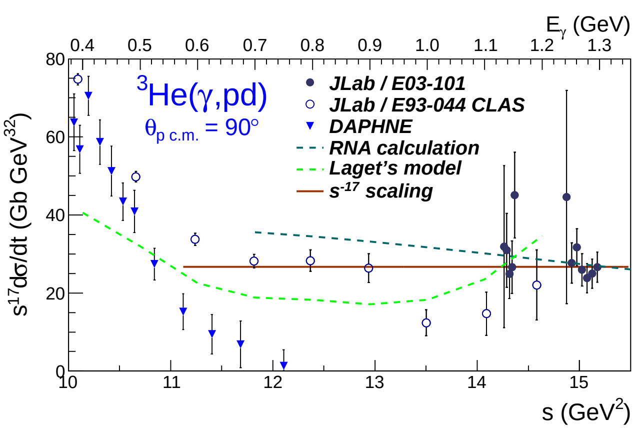

FIG. 3. The invariant cross section $d\sigma/dt$ multiplied by s^{17} to remove the expected energy dependence. The DAPHNE data is taken from [37]. The RNA [17] calculation is normalized to our highest energy data point from JLab/E03-101. The prediction of Laget is based on a diagrammatic hadronic model [38]. For a comment on the comparison between the CLAS and DAPHNE data see [39].

scaling for photodisintegration of an $A > 2$ system. We note that our data point at $s \sim 13.5$ GeV^2 is about 3.5 standard deviations below the scaling prediction. Due to the limited statistics we have in this kinematic bin we cannot study in further detail whether the origin of this deviation is random or is due to physics.

Starting at threshold, the scaled invariant cross section, $s^{17}d\sigma/dt$, decreases smoothly to E_γ=0.7 GeV where it levels out, a transition different from meson photoproduction [6] or pp breakup [16], where "resonance-like" structures are observed. Since our data are taken in the resonance region (at $W < 2$ GeV, where W is the total center-of-mass energy in the initial state assuming a free nucleon target), this suggests that two- and three-nucleon mechanisms dominate the reaction dynamics or nucleon resonance contributions are strongly suppressed.

The scaled cross section of ~30 Gb·GeV^{32} corresponds to an invariant cross section of $d\sigma/dt \sim 0.4$ nb/GeV^2 for $E_\gamma \sim 1.3$ GeV. The corresponding cross section for $\gamma d \to pn$ at this energy is about 30 nb/GeV^2, about two orders of magnitude larger, while the scaled cross section for $\gamma{}^3\text{He} \to pp + n_{spectator}$ at this energy is about 13 nb/GeV^2, about 30 times larger. If one adopts the view that large momentum transfer reactions select initial states in which all the quarks and nucleons are close together, it is much more likely that there is a short-range, and thus high-momentum, pn pair than pp pair. This is what has been found in recent studies for nucleons above the Fermi surface that have momenta of several hundred MeV/c [40, 41]. Furthermore, in ^{3}He there is nearly as large a probability for a short-range pd pair as for a pp pair [42].

The reduced nuclear amplitudes (RNA) prescription [17] was developed as a way of extending the applicability of pQCD to lower energy and momentum scales, by factoring out non-perturbative dynamics related to hadron structure through phenomenologically determined hadronic form factors. It should be noted that deuteron photodisintegration follows the dimensional scaling better than it follows the RNA prediction [14]. The RNA prescription for $\gamma{}^3\text{He} \to pd$ is:

$$\frac{d\sigma}{dt} \propto \frac{1}{(s - m_{^3\text{He}}^2)^2} F_p^2(\hat{t}_p) F_d^2(\hat{t}_d) \frac{1}{p_T^2} f^2(\theta_{c.m.}). \quad (3)$$

Here F_p (F_d) is the proton (deuteron) form factor, $\hat{t}_p$ ($\hat{t}_d$) is the momentum transfer to the proton (deuteron) and f is an unknown function of the c.m. angle that must be determined from experimental data. The overall normalization is also unknown, and ideally should be determined from data at asymptotically large momentum transfer. Figure 3 shows the RNA prediction, normalized to our highest energy data point from E03-101. The experimental data appear to agree better with dimensional scaling than with the RNA prediction.

If the reaction dynamics are dominated by nucleon rescattering, it appears that hard pn rescattering is more likely than hard pp rescattering – which is known to be the case from cancellations in the pp amplitude [19], and that hard pd rescattering is also suppressed, due to the likelihood of breaking up the deuteron in a hard scattering and the small probability of a pickup reaction that create a deuteron from a scattered proton or neutron.

Calculation of the cross section in the framework of the Hard Rescattering Model (HRM) [18] using elastic *pd* scattering data is in preparation [43].

The model of Laget [38] is a hadronic model based on a diagrammatic approach for the calculation of the dominant one-, two-, and three-body mechanisms contributing to the reaction. This calculation provides good accounting of the absolute magnitude of the cross section and reproduces the scaling exhibited by the data over a limited energy range. Overall, the data appear to agree better with dimensional scaling than with the model.

We observe the onset of scaling at $\theta_{c.m.} = 90^\circ$ at a momentum transfer to the deuteron $|t| > 0.64$ (GeV/c)^2 and a transverse momentum $p_\perp > 0.95$ GeV/c. These momentum thresholds for scaling are remarkably low. For other processes, such as deuteron photodisintegration, the onset of scaling has been observed at $p_\perp > 1.1$ GeV/c [8–15]. Both the deuteron form factor and the reduced deuteron form factor [17] show scaling at $|t| > 2$ (GeV/c)^2. This comparison suggests that non-perturbative interpretation of our data may be more appropriate. Such interpretation in the framework of AdS/CFT means that the observed scaling is due to the near-constancy of the effective QCD coupling at low Q ("conformal window" [44]) and we are in the non-perturbative regime of QCD. A further test of this interpretation would require data for this process over a higher-energy range where the transition from non-perturbative to perturbative dynamics would manifest itself in breaking dimensional scaling. The latter would be observed again at asymptotically large invariants when pQCD sets in.

Our result not only indicates that dimensional scaling is a feature of non-perturbative strong dynamics, but also that QCD studies of nuclei are meaningful at energies as low as $E_\gamma = 0.7$ GeV and that the three-nucleon bound system may be an equally good laboratory for such studies as the deuteron. Moreover, since the cross section for our process had been previously measured down to beam energies of a few MeV, our data combined with the low-energy data allow to map for the first time the transition from meson-nucleon to partonic degrees of freedom cleanly, without the complication of resonance structures, as has been the case in previous studies involving $A = 1$ or A=2 nuclear systems.

We have observed for the first time scaling in an exclusive reaction initiated by a photon beam and involving an $A = 3$ nucleus, the two-body photodisintegration of ^{3}He. The scaling power of s^{-17} for $E_\gamma > 0.7$ GeV, is the highest quark-counting power-law dependence observed to date in leptoproduction. This is only one of a few examples of scaling in a nuclear photoreaction, and it remains unclear whether there is any unified explanation for the various onsets of scaling in the different photoreactions. If AdS/CFT correspondence is the proper framework to understand the origin of dimensional scaling, then the observed scaling is a result of the near-constancy of the QCD coupling. This assumption may be validated through the study of this reaction in a higher energy range.

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