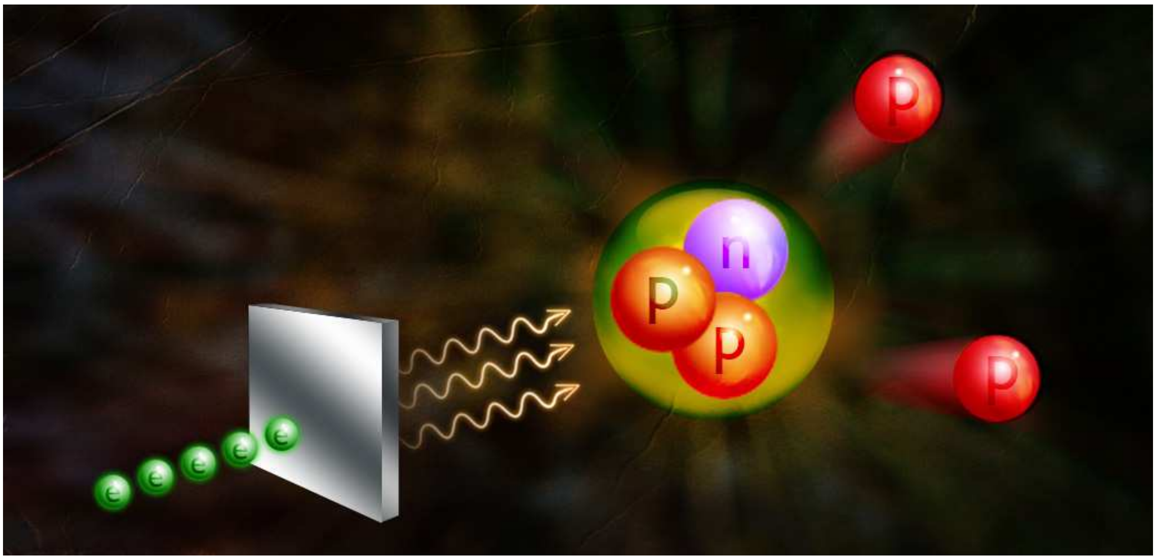
Hard Photodisintegration of a Proton Pair

The Jefferson Lab Hall A Collaboration



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ABSTRACT

Extensive studies of high-energy deuteron photodisintegration over the past two decades have probed the limits of meson-baryon descriptions of nuclei and reactions. At high energies, photodisintegration cross sections have been shown to follow the constituent counting rules, which suggests that the quarks are the relevant degrees of freedom.

In an attempt to more clearly identify the underlying dynamics at play in high-energy photodisintegration, E03-101 measured in 2007 the hard photodisintegration of two protons, using ^{3}He. The basic idea is that theoretical models should be able to predict the relative size of *pp* versus *pn* disintegration. E03-101 results clearly indicate the onset of scaling but lack sufficient statistics to determine the underlying mechanism that produces high transverse momentum proton pairs.

We propose here to take higher statistics data in the scaling regime at energies of 2.2 and 4.4 GeV. This measurement will determine whether deviations from constituent counting rules scaling exist in this reaction. If the predicted oscillations of the cross section with photon energy are observed, re-scattering is the dominant mechanism responsible for the hard process. Furthermore, we will measure the light-cone momentum distribution of the spectator neutron, which serves as an independent way of checking the underlying mechanism of hard *pp* pair production.

The experimenters request 15 days to run the experiment in Hall A, which requires no new equipment and no special setup or development time

I. SCIENTIFIC BACKGROUND AND MOTIVATION

A. Overview

One of the central interests of nuclear physics in recent decades has been determining if there is a need for quarks and Quantum Chromodynamics (QCD) to understand nuclear structure and reactions. In general, modern effective NN forces determined from NN scattering data provide excellent predictions of the nuclear structure of light nuclei. Supplemented by interactions determined from pion photo-production, one has very good predictions of electromagnatic properties (nuclear form factors) and reactions such as photo-disintegration. Apparently, either the quark effects are small, or they are already effectively incorporated in modern NN forces.

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 Δ-resonance region, photodisintegration of the deuteron is well understood, although certain detailed problems remain [9–12]. Above $\sim$1 GeV, deuteron photodisintegration cross sections have been shown to follow the constituent counting rules [8, 13–16], which have been derived from dimensional analysis, QCD and AdS/CFT correspondence [15, 17, 18].

We define a hard photodisintegration of a nucleon pair as a process in which a high energy photon is absorbed by a nucleon pair and as a result the pair is disintegrated by emitting two nucleons with large transverse momenta, greater than about 1 GeV/c. As defined in this process, the Mandelstam parameters s and t (the square of the total energy in the c.m. frame and the four-momentum transfer from the photon to the nucleon) are large.

In an attempt to more clearly identify the underlying dynamics at play in high-energy photodisintegration, E03-101 measured the hard photodisintegration of two protons, using ^{3}He. The basic idea is that theoretical models should be able to predict the relative size of pp versus pn disintegration [19]. Also, if the pp and pn disintegration are related to the corresponding pp and pn elastic scattering via hard re-scattering [20], deviations from power scaling in the elastic scattering should be reflected in corresponding differences in the photodisintegration processes.

Experiment E03-101 ran in Hall A during the summer of 2007 and measured the cross section of the photodisintegration of a proton pair in ^{3}He at $\theta_{c.m.} = 90^\circ$ for photon energies in the range of 0.8 - 4.7 GeV [21]. We propose here to take higher statistics data at energies of 2.2 and 4.4 GeV.

Figure 1 shows the $\gamma + \mathrm{d} \rightarrow p + n$ and $\gamma + {}^3\mathrm{He} \rightarrow p + p + n$ cross section at $\theta_{c.m.} = 90^\circ$ scaled by s^{11}. The ^{3}He(γ,pp)n events were selected with $p_n < 100$ MeV/c. The cross section is compared to predictions for the photodisintegration of both pn and pp pairs from theoretical models, which are discussed below [19].

B. Theoretical models

In the *scaling* region the cross section for both 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 pn pairs 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 a charged pion cannot be exchanged between the protons.

The reduced nuclear amplitude (RNA) formalism [22] after normalization to the deuteron data [19] yields cross sections that are about 200 times larger than the present data. The quark-gluon string model (QGS) [23, 24], as estimated in [19], predicts cross sections about a factor of 5 larger than measured. The QCD hard re-scattering model (HRM) [25] provides 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 the deuteron data reasonably well and the proton pair cross section. The HRM model predicts an energy dependence of the scaled cross section that the data is not accurate enough to either confirm or reject.

C. Summary of goals

1. Energy dependence of the cross section

Figure 2 shows the pp breakup cross section in the scaling region. The uncertainty above 3.1 GeV in the data is dominated by statistics. One can see that the four data points (filled

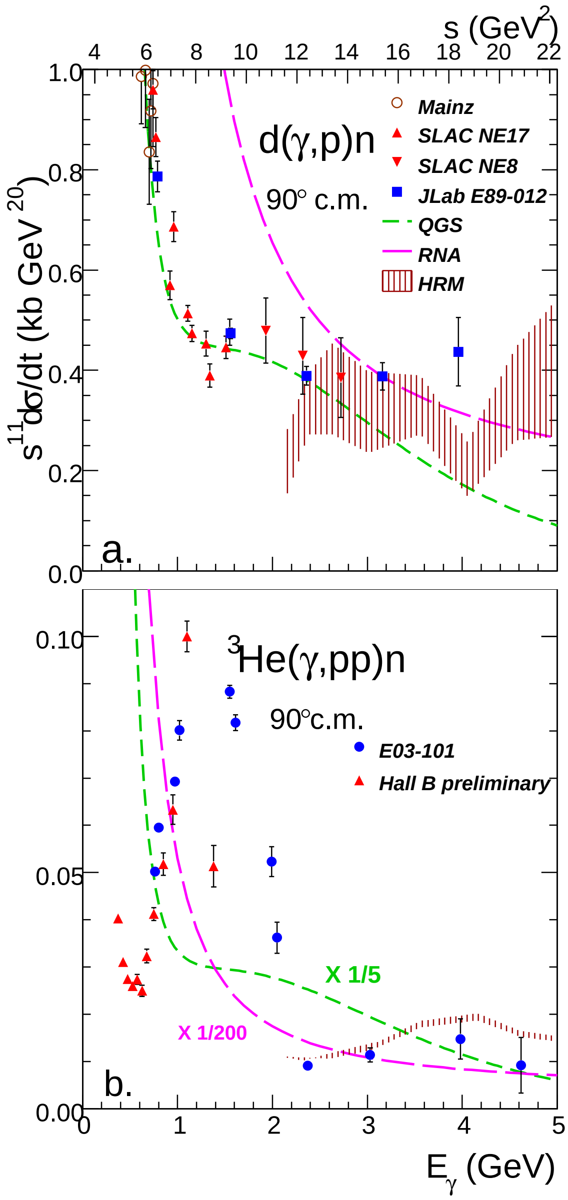

FIG. 1: The d(γ,p)n (a) and ^{3}He(γ,pp)n (b) invariant cross section scaled by s^{11}. ^{3}He(γ,pp)n events were selected with $p_n < 100$ MeV/c. Up to 2.1 GeV, the photon energy bins are 70 MeV, and above it 140 MeV. Model predictions are taken from [19, 20]. In (b), RNA is divided by a factor of 200 and QGS by a factor of 5 to be shown on this scale. Error bars represent statistical uncertainty.

circles) are in good agreement with the HRM prediction as well as with scaling (a constant). Our first goal in this proposed measurement is to reduce the uncertainty of the ^{3}He(γ,pp)n cross section in the scaling region, to look for evidence of the oscillation predicted by the

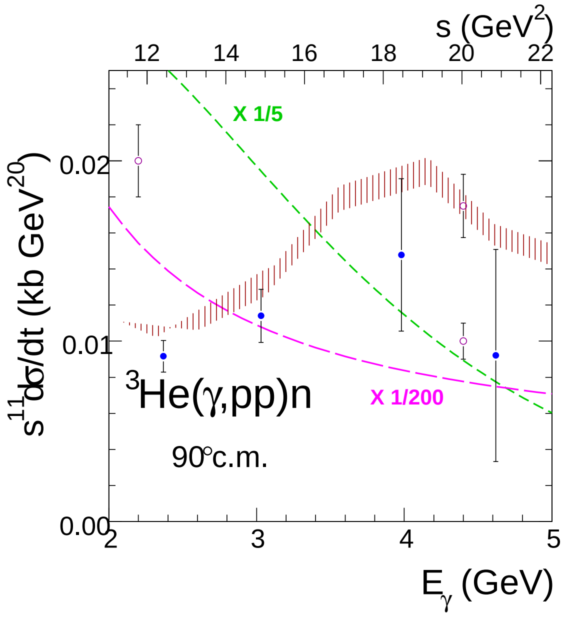

FIG. 2: The ^{3}He(γ,pp)n invariant cross section scaled by s^{11} in the scaling region. Event selection and colors are same as in Figure 1. The magenta open circle at 2.2 GeV is interpolated from E03-101 data, and the magenta open circles at 4.4 GeV illustrates the capability to separate model predictions with 12% uncertainty.

HRM. Appearance of this oscillation will serve as evidence for the dominance of FSI in this reaction in the form of hard p-p rescattering. A 4.4 GeV (2 pass) data point with 12% (stat.+sys.) error will enable us to determine if the cross section oscillates. Since the count rate is very high at lower energies, we would also like to take data for a couple of days at 2.2 GeV (1 Pass) for calibration purposes.

2. α_n Distribution

The recoil neutron in γ ^{3}He $\rightarrow pp + n$ gives an additional way to check the underlying mechanism of hard pp pair production. The observable which is best suited for this purpose is the light-cone momentum distribution of the recoil neutron, defined as $\alpha_n = \frac{E_n - p_n^z}{m_{^3He}/3}$. We use light-cone variables in which the α's are defined as follows:

$$\alpha = A\frac{E^N - p_z^N}{E^A - p_z^A} \approx \frac{E_N - p_z^N}{m_N}, \tag{1}$$

where the z direction is chosen in the direction of the incident photon beam.

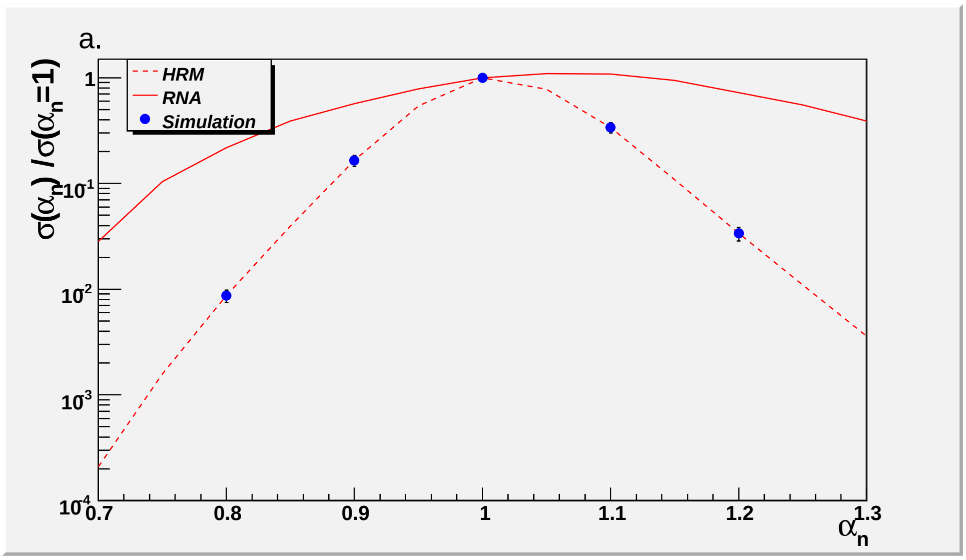

FIG. 3: *α distribution of the spectator neutron at E_e= 2.2 GeV. Cross section calculated within RNA (bold red solid line) and HRM (bold red dashed line) models, and simulated data points (blue). $\sigma(\alpha_n)$ corresponds to the differential cross section scaled by s^{11}_{pp}. Anticipated uncertainties are for 1 day of beam-time at 2.2 GeV.*

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. [26]. As a result, the experimentally determined α_n coincides with the value of α_n in the initial state and measures the light-cone fraction of the two-proton subsystem in the ^{3}He wave function. Furthermore, in the ^{3}He wave function the c.m. momentum distribution of the NN pair depends on the relative momentum of the nucleons in the pair, so one can probe indirectly the magnitude of the momentum in the pp pair involved in the hard disintegration by the measured alpha distribution.

To illustrate the sensitivity of the α_n distribution to the mechanism of the high-p_T disintegration of a pp pair, we compare in Fig. 3 (a) 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 results presented in Fig. 3 provide substantially different predictions for the α_n distribution. Qualitatively, the much broader distribution of α_n in the RNA model is due to the selection of large momenta of protons in the ^{3}He wave function, which leads to a broader distribution of neutron momenta. The simulated data points (blue) where generated by sampling the wave function of the neutron in ^{3}He [12] up to 100 MeV/c (same assumption as in the HRM).

II. EXPERIMENTAL DETAILS

A. Experimental overview

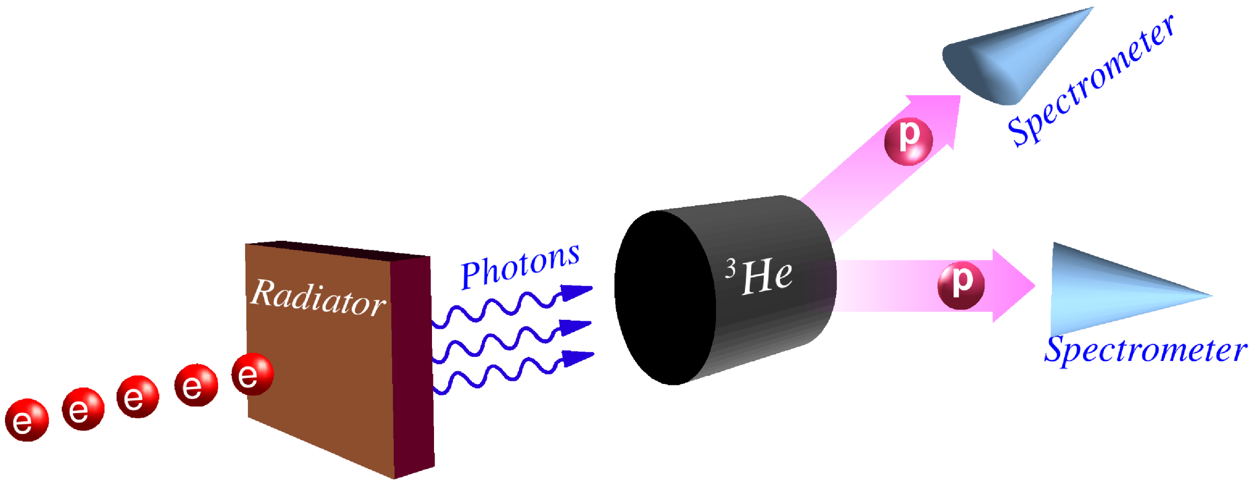

FIG. 4: Experimental setup: Bremsstrahlung photons generated in a copper radiator by an electron beam impinged on a ^{3}He gas target. Protons were detected with the spectrometers. Elements are not to scale.

We propose to measure $\gamma\ ^3\mathrm{He} \rightarrow pp{+}n$ in Hall A. The experimental setup is schematically described in Fig. 4. Bremsstrahlung photons, produced by the electron beam passing through a photon radiator, 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. The target, downstream of the radiator, is irradiated by the photons and the primary electron beam. The two outgoing protons, each with about half the incident beam energy, are detected in coincidence with the two High Resolution Spectrometers (HRS), each set for positively charged particles. We will measure the energy dependence of the differential cross section for $\theta_{\mathrm{c.m.}} \approx 90°$.

B. Photon radiator

The radiator is the standard Hall A Cu radiator with a 6% radiation length thickness [27]. To limit divergence of the beam and interactions with the target walls and flow diverters, it is preferred to use a radiator foil mounted directly in the cryotarget cell block, about

15 cm upstream of the center of the target. Since the radiator is directly cooled by the cryotarget, melting is not an issue. The main constraint on maximum beam current is the site boundary radiation level. We propose to do the measurement with a 50 μA beam and with the standard cryotarget raster, as has been done in earlier Hall A photodisintegration experiments. The power deposited in the Cu is about 125 W for a beam current of 50 μA.

C. Target

We will use the 20 cm long narrow ”race track” cryotarget cell, which was used in E03-101. That target has proved to be successful both in reducing the uncertainty associated with the cuts (subtractions of end cap background) and decreasing multiple scattering of the ejected particles, which leads to improved momentum and energy resolution. We expect that the target will be able to operate at the same temperature, pressure and density as in the previous run, leading to a ^{3}He density of 0.079 g/cm^3.

D. Spectrometers

We will use the two Hall A spectrometers (HRS$_L$ and HRS$_R$) to measure the two protons in coincidence. This measurement requires no changes from the standard electronics and operation of the spectrometers. For this experiment, the spectrometer momentum range is $\approx 1.8 - 3.0$ GeV/c and the angular range is $42 - 53°$ lab. All necessary equipment including detectors, electronics and data acquisition are already available.

E. Systematic uncertainties

The systematic uncertainties involved in the cross section calculation were thoroughly studied in the analysis of E03-101. They are governed by:

- The background subtraction of electroproduction events, which requires an estimation of the number of Bremsstrahlung photons per electron taken from theory.
- The evaluation of the two coincident protons acceptance of the two HRS, which is done by simulation. It is dependent on the wave function of the spectator neutron taken from theory.

TABLE I: *Kinematics, estimated cross sections, rates and requested time.*

Run	$E_e \approx E_\gamma$	Target	α_n	θ_p	P_p	$\frac{d\sigma}{dt}$	$s^{11}\frac{d\sigma}{dt}$	rate	time	yield
	[GeV]			[deg]	[GeV/c]	[pb/GeV^2]	[kb GeV^{20}]	[cnt/Hr]	Hr	# evts
1a	2.2	^{3}He	0.8	56.36	1.795	2.50	0.001	10	6	54
1b	2.2	^{3}He	0.9	54.42	1.805	19.9	0.007	72	2	144
1c	2.2	^{3}He	1.0	52.55	1.808	57.5	0.02	210	4	840
1d	2.2	^{3}He	1.1	50.66	1.806	10.9	0.004	39	3	117
1e	2.2	^{3}He	1.2	48.76	1.799	1.6	0.001	6	8	46
1f	2.2	d	1.0	52.55	1.808	1150	0.4	8400	1	8400
2a	4.4	d	1.0	42.72	2.990	2.76	0.4	21	48	1008
2b	4.4	^{3}He	1.0	42.72	2.990	0.02	0.01	0.45	222	100

The total systematic uncertainty in the scaled cross section is estimated to be less than 7% for these two energy points.

III. KINEMATICS AND REQUESTED BEAM TIME

We propose to measure the $\theta_{\rm c.m.} = 90^\circ$ cross section at $E_\gamma = 2.2$ and 4.4 GeV and the α_n distribution at 2.2 GeV. The kinematics and the predicted differential cross sections are shown in Table I. They have been calculated based on interpolation from E03-101 data.

The kinematics, the predicted differential cross sections and expected count rates are shown in Table I. Both the cross sections and count rates have been calculated base on interpolation from E03-101 data points, assuming the same running conditions of 50 μA current, a 6 % copper radiator and the Hall A unpolarized ^{3}He target. We will also form single arm measurements of $\gamma\, d \to p+n$ to calibrate the coincidence ^{3}He measurements with previous results. The yields in Table I for the deuteron target were projected from previous results.

The beam time request is summarized in Table II for a total of 15 days.

TABLE II: *Summary of the requested beam time.*

Measurement	Time [days]
Setup & Checkout	1
Measurement at 2.2 GeV 5 Kinematic changes 1 Target change	2
Measurement at 4.4 GeV Energy and target change	12
TOTAL REQUESTED BEAM TIME	15

A note for the reviewer

We are currently considering to add the neutron array in order to measure ^{3}He(γ,pn)p channel. This direct comparison between a free-deuteron and a np-pair within ^{3}He photo-disintegration can help to explain the large difference in magnitude between ^{3}He(γ,pp)n and d(γ,p)n cross sections.

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