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Deuteron Photodisintegration: New Results from TJNAF

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Abstract

The first measurements of the differential cross section from $d(\gamma, p)n$ up to 4.0 GeV were performed at the Thomas Jefferson National Accelerator Facility (TJNAF, formerly CEBAF). Bremsstrahlung photons from electron beam impinging on a copper radiator and a liquid deuterium target were employed for this experiment. The experiment was performed in Hall C where the photoprotons at forward angles in the center-of-mass were detected in the High Momentum Spectrometer (HMS) and photoprotons at backward angles were detected in the Short Orbit Spectrometer (SOS). The bremsstrahlung photon energy was reconstructed

from the measured proton momentum and angle using the two-body kinematics. We report the cross section results at the proton center-of-mass angles of 37° and 90°. These results are in good agreement with previous lower energy measurements. The 90° data continue to show the constituent-counting-rule behavior up to 4 GeV. The results will be compared with models based on QCD as well as those based on meson-exchange theory.

Introduction

One of the very important questions in nuclear physics is when it is justified to make a transition from meson-nucleon degrees of freedom to quark-gluon degrees of freedom in the description of a nuclear reaction. A possible signature for this transition is that the reaction cross section scales[a] at some high energy. If scaling were indeed observed, characterization of the approach would be important to understand how the dynamics is simplified. High energy two-body photodisintegration of the deuteron ($\gamma d \to pn$) is particularly well suited for these studies because it is amenable to theoretical calculation and relatively high momentum transfer to the constituents can be achieved at relatively modest photon energies[1].

For the exclusive two-body scattering process A+B → C+D at high energy and large transverse momentum, dimensional analysis predicts the following constituent counting rule for the differential cross-section[2]:

$$\frac{d\sigma}{dt} \propto s^{-(n-2)}, \tag{1}$$

where s and t are the Mandelstam variables, and n is the total number of elementary fields (photon, quark, etc.,) in the initial and final states. The constituent-counting-rule behavior has been observed in exclusive processes such as proton-proton scattering[3]. One of the very important questions in nuclear physics is whether nuclear reactions obey any scaling at high energy and large transverse momentum. For the $d(\gamma,p)n$ process, the constituent counting rule predicts:

$$\frac{d\sigma}{dt} \propto s^{-11}. \tag{2}$$

Fig. 1 shows the previous data for this reaction at $\theta_{c.m.} = 90°$ of $s^{11} d\sigma/dt$ as a function of the photon energy. The SLAC NE17[4] and NE8[5] measurements are shown as the open circle and the open triangles, respectively. All the other data are from reference [6]. These data

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[a] Scaling in this context implies a dependence on a reduced set of kinematic variables indicating a simplification of the reaction dynamics.

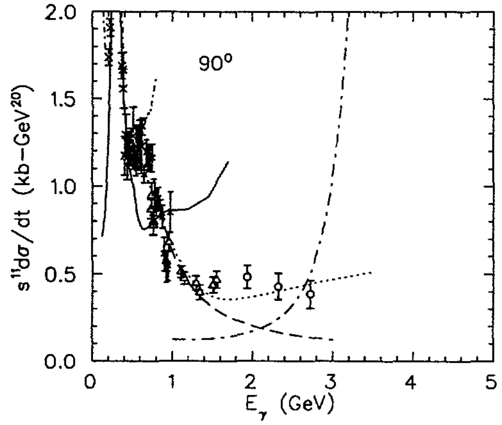

Figure 1: Existing data on deuteron photodisintegration as a function of the photon energy at $\theta_{c.m.} = 90°$. The open circles are the SLAC NE17 data, the open triangles are the SLAC NE8 data, and the crosses are all the other existing data. The solid line is a Lee's traditional meson-exchange calculation, and the short dash-dotted line is Laget's meson-exchange model calculation. The dashed line is a reduced nuclear amplitude calculation, the dotted line is Nagornyi's calculation and the dash-dotted line is the quark gluon string model calculation.

indicate scaling behavior starting at photon energies around 1 GeV, corresponding to proton transverse momenta of ~ 1.0 GeV/c. The solid line represents Lee's meson-exchange calculation[7], which is a traditional calculation that reproduces the measured NN phase shifts up to 2.0 GeV and is also constrained by photomeson production data. Below 500 MeV the calculation gives a reasonable description of the data, but above 1.0 GeV the calculation disagrees with the data. The short dash-dotted line is Laget's meson-exchange model calculation[8], which is in good agreement with Lee's calculation in the resonance region. The dashed line represents a reduced nuclear amplitude (RNA) calculation[9] with a normalization factor chosen to agree with a datum 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 asymtotic meson-exchange model approach by Nagornyi *et al.* [10] is shown as dotted line. While this calculation predicts different scaling behavior for the differential cross section than that from the constituent counting rule, it describes the data reasonably well in the photon energy region between 1.0 and 3.0 GeV. The long-dashed line shows the quark-gluon string (QGS) model calculation by Kondratyuk *et al.* [11], which is a calculation based on the Regge phenomenology and is expected to be only valid at most forward angles.

Fig. 2 shows a similar plot of the SLAC NE17 data[4] at $\theta_{c.m.} = 37°$. The dashed line and the dash-dotted line represent the RNA and the QGS calculations, respectively. The experimental uncertainties preclude any conclusion with regard to the scaling behavior in the photon energy range below 3 GeV.

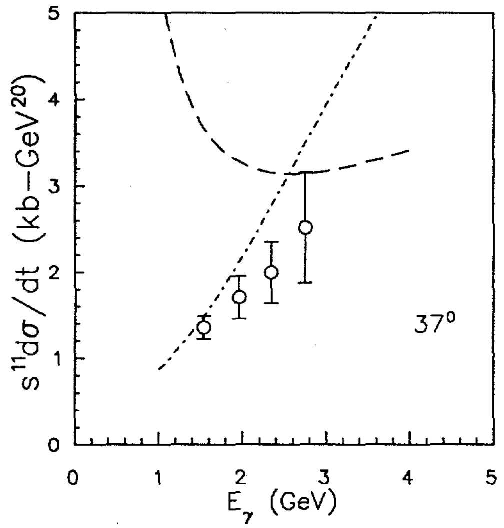

Figure 2: Existing data on deuteron photodisintegration as a function of the photon energy at $\theta_{c.m.} = 37°$ from the SLAC NE17 experiment. The dashed line and the dash-dotted line represent the RNA and the QGS calculations, respectively.

Experimental Overview

In the present experiment (TJNAF E89-012) an untagged bremsstrahlung photon beam was incident on a cryogenic liquid deuterium target. The bremsstrahlung photons are produced by an electron beam incident on a copper radiator. Photoprotons are detected using a magnetic spectrometer. Since the $\gamma d \rightarrow pn$ reaction is a two-body process, the photon energy can be reconstructed by detecting the final state proton momentum and scattering angle. Events with pion production can be excluded by accepting only the protons with the highest momentum. The advantage of using an untagged bremsstrahlung photon beam near the end point is a photon flux that is several orders of magnitude higher than that of a tagged photon beam. This is very important for extending the measurement to higher energies because the cross section falls off very rapidly as the beam energy increases.

Experiment E89-012 was performed in Hall C at the Thomas Jefferson National Accelerator Facility (formerly CEBAF) in the spring of 1996. A 20 μA continuous (CW) electron beam at beam energies of 0.845 to 4.045 GeV in steps of 0.8 GeV was used. A 15-cm liquid deuterium target and a 6% copper radiator were employed for the experiment. The high momentum spectrometer (HMS) was used to detect protons at forward angles in the center-of-mass system and the short orbit spectrometer (SOS) was used for the backward angles. Both spectrometers have similar detector systems. Plastic scintillators were used to form the triggers and also to provide the time-of-flight information for particle identification. Drift chambers were employed for measuring the particle momentum and scattering angle. In addition, a gas Čerenkov counter and a shower counter were part of the detector system for particle identification. This experiment had good overlap with the previous SLAC measurements [4] [5]. It not only extended the measurements to higher energies (4.0 GeV), but also had a more complete angular coverage.

Data Analysis

As was discussed earlier the photon energy can be reconstructed from the two-body kinematics by detecting the final state proton momentum and angle. Thus, it is important to distinguish protons from pions and deuterons. For a proton momentum less than 2.7 GeV/c, a time-of-flight (TOF) cut was sufficient to separate protons from pions and deuterons. For a proton momentum larger than 2.7 GeV/c, time-of-flight together with a gas Čerenkov counter provided the required proton/pion separation and the deuteron (TOF) rejection. In addition to the particle identification, reliable cuts on the reconstructed spectrometer quantities, both at the target and the focal planes, were applied. Background contributions from the target windows were removed by placing cuts on the reconstructed target position and subtracting the results obtained with a hydorgen target cell 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 a correction factor taking into account the modification of the electron beam's flux and energy distribution by the radiator [12].

Preliminary Results

To obtain the differential cross-section from the measurements, protons in the reconstructed photon energy bin of $E_0 - 85$ MeV $\leq$ E_γ $\leq$

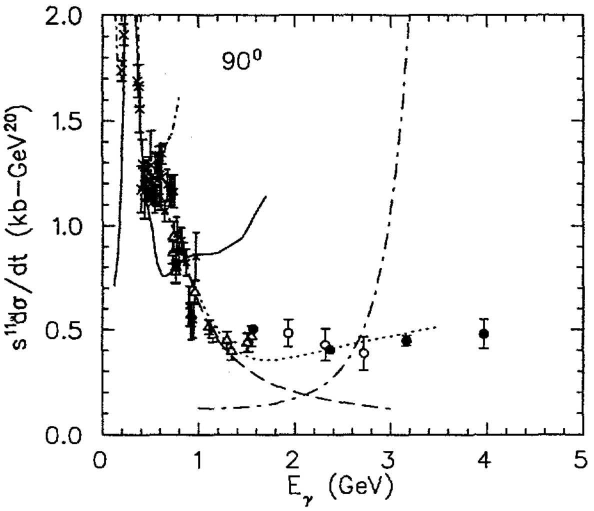

Figure 3: The preliminary TJNAF data together with the existing data as a function of the photon energy at $\theta_{c.m.} = 90°$. The solid circles are the TJNAF data with statistical uncertainties only.

$E_0 - 25$ MeV were selected for $\theta_{c.m.} = 37°$, where E_0 is the electron beam energy. This energy bin was chosen so that no protons from photopion production would be identified as protons from $d(\gamma,p)n$ process and also that the bremsstrahlung end point was eliminated. Likewise for $\theta_{c.m.} = 90°$, a reconstructed photon energy bin of $E_0 - 125 \text{ MeV} \leq E_\gamma \leq E_0 - 25$ MeV was chosen. The bremsstrahlung photon flux was calculated with an estimated 3% uncertainty using the thick-target bremsstrahlung computer codes of Matthews and Owens [13], which were cross-checked by an independent code developed by Belz [12]. The spectrometer solid angle for the extended target was obtained from Monte Carlo simulations for each deuteron photodisintegration kinematics. The simulated acceptance agrees with the measurement to better than 5%. A proton absorption correction was applied to compensate for the proton loss going through the detector stack. This correction factor was measured for this experiment to be (8% ± 1%). Corrections were also applied for the computer deadtime and the tracking efficiency.

The overall systematic uncertainty is found to be $\leq 14\%$ and is dominated by the background correction. Events above the photon endpoint were observed at the high energy forward angle kinematics. The worst case was at the 4 GeV and 37° kinematic setting in which the background contributed as much as 30% of the overall signal in the photon energy region used in the analysis. This background is believed to come from a two-step process in which a hadron originated in the target and subsequently scattered in the spectrometer. Although no cuts were found to remove this background efficiently, the background shape was best described by the photon spectrum from the hydrogen target run. Thus, the background was corrected using the hydrogen spectrum and the systematic uncertainty was estimated to be less than 10%. The systematic uncertainty from the spectrometer acceptance is 5%. The effective target thickness after applying the cut to eliminate the target windows in the analysis was known to 3%. The uncertainties from the beam current measurement, beam energy determination and photon energy reconstruction to the measured quantity $s^{11}d\sigma/dt$ were less than 3%. The uncertainty from the particle identification is negligible.

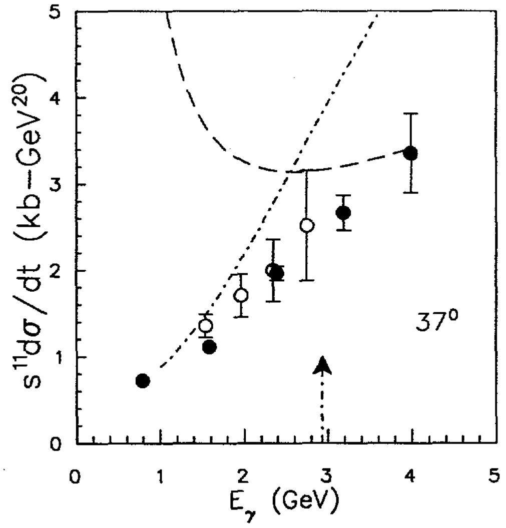

Figure 4: The preliminary TJNAF data together with the SLAC NE17 data as a function of the photon energy at $\theta_{c.m.} = 37°$. The TJNAF data are shown with the statistical uncertainties only.

Fig. 3 shows the preliminary TJNAF data at $\theta_{c.m.} = 90°$ together with the previous data. The TJNAF data are in good agreement with the previous SLAC data in the overlapping region, and the TJNAF data continue to show scaling behavior up to the highest beam energy of 4.0 GeV. Fig. 4 shows the preliminary TJNAF data at $\theta_{c.m.} = 37°$

together with the SLAC NE17 data[4]. The solid circles are the TJNAF data with statistical uncertainties only and are in good agreement with the SLAC NE17 data. The 90° data shows clearly the onset of the scaling behavior at the transverse momentum P_t of $\sim$ 1.0 GeV/c, where ${P_t}^2 = \frac{1}{2} M_d E_\gamma \sin(\theta_{cm})^2$ with M_d the deuteron mass. Because of the large statistical uncertainty, it is not clear whether scaling behavior starts at P_t of $\sim$ 1.0 GeV/c, corresponding to a photon energy of $\sim$ 3 GeV (indicated by the arrow in Fig. 4), in the 37° kinematics from the preliminary TJNAF measurement.

Summary

The TJNAF data show good agreement with the previous SLAC data in the overlapping region. The data at $\theta_{c.m.} = 90^\circ$ continue to show scaling behavior. However, it is not conclusive whether scaling sets in at a proton transverse momentum of about 1.0 GeV/c in the 37° kinematics. It is surprising that the counting rule appears to work so well in the 90° kinematics considering the fact that the momentum transfer to the individual quark is not above 1.0 $(\mathrm{GeV/c})^2$. Understanding the underlying mechanism responsible for the onset of the scaling behavior in the $d(\gamma, p)n$ process requires cross section measurement at higher energies, this is especially important at forward angles, and also measurement where polarization degrees of freedom are involved. Measurements[14] of the differential cross section from $d(\gamma, p)n$ up to 5.5 GeV are planned at proton center-of-mass angle 37°, as well as proton polarization measurements[15] from $d(\gamma, \vec{p})n$ to test hadron helicity conservation.

Measurements at higher energies at 37° are planned at TJNAF[14].

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