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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.

The kinematics measured in our experiment consisted of three missing momentum settings: $p_r = 80, 580$ and 750 MeV/c. The spectrometer settings were 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, ${}^1H(e, e'p)$ 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 to cover the entire SHMS momentum acceptance range for spectrometer optics studies and calibration.

The event selection criteria 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.

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