NEXT GENERATION OF PHOTODISINTEGRATION MEASUREMENTS AT JEFFERSON LAB

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Several highly-rated experiments investigated high-energy, hard photodisintegration of the deuteron. We will briefly review the results and the theoretical work that devoted to understand them. We discuss here the extension of this program to hard photodisintegration of a *pp* pair in the ^{3}He nucleus. A prediction, is that the *pp* breakup cross section is not much smaller than the one for *pn* break up, a clear indication to quark-gluon dynamics. In some models, the energy-dependent oscillations observed for *pp* scattering are predicted to appear in the $\gamma\ ^3\text{He} \to pp + n$ reaction. We also claim that the measurement of the light-cone momentum distribution of the recoil neutron probes the underlying dynamics. The experiment is proposed for Hall A at Jefferson Lab (TJNAF) with beam energies of 2 – 5 GeV.

1. THE HARD DEUTERON PHOTODISINTEGRATION

Deuteron photodisintegration cross sections are available for photon energies up to 5 GeV [1–5]. For energies up to 2.5 GeV there are also measured angular distributions [6, 7] and recoil polarizations [8]. Fig. 1 shows the measured energy dependence of $s^{11}\frac{d\sigma}{dt}$ for 90° c.m. The quark counting rule prediction [9–11] that this quantity becomes independent of energy, is demonstrated clearly in this figure. High-energy deuteron photodisintegration cross sections at other angles are also in good agreement with scaling once $p_T \geq 1.3$ GeV/c.

Contrary to the good agreement of the data with the quark counting rule prediction pQCD underestimates cross sections for intermediate energy photo-reactions [12–14]. Thus, it seems as if the onset of the quark-gluon degrees of freedom is achieved in this reaction, but that the underlying physics probably is nonperturbative QCD or involves higher order of pQCD.

A variety of theoretical models exist which explicitly account for quark-gluon degrees of freedom in the reaction with an attempt to incorporate the nonperturbative QCD effects. For a recent review, see [15]. We show some of the calculations in Fig. 1 together with the data. The reduced nuclear amplitude (RNA) formalism [16] attempts to incorporate some of the soft physics by using experimentally determined nucleon form factors to describe the gluon exchanges within the nucleons. The two-quark coupling (TQC) model [17] is based on the idea that the photon interacts with a pair of quarks being interchanged between the two nucleons. There is no absolute normalization predicted by these two models; instead they are normalized to the data (at the 3 GeV data point). The quark-gluon string model (QGS) [18] views the reaction as proceeding through three-quark exchange, with an arbitrary number of gluon exchanges. The cross section is evaluated using Regge theory techniques. The QCD hard rescattering model (HRM) [19] assumes that the nuclear scattering amplitude can be expressed as a convolution of the large angle *pn* scattering amplitude (taken from data), the hard photon-quark interaction vertex and the low-momentum nuclear wave function. The HRM model allows calculation of the absolute cross section using no adjustable parameters, however the poor accuracy of the *pn* data restricts the overall accuracy of the calculation to the level of 20% (shown as an error band in the figure).

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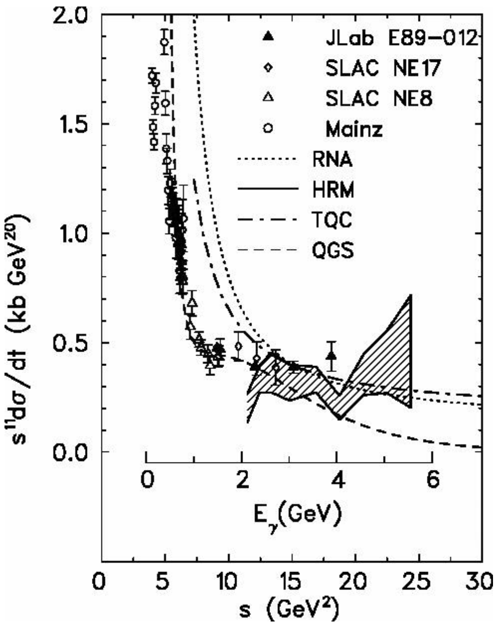

FIG. 1: The energy dependence of $s^{11}\frac{d\sigma}{dt}$ for 90 ° c.m. photodisintegration of the deuteron. The HRM result is shown as a shaded band. The QGS calculation is the long dashed line. The RNA result is the dotted line, normalized to the data point at 3 GeV. The dot dash line shows the TQC formula, normalized to the 3 GeV data point. The experimental data is labeled by the laboratory and the experiment number.

As can be seen in Fig. 1 the very different models with the very different assumptions all yield about equal quality description of the data and no conclusive conclusion can be drawn about the underline dynamics. We therefore refer to the study of the hard pp photodisintegration reaction for future insight.

2. THE HARD PHOTODISINTEGRATION OF A *pp* PAIR

We suggest a new venue for studying the dynamics of hard photodisintegration reactions. We will discuss how it can, together with the existing deuteron data, deepen our understanding of the process. We propose the investigation of the reaction

$\gamma\ {}^3\text{He} \to pp + n$ in which we define the measurement conditions so that the neutron in ^{3}He can be considered, at least approximately, as a static spectator, while two protons are produced at 90° in the c.m. frame of the γpp system. This can be done experimentally by selecting events in which the reconstructed missing neutron momentum is less than 100 MeV/c.

Although many of the considered models do not predict the absolute cross section, still they can predict the relative cross section of the hard $\gamma(pp) \to pp$ reaction as compared to the $\gamma(pn) \to pn$ reaction. The pn data from the deuteron already exist and can be used to provide an overall normalization so that absolute γ^3He cross sections, rather than just the s dependence of the γpp cross section, can be predicted. Fig. 2 shows predictions based on the models considered above for 90° two-body break-up kinematics. The $\gamma\ {}^3\text{He}\to pp + n$ cross section has been integrated over the neutron momentum up to 100 MeV/c.

These predictions ignore nuclear corrections due to the soft rescattering of the nucleons in the final state which are only small corrections in the kinematics discussed. This effect can be reliably calculated within the eikonal approximation. Preliminary estimates yield 5 – 10 % corrections in the range of 40 – 90° c.m. angles. Another correction is due to primary reactions on the pn pair,

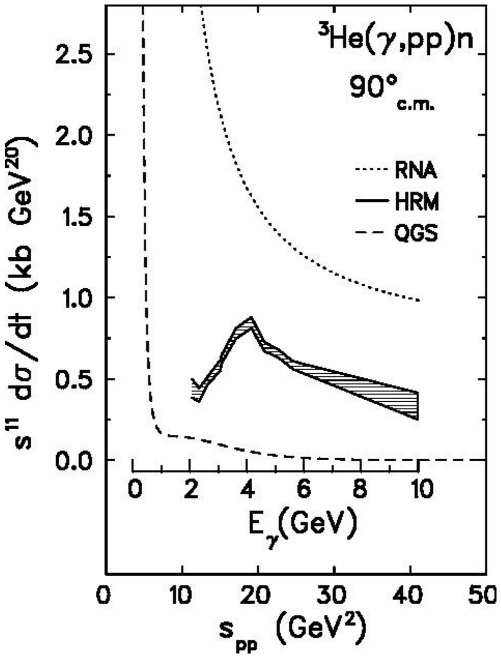

FIG. 2: Predictions for $\gamma\ ^3\text{He}\to pp + n$ at $\theta_{\text{c.m.}} = 90\,°$. The line types are the same as for Fig. 1. The horizontal scale is s for the γpp system; the photon energy scale is also shown.

with subsequent soft $pn \to np$ charge-exchange rescattering of the energetic neutron with the slow spectator proton. In the energy range of this study, it results in only a 1 – 2 % correction. This estimate takes into account the larger probability of pn than pp pairs in ^{3}He.

Notice that the models considered above predict a sizable cross section for the break up of the pp pair, larger than that for the pn pair. This prediction is rather striking since at low energies it is well known [21] that photodisintegration of the pp system is suppressed as compared to pn. This large cross section is a clear indication to the dominance of quark-gluon picture. Within a mesonic description of the interaction, the 90° break up of a pp pair will be significantly suppressed as compared to pn since for the pp pair the exchanged mesons are neutral and do not couple to the photon. The nature of the transition from meson exchange at low energies to quark-gluon picture at TJNAF high energies can be study by measuring the ratio of pp to pn 90° photodisintegration cross section as a function of the photon energy.

The quark counting rule predicts $\frac{d\sigma}{dt} \sim s^{-10}$ for high-energy, large-angle $pp \to pp$ elastic scattering. The pp elastic data are globally consistent over a large number of decades with the power law [22, 23]. However a more detailed examination of the data indicates significant deviations from scaling [24]. The deviations are known as "oscillations" and were interpreted as resulting from interference between the pQCD amplitude and an additional nonperturbative component [25, 26]

If the hard two-body break-up reaction proceeds through the hard interaction of two protons, similar oscillations could be seen in the $\gamma\ ^3\text{He} \to pp + n$ cross section, normalized by a factor of s^{11}, as a function of the incident photon energy, in the same region of s where pp oscillations are observed.

Fig. 3 compares the energy dependence of pp cross section with that of $\gamma\ ^3\text{He} \to pp + n$ cross section at 90^0 $\gamma - (pp)$ center of mass scattering, calculated within the HRM model, which assumes the dominance of the contribution of hard pp rescattering in the photodisintegration reaction. In contrast to the situation displayed in Fig. 1, the precision of the pn and the $\gamma d \to pn$ data is insufficient to show if oscillations are indeed present for those reactions.

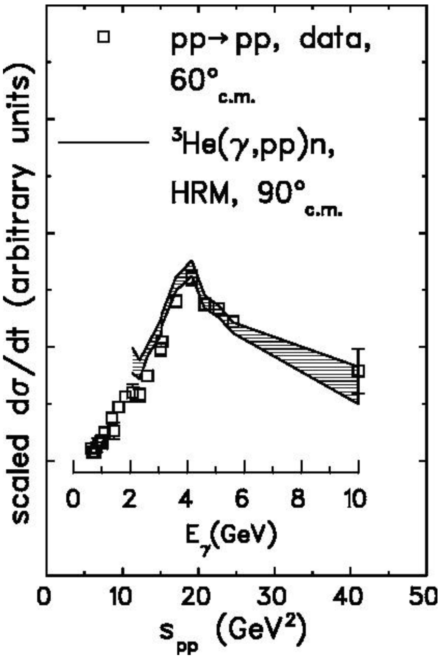

FIG. 3: Energy dependence of the γ ^{3}He$\rightarrow$ $pp+n$ cross section predictions multiplied by s^{11}, compared with the energy dependence of the $pp \rightarrow pp$ cross section multiplied by s^{10} and rescaled by an overall constant, to emphasize the similarity in the energy dependences. The horizontal scale is s for the γpp and pp systems; the photon energy scale is also shown. The different angles for the two reactions are chosen to match the momentum transfers, as discussed in the text. The shaded band is the HRM result, which is based on the pp elastic data.

The light cone momentum distribution of the recoil neutron in γ ^{3}He $\rightarrow$ $pp+n$, defined as $\alpha_n = \frac{E_n - p_n^z}{m_{^3He}/3}$ allows another way to study the dynamics of the hard process under discussion. The α for the incident photon is exactly zero, while α for the ^{3}He target is 3. Conservation of α allows therefore determination of α_n from the measurement of the light-cone fractions of the protons: An important feature of high-energy small-angle final-state rescattering is that it does not change the light-cone fractions of the fast protons – see e.g. [27].

We compare in Fig. 4 the α_n dependence of the differential cross section $\frac{d\sigma}{dtd^2p_Td\alpha_n/\alpha_n}$ calculated in the framework of the RNA and HRM models. The calculations are done for a fixed initial photon energy $E_\gamma = 4$ GeV and $\theta_{\rm c.m.} = 90^\circ$. Fig. 4 shows a substantial difference in α_n distributions. The much broader distribution of α_n in the RNA model is due to selection of very large momenta of protons in the ^{3}He wave function ($p_t \sim GeV/c$), which leads to a much broader distribution of neutron momenta.

Another feature of the α_n distribution is due to the the strong s dependence, $\sim s^{-11}$, of the hard disintegration cross section. This tend to suppress/increase the contribution from those values of α_n which increase/decrease the effective total c.m. energy of the $\gamma+pp$ system (s_{pp}). This causes the α distribution to be asymmetric about $\alpha_n = 1$. The extent of the asymmetry depends strongly on the exponent in the s dependence of hard disintegration cross section. To illustrate this phenomenon, in Fig. 4 we compare the α_n distributions within RNA and HRM model rescaled in one case by s_d^{11} ($s_d = 2E_\gamma M_d + M_d^2$) (bold solid and dashed lines) and in other case by s_{pp} (thin lines). This comparison demonstrates the sensitivity of the α_n asymmetry to the energy (s) dependence of the disintegration cross section.

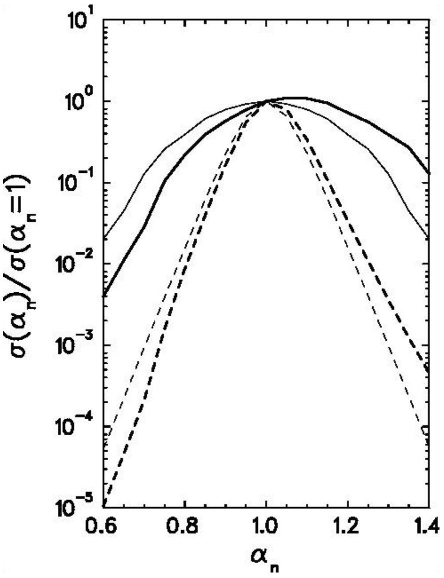

FIG. 4: The α_n dependence of the $\gamma\ {}^3\text{He}\rightarrow pp+n$ cross section calculated within RNA (bold solid line) and HRM (bold dashed line) models. $\sigma(\alpha)$ corresponds to the differential cross section scaled by s_d^{11}. Thin solid and dashed lines correspond to the same calculations scaled by s_{pp}^{11}. All calculations are normalized to one at $\alpha_n = 1$.

3. EXPERIMENTAL DETAILS

We propose to measure $\gamma\ {}^3\text{He} \rightarrow pp + n$ in Hall A. A schematic view of the exprimental setup is shown in Fig. 5.

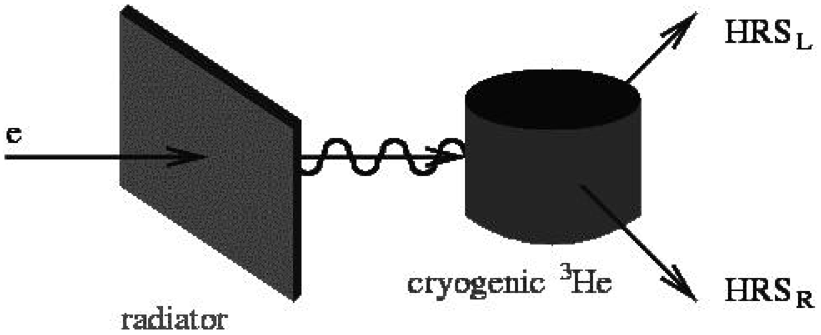

FIG. 5: The proposed experimental set up for Hall A /TJNAF.

Bremsstrahlung photons, produced by the electron beam (A 50 μA, 80 % polarized) passing through a photon radiator (Cu with a 6% radiation length thickness), will impinge on a cryogenic gas ^{3}He target. The maximum energy of the Bremsstrahlung beam is essentially equal to the incident electron kinetic energy, and the polarization of the photons is essentially equal to that of the beam, for near-endpoint photons. It is preferable to limit divergence of the beam and interactions with the target walls and flow diverters, by using a radiator foil mounted directly in the cryotarget cell block, about 15 cm upstream of the center of the target, as used in the last few Hall A photo-experiments.

The target, downstream of the radiator, is irradiated by the photons and the primary electron beam. The nearly real virtual photons and the real photons lead to protons with the same polarization. Previous Hall A unpolarized ^{3}He experiments have used a 10 cm diameter "tuna can" cryogenic gas target, operating at $T \approx 5.8$ K, $P \approx 15$ atm, and areal density $x\rho \approx 0.81$ g/cm^2. A 20 cm long "race track" cryotarget cell is presently under construction. This experiment could in principle be run with either cell. The later will give better momentum and energy resolution.

The two outgoing protons, each with about half the incident beam energy, are detected in coincidence with the two HRS spectrometers, each set for positively charged particles. The desired detector stacks consist of VDCs for tracking, scintillators for triggering, and Aerogel Cerenkov detectors for rejection of small π^+ backgrounds. It is desirable, but not critical, to run without the gas Cerenkov detectors installed. The maximum central momentum of HRS$_R$ (≈3.1 GeV/c) limits the maximum achieved s in this measurement.

We will measure the energy dependence of the differential cross section for $\theta_{\text{c.m.}} \approx 90°$ from 1.6 GeV (overlap with data from Hall B available up to that energy [28]) and up to 5 GeV. We will also measure a partial angular distribution for $E_\gamma = 3.2$ GeV and the transfer polarization at 1.6 GeV.

4. SUMMARY

We propose a new generation of hard photodisintegration study to continue the deuteron extensive measurements. The first measurement was recently approved for running in Hall A at Jefferson Lab. In this work we briefly review the ideas and the results. More details on the data and calculation concerning the deuteron photodisintegration can be found in a recent review [15]. More details on the theory can be found in [29]. More details on the experimental aspects are in the proposal (E03-005) and its update [30].

5. ACKNOWLEDGMENT

We wish to thanks Drs. S.J. Brodsky, L. Frankfurt, J.R. Hiller, G.A. Miller, A. Radyushkin, M. Strikman for their theoretical input. We acknowledge the support of different agencies. EP is supported by the Israel Science Foundation founded by the Israel Academy of Science and Humanities. RG is supported by the U.S. National Science Foundation, grant PHY-00-98642. The Southeastern Universities Research Association operates the Thomas Jefferson National Accelerator Facility under U.S. DOE contract DE-AC05-84ER40150. MS support is by the U.S. DOE under contract DE-FG02-01ER-41172.

[1] J. Napolitano *et al.*, Phys. Rev. Lett. 61(1988)2530 ; S.J. Freedman *et al.*, Phys. Rev. C 48(1993)1864.
[2] J.E. Belz *et al.*, Phys. Rev. Lett. 74(1995)646.
[3] R. Crawford *et al.* Nucl. Phys. A 603(1996)303.
[4] C. Bochna *et al.*, Phys. Rev. Lett. 81(1998)4576.
[5] E. Schulte *et al.*, Phys. Rev. Lett. 87(2001)102302.
[6] E. Schulte *et al.*, Phys. Rev. C 66(2002)042201R.
[7] P. Rossi, private communication, Hall B experiment 93-017.
[8] K. Wijesooriya *et al.*, Phys. Rev. Lett. 86(2001)2975.
[9] S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett. 31(1973)1153; V.A. Matveev, R.M. Muradyan and A.N. Tavkhelidze, Lett. Nuovo Cim. 7(1973)719.
[10] G.P. Lepage and S.J. Brodsky, Phys. Rev. D22(1980)2157.
[11] J. Polchinski and M. J. Strassler, Phys. Rev. Lett. 88(2002)031601 [arXiv:hep-th/0109174].

[12] G. R. Farrar, K. Huleihel and H. Y. Zhang, Phys. Rev. Lett. 74(1995)650.
[13] G. R. Farrar, K. Huleihel and H. Y. Zhang, Nucl. Phys. B 349(1991)655.
[14] T. C. Brooks and L. J. Dixon, Phys. Rev. D 62(2000)114021.
[15] R. Gilman and F. Gross, J. Phys. G 28(2002)R37.
[16] S.J. Brodsky and J.R. Hiller, Phys. Rev. C 28(1983)475; Phys. Rev. C 30(1984)412(E).
[17] A. Radyushkin, private communication.
[18] V. Yu Grishina *et al.*, Eur. J. Phys. A 10(2000)355.
[19] L.L. Frankfurt, G.A. Miller, M.M. Sargsian and M.I. Strikman, Phys. Rev. Lett. 84(2000)3045.
[20] M.M. Sargsian *et al.*, *in preparation.*
[21] See, e.g., D.J. Tedeschi *et. al.*, Phys. Rev. Lett. 73(1994)408.
[22] M.K. Carter, P.D.B. Collins and M.R. Whalley, Compilation of Nucleon-Nucleon and Nucleon-Antinucleon Elastic scattering Data, Rutherford Appleton Lab, (RAL-86-002) 1986.
[23] P.V. Landshoff and J.C. Polkinghorne, Phys. Lett. B 44(1973)293 and references therein.
[24] A. Hendry, Phys. Rev. D 10(1974)2300.
[25] J. Ralston and B. Pire, Phys. Lett. 117 B(1982)233.
[26] S.J. Brodsky and G.F. deTeramond, Phys. Rev. Lett. 60(1988)1924.
[27] M.M. Sargsian, Int. J. Mod. Phys. E 10(2001)405.
[28] Jefferson Lab Hall B experiment 93-044, B.L. Berman *et al.*; B.L. Berman, private communication.
[29] S.J. Brodsky, L. Frankfurt, R. Gilman, J.R. Hiller, G.A. Miller, E. Piasetzky, M. Sargsian, and M. Strikman, submitted to Phys. Lett. B, (May, 2003), preprint nucl-th/0305068, JLAB-THY-03-34.
[30] E. Piasetzky, R. Gilman (spokepersons). Hard Photodisintegration of a Proton Pair", Experiment 03-005, Proposal to Jefferson Laboratory, 2003 (unpublished).