Deuteron Electro-Disintegration at Very High Missing Momenta

Carlos Yero
Major Advisor: Dr. Werner Boeglin

October 2016

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. 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 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[8]. 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[10].

In nuclear structure studies in general, electron-nucleon scattering serves as the most valuable tool since the interaction is described by ~~the theory of~~ 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[2]. 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 ~~giving us an insight~~ the deuteron wavefunction beyond relative internal momenta of 400 MeV/c. ~~Also,~~ at such high energies, one will be able to probe if effects due to ~~the limits of nucleonic degrees of freedom before~~ Quantum Chromodynamics (QCD) ~~effects~~ start playing a more significant role.[8]

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

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

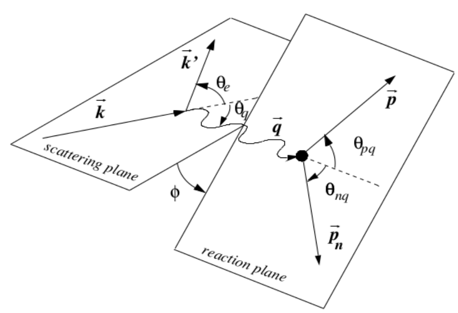

Figure 1: Feynmann diagram of deuteron electro-disintegration

where the incoming electron 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,[2]

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

where σ_{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, θ_e) and the functions (R_i, R_{ij}) are nuclear response functions and depend on nuclear charge and current density operators.[4]

should be a vector

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 (p_m) ~~same as its momentum inside the deuteron $(p_{i,n})$~~. 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)

The relation between the recoil momentum and the initial momentum of the struck nucleon is p_m = -p_i

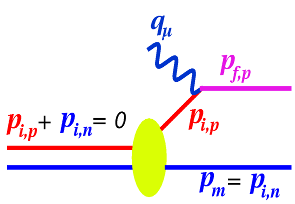

Figure 2: Feynmann diagram for PWIA, where the proton(red) is knocked by the photon, and the neutron(blue) scatters as a spectator

From the PWIA assumptions, the general (e,e'p) cross section (See Eq.1) can be factorized into

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

where K is a kinematic factor, σ_{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]

this is not that important here

~~In addition to the PWIA, the virtual photon may also couple to the neutron. This process, known as the Plane Wave Born Approximation (PWBA), is enough to break factorization of the (e,e'p) cross section provided the neutron carries a significant portion of the transferred energy and momentum comparable to that of the proton.~~

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.[3]

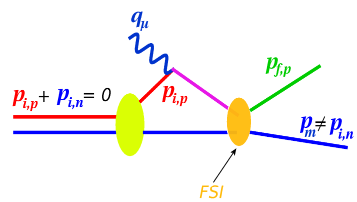

Figure 3: Feynmann diagram for FSI, where the proton(red), after excitation by the photon, undergoes subsequent interactions (orange) with the neutron(blue) resulting in a re-scattering of both final state particles.

Another possibility is that

~~In a process known as Meson Exchange Currents (MEC),~~ the photon may ~~also~~ couple to the virtual meson being exchanged between the nucleons. (See Figure 4) (meson exchange currents)

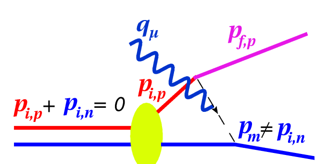

Figure 4: Feynmann diagram for MEC, where the virtual photon couples to the exchange meson (dashed line) causing the spectator neutron(blue) to re-scatter off the proton(red)

or

~~In another process,~~ the photon may excite either nucleon in the deuteron ~~into a Δ or N^* resonance, which decays to the groundstate through the exchange of a virtual meson with the spectator nucleon. This process is known as~~ Isobaric Configuration (IC). (See Figure 5)

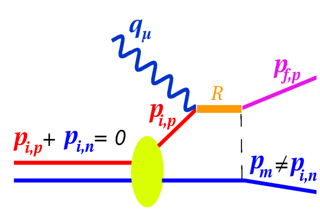

Figure 5: Feynmann diagram for IC, where the proton(red) is excited by the photon into an intermediate state (orange) R. The excited state decays and rescatters off the neutron(blue) in the process

~~From the processes described above, only the PWIA allows us to probe inside the deuteron through the measurement of missing momentum~~

~~in an experiment. Also, from the PWIA cross section,~~ it is possible to extract the reduced cross section σ_{red} by dividing Eq. 2 by K and σ_{ep} and integrating over the missing energy to obtain

$$\sigma_{red} \equiv \frac{\sigma_{exp}}{K\sigma_{ep}} \tag{3}$$

If PWIA were valid

The reduced cross section is d~~irectly related to~~ the momentum distribution~~s~~ inside the deuteron, therefore ~~therefore,~~ it is important to study at which kinematic settings ~~are these~~ competing processes are suppressed (MEC, IC), or at least under control (FSI).[8] ~~From theoretical calculations of the MEC and IC scattering amplitude, the cross section for these processes have been shown to be suppressed at high Q^2 (≥ 1 (GeV/c)^2) and Bjorken scale of $x_{Bj} = \frac{Q^2}{2M_p\omega} \geq 1$.[9]~~

are well described by ~~For~~ FSI, the Generalized Eikonal Approximation (GEA) ~~is established~~ in the high energy limit($Q^2 \geq 1$ (GeV/c)^2). The GEA predicts a strong angular dependence of FSI ~~with~~ as a function of the scattering angle θ_{nq} between spectator nucleon and virtual photon, which opens a kinematic window at which FSI are reduced (See Figure 6).[9]

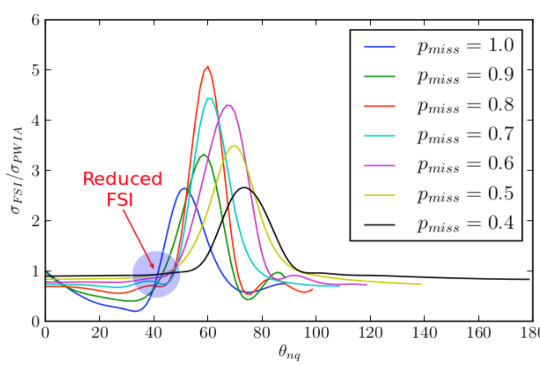

Figure 6: Ratio of FSI/PWIA cross-section vs. scattering angle between spectator neutron and virtual photon, θ_{nq}, for various missing momenta up to 1 GeV/c. [9]

~~This kinematic window gives, for the first time, a possibility to study the short-range structure of the deuteron at high missing momenta without the overwhelming effects of FSI.~~

A previous Hall A experiment (E01-020) [7] at $Q^2 = 3.5$ (GeV/c)^2 and various θ_{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 θ_{nq} angles without the inclusion of FSI (See Figure 7 (a) and (b)).

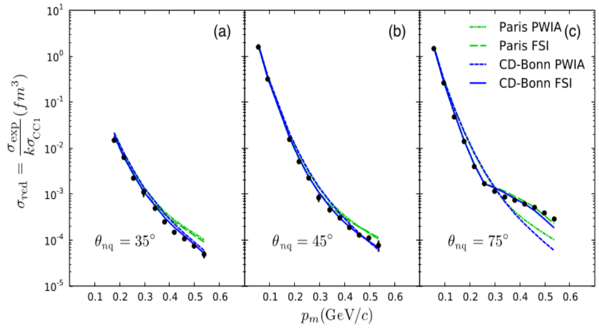

Figure 7: Reduced cross-section σ_{red} vs. missing momenta p_m for angles (a) $\theta_{nq} = 35°$, (b) $\theta_{nq} = 45°$ and (c) $\theta_{nq} = 75°$.[7]

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 angles $\theta_{nq} = 35° \sim 40°$ where FSI are expected to be reduced.

~~With respect to my progress,~~ I am currently working on setting up a coincidence trigger[1] between various detectors in the High Momentum Spectrometer (HMS) [1] in order to discriminate between actual particles and background events. A general trigger will also be set up for a second spectrometer (Super HMS), and ultimately, between the two spectrometers. These are called general triggers, in which the setup will apply to all experiments to take place in Hall C. Individual experiments will however, require modifications of the general trigger setup in order the meet the physics requirements of the experiment in question.

~~As a side project,~~ I am also working on restoring the HMS Wire Chamber [6], used for reconstruction of scattered charge particles momenta. The chamber consists of six planes, each with hundreds of field and sense wires. Many sense wires were damaged and need to be re-strung. The sense wires are 25μm gold-plated tungsten, and so they must be handled with extreme care.

I also plan to work on a Detector Monitoring software project, in which software is written to monitor detector outputs to diagnose detector problems and ensure that each detector is operating optimally.

[1]See [5, p. 287]

Combine these two sections into one and add more on the experiment for your thesis: which settings are going to be measured, what calibration measurements and what the analysis will entail.

References

[1] Arrington, J., et al. Conceptual Design Report Hall C 12 GeV/c Upgrade. Tech. rep., Thomas Jefferson National Laboratory, November 2002.

[2] Boeglin, W. U. Coincidence experiments with electrons. *Czechoslovak Journal of Physics 45*, 4/5 (1995), 296–335.

[3] Ibrahim, H. F. *The ^{2}H(e,e'p)n Reaction at High Four Momentum Transfer.* PhD thesis, Norfolk, VA, 2006.

[4] Khanal, H. *Experimental Deuteron Momentum Distributions with Reduced Final State Interaction.* PhD thesis, Miami, FL, 2014.

[5] Leo, W. *Techniques for Nuclear and Particle Physics Experiments: A How-to-Approach.* Springer-Verlag New York, LLC, New York, 1987.

[6] O.K. Baker, J. B., et al. The high momentum spectrometer drift chambers in Hall C at CEBAF. *Nuclear Instruments and Methods in Physics Research A.367* (1995).

[7] Ulmer, P., et al. Probing the high momentum component of the deuteron at high q^2. *Physics Review Letters 107.26* (2011).

[8] Werner U. Boeglin, M.K. Jones, K. A., et al. Deuteron Electro-Disintegration at Very High Missing Momenta. http://arxiv.org/pdf/1410.6770.pdf, October 2014. *Jefferson Lab Proposal E12-10-003.*

[9] Werner U. Boeglin, M. M. S. Modern Studies of the Deuteron: From the Lab Frame to the Light Front. *International Journal of Modern Physics E 24* (2015), 24.

[10] Werner U. Boeglin, M.K. Jones, P. U., et al. Short-Distance Structure of the Deuteron and Reaction Dynamics in ^{2}H(e,e'p)n. https://www.jlab.org/exp_prog/proposals/01/PR01-020.pdf, 2001. *Jefferson Lab Proposal E01-020.*