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First Measurements of the $D(e,e'p)n$ Cross Section at Very High Recoil Momenta and Large Q^2

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First results of cross section measurements of the $^2H(e,e'p)n$ reaction at 4-momentum transfers $4 \leq Q^2 \leq 5$ (GeV/c)² and neutron recoil momenta up to 1.18 GeV/c are presented. At the selected kinematics, Meson Exchange Currents (MEC) and Isobar Configurations (IC) are suppressed. Final State Interactions (FSI) have also been suppressed by choosing a kinematic region where the neutron recoil angle (θ_{nq}) is between 35 and 45 degrees with respect to the 3-momentum transfer, \vec{q} . In this region, the Plane Wave Impulse Approximation (PWIA) dominates and comparison to recent theoretical calculations show data to be sensitive to momentum distributions up to ~ 700 MeV/c recoil momenta.

Being the most simple np bound state, the deuteron serves as a starting point to study the strong nuclear force at the subfermi level which is currently not well understood. At such small internucleon distances the NN (nucleon-nucleon) potential is expected to exhibit a repulsive core in which the interacting nucleon pair begins to overlap. The overlap is directly related to two-nucleon short range correlations (SRC) observed in $A > 2$ nuclei [1–4]. Short-distance studies of the deuteron are also important in determining whether or to what extent the description of nuclei in terms of nucleon/meson degrees of freedom must be supplemented by the inclusion of explicit quark effects, which is an issue of fundamental importance in nuclear physics[5]. To date, there are only a few nuclear experiments for which a transition between nucleonic to quark degrees of freedom can be observed [6–8]. This Letter presents first results of $^2H(e,e'p)n$ in which kinematics were taken to the limit where a transition to non-nucleonic degrees of freedom is expected.

The most direct way to study the short range structure of the deuteron wavefunction (or equivalently, its high momentum components) is via the exclusive deuteron electro-disintegration reaction at very high neutron recoil (or missing) momenta and within the PWIA kinematics. In this approximation, the virtual photon couples to the proton which is ejected from the nucleus without further interaction with the recoiling neutron, which carries a momentum equal in magnitude but opposite in direction to the initial state proton, $\vec{p}_r = -\vec{p}_{i,p}$. This gives direct access to the deuteron momentum distributions since the scattered neutron momentum remains unchanged.

In reality, the ejected particles undergo subsequent interactions resulting in re-scattering of the proton and neutron (FSIs). Another possibility is that the photon may couple to the virtual meson being exchanged between the nucleons (MECs), or the photon may excite either nucleon in the deuteron into a resonance state (ICs) which decays back into the ground state nucleon causing further re-scattering between the proton and neutron. The above-mentioned long-range processes alter the final neutron momentum making the deuteron momentum distributions difficult to access.

Previous deuteron electro-disintegration experiments performed at Jefferson Lab (JLab) have helped disentangle and quantify the contributions from FSI, MEC and IC on the $^2H(e,e'p)n$ cross-section and determine the kinematics at which they are either suppressed (MECs and ICs) or under control (FSIs). The first of these was performed in Hall A [9] at a relatively low momentum transfer of $Q^2 = 0.665$ (GeV/c)² and neutron recoil momenta up to $p_r = 550$ MeV/c where it was shown that for $p_r > 300$ MeV/c, the inclusion of FSI, MEC and IC was necessary in Arenhovel's calculations for a satisfactory agreement between the theory and data.

The next experiment was performed in Hall B [10] using the CEBAF Large Acceptance Spectrometer (CLAS) which took advantage of its large detector acceptance to simultaneously measure a wide variety of kinematic settings giving an overview of the $^2H(e,e'p)n$ reaction kinematics. This was the first experiment to probe the deuteron at high momentum transfers ($1.75 \leq Q^2 \leq 5.5$ (GeV/c)²) and presented angular distributions of

cross-sections that confirmed the onset of the General Eikonal Approximation (GEA), predicting a strong angular dependence of FSI with neutron recoil angles with FSI peaking at $\theta_{nq} \sim 70^\circ$. The cross-sections versus neutron recoil momenta up to 2 GeV/c were also presented with integrated neutron recoil angles in the range $20^\circ < \theta_{nq} < 160^\circ$ to gain better statistical precision. As a result, it was not possible to choose kinematical regions binned in θ_{nq} in which FSI were minimal to extract the momentum distributions.

Finally, a third ${}^2H(e, e'p)n$ experiment was performed in Hall A [11] at $Q^2 = 0.8, 2.5, 3.5$ (GeV/c)² and recoil momenta up to 550 MeV/c at kinematics which allowed the extraction of angular and momentum distributions for significantly smaller kinematical bins than in Hall B/CLAS. The angular distributions were presented as the cross-section ratio, $R = \sigma_{exp}/\sigma_{PWIA}$ versus θ_{nq} , and verified the strong anisotropy of FSI with recoil angle previously observed in Hall B. Most importantly, for recoil neutron momentum bins, $p_r = 0.4 \pm 0.02$ and 0.5 ± 0.02 GeV/c, the ratio $R \sim 1$ for $35^\circ \leq \theta_{nq} \leq 45^\circ$ indicating a reduced sensitivity of the experimental cross-section to FSI, in which, $\sigma_{exp} \sim \sigma_{PWIA}$. This kinematic window in which FSI are small can also be seen in the momentum distributions for $\theta_{nq} = 35 \pm 5^\circ$ and $45 \pm 5^\circ$, where data and theory agree well within the PWIA kinematics. The experiment concluded that the kinematic window found at $35^\circ \leq \theta_{nq} \leq 45^\circ$ gives for the first time a direct access to the high momentum components of the deuteron momentum distribution.

The experiment presented on this Letter takes advantage of the kinematic window found previously in Hall A and extends the ${}^2H(e, e'p)n$ cross section measurements to $Q^2 = 4.5$ (GeV/c)² and neutron recoil momenta up to 1.18 GeV/c. In this configuration, MECs and ICs are suppressed and FSIs are under control for neutron recoil angles between 35 and 45 degrees giving access to unprecedented high momentum components of the deuteron wavefunction.

This experiment was part of a group of four experiments that commissioned the new Hall C Super High Momentum Spectrometer (SHMS) as part of the 12 GeV upgrade at JLab. An electron beam was incident on a 10 cm long liquid deuterium target (LD2). The scattered electron and knocked-out proton were detected in coincidence by the SHMS and High Momentum Spectrometer (HMS), respectively. The “missing” (undetected) neutron was reconstructed from momentum conservation laws. The beam currents delivered by the accelerator ranged between 40-60 μ A due to frequent beam trips at higher currents and the beam was rastered over a 2x2 mm² area to reduce the effects of localized boiling on the cryogenic targets (hydrogen and deuterium).

Both spectrometers at Hall C have similar standard detector packages, each with 1) four sets of hodoscope planes (scintillator arrays) used for triggering, 2) a pair

of drift chambers used for tracking, 3) a calorimeter used for e^-/π^- discrimination and 4) a gas Čerenkov used also for e^-/π^- and an additional Noble Gas Čerenkov used in the SHMS for $e^-/\pi^+/K^+$ at momenta > 6 GeV/c. Due to the absence of significant background on this experiment and the low coincidence trigger rates ($\sim 1 - 3$ Hz) at the higher missing momentum settings, the use of additional particle identification (PID) was found to have little to no effect on the final cross section.

We measured three missing momentum settings: $p_r = 80, 580$ and 750 MeV/c. In the high missing momentum settings the spectrometer configuration was changed multiple times resulting in either the spectrometer angle or momentum not being exactly the same. As a result, two separate data sets measured for the 580 MeV/c and three data sets for the 750 MeV/c setting. The spectrometer central settings are approximately as follows: the SHMS central angle and momentum settings were kept fixed at (12.194 deg, 8.5342 GeV/c) and the HMS central angle and momentum settings were changed from (38.896 deg, 2.840 GeV/c) at the 80 MeV setting to (54.992 deg, 2.1925 GeV/c) and (58.391 deg, 2.0915 GeV/c) at the 580 and 750 MeV/c settings, respectively. At these kinematics, the 3-momentum transfer is $|\vec{q}| = 2.86$ GeV/c and is on the order of the final proton momentum indicating that most of the energy and momentum are transferred to the proton. As a result, the ejected proton scatters at angles $\theta_{pq} \sim 0$, relative to the \vec{q} . This configuration is known as the “parallel-kinematics” and suppresses the process in which the neutron is struck and the proton is a spectator.

In addition to deuteron kinematics, ${}^1H(e, e'p)$ elastic data was also taken at kinematics close to the deuteron 80 MeV setting for cross-checks with the spectrometer acceptance model as well as for normalization purposes using the Hall C Monte Carlo simulation program, SIMC. Additional ${}^1H(e, e'p)$ data was also taken at three other kinematic settings that covered the entire SHMS momentum acceptance range and were used for spectrometer optics studies and calibration.

The event selection criteria for the hydrogen and deuteron data was determined by making 1) standard cuts on the spectrometer momentum fraction (δ) to select a region in which the reconstruction optics is well known, 2) an HMS collimator cut to restrict the spectrometer solid angle acceptance to events that only passed through the collimator and not by re-scattering from the edges, 3) a missing energy cut (peak ~ 2.2 MeV for the deuteron) to select true ep coincidences and not events from the radiative tail, 4) a coincidence time cut to select true coincidence events and not accidentals, 5) a PID cut on the SHMS calorimeter to select electrons and not other sources of background, mostly pions and 6) a z-vertex difference cut between the HMS and SHMS z reaction vertex difference to select events that truly originated from the same reaction vertex at the target.

The experimental data yield was normalized by the accumulated charge and corrected for tracking efficiencies, total live time, proton absorption and target boiling factors. For $^1H(e, e'p)$, the corrected data yield was compared against SIMC using P. Bosted's proton form factor parametrization[12] to check the spectrometer acceptance model. The data to SIMC yield ratio was determined to be 1.0 within uncertainty, and there was no need to include an overall hydrogen normalization factor. For the $^2H(e, e'p)$ data, the theoretical cross section calculation from J.M. Laget using the Paris potential was incorporated into SIMC as a subroutine. The events generated over phase space were weighted by the theoretical cross sections using either the PWIA or FSI models and were compared to the corrected data yield for the 80 MeV setting. Variations of up to $\sim 20\%$ for recoil momentum up to ~ 250 MeV/c were observed which are typical for this setting. The 80 MeV data was also checked for reproducibility against the Hall A data at this setting. This agreement gives us confidence on the measurements made at higher missing momentum setting for which no data exists.

The experimental sections were determined by dividing the normalized data yield by the phase space over the spectrometers acceptances generated in SIMC. The data was radiatively corrected by multiplying measured cross sections by the ratio of the SIMC yield (using the Paris potential, FSI model) without and with radiative effects for each bin in (θ_{nq}, p_r) . The data was also bin-centered corrected by multiplying the radiative corrected cross sections by the ratio of theoretical cross section at the averaged kinematics to the average SIMC model cross sections at the bin-centered value in (θ_{nq}, p_r) . The theoretical cross sections were determined external to SIMC using J.M. Laget's calculations at the averaged kinematics.

The systematic uncertainties on the measured cross sections are separated in two categories: 1) normalization and 2) kinematic uncertainties. The normalization uncertainties on the $^2H(e, e'p)n$ cross section were determined to be: tracking efficiencies (0.40%-HMS, 0.59%-SHMS), target boiling (0.39%), total live time (3.0%) and total charge (2.0%) for an overall normalization uncertainty of 3.7% added in quadrature.

The kinematic uncertainties were determined point-to-point for (θ_{nq}, p_r) bins for each data set independently, and added in quadrature for overlapping p_r bins of different data sets. The variations of the cross section with spectrometer kinematics in beam energy, electron angle and momentum and proton angle were determined from Laget PWIA model and the uncertainties in the kinematic variables were determined from a fit to the $^1H(e, e'p)$ elastic data. The overall systematic uncertainty in the cross section was determined by the quadrature sum of the normalization and kinematic uncertainties. This results was then added in quadrature to the

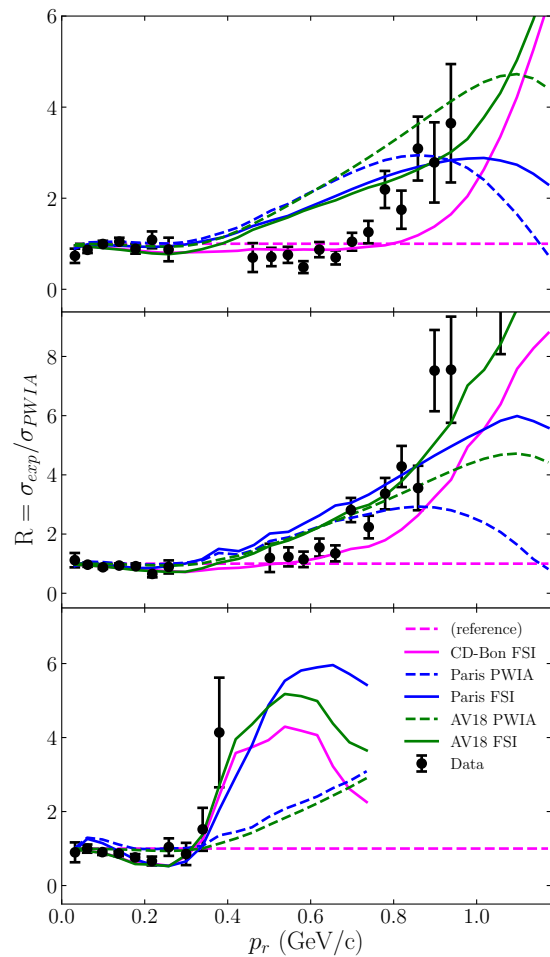


FIG. 1. The ratio $R(p_r) = \sigma_{exp}/\sigma_{PWIA}$ is shown in (a)-(c) for $\theta_{nq} = 35^\circ, 45^\circ$ and 75° , respectively, each with a bin width of $\pm 5^\circ$. The dashed reference (magenta) line refers to CD-Bonn PWIA for which the data and all models are divided.

statistical uncertainty to obtain the final uncertainty in the cross section.

The $^2H(e, e'p)n$ reduced cross sections for each data set were determined within the PWIA by:

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{K f_{rec} \sigma_{cc1}} \quad (1)$$

where σ_{exp} is the 5-fold experimental (or model) cross section, K is a kinematical factor, f_{rec} is a the recoil factor that arises from the integration over missing energy and σ_{cc1} is the de Forest[13] electron-proton offshell cross section. In the PWIA, σ_{red} is interpreted as the momentum distributions inside the deuteron where most of the kinematical dependencies that arise from the cross section have been factored out.

In Figure 1, the ratio of the experimental to the PWIA reduced cross sections is plotted against neutron recoil momentum, p_r .

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