Two-Body Photodisintegration of the Deuteron up to 2.8 GeV

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Measurements were performed for the photodisintegration cross section of the deuteron for photon energies from 1.6 to 2.8 GeV and center-of-mass angles from 37° to 90°. The measured energy dependence of the cross section at $\theta_{\text{c.m.}} = 90°$ is in agreement with the constituent counting rules.

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One of the most intriguing issues in nuclear physics is whether perturbative quantum chromodynamics (pQCD) is applicable to exclusive nuclear reactions at energies of a few GeV. While it is widely believed that pQCD is applicable at sufficiently high energies, the reason that exclusive reactions appear to be well described by the constituent counting rules [1,2] remains uncertain. Exclusive photo-reactions in few-body systems are well suited to address this question because large momentum transfers to the constituents can be obtained with photon energies of only a few GeV [3]. Previous studies [4,5] of deuteron photodisintegration suggested the onset of asymptotic scaling near a photon energy of 1.5 GeV, although agreement with the constituent counting rules was observed only over a small energy interval from 1.4 to 1.8 GeV. Furthermore, the data from 0.8 to 1.6 GeV were consistent with another QCD-based approach, the reduced nuclear amplitude analysis [6] discussed below. Here we report data up to a photon energy of 2.8 GeV as a test of the asymptotic models.

For a pQCD description of these reactions to be valid, the amplitudes must be dominated by short range processes involving hard gluon exchanges between quarks. Thus the observation of constituent counting rule behavior in reactions on the deuteron is particularly surprising, considering that the nucleon-nucleon interaction has a hard core. Thus far, experimental observation of scaling according to the constituent counting rules has been limited to systems involving free hadrons and mesons, but not nuclei. Exclusive photo-reactions for the proton appear to scale according to the constituent counting rules above 2 GeV [7]. Furthermore, high energy nucleon-nucleon reactions appear to scale according to the constituent counting rules above energies larger than the nucleon masses [8]. Thus data above a photon energy of 2 GeV are crucial.

The constituent counting rules [1,2] predict that the differential cross section $d\sigma/dt$ should scale with energy as $1/s^{n-2}$, where s is the square of the center-of-mass energy and n is the total number of pointlike constituents involved in both the initial and final states of the reaction. For the $\gamma d \rightarrow pn$ reaction, we expect that when scaling is achieved, the cross section will have the form

$$\frac{d\sigma}{dt} = \frac{h(\theta_{\text{c.m.}})}{s^{11}}, \tag{1}$$

where a calculation of the function $h(\theta_{\text{c.m.}})$ requires a model of the dynamics. Traditionally, experimental evidence for asymptotic scaling in exclusive reactions consists of two tests: (i) whether the data obey the constituent counting rules [1,2] and (ii) whether hadron helicity conservation [9] is satisfied. No polarization data exist for high energy photo-reactions to date, and all investigations have focused on cross section measurements.

Because the momentum transfer per quark is relatively small (<1 GeV$^2/c^2$) for existing elastic e^-d scat-

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tering data, the counting rules are not expected to apply. Brodsky and Chertok introduced the reduced nuclear amplitudes (RNA) approach [10] to circumvent the problem. Indeed the counting rules do not work for the existing $e^- d$ cross section which extends up to 4 GeV [11]. In the RNA analysis, the amplitude is described in terms of quark interchange between the two nucleons; furthermore, the soft components responsible for quark binding within the nucleons are removed by dividing out the empirical nucleon form factors so that the RNA approach is expected to provide a better description of reactions at intermediate energy. Following its dramatic agreement with the elastic $e^- d$ scattering cross section [11] from 1 to 4 $(\mathrm{GeV}/c)^2$, Brodsky and Hiller [6] applied the RNA approach to the $\gamma d \rightarrow pn$ reaction. In this case, one has

$$\frac{d\sigma}{d\Omega_{\mathrm{c.m.}}} = \frac{1}{[s(s - m_d)]^{1/2}} F_p^2(\hat{t}_p) F_n^2(\hat{t}_n) \frac{1}{p_T^2} f^2(\theta_{\mathrm{c.m.}}), \quad (2)$$

where the $F_N(\hat{t}_N)$ are the nucleon form factors evaluated at the average four-momentum transfer to the outgoing nucleons, p_T^2 is the transverse momentum, and $f(\theta_{\mathrm{c.m.}})$ is the reduced nuclear amplitude. If the RNA approach applies, the angular dependence is given by the nucleon form factors and the energy independent function $f^2(\theta_{\mathrm{c.m.}})$. Presently, the reaction $\gamma d \rightarrow pn$ provides the only other test of the RNA approach over a wide range of momentum transfers.

As an alternative to the QCD-based models, T.-S. H. Lee [12] and S. I. Nagornyĭ *et al.* [13] have performed meson-exchange calculations for the $\gamma d \rightarrow pn$ reaction. Although traditional meson-exchange models [12,14,15] describe the data rather well below a photon energy of 1 GeV, the extension of these models to higher energies is problematic because of the large number of heavy resonances that can contribute and the need to include relativistic effects.

The present experiment was performed in End Station A at the Stanford Linear Accelerator Center, using a technique similar to that of earlier work [5]. Electron beams from the NPI injector were accelerated to energies from 1.6 to 2.8 GeV and passed through a removable copper radiator 0.086 cm thick to produce a beam of bremsstrahlung photons. The uncollimated photons and remaining electron beam then passed through a 15 cm long cryogenic liquid deuterium target, as shown in Fig. 1. Charged particles from the target were detected in the 8 GeV/c spectrometer by an array of plastic scintillators and a set of ten wire chambers. Protons were easily separated from deuterons (produced in the Al target windows) with a time-of-flight system. Both e^+ and π^+ trigger rates were negligible.

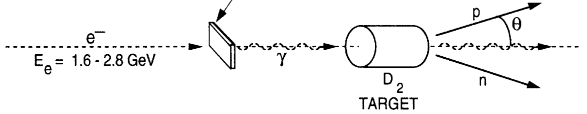

FIG. 1. The target region showing the bremsstrahlung radiator, the deuterium target, and the spectrometer pivot.

In addition to photo-protons from $d(\gamma, p)n$, there were several sources of background protons: electrodisintegration of the deuterium target, events from the target windows, and photo-reactions with pion production, such as $d(\gamma, p)n\pi^0$. Contributions from the target windows were removed by subtracting the results obtained with a liquid hydrogen target of identical dimensions. The yield from electrodisintegration was measured by repeating the procedure without the radiator present. This background was subtracted from the photodisintegration yield with an energy-dependent weighting function to account for the modification of the electron beam's flux and energy distribution by the radiator. Events with pion production were excluded by accepting only the photo-protons with the highest momenta. Finally, the bremsstrahlung photon's energy was calculated from the proton's momentum and scattering angle. The overall normalization of the incident photon flux was calculated to within 3% with the thick-target bremsstrahlung computer codes of Matthews and Owens [16], and independently with a code developed at Caltech [17]. The solid angle of the spectrometer was calibrated to 3% using the $^1\mathrm{H}(e, e'p)$ and $^1\mathrm{H}(e, e'p)$ reaction, and is consistent with detailed simulations of the spectrometers [18]. The measured cross sections appear in Table I.

It is convenient to discuss the results in terms of the quantity $s^{11} d\sigma/dt$, which should approach a constant value at fixed $\theta_{\mathrm{c.m.}}$ according to the constituent counting rules. This quantity is plotted versus E_γ in Fig. 2(a) for the $\theta_{\mathrm{c.m.}} = 90°$ data, along with lower energy measurements. The data are consistent with the scaling behavior suggested by the previous measurements [4,5] above $E_\gamma = 1.0$ GeV. Fitting the available data above $E_\gamma = 1.15$ GeV with the form $d\sigma/dt \propto 1/s^n$ yields $n =$

TABLE I. Average photon energy, center-of-mass angle, and center-of-mass cross section and total uncertainty. Statistical and systematic errors have been added in quadrature.

E_γ (GeV)	$\theta_{\mathrm{c.m.}}$ (deg)	$d\sigma/d\Omega$ (nb/sr)	Uncertainty (nb/sr)
1.522	84.2	3.8	0.5
1.539	52.5	5.6	0.7
1.543	36.7	10.9	1.1
1.934	88.3	1.0	0.2
1.956	52.6	1.6	0.3
1.961	36.7	3.3	0.5
2.321	89.4	0.27	0.05
2.343	52.6	0.43	0.08
2.344	36.8	1.2	0.2
2.721	89.4	0.08	0.02
2.748	36.8	0.5	0.1

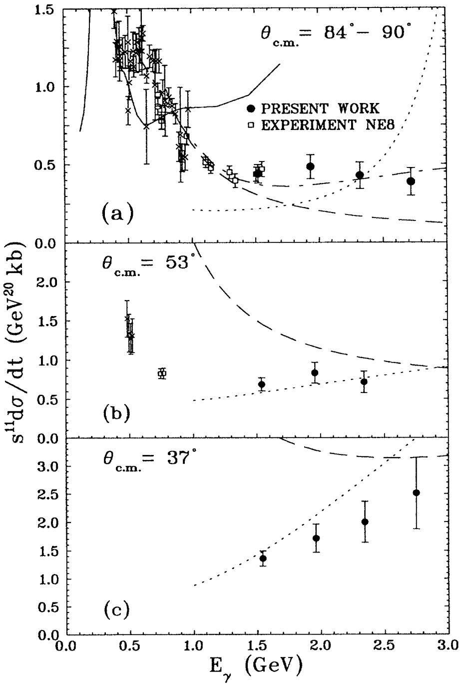

FIG. 2. $s^{11}d\sigma/dt$ vs E_γ for (a) $\theta_{\mathrm{c.m.}} = 90°$, (b) $\theta_{\mathrm{c.m.}} = 53°$, and (c) $\theta_{\mathrm{c.m.}} = 37°$. The present work is plotted as circles, and earlier data are plotted as squares [5] and crosses [19–22]. The dashed curve represents the reduced nuclear amplitudes analysis, the dotted line is the QGS model, the dot-dashed line is from [13], and the solid line is a traditional meson-exchange calculation, as discussed in the text.

11.2 ± 0.2, in good agreement with the counting rules. The dashed line in Fig. 2(a), representing the RNA analysis, was calculated from Eq. (2) using a value of $f^2(\theta_{\mathrm{c.m.}})$ chosen to agree with a data point at $E_\gamma = 0.8$ GeV. This curve falls below the high E_γ data, and does not reach an asymptotic limit at these energies.

The dot-dashed line, taken from [13], was calculated without including subnucleonic degrees of freedom, and is in good agreement with the data above $E_\gamma = 0.6$ GeV. Nevertheless, the calculation is normalized to the data at 1 GeV, and the energy dependence is determined by an arbitrary parameter. Recently, Kondratyuk *et al.* [23] have applied a quark-gluon string model (QGS) and Regge phenomenology to the reaction $\gamma d \rightarrow pn$ (dotted line). The calculation at 90° is constrained by data at other angles, although there are a large number of free parameters. The model exhibits scalinglike behavior over a limited region of s, however, there is strong disagreement with the data at the highest energy. The solid line represents Lee's meson-exchange calculation [12], which is a traditional calculation that reproduces the measured *NN* phase shifts up to 2 GeV and is also constrained by photo-meson production data. Below 500 MeV the calculation gives a reasonable description of the data, but above 1 GeV the calculation disagrees with both the energy and angular dependence. At the other two angles the calculation is off scale.

The data at $\theta_{\mathrm{c.m.}} = 53°$, shown in Fig. 2(b), are also consistent with the quark counting rules. A fit to the scaling behavior from 1.54 to 2.34 GeV gives $n = 10.6 \pm 0.6$. The data are also consistent with the QGS model (dotted line). The dashed line represents the RNA calculation with the same normalization as the 90° data. Because calculations of $f^2(\theta_{\mathrm{c.m.}})$ are not yet reliable, we choose $f^2(\theta_{\mathrm{c.m.}}) \equiv$ constant and concentrate on the energy dependence of the fixed-angle cross sections.

At $\theta_{\mathrm{c.m.}} = 37°$ the quantity $s^{11}d\sigma/dt$ is a rising function of energy [Fig. 2(c)], and a fit to the scaling behavior gives $n = 9.5 \pm 0.4$. Both the RNA calculation and QGS calculation predict too large a cross section. The 37° data all correspond to transverse momenta of less than 1 $(\mathrm{GeV}/c)^2$ to the outgoing neutron. The lack of scaling behavior here is consistent with a threshold in the applicability of scaling behavior at a p_T^2 of approximately 1 $(\mathrm{GeV}/c)^2$.

The results reported here demonstrate that at $\theta_{\mathrm{c.m.}} = 90°$ the cross section for the process $\gamma d \rightarrow pn$ is in good agreement with the constituent counting rule predictions for incident photon energy greater than 1.5 GeV. Although this is qualitatively similar to measurements of other electromagnetic processes on elementary systems at energies of several GeV, it is in sharp contrast to elastic electron-deuteron scattering where the asymptotic region has not yet been reached and the data are well described by the RNA approach. The present data disagree with the RNA approach at all three reaction angles. Whether the observed scaling at intermediate energy in exclusive reactions is indeed attributable to pQCD is still under debate [24]. Further insight into this question may be obtained with cross section measurements at higher energy [25] and from measurements of polarization observables in this reaction [26].

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