Studying neutron structure at Jefferson Lab through electron scattering off the deuteron, using CLAS12 and the Central Neutron Detector

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Abstract. Generalised Parton Distributions (GPDs) offer a way of imaging nucleons through 3D tomography. They can be accessed experimentally in processes such as Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP), where a high energy electron scatters from a quark inside a nucleon and a high energy photon or meson is produced as a result. Jefferson Lab has recently completed its energy upgrade and Hall B houses the new, large-acceptance CLAS12 detector array optimised for measurements of DVCS and DVMP in the newly accessible kinematic regime. Measurements on the proton and neutron are complementary and both are necessary to facilitate access to the full set of GPDs and enable their flavour separation. Neutron DVCS and DVMP are possible with the use of a deuteron target – the first CLAS12 experiment with which has started taking data this year. To enable exclusive reconstruction of DVCS and neutral-meson DVMP, a dedicated detector for recoiling neutrons – the Central Neutron Detector (CND) – was integrated into CLAS12. We present the first CLAS12 deuteron-target experiment, with a focus on the performance of the CND.

1. Introduction – Generalised Parton Distributions

Generalised Parton Distributions (GPDs) have been a compelling area of both theoretical and experimental research for the last couple of decades. GPDs are functions which describe the spatial and momentum distributions of partons inside hadrons by relating the longitudinal momentum fraction, x, of a specific parton to its transverse position. This means that GPDs make it possible to build a 3D tomographic image of hadrons by considering spatial distributions at fixed values of longitudinal momentum (figure 1). GPDs also encode other information such as the composition of spin within the hadron, and mechanical properties such as pressure [1].

GPDs arise from QCD where, in certain exclusive scattering processes and under specific kinematic constraints, interactions between leptons and hadrons can be factorised into a "hard", perturbative part and the "soft", non-perturbative part of the scattering amplitude. This soft part can be defined in terms of GPDs which describe the internal quark-gluon dynamics of the nucleon [1].

There are eight GPDs at QCD leading-order: H, $\tilde{H}$, E, $\tilde{E}$, H_T, $\tilde{H}_T$, E_T, $\tilde{E}_T$ where the tilde represents the GPDs which are sensitive to helicity distributions and the subscript T represents
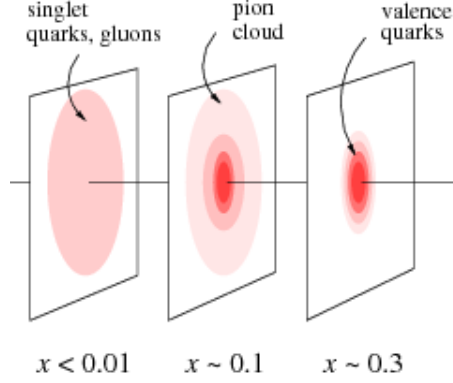
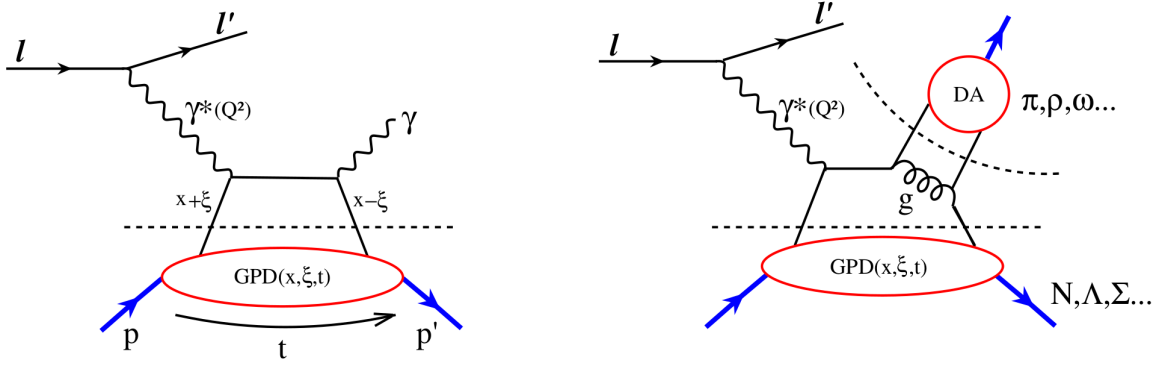Figure 1: Illustration of nucleon tomography at various values of longitudinal momentum fraction x [2].

Figure 2: "Handbag" diagrams of DVCS (left) and DVMP (right) at leading-twist, where "DA" represents the Distribution Amplitude which encodes the soft structure of the meson [5].

the chiral-odd, so-called "transversity", GPDs. All together these encode different combinations of parton and nucleon helicities [1].

GPDs can be extracted from measurements of hard, exclusive processes such as Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). These processes can occur when there is a sufficiently high 4-momentum transferred from the scattering electron (Q^2). In the case of DVCS at leading-twist, an electron scatters off a single quark inside of the nucleon, exchanging a high-virtuality photon, and a high-energy real photon is produced as a result of the interaction. In DVMP, a meson is produced as a result of the interaction [3][4]. Schematics of these processes can be found in figure 2, where the dotted-line represents the factorisation of the hard scattering and the soft internal dynamics.

GPDs are functions of three variables: x, ξ and t. The variable x is the average longitudinal momentum fraction of the interacting quark (ie. fraction of the nucleon's total longitudinal momentum). ξ is known as the skewness parameter and represents the difference in the momentum of a struck quark before and after the interaction where $x+\xi$ and $x-\xi$ are the quark's longitudinal momentum fraction before and after an interaction, respectively. The skewness parameter can be related to the scaling variable x_B (Bjorken-x) as:

$$\xi \simeq \frac{x_B}{2 - x_B}$$

Lastly, t is the squared four-momentum transferred to the target nucleon. For DVCS, this is
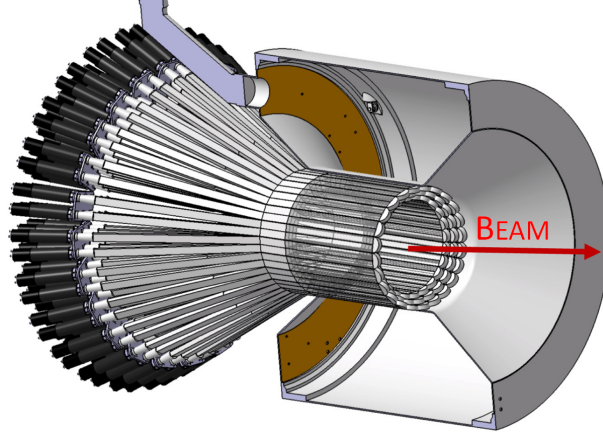
Figure 3: Schematic view of CND showing an open cross-section through the solenoid. Adapted from [7].

also the difference of the four-momentum transferred to the interacting quark and the four-momentum of the emitted photon [6].

2. CLAS12 and the Central Neutron Detector

Since free neutron targets do not exist, measurements from the neutron require nuclear targets, typically deuterium, where the neutron's Fermi momentum complicates the event reconstruction. The added challenge of detecting neutrons means that the largest body of work on extracting GPDs from DVCS and π_0 DVMP has been done using proton targets. However, accurate measurements on both protons and neutrons are required for a full understanding of the nature of the nucleons, and would allow for flavour separation of GPDs:

$$H^p(x,\xi,t) = \frac{4}{9}H^u + \frac{1}{9}H^d \qquad\qquad H^n(x,\xi,t) = \frac{1}{9}H^u + \frac{4}{9}H^d$$

where the subscripts p and n refer to protons and neutrons, respectively, and u and d indicate up and down flavours.

In pursuit of making measurements on a neutron target, the Central Neutron Detector (CND) was included in the CLAS12 expansion of CLAS (Continuous Electron Beam Accelerator Facility Large Acceptance Spectrometer) at Jefferson Laboratory.

2.1. CND Design

The CND was proposed primarily for the purposes of complementing the existing work on proton targets by using a deuterium target to make measurements of DVCS off a neutron (nDVCS) [7]. DVMP off neutrons is an alternate process of which exclusive measurements can also be used to extract GPDs [3].

The CND is a scintillating barrel detector which is comprised of 3 radial layers each containing 24 sectors, where each sector is made up of two scintillating paddles which are paired via a semicircular light-guide in the downstream direction. In the upstream direction, each paddle is connected to a long light-guide leading to Photo-Multiplier Tubes (PMTs) for read out. A schematic view of this is given in figure 3. The detector is centred on the beam-line around the target cell as, kinematically, the recoiling neutrons are typically ejected at large angles [7].

Figure 4: Illustration of a hit in a paddle of the CND. Adapted from [8].

2.2. Reconstruction and PID

Neutron detection within the CND relies upon strong-interactions between the recoiling neutron and a proton within the scintillator paddles. This proton would then be ejected, and produce scintillation light as it travelled through the paddle. The total neutron detection efficiency of the central detectors of CLAS12 is ~10%, with each layer contributing ~3%, and a ~1% contribution from the Central Time Of Flight (CTOF) detector, which is a single-layered scintillator detector encompassed by the CND [7].

When a hit occurs in a paddle of the CND, scintillation light propagates in both directions giving signals in both PMTs (illustrated in figure 4). These signals are then digitised into channels by an ADC and high-resolution timing information is extracted from the signals using Constant Fraction Discriminators and TDCs [7]

The difference in time read out for two coupled paddles, t_{left} & t_{right}, is used to calculate the location of hit in the CND (equation 1), while the time of the event is proportional to their average (equation 2).

$$z \propto \frac{1}{2} \cdot v_{eff} \cdot (t_{left} - t_{right}) \tag{1}$$

$$t \propto \frac{(t_{left} + t_{right})}{2} \tag{2}$$

After calculating the position of the hit and the time of flight, β, the velocity of the particle as a fraction of that of light, can be calculated. An event in the CND is identified as neutral by a lack of track in the Central Vertex Tracker (CVT), which is seated between the CTOF and the target cell. Neutrons are then separated from photons via a cut on β.

2.3. Preliminary Study of CND Performance

The following plots are from data taken in the Spring 2018 run of the experiment proposed in [8] and are very preliminary. Figures 5a and 5b give a gauge of spatial and timing reconstruction. Charged particles are used to benchmark the time and position reconstruction of events. Comparing the hit position obtained from the CND with that extrapolated from the CVT, it can be seen that the difference in z-position is centred at zero. The timing resolution is 164ps, very close to the design goal of 150ps. This is determined by comparing the time of flight determined by the CND with the expected time of flight based on the momentum of the particle as determined by the CVT.

Figure 6 shows β vs deposited energy for neutral particles detected in the CND. The signal for photons can be resolved from that of neutrons which is an important validation of the detector performance. The hot-spot around $\beta = 0.2$ has been shown by simulation to be backscatter from the solenoid magnet.

3. Conclusion and Current Challenges

A preliminary look at data with a deuterium target gives a promising indication that the CND will work well within the design goals of the detector, with good spatial and timing resolution, and good resolution between neutral particles. It will be exciting to see the results that CLAS12 will contribute to the extraction of GPDs for neutrons.

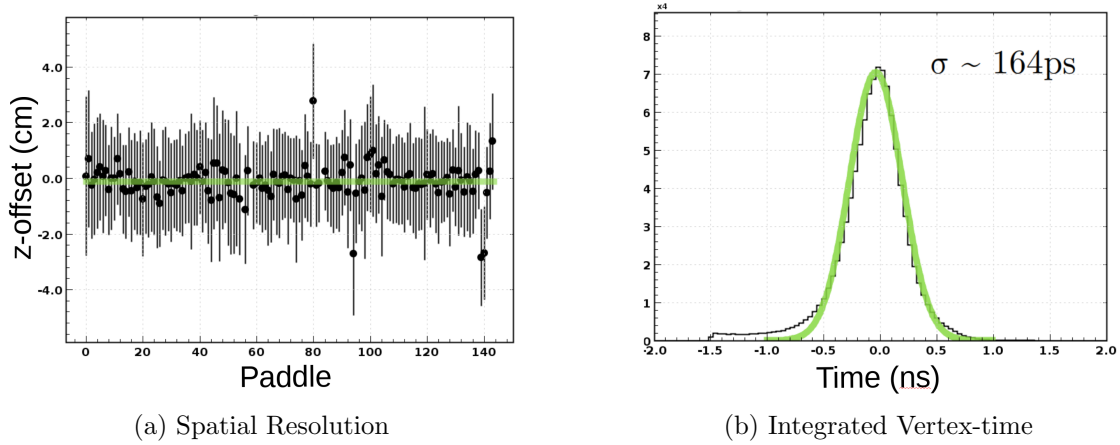(a) Spatial Resolution

(b) Integrated Vertex-time

Figure 5: (a) Difference in z-position extrapolated from the CVT track and z-position reconstructed from the CND. (b) Difference in time of flight from the CND and the time of flight expected from the momentum, integrated across all paddles.
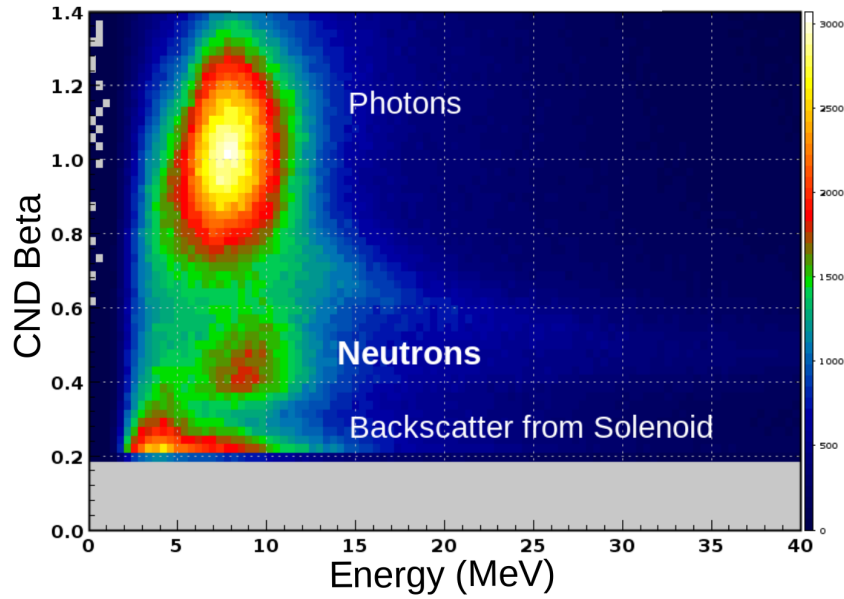

Figure 6: Plot of β vs.energy deposited in the CND for neutral particles.

Currently, work is ongoing to resolve an issue with proton pollution of the neutron signal. The reconstruction efficiency of the CVT for protons is currently lower than expected. Therefore, some protons are being detected in the CND without leaving a track in the CVT, leading them to be identified as neutral in the reconstruction. As the cross-section for DVCS and DVMP of neutrons is lower than protons, this is a significant contribution to the neutron signal. Work is currently underway to determine means of vetoing protons from the neutron signal relying only on the CND and CTOF. Veto criteria include hit multiplicity, layer multiplicity and energy deposited in the scintillators. Reconstruction of simulated data using these veto criteria restored neutron purity to $\sim 90\%$, which will greatly improve event identification when these criteria have been integrated into the reconstruction process.

References

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