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Deeply Virtual Compton Scattering off the Neutron: Measurements with CLAS and CLAS12 at Jefferson Lab

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Measurements of Deeply Virtual Compton Scattering (DVCS) give access to Generalised Parton Distributions (GPDs) which provide a 3D image of the nucleon and carry information on the composition of its spin. Data from both proton and neutron targets is highly desirable for an extraction of all GPDs and to allow their flavour-decomposition. Although a number of measurements have been made on proton targets, data on the neutron is almost non-existent. We present preliminary results in the extraction of beam-spin asymmetry in neutron DVCS from CLAS and the proposed experimental programme with CLAS12 at Jefferson Laboratory.

KEYWORDS: DVCS, neutron, CLAS, nucleon structure

1. Introduction

A wealth of information on the structure of a nucleon can be encoded in Generalised Transverse Momentum Distributions (GTMDs), whose Fourier Transform yields the Wigner distributions which describe the nucleon's internal dynamics in terms of the three momentum and two positional variables of the partons [1]. Although GTMDs are currently not accessible experimentally, they can be integrated over transverse momentum to give Generalised Parton Distributions (GPDs), functions which can be accessed in certain exclusive reactions and which relate, via a Fourier Transform, the longitudinal momentum of a parton to its transverse position [2]. As such, they contain information on the angular momentum of quarks.

Deeply Virtual Compton Scattering (DVCS), a process in which an electron scatters from an individual quark in the nucleon and a high-energy photon is produced as a result, is considered the "golden channel" for the experimental extraction of GPDs. At high Q^2 (the squared four-momentum transferred during the scattering) and leading order in perturbation theory, it gives access to four GPDs for each quark-flavour: E, $\tilde{E}$, H and $\tilde{H}$, which are themselves functions of the squared four-momentum change of the nucleon, t, the longitudinal momentum of the struck quark (as a fraction of the nucleon momentum), x, and twice the change in x as a result of the scattering, ξ. The DVCS process does not, however, give direct access to x and consequently the GPDs cannot be directly extracted from it. Rather, DVCS cross-sections and spin asymmetries are parametrised in terms of Compton Form Factors (CFFs), complex functions which are related to the x-integrated GPDs. Specifically, cross-sections and double-spin asymmetries are sensitive to GPDs integrated over x (the real parts of the CFFs), while single-spin asymmetries yield (at leading order) GPDs at certain values of x, namely where $x = \xi$ [3], from the imaginary parts of the CFFs.

Measurements off both isospin states of the nucleon are highly desirable to enable flavour-separation of the GPDs. Additionally, experiments with both target nucleons (proton and neutron) and various combinations of electron and nucleon polarisation have different sensitivity to the CFFs. For example, the beam-spin asymmetry in DVCS off the neutron is dominated by the imaginary part of the CFF associated with E, the least known and least constrained of the four GPDs accessible in DVCS at leading order and leading twist. It is, however, of particular interest as it appears, along with H, in Ji's relation for the total angular momentum contribution of each flavour quark, J^q [4]:

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx \{H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\} \tag{1}$$

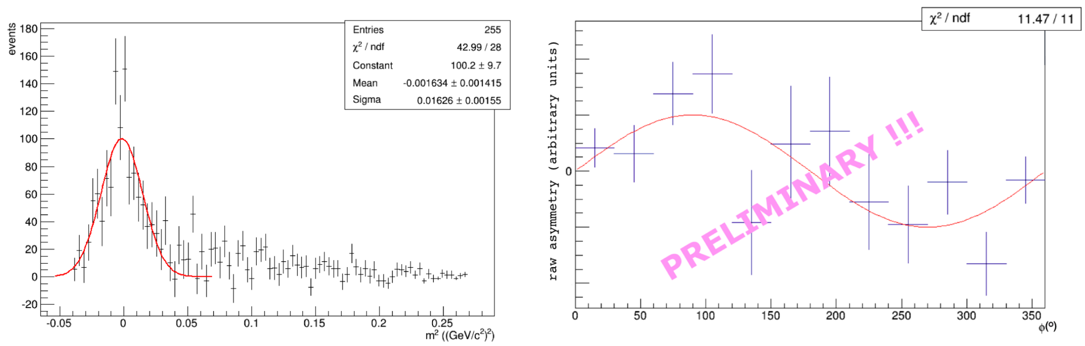
There has been only one previous measurement of the beam-spin asymmetry in neutron DVCS, which was not wholly exclusive, contained low statistics and yielded a result consistent with zero [5]. It is clear that precise measurements across a wider kinematic range are desirable. This article presents the preliminary results of a neutron DVCS analysis carried out on CLAS data and the dedicated neutron DVCS experiments planned with CLAS12 at Jefferson Lab.

2. The eg1-dvcs experiment at CLAS

Jefferson Laboratory is home to CEBAF, the Continuous Electron Beam Accelerator Facility, which until recently delivered electron beams up to 6 GeV in energy to three experimental halls, A, B and C. The experiment in question took place in 2009 in Hall B, making use of CLAS, the CEBAF Large Angle Spectrometer which provided almost complete angular coverage and consisted of drift chambers within a toroidal magnetic field for charged particle tracking, scintillator bars for precise timing, Čerenkov counters for electron / pion separation and an electromagnetic calorimeter (EC, lead-scintillator sandwich) for photon and neutron detection. Additionally, to detect DVCS photons which are preferentially emitted in the forward direction, a wall of scintillator crystals (called the Inner Calorimeter) was integrated downstream of the target.

The experiment, which was termed "eg1-dvcs" in the JLab nomenclature, ran over a total of 129 days with a $4.7 - 6$ GeV electron beam, polarised to $\sim 85\%$, and was primarily aimed at measuring DVCS off polarised protons. It had a frozen ammonia ($^{14}NH_3$) target, held at 1K in a 5T field, which was dynamically polarised in the longitudinal direction with the application of microwaves. One quarter of the data, however, was obtained with a similarly-polarised $^{14}ND_3$ target, which provided a source of quasi-free target neutrons, polarised to $\sim 40\%$, within the deuteron. This data was used to extract the $ed \to e'n'\gamma(p)$ event sample. The scattered electron was identified via tracking and timing information from the drift chambers and time-of-flight scintillation counters, with the π^- background almost entirely suppressed using information from the EC and Čerenkov counters. The photon was identified as a neutral particle depositing energy in the EC or IC with a velocity close to that of light while the recoil neutron was also identified with the EC on the basis of a slower velocity. Once the $e'n'\gamma$ final state was selected, a number of other cuts typical for deep inelastic scattering were applied: $W > 2$ GeV/c^2, where W is the "missing mass" of X in the $en \to e'X$ reaction, to exclude the majority of states where the $n'\gamma$ pair corresponding to X forms a resonance, $Q^2 > 1$ GeV$^2/c^4$ and $Q^2 > -t$ to correspond with the assumptions of the theoretical formalism. In addition, DVCS cuts required a high energy photon, at least $E_\gamma > 1$ GeV, and a recoiling neutron with a sufficiently large momentum, $p_n > 0.4$ GeV/c. The remaining cuts were aimed at ensuring the exclusivity of the reaction and are still under optimisation. They include a requirement for the "missing" momentum of X in $ed \to e'n'\gamma X$ to be consistent with that of a spectator proton, ie: the Fermi momentum in a deuteron, a cut on "missing" mass of X to be consistent with the mass of a proton, a requirement for the plane formed by the virtual photon and recoil neutron to be consistent with the plane formed by the virtual and real photons and a cut to ensure that the detected photon momentum aligns in direction with the expected vector. Fig. 1a shows the distribution of the "missing" mass of X in $en \to e'n'\gamma X$, after all of the cuts above and after subtraction of the nuclear background.

The beam-spin asymmetry (A_{LU}) is defined as $A_{LU} = \frac{d\sigma^{\to} - d\sigma^{\leftarrow}}{d\sigma^{\to} + d\sigma^{\leftarrow}}$ where the superscripts on the differential cross-sections indicate whether the beam helicity is parallel ($\to$) or antiparallel ($\leftarrow$) to the virtual photon vector. A preliminary raw asymmetry can be seen in Fig.1b where it is plotted as a function of ϕ, the angle between the leptonic plane (of the incoming and scattered electrons) and the hadronic plane (of recoiling neutron and produced photon). It should be noted that the raw asymmetry shown has not yet been corrected for the contribution from deeply virtual π^0 production (when one of the photons from the decaying π^0 is not detected and the final state mimics that of DVCS), which has an asymmetry of its own, nor have the final cuts been optimised. Indication of an non-zero asymmetry can, however, be observed. Additionally, an extraction of the never-before measured target-spin asymmetry in neutron DVCS is also currently underway.



(a) (b)

Fig. 1. (a) "Missing" mass squared of X in $en \rightarrow e'n'\gamma X$, fitted with a Gaussian function over the peak at zero. The contribution of neutrons in the nuclear (nitrogen) medium was removed by subtracting, from the result on ND_3 data, the equivalent scaled distribution produced on NH_3 data with the application of the same cuts. b) Very preliminary raw beam-spin asymmetry as a function of ϕ, fitted with $y = p_0 sin\,\phi$ (the dominant term in the asymmetry, [7]) to guide the eye. $\langle Q^2 \rangle = 2.2\ GeV^2/c^4$, $\langle x_B \rangle = 0.3$, $\langle -t \rangle = 1.2\ GeV^2/c^4$.

3. Neutron DVCS with CLAS12

Jefferson Lab has just finished an upgrade of its accelerator to operate at a maximum energy of 12 GeV, with up to 11 GeV available for Hall B, where the main focus of the experimental programme will be on measurements of nucleon structure. In order to maximise coverage of the greatly extended region of kinematic phase space which is becoming available, a new array of detectors, CLAS12, has been constructed. With a design luminosity of $\sim 10^{35}$ cm^{-2} s^{-1} and a very large acceptance, it is optimal for the reconstruction of deeply virtual exclusive processes, along with inclusive and semi-inclusive reactions. Measurements of neutron DVCS with CLAS12 are of particular interest, both in complement to the proton DVCS programme as a means of achieving flavour-separation of the GPDs and for the unique information which they can provide on nucleon structure. Specifically, predictions of the GPD model by Vanderhaeghen, Guichon and Guidal (VGG [6]) show particular sensitivity of the beam-spin asymmetry in neutron DVCS to the different contributions of the total angular momentum from the up and down quarks [8]. A proposal to measure the beam-spin asymmetry in neutron DVCS with a polarised 11 GeV beam and a deuterium target has been approved and granted 80 days of beam-time, allowing coverage of the kinematic region up to ~ 8 GeV$^2/c^4$ in Q^2 and ~ 0.65 in x_B (where $x_B \cong 2\xi/(1+\xi)$) [8]. The measurement of target and double-spin asymmetries with a longitudinally polarised ND_3 target, which will be crucial for flavour-decomposition of the GPDs, has also been proposed and as yet conditionally approved [9].

3.1 Central Neutron Detector

The CLAS12 capabilities are well-suited for the detection of the scattered electron and produced photon in the DVCS process, however, exclusive reconstruction of the $en \rightarrow e'n'\gamma$ reaction requires the additional detection of the recoiling neutron, for which no significant possibility existed in the base detectors. We have therefore constructed a dedicated Central Neutron Detector (CND), optimised for the simulated kinematics of neutron DVCS with an 11 GeV beam: neutron momenta in the range 0.2 - 1.2 GeV/c peaked at scattering angles 40° - 70° in the lab. The detector design was constrained by space restrictions (10 cm of radial space available at a distance of 30 cm from the beamline) and a high magnetic field (5T) in that region, resulting in a three-layer barrel with 48 scintillator paddles in each layer. Signal read-out is obtained from both ends of each paddle: in the upstream direction via a long light-guide leading to a Hamamatsu photomultiplier (PMT) positioned outside of the high magnetic field, and in the downstream direction, where space is very limited and the field is large, via a "u-turn" semi-circular lightguide which transports the light along the neighbouring paddle and out to its upstream PMT (Fig.2).

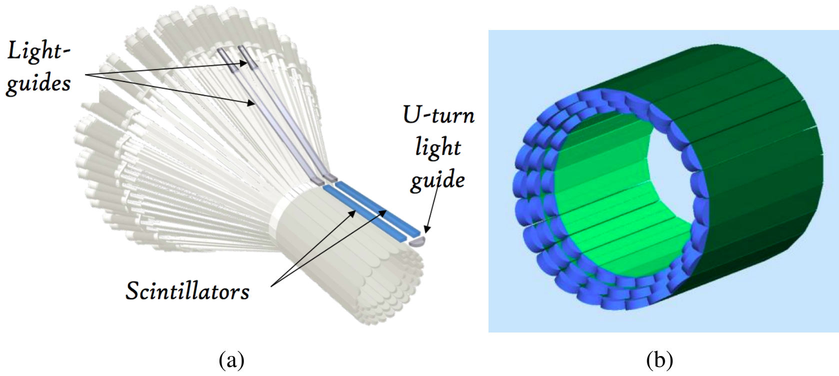


Fig. 2. Central Neutron Detector: a) drawing (*J. Bettane, IPNO*), b) GEANT4 image showing the three layers of scintillator paddles (green) and "u-turn" lightguides (blue).

Reconstruction of a neutron is based on time and position of the hit (obtained from the upstream and downstream timing information), which is used to calculate the velocity of the particle as a fraction of the speed of light, β, and information from tracking detectors to veto charged particles. Simulations on the basis of the measured time-resolution indicate the following resolutions of the detector: $2-3°$ in the polar angle, 3.75° in the azimuthal angle (dictated by the segmentation of the paddles) and $5-12\%$ in momentum. The neutron detection efficiency is $\sim 9\%$ and good separation from photons on the basis of β is achievable at neutron momenta up to $\sim$ 1 GeV/c [8]. The constructed CND is currently awaiting final testing and installation within CLAS12.

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