Measurement of the Differential Cross Section for the Reaction $^2H(\gamma,p)n$ at High Photon Energies and $\theta_{c.m.}=90°$

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We have measured the differential cross section for two-body deuteron photodisintegration at $\theta_{c.m.}=90°$ and for photon energies between 0.8 and 1.6 GeV. At energies above $\simeq 1.2$ GeV, the data appear to obey a simple scaling law predicted by constituent-counting rules assuming parton degrees of freedom for the deuteron and nucleons. Agreement with model calculations based on meson exchange or "reduced nuclear amplitudes" is discussed.

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One of the most interesting and challenging issues to emerge in nuclear physics during the past decade concerns subnucleonic degrees of freedom. Pursuing this issue has led to attempts to describe nuclei in terms of the fundamental quark and gluon fields, rather than as collections of nucleons and mesons.[1] However, there is little experimental evidence to support these descriptions.

In this Letter, we present results of a measurement of the differential cross section for the reaction $^2H(\gamma,p)n$ at $\theta_{c.m.}=90°$ and photon energies between 0.8 and 1.6 GeV. This reaction has several features which suggest that it may serve as a testing ground for nucleon-meson versus quark/parton descriptions of the deuteron. First, it is an exclusive process which according to simple constituent-counting rules[2] should be described by $d\sigma/dt \propto 1/s^{11}$ for fixed $\theta_{c.m.}$ and large enough values of s. [We use the standard definitions of s and t, namely that for the reaction $A+B \rightarrow C+D$, $s=(p_A+p_B)^2$ and $t=(p_A-p_C)^2$ where p_i is the four-momentum of particle i.] Second, a well-developed picture of this reaction in terms of nucleon and meson degrees of freedom exists and has been tested at lower energies.[3,4] Third, Brodsky and Hiller[5] have formulated a QCD-based description of this reaction in terms of "reduced nuclear amplitudes." (This approach has been successful in describing the elastic form factor of the deuteron[6] at energies well below the onset of constituent-counting behavior.) Our results strongly disagree with an existing meson-exchange calculation and suggest that, at the highest energies of our measurement, the cross section behaves according to the simple constituent-counting rule.

The experiment used the Nuclear Physics Injector at SLAC (NPAS) and facilities in end station A. Electrons were delivered in $\simeq 1.5$-μsec-long pulses with peak current up to $\simeq 20$ mA at a rate of $\simeq 90$/sec. The energy spread of the electron beam was defined using collimators which restricted the full width to $\simeq 0.25\%$. The integrated electron current was monitored by two toroids whose accuracy was better than 0.3%. We measured the beam energies to better than $\simeq 0.3\%$. The electron beam passed through removable 4% or 6% Cu radiators producing bremsstrahlung photons. Both electron and photon beams passed through the target before being absorbed in a water cooled beam dump.

Protons from the reaction $^2H(\gamma,p)n$ corresponding to photon energies near the bremsstrahlung end point were momentum analyzed in the SLAC 1.6-GeV/c spectrometer[7] and detected in a multilayer system of plastic scintillator hodoscopes and drift chambers. An aerogel Cherenkov counter was used to help identify pion backgrounds. Five hodoscope layers, two segmented in the direction of momentum dispersion (X) and three in the direction of scattering angle (Y), triggered the apparatus and measured time of flight (TOF) over a $\simeq$3-m flight path. Three drift chambers were used, each having two planes in both the X and Y directions with $\simeq$1 cm wire spacing. Particles were tracked through the drift chambers allowing full reconstruction of momentum and trajectory. The overall rms momentum resolution obtained, including beam-energy spread, was $\simeq$0.3%. For the energies and angles studied, this was sufficient to separate protons due to the reaction $^2H(\gamma,p)n$ from those due to reactions leading to additional final state particles. For each beam energy, one momentum setting was sufficient to cover the highest $\simeq$100 MeV of the bremsstrahlung spectrum as well as $\simeq$50 MeV above the end point. Measurements were made at a variety of center-of-mass angles. In this Letter we report results for $\theta_{c.m.}=90°$ only.

Data were acquired through CAMAC electronics and read into a VAX-11/780 host computer through a PDP-11 "front-end" computer. The data-acquisition system was limited to one trigger per beam pulse so that all triggers were scaled and the extracted yields corrected. This correction was typically a few percent and 10% in the worst case. Dead-time corrections due to triggering electronics were negligible.

We used a 15-cm-long circulating liquid-deuterium (LD_2) target cell with 0.003-in. aluminum entrance and exit windows. A liquid-hydrogen (LH_2) target of identical dimensions was used for background subtraction. The transverse dimensions of the targets fully intercepted the electron and photon beams. The dominant background was from the reactions $^{27}Al(\gamma,p)X$ and $^{27}Al(\gamma,d)X$ on the target windows. We calculated the mass of each detected particle from its measured momentum and the velocity determined by the TOF system. This provided clear separation of protons from deuterons, and we confirmed that the deuteron background subtracted to zero using the LH_2 target. The pion and positron background rates were negligible for this analysis. The spectrometer was measured with use of elastic electron-proton scattering and checked by computer modeling. At present, the overall uncertainty in the absolute normalization is approximately $\pm$10%.

For each event, we determine the photon energy E_γ using the reconstructed momentum and scattering angle and assuming $^2H(\gamma,p)n$ reaction kinematics. The resulting photon energy spectra are reduced by subtracting the LH_2 target yields from LD_2 target yields separately for runs with the "radiator in" and the "radiator out." Finally, the remaining radiator-out yield is subtracted from the radiator-in yield. The resulting spectrum is assumed to come from real photons produced in the external Cu radiator. The final yield spectra are shown in Fig. 1 for our lowest and highest beam energies at $\theta_{c.m.}=90°$. It is clear that the yield beyond the end point is consistent with zero, thereby providing additional evidence that backgrounds have been correctly subtracted.

Two cross-section values are determined from each subtracted yield spectrum of the type shown in Fig. 1. The yield below the end point is divided into two regions, excluding the highest 25 MeV and also excluding effective photon energies which allow yield from reactions with additional particles in the final state, e.g., $^2H(\gamma,p)n\pi^0$. For each of these two regions, we average the yield and determine the cross section from the target thickness and density, our measured spectrometer acceptance, and the calculated bremsstrahlung yield[8] (corrected for energy loss effects in the radiator[9]). The photon energy for each of the two regions is calculated with an average weighted by the bremsstrahlung yield. The curves in Fig. 1 are determined by a linear interpolation for the cross section, multiplying by the bremsstrahlung shape, and convoluting the product with a Gaussian response function with the expected photon energy resolution. The agreement is quite good over the entire range of photon energies supporting our simple method of extracting cross sections over a small energy range.

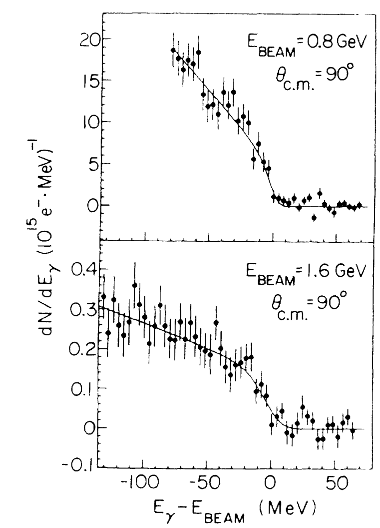

FIG. 1. Background-subtracted bremsstrahlung yields dN/dE_γ as functions of reconstructed photon energy, for protons detected from the reaction $^2H(\gamma,p)n$ at two different beam energies. The yields are normalized by the number of collected beam electrons. The solid curve is the product of the calculated bremsstrahlung yield and the measured cross section folded with a Gaussian response function. The cross section is assumed to be linear in energy over the range of each spectrum. The yields are consistent with zero beyond the end point.

Our results are presented in Fig. 2 where we plot the cross section after taking out certain "scaling" factors corresponding to simple constituent counting[2] [Fig. 2(a)] and to the reduced-nuclear-amplitudes approach[5] [Fig. 2(b)]. Evidence for either description then takes the form of the data becoming a (undetermined) constant above some photon energy. In each plot, we include the result of a recent calculation based on meson exchange,[4] scaled in the same fashion. Data from previous experiments[10] at lower energies are also included.

According to constituent-counting rules, the differential cross section for a particular exclusive process at fixed center-of-mass angle should approach the form $d\sigma/dt \propto 1/s^{n-2}$ where n is the total number of elementary fields. Consequently, for the reaction $^2\mathrm{H}(\gamma,p)n$ we might expect the quantity $s^{11}\, d\sigma/dt$, plotted in Fig. 2(a), to approach a constant above some energy.

The approach taken by Brodsky and Hiller[5] using the reduced nuclear amplitudes implies that the differential cross section should be given by the expression

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

where

$$\hat{t}_i = (p_i - \tfrac{1}{2} p_d)^2 .$$

The nucleon elastic form factors are approximated by $F_N(t) = 1/[1 - t/(0.71\ \mathrm{GeV}^2)]^2$ and p_T is the nucleon transverse momentum. Accordingly, we plot the quantity $f^2(\theta_{\mathrm{c.m.}} = 90°)$ in Fig. 2(b) as a function of photon energy. We note that while $f^2(\theta_{\mathrm{c.m.}}) = \mathrm{const}$ is equivalent to satisfying simple constituent counting for higher photon energies, the ratio of their respective energy-dependent scaling factors changes by roughly a factor of 2 between 1.0 and 1.6 GeV. In principle, we might expect the use of reduced nuclear amplitudes to describe the data better at lower energies than by using simple constituent counting. Indeed, this appears to be true in the case of the deuteron elastic form factor.[6]

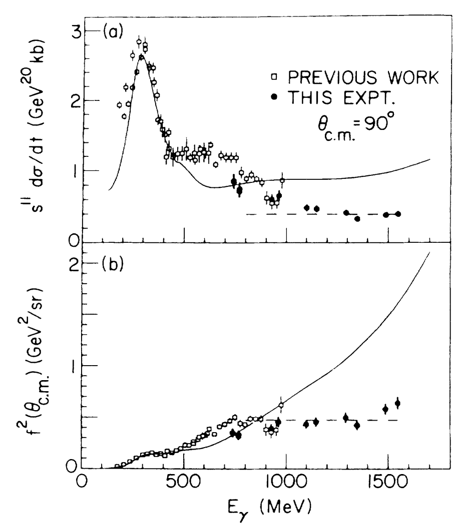

FIG. 2. Results of our experiment at $\theta_{\mathrm{c.m.}} = 90°$ along with results of previous experiments at lower energies. The data are plotted so as to elucidate "scaling" as determined by (a) simple constituent counting (Ref. 2) and by (b) a formalism based on the reduced nuclear amplitudes (Ref. 5). The solid lines are the result of a recent calculation based on meson exchange (Ref. 4). The dashed lines represent constants that approximate the data at high energy but whose magnitudes are not predicted by any model. Only statistical errors and errors due to the uncertainty in the end-point energy are shown.

It is immediately clear from Fig. 2 that the meson-exchange calculation of Ref. 4 does not describe the data above $E_\gamma = 500$ MeV. It does not appear that agreement with our data can be achieved by adjusting the various parameters in the calculation, although this is not surprising since the calculation does not incorporate all possible degrees of freedom.[4] Indeed, fully relativistic calculations which exploit the range of assumptions about, for example, deuteron wave functions and the specific nature of the exchange currents, as well as including all relevant degrees of freedom, must be done before definite statements can be made about agreement with an entire class of such models. We note that such calculations are largely constrained by data from other reactions.

Despite the very low energy ($s \simeq 2M_d^2$), our data seem to be described by the simple constituent-counting relation for $E_\gamma \gtrsim 1.2$ GeV,[2] although the data do not extend to high enough energy to identify logarithmic or otherwise slowly varying deviations as suggested from QCD. We note that a fit to the data above 1.2 GeV with the form $d\sigma/dt = A/s^n$ yields $n = 10.5 \pm 0.7$. The data are reasonably described by the formalism of Brodsky and Hiller,[5] although it deviates somewhat at the highest photon energies. Higher-energy data are needed to distinguish conclusively between the two "quark/parton" descriptions and to determine whether or not the s^{-11} dependence persists over a larger range in energy.

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