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2010

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ARTICLE INFO

ABSTRACT

We present a study of high energy photodisintegration of proton-pairs through the $\gamma + {}^3\text{He} \rightarrow p + p + n$ channel. Photon energies, E_γ, from 0.8 to 4.7 GeV were used in kinematics corresponding to a proton pair with high relative momentum and a neutron nearly at rest. The s^{-11} scaling of the cross section, as predicted by the constituent counting rule for two nucleon photodisintegration, was observed for the first time. The onset of the scaling is at a higher energy and the cross section is significantly lower than for deuteron (pn pair) photodisintegration. For E_γ below the scaling region, the scaled cross section was found to present a strong energy-dependent structure not observed in deuteron photodisintegration.

A common problem in describing quantum mechanical systems is identifying the relevant degrees of freedom needed to efficiently describe the underlying reaction dynamics. Conventional nuclear physics descriptions use meson–baryon degrees of freedom, and it is an ongoing challenge of modern nuclear physics to identify phenomena in which the underlying quark–gluon degrees of freedom are important for their description. In exclusive nuclear reactions, no apparent phase transitions have been identified which make clear that the relevant degrees of freedom have changed from hadrons to quarks and gluons. Hard two-body processes, where all Mandelstam variables s, $-u$, and $-t$ are larger than the Λ_{QCD}^2 scale are natural candidates to reflect the quark substructure of the hadrons and nuclei, since they involve short distance scales.

Extensive studies of high-energy deuteron photodisintegration over the past two decades have probed the limits of meson–baryon descriptions of nuclei and reactions [1–8], and the effects of the

underlying quark–gluon degrees of freedom. At low energies, up through the region of Δ resonance excitation, photodisintegration of the deuteron is well understood, although certain detailed problems remain [9–12]. The calculations are based on meson–baryon degrees of freedom, constrained by data on NN scattering and pion photo-production [9–11].

Above ~ 1 GeV, deuteron photodisintegration at large angles leads to a large total cm energy and large transverse momenta — this is the hard photodisintegration regime. At these high energies photodisintegration cross sections have been shown to follow the constituent counting rules [8,13–16], that have been re-derived from quantum chromodynamics (QCD) and string theory, using the Anti-de Sitter/Conformal Field Theory (AdS/CFT) correspondence [15,17,18]. Since the s-dependence of the cross section at fixed c.m. scattering angle[1] would naturally arise from the underlying quark degrees of freedom, the behavior suggests that the quarks are the relevant degrees of freedom. Furthermore, meson–baryon calculations cannot handle the hundreds of available resonance channels that can be excited, and quark degrees of freedom naturally sum over the baryon resonances [19]. Several quark model calculations have been used to explain the behavior of high-energy photodisintegration [20–22], and moderate success has even been achieved in explaining some polarization observables [21–25].

In an attempt to more clearly identify the underlying dynamics at play, we present in this work the first high-energy measurement of photodisintegration of two protons, using ^{3}He. In these measurements the transverse momentum of the protons exceeded 1 GeV/c. The basic idea is that theoretical models should be able to predict the relative size of pp versus pn disintegration [26]. Also, if the pp and pn disintegration are related to the corresponding pp and pn elastic scattering via hard re-scattering, the differences in the elastic scattering should be reflected in corresponding differences in the photodisintegration processes. Finally, the relative smallness of the low-energy $\gamma - pp$ disintegration process, compared to $\gamma - pn$, has been explained as resulting from the small magnetic moment of the pp pair [27]. One of the motivations for this measurement is to check if this behavior continues at higher energies.

The experiment (E03-101) ran in Hall A of the Thomas Jefferson National Accelerator Facility (JLab) [28]. The experimental setup is schematically described in Fig. 1. Bremsstrahlung photons were generated when the electron beam with energy 0.8, 1.1, 1.7, 2.1, 2.5, 3.1, 4.1 or 4.7 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 ^{3}He gas target, with density of 0.079 g/cm^3. The size of the photon beam spot on the target, ~ 2 mm, is dominated by electron beam rastering intended to distribute the heat load across the targets, and is much smaller than the ~ 1 cm size target windows and apertures. Protons from the target were detected with the Hall A high-resolution spectrometers (HRSs) at kinematic settings corresponding to the $\theta_{\text{c.m.}} = 90°$ photodisintegration of a proton pair at rest. For each spectrometer, the scattering angles, momenta, and interaction position 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.

The incident photon energy, as well as the neutron's recoil momentum were reconstructed from the momentum and angles
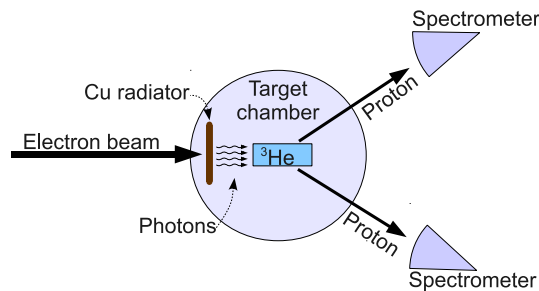

Fig. 1. (Color online.) Experimental setup: Bremsstrahlung photons generated in a copper radiator by an electron beam impinged on a ^{3}He gas target. Protons were detected with the spectrometers. Elements are not to scale.
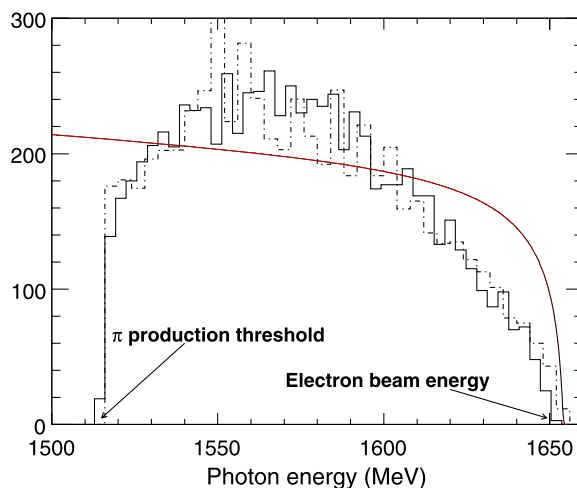

Fig. 2. (Color online.) Photon energy distributions for an electron beam of 1.655 GeV. Solid line represent the reconstructed photon energy of the photodisintegration events, dashed line the simulation results. The calculated bremsstrahlung spectrum [29] is shown as a solid red line. The difference between the data/Monte Carlo and the bremsstrahlung shapes results from the spectrometer acceptances and resolutions plus the energy dependence of the cross section. All distributions are normalized to the measured yield.

of the scattered protons under the assumption of ppn final-state kinematics. In order to assure the validity of this assumption, only events between the bremsstrahlung endpoint and the pion production threshold were used in the analysis. Fig. 2 shows the photon energy distributions for an electron beam total energy of 1655 MeV.

Proton pairs produced in coincidence 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. As in [5], due to low rates, measurements without the radiator were taken only up to $E_\gamma = 3.1$ GeV. As theoretical guidance [30,31] indicates that the ratio of electro- to photo-disintegration should vary slowly with energy, the correction for higher photon energies was extrapolated from the measurements at the lower energies. With the momentum and path well determined by the narrow spectrometer acceptances, protons were selected by cutting on the time of flight. The reconstructed reaction point location was selected to be within the central 10 cm of the target. Random events were removed with narrow cuts on the coincidence time and the difference between the reaction points, independently reconstructed for each spectrometer. A photon energy cut was placed as described above. A cut was placed on the reconstructed neutron momentum to be less than 100 MeV/c. With these measurement conditions, the neutron in the ^{3}He can be considered, at least approximately, as a static spectator [26,32]. Correc-

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[1] Generally, $d\sigma/dt \sim s^{-n}$ where the exponent n is two less than the number of point-like constituents in the initial and final states. For $\gamma NN \to NN$, $n = 13 - 2 = 11$.
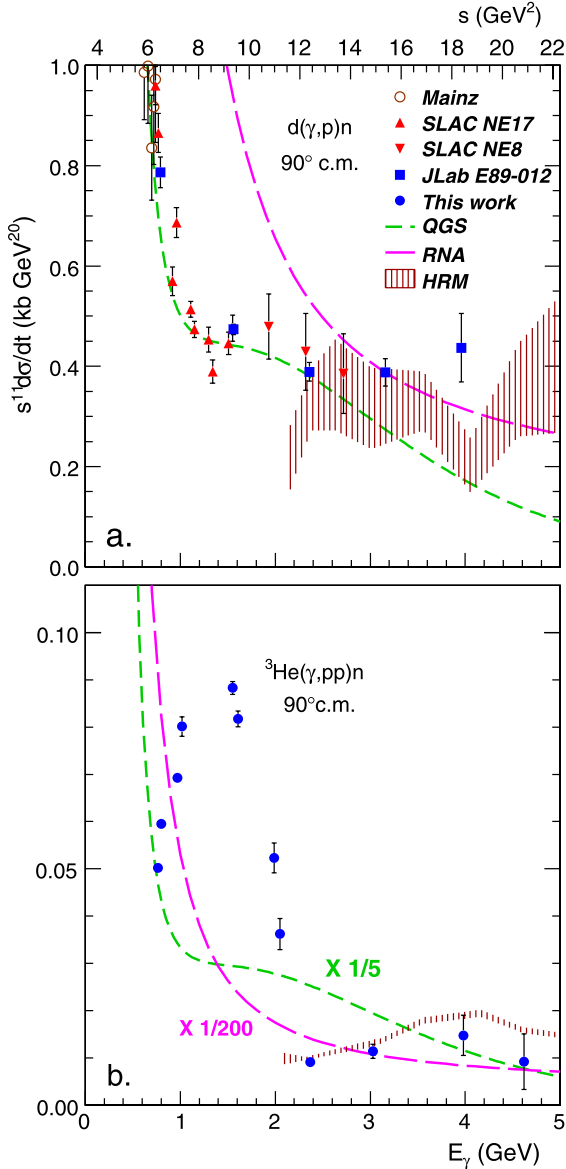
Fig. 3. (Color online.) Invariant cross section scaled by s^{11} for $d(\gamma, p)n$ (a), taken from previous work [1–8] and for ^{3}He$(\gamma, pp)n$ (b), from this work. The ^{3}He$(\gamma, pp)n$ events were selected with $p_n < 100$ MeV/c. Up to 2.1 GeV, the photon energy bins are 70 MeV, and above it 140 MeV. Model predictions are taken from [26,34]. In (b), RNA is divided by a factor of 200 and QGS by a factor of 5 to be shown on this scale. Only the statistical uncertainty is shown.

tion for the finite acceptance of the spectrometers was done using the standard Hall A Monte Carlo simulation software MCEEP [33].

Fig. 3 shows the $\gamma + d \rightarrow p + n$ and $\gamma + ^3$He $\rightarrow p + p + n$ $\theta_{\text{c.m.}} = 90°$ cross section scaled with s^{11}. The ^{3}He$(\gamma, pp)n$ events were selected with $p_n < 100$ MeV/c. A fit of the $\theta_{\text{c.m.}} = 90°$ cross section to $A \times s^n$ yielded $n = -11.1 \pm 0.1$ for the deuteron for $E_\gamma \sim 1$ GeV. For the pp pairs $n = -10.5 \pm 0.6$ and the scaling commences at $E_\gamma \approx 2.2$ GeV. In the scaling region, the $\theta_{\text{c.m.}} = 90°$ cross section for ^{3}He$(\gamma, pp)n$ is about 40 times smaller than that for $d(\gamma, p)n$. Correcting for the abundance of pp pairs with low neutron momentum ($p_n < 100$ MeV/c) as calculated from [12], yielded ~ 20 times smaller cross section for disintegration of a pp pair in ^{3}He than of a pn pair in the deuteron. The cross section is compared to theoretical models, discussed below, that produced predictions for the photodisintegration of the deuteron and a pp pair in ^{3}He [26].

The statistical uncertainty rises with the incident photon energy from less than 1% to 64%. The systematic error for all data is between 5 and 10%. At low energy, the systematic error dominates with the major contribution due to the large number of $\theta_{\text{c.m.}} = 90°$ proton pairs not detected by the spectrometers. This acceptance limitation is handled by the simulation, but introduces a larger systematic uncertainty. At high energy the systematic uncertainty is dominated by the ^{3}He electro-disintegration subtraction (due to the extrapolation from lower energies).

The photodisintegration of ^{3}He has also been measured with the Hall B/CLAS [35] detector at Jefferson Lab, using tagged photons of 0.35 to 1.55 GeV [32]. The large acceptance of the spectrometer allowed detection of the two outgoing protons over a wide range of momentum and angles. Events corresponding to $\theta_{\text{c.m.}} = 90°$ break-up of proton pairs were selected with various cuts on neutron momentum. Preliminary yet unpublished single differential cross section results from CLAS [36] in the range of 0.85 GeV $< E_\gamma < 1.1$ GeV agree within 10% with the data presented here.

Our new data along with previous low-energy data indicate that the ^{3}He two-proton disintegration can be divided into three energy regions. At *low* photon energies (below $E_\gamma \approx 0.5$ GeV), the dynamics of $\theta_{\text{c.m.}} = 90°$ proton-pair breakup is governed by hadron and meson degrees of freedom and the cross section has a large three-body component [37].

In a *transition* region (1 GeV $< E_\gamma < 2.2$ GeV) the scaled cross section for deuteron (pn pairs) breakup is flat while for pp pairs a significant structure is observed. This structure may be the result of resonances in the γN or γNN systems. The energy dependence in the transition region more closely resembles the energy behavior of the photo-induced pion production [38–40] than that of deuteron photo-disintegration. It has been suggested that the structure might result from a meson photo-produced on a proton and then absorbed on a pn pair [41].

In the *scaling* region the cross section for both deuteron (pn) and pp breakup scales in agreement with the constituent counting rule [15,17,18]. For proton-pair break-up, the onset of the scaling is at $E_\gamma \approx 2.2$ GeV, while for deuteron (pn pair) scaling commences at $E_\gamma \approx 1$ GeV [6]. The scaling in the ^{3}He case indicates that in this regime the two-body process is dominant. It further suggests (in a relatively model-independent way) that the relevant degrees of freedom that govern the dynamics are the quarks. In a hadronic picture, two-body/one-step processes are strongly suppressed since no charge can be exchanged between the protons.

The reduced nuclear amplitude (RNA) formalism [20] after normalization to the deuteron data [26] yields cross sections that are about 200 times larger than the present data. The quark–gluon string model (QGS) [21,42], as estimated in [26], predicts cross sections about a factor of 5 larger than measured. The QCD hard re-scattering model (HRM) [22] allows an absolute calculation of the cross sections for both pn and pp pair photodisintegration from nucleon–nucleon measured cross sections without adjustable parameters. It reproduces reasonably well the deuteron data and the proton pair cross section.

An explanation for the low magnitude of the scaled cross section of proton-pair breakup is given in the HRM [34] by a cancellation of the opposite sign of the NN helicity amplitudes ϕ_3 and ϕ_4 in the pp breakup.[2] The energy dependence predicted by the HRM in the scaling region agrees well with the data. Therefore, hard

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[2] ϕ_3 and ϕ_4 are the NN elastic scattering helicity amplitudes that connect zero helicity in the initial states to zero helicity in the final state. ϕ_3 does it with no helicity exchange. ϕ_4 exchanges helicity between the scattered nucleons. This cancellation of ϕ_3 and ϕ_4 was not recognized in [26].

re-scattering is a plausible explanation for the origin of the large transverse momenta. Models that hold compact NN pairs in the initial state to be the reason for the large transverse momenta [20] would have to assume either a fairly low abundance of *pp* pairs within the ^{3}He wave function or the same type of nuclear amplitude cancellation in order to explain the low magnitude of the *pp* break-up scaled cross section.

Another possible explanation for the cross section magnitude may lie in tensor correlations [43–45]. These nucleon–nucleon correlations cause the ratio of *pp* to *np* pairs to be $\sim 5\%$ in the relative momentum range of 300–600 MeV/*c* for both high-energy electron and proton scattering [46–48]. Starting with such a pair and final state re-scattering might lead to the observed relative transverse momentum and would explain the relatively small cross sections.

In conclusion, we have presented the first high-energy measurements of *pp* photodisintegration through the $\gamma + {}^3\text{He} \rightarrow p + p + n$ reaction. For energies between about 1 and 2 GeV, the cross section shows a large structure, possibly related to excitation of baryon resonances. Above about 2 GeV, the measured cross section scales as s^{-11}, but at a level about 20 times smaller than the deuteron disintegration cross section. This arises naturally from the hard rescattering model due to cancellation of *pp* scattering amplitudes. Other models tend to over-predict the *pp* disintegration cross section. If the underlying dynamics of photodisintegration are sensitive to nucleon pairs in the relative momentum range 300–600 MeV/*c*, then an alternative explanation for the relative cross section magnitude of γd to γpp arises from tensor correlations.

Acknowledgements

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