# Deuteron Electro-Disintegration at Very High Missing Momenta

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## 1 Motivation

The deuteron ($^2$H) was discovered in 1931 by Harold Urey, and it remained a mystery until the discovery of the neutron by James Chadwick the following year [8]. Since then, the deuteron has been under intensive research in an attempt to understand what binds the atomic nucleus. Being a 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 $A \geq 2$ nuclei [7]. 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 [9].

In nuclear structure studies in general, electron-nucleon scattering serves as the most valuable tool since the interaction is described by Quantum Electro-Dynamics (QED), which is well-understood and capable of making accurate predictions. Electron scattering experiments can be separated into inclusive or exclusive scattering experiments. In the first of these, only the electron is detected in the final state (single-arm experiments), and so one studies the nucleus in question by integrating over all possible final states [1]. In the exclusive type, one or more particles are detected in coincidence with the scattered electron which allows one to investigate properties unique to the specific reaction in question. In deuteron electro-disintegration, for example, one detects the scattered electron in coincidence with a proton and the missing neutron is reconstructed from four-momentum conservation. This reaction proves to be the most direct way of probing the internal structure of the deuteron since it is possible to deduce the internal momentum of the nucleons from the neutron missing momentum.

With the 12 GeV Upgrade at Jefferson Lab, the short-range ($\leq$ 1 fm) structure of the deuteron will become experimentally accessible via data on the deuteron wavefunction beyond relative internal momenta of 400 MeV/c. At such high energies, one will be able to probe if effects due to Quantum Chromodynamics (QCD) start playing a more significant role [7].

## 2 Theoretical Framework of D(e,e'p)n

Deuteron electro-disintegration can be pictorially described by a Feynmann diagram (See Figure 1) where the incoming elec-

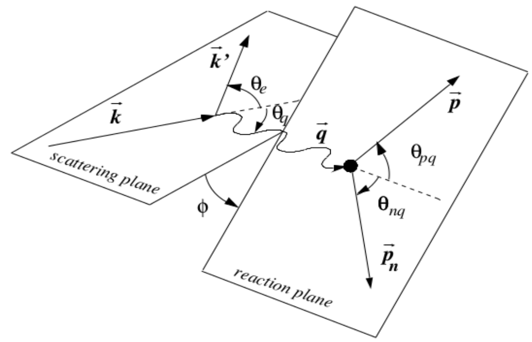


**Figure 1:** Feynmann diagram of deuteron electro-disintegration

tron interacts with the stationary deuteron to first order approximation via the exchange of a virtual photon. Given the relatively weak coupling constant for this process, higher order Feynmann diagrams involving multiple photon exchanges may be neglected. The interaction of the virtual photon with the deuteron is best described by the general unpolarized (e,e'p) cross section,[1]

$$\frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p} = \sigma_{Mott}(v_L R_L + v_T R_T + v_{LT} R_{LT}\cos\phi + v_{TT} R_{TT}\cos 2\phi) \tag{1}$$

where $\sigma_{Mott}$ is the Mott cross section describing electron scattering off an infinitely massive, spinless point charge. The quantities $(v_i, v_{ij})$ are dependent on electron kinematics (i.e., q, $Q^2$, $\theta_e$) and the functions $(R_i, R_{ij})$ are nuclear response functions and depend on nuclear charge and current density operators [4].

In the simplest approximation, the virtual photon couples to the proton which is ejected from the nucleus without further interaction with the recoiling nucleus which carries a momentum $\mathbf{p_m} = -\mathbf{p_{i,p}}$. Both final state proton and neutron are assumed to be plane waves (free particles), hence the name Plane Wave Impulse Approximation (PWIA). (See Figure 2)

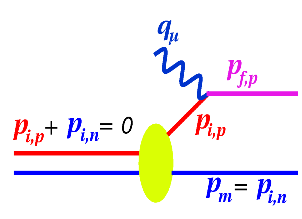


**Figure 2:** Feynmann diagram for PWIA, where the proton(red) is knocked by the photon, and the neutron(blue) scatters as a spectator

From the PWIA assumptions, the general (e,e'p) cross section

(See Eq.1) can be factorized into

$$\sigma_{exp} \equiv \frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p} = K\sigma_{ep}S(E_m, p_m) \qquad (2)$$

where $K$ is a kinematic factor, $\sigma_{ep}$ describes the elementary electron-proton cross section for electron scattering off a bound proton, and $S(E_m, p_m)$ is a spectral function which can be interpreted as the probability of finding a recoiling nucleon with missing energy and momentum [4].

In reality, the final state particles undergo subsequent interactions resulting in re-scattering of the proton and neutron. This process is known as Final State Interactions (FSI) (See Figure 3) and has been shown to have a significant contribution to the experimental cross section at high missing momenta (See Figure 7), therefore one cannot be confident that at large missing momenta, the high momentum component of the deuteron will be probed [2].

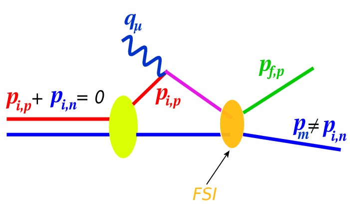


**Figure 3:** Feynmann diagram for FSI, where the proton(red), after excitation by the photon, undergoes subsequent interactions (orange) with the neutron(blue) resulting in a re-scattering of both final state particles.

Another possibility is that the photon may couple to the virtual meson being exchanged between the nucleons (Meson Exchange Currents or MEC). (See Figure 4)

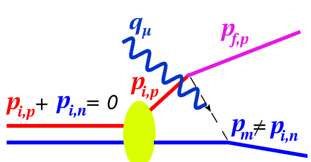


**Figure 4:** Feynmann diagram for MEC, where the virtual photon couples to the exchange meson (dashed line) causing the spectator neutron(blue) to re-scatter off the proton(red)

Or, the photon may excite either nucleon in the deuteron (Isobaric Configuration or IC). (See Figure 5)

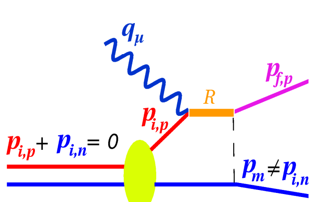


**Figure 5:** Feynmann diagram for IC, where the proton(red) is excited by the photon into an intermediate state (orange) R. The excited state decays and rescatters off the neutron(blue) in the process

It is possible to extract the reduced cross section $\sigma_{red}$ by dividing Eq. 2 by $K$ and $\sigma_{ep}$ and integrating over the missing energy to obtain

$$\sigma_{red} \equiv S(p_m) = \frac{\sigma_{exp}}{K\sigma_{ep}} \qquad (3)$$

If the PWIA were valid, the reduced cross section would be the momentum distribution inside the deuteron, therefore it is important to study at which kinematic settings competing processes are suppressed (MEC, IC), or at least under control (FSI) [7].

FSI are well described by the Generalized Eikonal Approximation (GEA) in the high energy limit($Q^2 \geq 1$ (GeV/c)$^2$). The GEA predicts a strong angular dependence of FSI as a function of the scattering angle $\theta_{nq}$ between spectator nucleon and virtual photon, which opens a kinematic window at which FSI are reduced [8]. (See Figure 6)

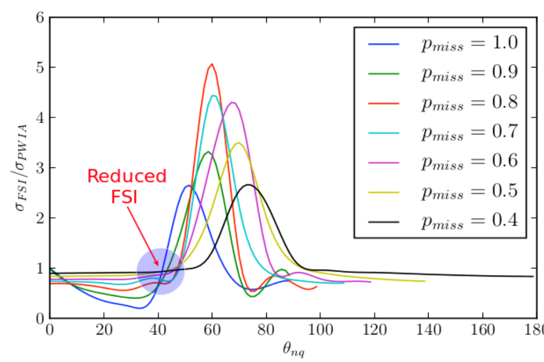


**Figure 6:** Ratio of FSI/PWIA cross-section vs. scattering angle between spectator neutron and virtual photon, $\theta_{nq}$, for various missing momenta up to 1 GeV/c [8].

A previous Hall A experiment (E01-020) [6] at $Q^2 = 3.5$ (GeV/c)$^2$ and various $\theta_{nq}$ examined the effect of FSI for missing momenta up to 0.55 GeV/c. The experiment verified the strong anisotropy of FSI as predicted by GEA. Furthermore, there was shown to be a good agreement between data and theory for reduced cross sections at large missing momenta ($\geq$ 300 MeV/c) for smaller $\theta_{nq}$ angles without the inclusion of FSI. (See Figure 7 (a) and (b))

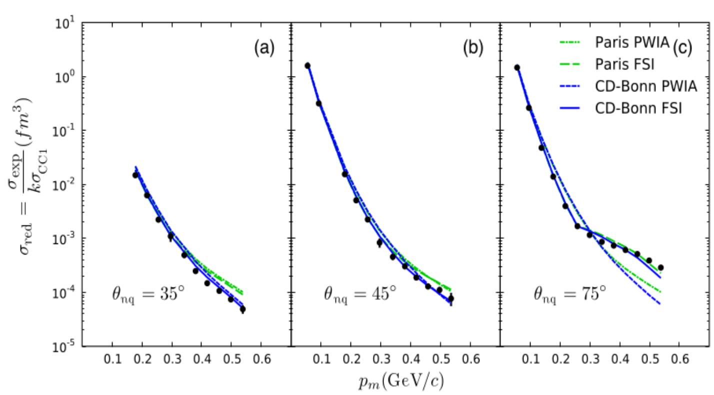


**Figure 7:** Reduced cross-section $\sigma_{red}$ vs. missing momenta $p_m$ for angles (a) $\theta_{nq} = 35°$, (b) $\theta_{nq} = 45°$ and (c) $\theta_{nq} = 75°$ [6].

# 3 Project Status

The Deuteron Electro-Disintegration at Very High Missing Momenta experiment (E12-10-003) will be the third of four commissioning experiments and is scheduled to run on April 2017 on Hall C, Jefferson Lab. The experiment will extend the the missing momentum range studied in E01-020 from $p_m = 0.5$ GeV/c to $p_m = 1.0$ GeV/c at a $Q^2 = 4.25$ (GeV/c)$^2$ and $x_{Bj}$=1.35 for $\theta_{nq} = 40°$ where FSI are expected to be reduced. (See Figure 6) The main focus of E12-10-003 will be to extract the unpolarized D(e,e'p)n cross section and momentum distribution for unexplored large missing momentum regions at high $Q^2$. Various physics simulations have been performed that predict the D(e,e'p)n experimental cross section as a function of missing momenta from 0.44 to 1.0 GeV/c for the abovementioned kinematic settings. The expected results and beam times for each momentum setting are shown in Figure 8[3]. To satisfy the E12-10-003 kinematic requirements, the High Momentum Spectrometer (HMS) and Super HMS (SHMS) housed in Hall C will be set to scattering angle and central momentum of $59.6° \geq \theta_p \geq 53.1°$, $2.12 \leq$ p$_{cent}$ $\leq 2.3$ GeV/c and $\theta_e = 12.17°$, p$_{cent} = 8.92$ GeV/c, respectively.

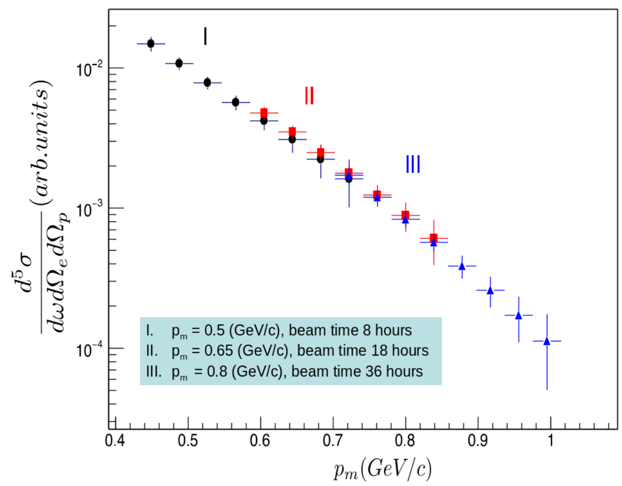


**Figure 8:** Expected D(e,e'p)n differential cross section as a function of missing neutron momenta for beam energy/current of 10.6 GeV/c and 70 $\mu$A for E12-10-003.[3]

Each spectrometer is comprised of a series of magnets followed by the detector stack (See Figure 9). The magnets are set for a point-to-point tune and transport (focus) the scattered particles to the detectors. The detectors are then read out by Analog- and Time- to Digital Convertors (ADC/TDC)(See p.281 of [5]). To extract meaningful information from the underlying physics, magnets and detectors (Hodoscopes, Wire Chambers, Čerenkovs and Calorimeters) must be properly calibrated.

The magnetic optics calibration main objective is to determine the transport matrix elements relating the particle coordinates measured in the focal plane to those in the reaction vertex in the target. Knowledge of the matrix elements will provide a one-to-one mapping of measured particle tracks to specific target location where the particle originated.

Calibration of every detector element in the stack involves the translation of ADC/TDC hits to equivalent energies and times which are used to extract meaningful physics quantities. Hodoscopes measure particle Time-of-Flight (TOF) from TDC values. These values must be corrected by accounting for photon propagation time through the scintillator as well as pulse height, given that signals travelling through a medium are attenuated.

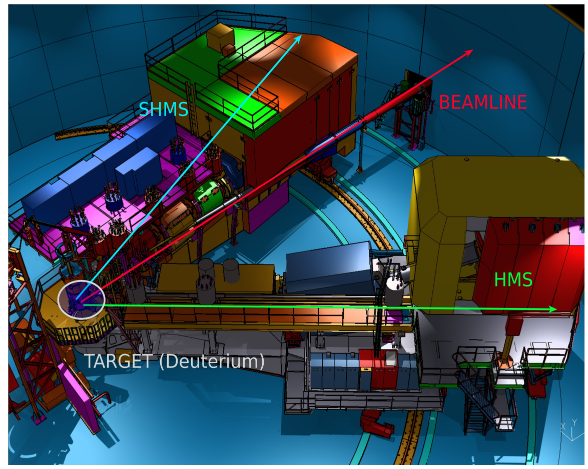


**Figure 9:** Artist view of Hall C HMS/SHMS

Drift Chambers measure particle position and must be calibrated to measure drift distance (distance between grounded sense wires and particle track). Drift distances are determined from raw TDC hits registered by the sense wires and Hodoscope timing information.

Gas Čerenkovs are used to discriminate particles based on threshold energies required to emit Čerenkov radiation in the gas. The calibration of such detectors will involve isolating single photoelectron peaks in the ADC spectrum for each phototube.

Calorimeters measure energy deposition of particles and are able to discriminate between particles based on the amount of energy deposited. To accurately measure energy deposited from raw ADC hits requires that the light attenuated inside individual calorimeter lead blocks be accounted for.

In addition to optics and detector calibrations, Beam Current Monitoring (BCM) and Target Boiling studies must be taken into consideration. In E12-10-003, since a 15-cm long liquid deuterium target ($T_{freezing}$ = 18.7 K, $T_{boiling}$ = 25.3 K) needs to be cooled to 22 K, the power delivered by the beam can cause local density fluctuations (local boiling) within the target, and so one needs to study the density fluctuations as a function of beam current in order to correct for target boiling effects [2].

I am currently working on setting up a primary trigger in HMS/SHMS by requiring 3/4 hodoscope planes in each spectrometer to fire (detect a hit) to consider the signal as a true event. The trigger then informs other detectors that the detected signal is indeed a true event coming from the target. Once a primary trigger is set in each spectrometer, a coincidence trigger (See p.287 of [5]) needs to be set up between the HMS/SHMS in order to determine whether the detected particles originated from the same interaction in the target. Depending on the nature of the experiment, additional triggers may also be incorporated.

I have also recently finished restoring one of the HMS Drift Chambers whose exposure to radiation over a period of 25 years of use resulted in the deterioration of 97 sense wires. All the broken sense wires have been recently re-strung and tested. The chamber has been re-installed in the HMS detector stack and we are currently taking a cosmic run to monitor the detector response and diagnose any problems that may arise.

# References


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