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Correlated protons in ^{3}He photo-disintegration

R. Gilman[1,2,a], D. Higinbotham[2], E. Piasetzky[3], I. Pomerantz[3], and S. Strauch[4]

[1] Rutgers University, Piscataway, NJ 08854-8019 USA
[2] Jefferson Lab, Newport News, VA 23606 USA
[3] Tel Aviv University, Tel Aviv, Israel
[4] University of South Carolina, Columbia, South Carolina 29208, USA

Abstract. We describe the high-energy photodisintegration program performed at CEBAF, focusing on the motivations and results for recent measurements of pp photodisintegration from 1 – 5 GeV. The experimental results give insight into how to understand the underlying quark dynamics.

1 Introduction

At low photon energies, measurements of photodisintegration of light nuclei, the deuteron and ^{3}He, test the ability to formulate precise theories in terms of meson-baryon (MB) degrees of freedom, whether in a conventional framework or in a quantum chromo-dynamics (QCD) inspired framework of effective field / chiral perturbation theory. The lowest energy data also constrain models of Big-Bang nucleosynthesis. There have been a number of recent nice results in this area from TUNL [1,2], but certain long-standing detailed problems with polarization observables remain unexplained [3,4].

As the photon energy rises, above pion production threshold into the resonance excitation region, only MB models have provided adequate descriptions of experimental data [5,6]. These models become significantly more difficult to formulate as the energy increases. The underlying NN potential becomes more complicated to understand / parameterize, due to increasing numbers of inelastic channels. A coupled-channels approach needs to include increasing numbers of excited baryon states, despite (often) poorly known excitation amplitudes and baryon-baryon interactions [7]. It is therefore perhaps not surprising that in the few hundred MeV region MB models and data start to diverge; the divergence is different for different observables presumably due to their differing sensitivity to the missing or poorly modeled physics. This region has been the subject of some recent experiments [8,9].

1.1 High-Energy Photodisintegration

There has been an ongoing program at CEBAF to study photodisintegration of the deuteron, and to a lesser extent ^{3}He, up to photon energies of 5 – 6 GeV. In general for inclusive (e, e') reactions, the sum over undetected recoiling final states, along with minimum four-momentum transfers of order $Q^2 \approx 1$ GeV^2 and an invariant mass of the hadronic recoiling system greater than about $W = 2$ GeV allow perturbative QCD (pQCD) to apply, and provide a theoretical framework for interpretation. Photodisintegration of light nuclei at GeV energies provides a similar large invariant mass W and four-momentum transfers $-t$ of order 1 GeV^2 (or transverse momentum p_T of order 1 GeV/c). The large momentum transfer provides a short-distance scale, while the large invariant mass provides a sum over large numbers of intermediate states; these are kinematics that should facilitate the construction of quark models.

Thus, high-energy photodisintegration provides potential insight into two related but distinct questions. The first question concerns the interplay of quark and hadronic degrees of freedom. Can a quark model be formulated for nuclear reactions? Do meson/baryon models break down? Is there a phase transition between a low-energy hadronic regime and a high-energy quark regime? The second question concerns how one generates two high relative momentum nucleons in the final state. Does the incoming photon break up a virtual pair that already has high relative momentum, ~1 GeV/c, even larger than has been studied in recent triple-coincidence $(e, e'pp)$ and $(e, e'pn)$ experiments [10,11]? Or does the absorption of the high-energy photon on a long-range pair lead to a high-momentum transfer rescattering, generating the high relative momentum pair?

There are two opposing points of view concerning the interplay between quark and hadronic degrees of freedom. The low-energy, hadronic perspective is as follows: quarks and hadrons form alternate complete sets of basis states. In principle one can formulate a theory in terms of either set of states. In practice, due to the nature of the underlying dynamics, it might be more efficient to use one set of degrees or freedom than to use the other. There might be an intermediate energy region in which acceptable theories can be formulated with both sets of basis states, or in which in practice we are not able to formulate a theory which adequately explains the data. The high-energy, quark perspec-

[a] e-mail: rgilman@physics.rutgers.edu

tive disagrees. The key point is that it is possible for nuclei to contain colored quasi-nucleons in addition to conventional nucleons. An estimate of the deuteron electromagnetic form factor in perturbative QCD, for example, suggests that hidden color states in the deuteron dominate its form factor at large Q^2 [12]. While the colorless combinations of quarks present in the initial and final states can all be represented in a hadronic basis, the hidden color states cannot. Thus, ultimately one needs a quark theory of the nucleus and nuclear reactions.

It is not entirely clear if in practice the quark theory argument holds. Hadronic theory is not based solely on theoretical arguments. It is an empirical theory that includes among its inputs the measured *NN* force. In so far as there are hidden color states in nuclei, there are also intermediate hidden color states when two nucleons interact. Although the kinematics of off-shell nucleons interacting in the nucleus differ from those of free nucleons interacting, the empirical *NN* force can be expected to largely already incorporate the effects of hidden color states. [1] A practical point of view is that the important thing is how well theories actually predict the data, so we now turn to the experimental high-energy photodisintegration program.

The largest part of the high-energy photodisintegration program at CEBAF has involved deuteron photodisintegration. Cross section experiments in Halls A [17], B [18], and C [19,20] have confirmed with a more extensive data set over a broader kinematic range earlier findings from SLAC [21–23] that the high-energy cross sections at constant center-of-mass angle follow the constituent counting rule (CCR) [24,25],

$$\frac{d\sigma}{dt} \sim s^{2-N} = s^{-11},$$

where the N represents the total number of fundamental particles – the photon and quarks in deuteron photodisintegration – in the initial and final states. Originally derived from dimensional arguments, the CCR was rederived from pQCD [26] and more recently from the AdS/CFT correspondence [27]. While violation of the CCR indicates that one does not simply have a dominant leading-order quark physics, the agreement of the cross sections does not prove that one does have a dominant leading-order quark physics.

Further, the CEBAF experiments have indicated that the onset of the CCR predicted behavior appears to follow a simple kinematic limit [28]: $p_T > 1.3$ GeV/c. The reason for this threshold is unknown. Indeed, it is know that the simple CCR works too well. The Reduced Nuclear Amplitude (RNA) model [29] attempts to extend the region of validity of the CCR by including various expected kinematic threshold factors. However in the region of photon energy above 1 GeV and $p_T > 1.3$ GeV/c, the CCR works better than does RNA.

Two experiments [30,31] in Hall A have studied recoil proton polarization in the 1 – 2.5 GeV range. In the absence of orbital angular momentum effects, one might expect the validity of hadron helicity conservation (HHC), which leads to simple predictions about the polarization observables. In particular, the recoil polarization observables p_y and $C_{x'}$ are expected to vanish at all angles, while $C_{z'}$ only vanishes at $\theta_{c.m.} = 90°$, due to expected relations between the helicity-conserving amplitudes at this angle [7]. While these observables are small at $\theta_{c.m.} = 90°$, an angular distribution [31] shows that this is because all the observables appear to have 0 crossings near 90°. It is now appreciated that quark orbital angular momentum is important in explaining nucleon form factors [32–35] and in resolving the nucleon spin puzzle [36]. For reactions such as photodisintegration, the effect of angular momentum on polarization observables has not been studied, but it has been shown to lead to a correction to the CCR.

Two models based on relating photodisintegration to the *NN* force through the underlying quark dynamics have some success in predicting both the cross sections and polarization observables above 1 GeV. The quark-gluon string (QGS) model [37,38] uses Regge theory to evaluate the three-quark exchange diagram. Similar approaches have had wide success at explaining a variety of high-energy exclusive reaction data. Most other models are based on a physical picture in which the photon is absorbed on a pair of quarks being exchanged between the two nucleons. The hard-rescattering model (HRM) [39,40] relates the amplitudes for this process to the amplitudes for *NN* scattering, taken from analyzing the *NN* data.

In summary, from deuteron photodisintegration we have experimentally determined that cross sections at high transverse momentum transfer scale, following the CCR too well. This may be taken as an indication, but not a proof, that underlying quark physics are dominant. Polarization observables show that orbital angular effects are important, and that two quark models with quite different pictures of the underlying dynamics have some success at explaining both cross sections and polarization observables.

1.2 High-Energy *pp* Photodisintegration

Further study of the underlying dynamics of high-energy photodisintegration requires expanding the observables measured to fundamentally different quantities with different sensitivities than previous investigations. The initial idea [41] was to use *pp* photodisintegration, from ^{3}He, to complement *pn* photodisintegration, from the deuteron. Most of the quark-based approaches to deuteron photodisintegration are in effect normalized to the data, since their absolute normalization is unknown. However, all models should be able to predict the ratio of *pp* to *pn* photodisintegration. Initial estimates of the ratio of *pp* to *pn* photo-

[1] Related to this argument is the search for medium modifications of nucleons [13–16]. From naive quark physics arguments, one might expect large effects. From meson-baryon theory arguments, medium modified nucleon structure is not an observable, it is a purely theoretical concept. Searches for “medium modifications” show that conventional meson-baryon theory works well, and inadequacies in the hadronic theory which one might like to attribute to medium modifications tend to be small and subtle. It might be that the physics that leads to medium modifcation in quark theories is largely already incorporated in the hadronic theory.

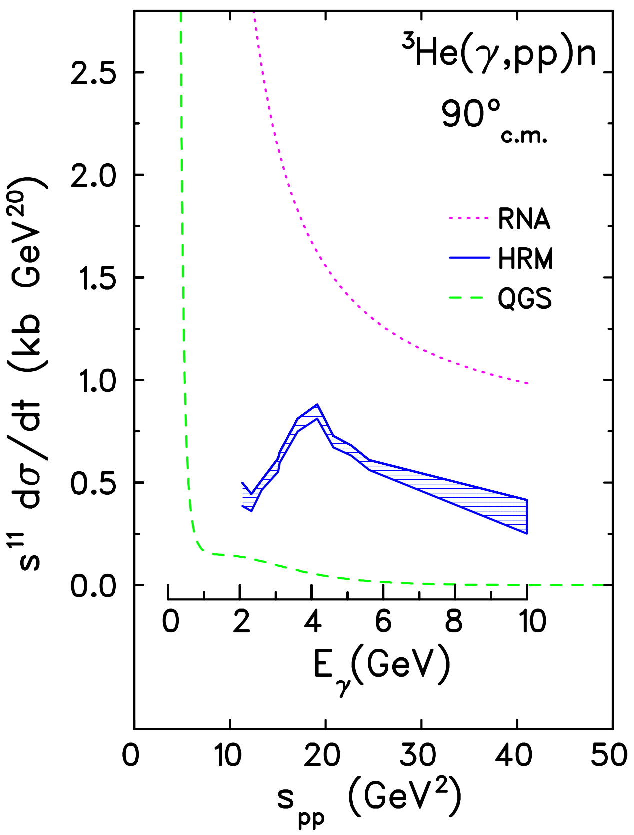

Fig. 1. Predicted cross sections for pp photodisintegration from ^{3}He. For comparison, high-energy deuteron photodisintegration has $s^{11}d\sigma/dt \approx 0.4$ kb GeV^{20}.

disintegration were in the range of about 1/5 to 5, from the various models; see Fig. 1.

Photodisintegration of a pp pair in ^{3}He has the difficulty and benefit of the "spectator" neutron. Ideally and unrealistically, an off-shell pp pair in the initial state is disintegrated while an on-shell spectator neutron in the initial state is unaffected. In general, rescatterings of a high transverse momentum pp pair with the spectator neutron are soft, so that the pp pair is largely unaffected. The neutron kinematics may change by a large relative, but small absolute amount. The result is that the light-cone momentum fraction of the neutron, defined as

$$\alpha_n = \frac{E_n - p_{zn}}{m},$$

where E_n is the neutron energy, p_{zn} is the neutron momentum in the z (beam) direction, and m is the nucleon mass, is largely unaffected – since the spectator neutron has low momentum, $E_n \approx m$, $p_{zn} << m$, and $\alpha_n \approx 1$. The conservation of light-cone momentum fraction is

$$\alpha_\gamma + \alpha_{^3He} = \alpha_{p_1} + \alpha_{p_2} + \alpha_n,$$

where all the α's are defined similarly to the neutron case above. In an experiment with two high transverse momentum protons detected, this leads to

$$\alpha_n = \alpha_\gamma + \alpha_{^3He} - \alpha_{p_1} - \alpha_{p_2} = 3 - \alpha_{p_1} - \alpha_{p_2},$$

since $\alpha_\gamma = 0$ from the definition of α above, and $\alpha_{^3He} = 3$ since the ^{3}He nucleus is at rest. The benefit of this quantity is that the width of the α_n distribution about unity directly reflects the short vs. long range nature of the photodisintegration process. For the HRM, with two nucleons at long distances, the neutron momentum is low, and the α_n distribution is sharply peaked about unity. For models like RNA, which rely on the short-distance structure of the nucleus, the initial-state pair has high relative momentum, which is expected through correlations in conventional nuclear wave functions to lead to a neutron with high momentum. The result is a broader peak in the neutron α_n distribution.

2 Experiment

There are two existing experimental results for high-energy ^{3}He photodisintegration; experiments ran in CEBAF Halls B [42] and A [43] – the experiment that is the focus of this report.

The Hall B experiment used the photon tagger and the CLAS spectrometer to provide nearly 4π kinematic coverage for three-nucleon final states, for photon energies from about 0.35 – 1.55 GeV. Except at the lowest energies, there is evidence in the cross section vs. neutron momentum (integrated over all angles) that there are two distinct kinematic regions. There is a narrow low momentum peak that corresponds roughly to a neutron Fermi momentum distribution, in which the neutron appears to receive little of the energy of the incident photon.[2] There is a much broader high-momentum peak, in which the three nucleons all share significant fractions of the incident photon energy. Thus, the data suggest one can differentiate between an apparent two-body + spectator region and a fully three-body breakup region. This conclusion is also borne out by a Dalitz plot.

The published CLAS data include further analysis into the quasi-two-body breakup region ($p + d$), the star configuration (all three nucleons have roughly equal momentum in the final state) and the neutron-spectator kinematic region - the pp disintegration region of interest here for comparison to deuteron photodisintegration. However, in the neutron spectator region the differential cross section was determined as a function of θ_n (lab angle of neutron), and of θ_{pp} (angle between the two protons in the pp center of mass frame). For comparison with the deuteron the cross section is needed as a function of θ_p (c.m. angle of proton). Preliminary data for the neutron-spectator cross section as a function of θ_p are available, but cannot be shown here. They are at present in reasonable agreement with the Hall A data shown below, and provide much more extensive kinematic coverage in their energy range, $E_\gamma <$ 1.55 GeV.

The Hall A experiment ran more recently, in 2007, using untagged Bremsstahlung at several incident beam energies and the two HRS spectrometers to cover photon en-

[2] Of course, a low neutron momentum does not guarantee that it was an on-shell spectator, and it should be noted that the neutron momentum distribution is not an observable.

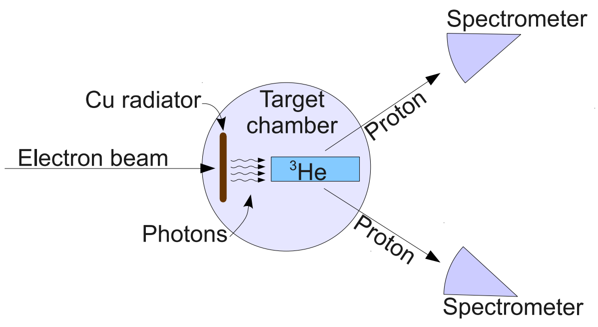

Fig. 2. Overview of the Hall A γ^3He $\rightarrow pp + n_{spectator}$ experiment.

ergies of 1 – 5 GeV. The untagged photon beam allows a broader energy coverage, but due to the limited acceptance of the spectrometers, the measurements are restricted to $\theta_{p\,c.m.} \approx 90°$. Furthermore, the requirement of two high-energy protons in the trigger forces the neutron to be in spectator kinematics. The experimental setup is shown in Fig. 2. Because the experiment detects two high-momentum particles with positive charge using well shielded high-resolution spectrometers with small acceptances, rates in the detectors are small, and proton identification is easy. Cuts are applied on the acceptance, coincidence time of flight, target interaction position, and the difference in interaction position from the two spectrometers.

The complete reaction kinematics can be reconstructed from the measured proton momenta, with two assumptions. First, one assumes that the photon beam is at 0°, which is a good assumption due to the narrowness of the high-energy Bremsstrahlung cone. Second one assumes that one has the reaction γ^3He $\rightarrow pp + n$. This assumption holds as long as the analysis is restricted to events close to the Bremsstrahlung endpoint, where pion production is kinematically forbidden.

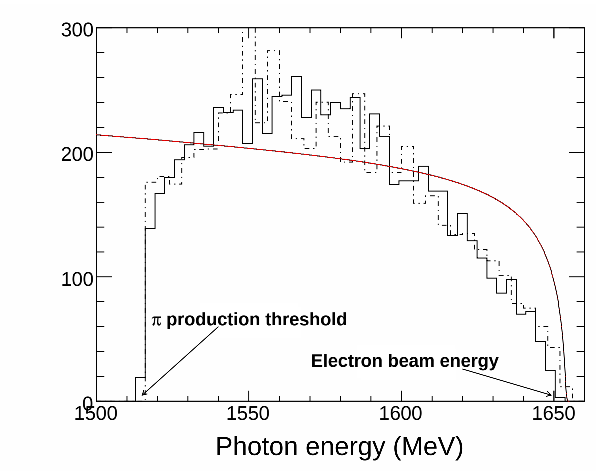

Fig. 3. Reconstructed photon-energy spectrum for the reaction γ^3He $\rightarrow pp + n$. The solid (dash-dot) line is the actual data (Monte Carlo simulation). The smooth curve is a calculated Bremsstrahlung spectrum, arbitrarily normalized.

Determination of the cross section requires a Monte Carlo study to correct for the limited acceptance of the detectors. Our studies show good agreement with the measured spectrometer momentum and angle distributions. Figure 3 compares the reconstructed photon-energy distribution for events at an electron beam energy of ≈1.65 GeV to the spectrum as determined from a Monte Carlo simulation. The good agreement can be seen. The inputs to the Monte Carlo simulation include the Bremsstahlung photon spectrum shown in Fig. 3, a neutron momentum distribution [44], spectrometer angles, central momenta, and acceptances. The difference between the Bremsstrahlung photon spectrum and the photon-energy spectrum reflects the variation of acceptance and cross section with photon energy. The ratio of actual events passing all cuts to events in the Monte Carlo that pass all cuts determines the experimental cross section.

2.1 Experimental Results

The resulting ^{3}He photodisintegration cross sections are compared to those for deuteron photodisintegration in Fig. 4. The "^{3}He" cross sections shown in this figure, including the theoretical estimates, are for the reconstructed neutron momentum $p_n < 100$ MeV/c, which is approximately the limit of our experimental acceptance. For comparison with deuterium, one has to correct for higher momentum neutrons, which is estimated to double the cross section.

In the case of the deuteron, in the upper panel, scaling starts at photon energies just above 1 GeV, with $s^{11} d\sigma/dt \approx 0.4$ kb·GeV^{20}. For two-body plus spectator disintegration of ^{3}He, the kinematics are essentially identical, but instead we have the onset of scaling at $E_\gamma \approx 2.2$ GeV, with a large peak – or possibly two peaks – between 1 and 2 GeV, and $s^{11} d\sigma/dt \approx 0.01$ or 0.02 kb·GeV^{20}, over an order of magnitude smaller. The s^{-11} scaling of the high-energy γ^3He $\rightarrow pp + n_{spectator}$ cross section provides an essentially model-independent confirmation that this is indeed two-body photodisintegration with a neutron spectator that is being measured at the highest energies; three-body mechanisms should fall as s^{-17}. The observations immediately lead to the questions of what leads to one or more peaks between 1 and 2 GeV, why is the onset of scaling at nearly twice the photon energy, and why is the scaled cross section so much smaller for pp photodisintegration from ^{3}He, as compared to deuteron photodisintegration.

A natural explanation for peaking between 1 and 2 GeV is that the underlying physics involves nucleon resonances. A 1 – 2 GeV photon incident on a single nucleon leads an invariant mass of the γN system of $W = 1.66 – 2.15$ GeV, generally in the resonance region. For incident photon energy near 1 GeV, the D_{15} and F_{15} resonances would be expected to be large, while the F_{37} resonance would be expected at about 1.6 GeV. But why would these resonances be seen in ^{3}He but not deuteron photodisintegration? One possible explanation is that in the case of the deuteron, the resonances are excited, and decay by emitting pions, so that the nucleons then fall out of the acceptance of the ex-

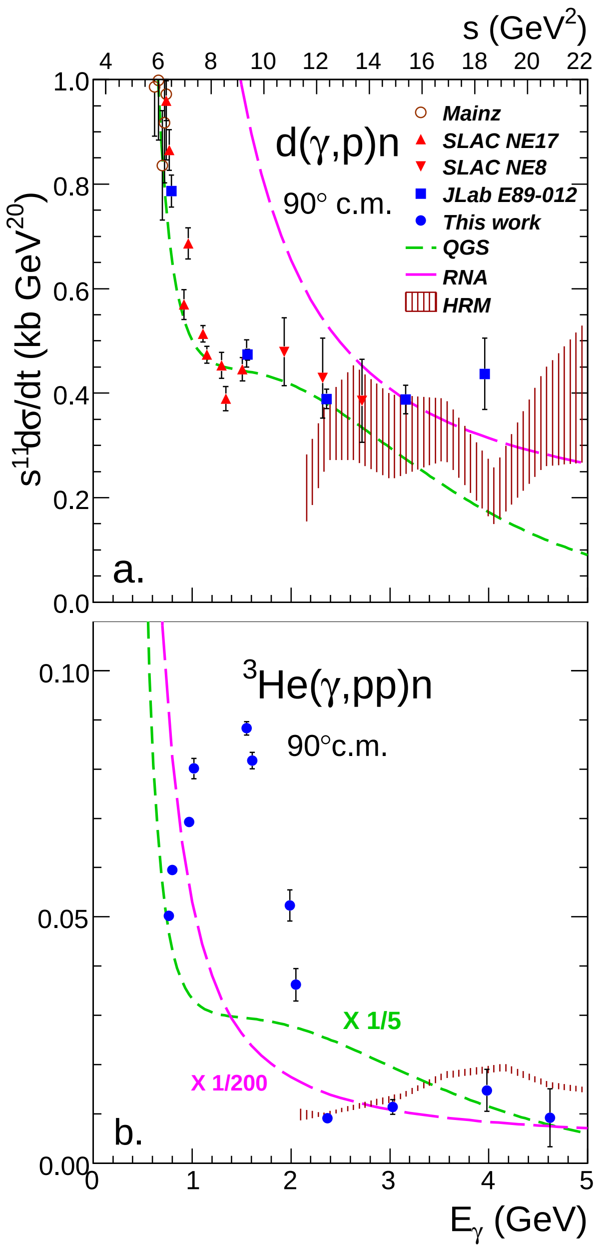

Fig. 4. Excitation functions at $\theta_{c.m.} = 90°$ for (top panel) deuteron photodisintegration into pn and for (bottom panel) ^{3}He photodisintegration into $pp + n_{spectator}$. The deuteron data shown are from Mainz [45], SLAC NE17 [23], SLAC NE8 [21,22], and JLab E89-012 [19].

periments. In the case of ^{3}He, there might be three-body mechanisms [46] in which the emitted decay mesons are reabsorbed leading to two high-momentum protons and a low-momentum neutron, keeping these events within the acceptance of the experiment, so that prominent resonance peaks are observed. Interestingly, the high-energy side of the peak falls off like s^{-17}, which naturally suggests the drop off of a three-body process. However, the exact falloff might be an artefact of the limited data. In summary, the data are insufficient to justify any firm conclusion at this point; other explanations are possible and calculations are needed.

In the 1 – 2 GeV region, the $pp + n_{spectator}$ cross section is only a few times smaller than the deuteron photodisintegration cross section. This is a large increase in the cross section ratio from lower beam energies, of a few hundred MeV. The small cross section at low energies was explained as the result of cancellation of the magnetic moments of the dominant pp pair configuration, with 0 spin and orbital angular momentum.

Why is the onset of scaled cross sections moved to a higher energy in the case of ^{3}He? Here one should recall that deuteron photodisintegration is unusual in its low and smooth onset of scaling. A number of meson photoproduction reactions have been measured, and the general observation is that resonance peaks are often found for photon energies up to about 2 GeV [47]. It is only for energies above this that the cross sections start to approximately scale.[3]

We now consider why is the scaled cross section so much smaller for pp photodisintegration from ^{3}He, as compared to deuteron photodisintegration. In the original predictions for the relative size of pp vs pn disintegration, the RNA model predicted the ratio was large, about 5, the HRM model predicted the ratio was around 1, and the QGS model predicted the ratio was small, about 1/5. In addition, there was an unpublished estimate that the cross section ratio was small, in the "TQC" model, due to cancellations between leading order diagrams [50]. The observation of our preliminary small cross sections for pp disintegration have led to a reexamination of the HRM calculation. It was found that there is a relative phase that was overlooked between the NN amplitudes ϕ_3 and ϕ_4; these amplitudes add for the unlike pn pair but cancel for the like pp pair, leading to a much smaller cross section of the right size. It needs to be studied whether such effects also come into play in the RNA and QGS models.

While the four high-energy points are entirely consistent with a constant scaled cross section – the QGS and RNA models both fall slightly too much in this energy region – they are also in agreement with the structure seen in the HRM calculation. In the HRM, the oscillations about a smooth fall off observed in the pp elastic scattering are reflected in the photodisintegraton by small variations from smooth scaling of the cross sections. The pp elastic data are much better quality than the pn elastic data, so it is desirable to look for this effect in pp photodisintegration. Unfortunately, because the cross sections are about a factor of 20 smaller than those used for planning the experiment, we do not have sufficient statistical precision to definitively confirm or disprove the presence of the structures suggested by the HRM calculation.

[3] To date there are few polarization data in the scaling region. One study found that the recoil polarizations in the case of π^0 photoproduction from the proton do not exhibit any simple behavior [48]. Another study of $K^+\Lambda^0$ photoproduction [49] found a simple behavior – the Λ^0 is polarized in the photon direction – that is however inconsistent with hadron helicity conservation.

One can also speculate about a possible indpendent mechanism that might lead to the large *pn* to *pp* cross section ratio for $E_\gamma = 2 - 4$ GeV. Recent experiments [10, 11] have confirmed predictions that the nuclear tensor force leads to a large excess in the number of *pn* pairs as compared to *pp* or *nn* pairs for nucleon momenta in nuclei just above the Fermi surface, around 300 – 500 MeV/*c*. Thus, if the underlying reaction dynamics favor photodisintegrating nucleon pairs just above the Fermi surface, this naturally leads to a suppression of the *pp* cross section compared to the *pn* cross section. Note that any dynamics of this sort must involve a final-state rescattering, as the experiment would be detecting few GeV/*c* relative momentum nucleons created from several hundred MeV/*c* relative momentum pairs. If in the underlying dynamics increasingly higher energies lead to increasingly short-distance pairs, then one expects from the tensor force a suppression for some intermediate range of energies. Thus, if the cross section ratio above 2 GeV tends to continue to increase with energy, rather than being flat following the CCR, or with a structure following the HRM, that suggests the suppresion results from the nuclear tensor force and intermediate-range reaction dynamics.

The quantity α_n is desirable to study in the scaling region as it probes the long vs. short-distance structure of the reaction. The 1 – 2 GeV region appears to involve 3-body mechanisms even though the neutron is left with no more than a small fraction of the incoming photon momentum. If 3-body mechanisms are important, the neutron cannot be thought of as a spectator, and the α_n distribution is likely affected by the reaction mechanism. At higher energies given the apparent 2-body nature of the disintegration, from the s^{-11} cross section scaling, one would expect minimal effects on the α_n distribution, so that the long vs. short-distance structure of the underlying dynamics can be determined. Unfortunately, again due to the smaller than anticipated statistics, we cannot determine the distribution sufficiently well to come to a conclusion.

3 Discussion and Outlook

In an effort to improve knowledge of the underlying dynamics of high-energy photodisintegration, producing high transverse momentum nucleon pairs, we have measured the reaction $\gamma^3\text{He} \rightarrow pp + n_{spectator}$, to complement previous measurements of $\gamma d \rightarrow pn$. We have discussed three kinematic regions:

- A low energy region, with $E_\gamma < 1$ GeV. Below a few hundred MeV, meson-baryon theories explain these reactions reasonably well. At several hundred MeV, some observables are reasonably well predicted, but others are not.
- A medium energy "resonance" region, from 1 – 2 GeV. Here deuteron photodisintegration exhibits CCR scaling, while *pp* photodisintegration appears to be dominated by three-body disintegration mechanisms. This is the only region in which *pp* disintegration is nearly as large as deuteron disintegration.
- A high-energy region, in which both reactions exhibit CCR scaling. Here *pn* disintegration is about 20 times larger than *pp* disintegration. Both sets of data are consistent with CCR scaling, but at the current level of precision it is not clear if structures seen in *NN* elastic scattering are reflected in the photodisintegration data or not.

The impact of these data on the interpretation of the underlying dynamics was affected by the statistics being smaller than planned due to the cross sections being smaller than generally anticipated. The HRM model generally provides a good account of both *pn* and *pp* disintegration data; it remains to be seen if the QGS and RNA estimates for *pp* disintegration from ^{3}He are also affected by the cancellation in *NN* amplitudes found for the HRM. A new higher precision experiment has been proposed [51] to attempt to better determine whether the cross section oscillations are present, and to better determine the α_n distribution and the long vs. short range nature of the dynamics. In addition, as suggested previously, a measure of *pn* disintegration has been included in the proposal so that *pp* vs. *pn* disintegration in ^{3}He can be directly compared, reducing nuclear structure uncertainties. The first measurements of high-energy ^{3}He photodisintegration suggest that with some additional effort, we might have a clean and consistent interpretation of the underlying dynamics as the data indicate the correct picture to tie the photodisintegration process to elastic *NN* scattering.

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