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A Compact Photon Source for the WACS Experiment At JLab

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ABSTRACT

Compton scattering off the nucleon is one of the simplest processes that can provide valuable information for the understanding of the nucleon structure. A Wide Angle Compton Scattering experiment requires a high intensity photon source based on the CEBAF electron beam, that can safely operate in Hall A at JLab. One of the hardware tasks for a team proposing an experiment is to consolidate the design of the photon source, simulate its performance, and then build it.

The solution illustrated here is an untagged bremsstrahlung γ source consisting of a 10% radiation length radiator and a normal conducting magnet to sweep incident beam electrons out of the beam line, with proper shielding inside and around the magnet, making it a sort of mini beam dump. The magnet bore has a tungsten-copper block with a set of small openings (2 mm by 20 mm), designed to be 1 m long. It will slowly move along a vertical axis to perform as a "mechanical raster", to protect the polarized target from local overheating.

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1. Introduction

Compton scattering off the nucleon is one of the simplest processes that can provide valuable information for the understanding of the nucleon structure [1, 2]. We discuss a project for a high-intensity photon source, Compact Photon Source (CPS), to study the Wide Angle Compton Scattering (WACS) process. The most important WACS observables are the spin-averaged cross sections, the recoil polarization observables and the spin correlation asymmetry. The spin-averaged cross section factorizes into a simple product of the Klein-Nishina (KN) cross section, describing the hard scattering from a single quark, and a sum of form factors R_V, R_A, R_T (respectively vector, axial vector and tensor form factor) depending only on the Mandelstam variable t [3, 4, 5, 6]:

$$\frac{d\sigma/dt}{d\sigma_{KN}/dt} = f_V\left[R_V^2(t) + \frac{-t}{4m^2}R_T^2(t)\right] + (1-f_V)R_A^2(t) \tag{1.1}$$

where f_V is a kinematic factor near to 1 for large sideway momenta. Recently the JLab PAC approved a new measurement of a WACS cross section at very large values of s and $-t$, see Ref. [7]. The longitudinal and transverse polarization transfer observables $K_{\rm LL}$ and K_{LS} are defined by equation 1.2, where the first arrow refers to the incident photon helicity and the second to the recoil proton helicity ($\uparrow$) or transverse polarization ($\rightarrow$).

$$K_{LL}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma(\downarrow\uparrow)}{dt}\right] \qquad K_{LS}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\uparrow\rightarrow)}{dt} - \frac{d\sigma(\downarrow\rightarrow)}{dt}\right] \tag{1.2}$$

The initial state helicity correlation parameter $A_{\rm LL}$ is defined by equation 1.3, where the first arrow refers to the incident photon helicity and the second to the initial state proton helicity.

$$A_{LL}\frac{d\sigma}{dt} = \frac{1}{2}\left[\frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma(\downarrow\uparrow)}{dt}\right] \tag{1.3}$$

In section 2 we review the WACS physics motivation and setup. In section 3 we describe in detail the CPS.

2. Wide Angle Compton Scattering Experiment

2.1 Physics Motivation

Wide Angle Compton Scattering from the nucleon with large values, with respect to the scale Λ^2_{QCD}, of the Mandelstam variables $s, -t, -u$, allows us to study the nucleon structure from a point of view complementary to Deeply Virtual Compton Scattering (DVCS) and high Q^2 elastic form factors. Two experiments, see Refs. [8, 9] and [10], have demonstrated the viability of the experimental real photon Compton scattering technique at JLab using an untagged photon beam of very high intensity mixed with an electron beam, and have provided high accuracy results for the cross section and polarization transfer parameter $K_{\rm LL}$, although at relatively low values of $s, -t, -u$. An A-rated JLab experiment of the 6-GeV era, E-05-101 [11], whose goal was to measure the spin correlation asymmetry $A_{\rm LL}$, did not get beam time, due to schedule complications and polarized target failure. Recently, PAC42 supported experiment E12-14-006 [12], which has a similar scope. The analysis completed in January 2015 of the experiment of Ref. [10] shows an unexpected result

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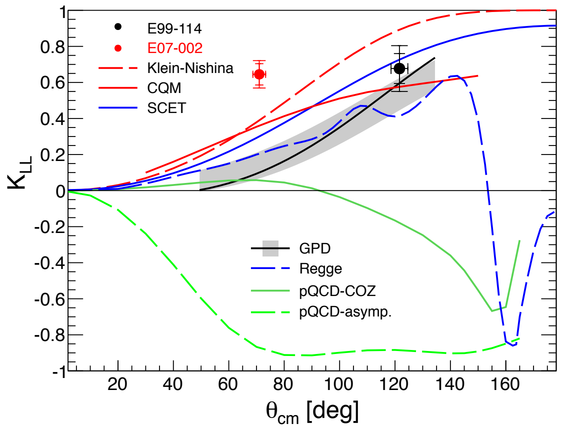

Figure 1: The experimental results for K_{LL} and predictions for A_{LL} in the GPD (Ref. [4]) and CQM (Ref. [13]) approaches, are shown along with the data on K_{LL} of experiments of Refs. [8] (black dot) and [10] (red dot).

for the parameter K_{LL}, which was found to be three times larger than predicted by the Generalized Parton Distributions (GPD) based model at $\theta_{cm} = 70^\circ$, see figure 1. Such news motivates the study of the polarization effect in WACS at significantly higher s than was done (or proposed) before [14].

There are several interesting issues that sugges further explorations of polarization observables in WACS at JLab:

1. What is the nature of the quark which absorbs and emits photons in the WACS process in the wide angle regime? Is it a constituent or a current quark?

2. What is the energy scale at which the GPD mechanism becomes dominant? This question has to be explored at large s, 8-16 GeV^2, and $-t$, 3-7 GeV^2.

3. If the GPD approach is correct, is it indeed true that the WACS reaction proceeds through the interaction of photons with a single quark?

4. What are the constraints on the GPD integrals imposed from the proposed measurement of the A_{LL} observable? What is the role of a diquark $u-d$ correlation in WACS?

It is essential to carry out measurements of A_{LL} for incident photon energies up to 8 GeV (s= 8 to 16 GeV^2) for several scattering angles between θ_{cm} = 80° and θ_{cm} = 100° (corresponding to $-t$ = 3.0-7.0 GeV^2). These conditions are optimal to test the applicability of GPD. The specific physics goals are as follows:

1. To make a measurement of A_{LL} at largest possible $s, -t$, and $-u$ where one expects the applicability of GPD-based calculations to be under control. A high precision measurement is likely to resolve the discrepancy between the surprising results from Ref. [10] experiment and the GPD's predictions, which are in reasonable agreement with Hall A measurements.

2. To provide a test that can expose in an unambiguously way how the WACS reaction proceeds, either via the interaction of photons with a current or a constituent quark.

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3. To extract the form factor ratio R_A/R_V (see eq. 1.1) from the measurement of A_{LL} and correlate this result with the Sachs form factors ratio F_2/F_1 determined from elastic electron scattering.

2.2 WACS Experimental setup

To study the WACS reaction, an apparatus is shown in figure 2, which utilizes an untagged bremsstrahlung photon beam and a polarized target, with the target field oriented along the beam direction. The scattered photon is detected in the Neutral Particle Spectrometer (NPS) [15], while the coincident recoil proton is detected in the Super Bigbite Spectrometer (SBS)[16]. The Neutral Particle Spectrometer, see figure 3, will be used by other approved JLab experiments, E12-13-007 [17] and E12-13-010 [18]. The sensitive region of this calorimeter is 30 (horizontal) x 36

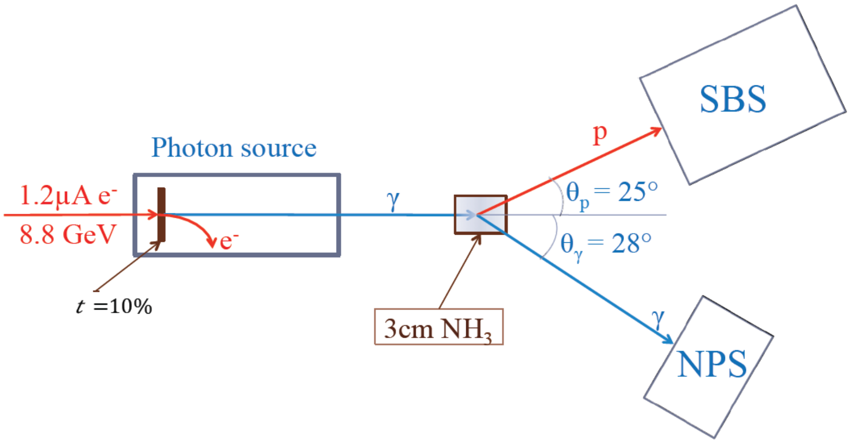

Figure 2: Schematic of the experimental setup. The target is longitudinally polarized (along the beam). The scattered photon is detected by the NPS and the recoil proton is detected by the SBS. The photon source provides a narrow (0.9 mm diameter on the target) untagged bremsstrahlung photon beam.

(vertical) inches, sitting on a frame allowing for easy movement. The position resolution of the NPS is 3 mm and the energy resolution, σ_E/E, is better than 3%. The large SBS and NPS angular and momentum acceptances allow binning of the experimental data into several s and t bins.

We will produce an intense photon beam in the Compact Photon Source [19], located at a distance of 2 m from the target and cleaned from an electron beam by means of a shielded magnet-dump.

The incident electron beam energy is 8.8 GeV with 80% polarization, and an intensity of 1.2 μA, which is large enough to allow precision beam measurements, in order to check the primary beam stability and quality. Using the magnet sweeper/dump combination and the radiator produces a narrow photon beam. The heat load of the beam on the polarized target is a factor of 30-40 times lower than a corresponding mixed-beam of similar intensity.

2.2.1 Target and Radiator

The longitudinally polarized target, schematically represented in figure 4, is the one developed for the JLab experiments [20, 21]. During operations, the protons in the ammonia target are polar-

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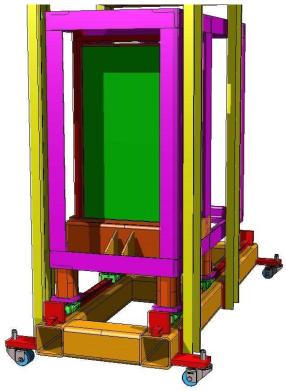

Figure 3: The front view of the Neutral Particle Spectrometer from Ref. [15].

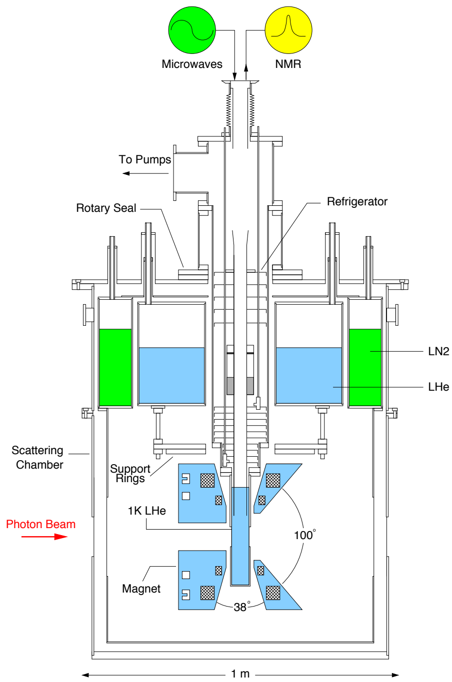

Figure 4: Cross section view of the polarized target to be used by a WACS measurement from Ref. [21].

ized, up to 95%, by taking advantage of the Dynamic Nuclear Polarization technique: the target is in a high magnetic field (5 Tesla) at 1 K and is exposed to 140 GHz microwaves [21].

The heating of the target by the beam, mainly due to photo production of the electron-positron pairs in the target materials, causes an initial drop of a few percent in the polarization. Radiation damage also causes a slow decrease in the polarization, although most of the radiation damage can be repaired by annealing the target at about 80 °K, until the accumulated dose reaches $> 2 \times 10^{17}$ per cm^2 electrons, at which point the material needs to be changed. Due to limitations in the heat removal by the refrigerator, the electron beam intensity on the target is limited to 90 nA.

At the planned electron current of 1.2 μA, the effective beam on the target is 30-40 nA. At such intensity the target annealing needs to be performed only one time during the run and tar-

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get polarization could be maintained close to 85%. The target polarization direction is reversed after each annealing by adjusting the microwave frequency, in order to minimize the sources of systematic errors.

3. Compact Photon Source Design

A real photon source is consequently necessary to perform our experimental program on WACS.

Key features and advantages of the CPS are: a photon spot of 0.9 mm (important for physics background reduction), 6×10^{11} eq. γ/s photon flux (about 10 times larger than e-γ mixed beam usable with a polarized NH3 target) with acceptable radiation level in the Hall and target, and finally a simple beam line without a chicane (needed in the case of a mixed e-γ for a transversely polarized NH3 target).

The untagged bremsstrahlung γ source consists of the following components, see figures 5 and 6:

- A 10% radiation length tick radiator.
- A normal conducting magnet providing a dipole field with a large enough $\int \vec{B} d\vec{l}$ to sweep primary beam electrons out of the beam line.
- Iron shielding which surrounds the magnet itself, whose dimensions would be 100 x 50 x 60 cm^3, to reduce the background radiation level. In particular, the radiation level at the Hall boundaries should not exceed allowable limits. Note that this shielding makes the magnet a sweeper/mini beam dump combination.
- A magnet bore containing a one meter long, slowly moving tungsten-copper block with 2 mm by 20 mm slots. The block motion synchronized with a slow raster applied to the primary beam, effectively forms a "mechanical raster" protecting the polarized target from local overheating.
- A small opening just for the photons, which provides collimation of the radiation background.

Any research project on WACS has to overcome a number of experimental challenges, including 1) the larger photon beam intensity necessary to take into account the drop of the counting rate (a factor of about 180 when going from s=8 to 16 GeV^2), and 2) neutral pion background (physics dilution). The only way to reduce the latter is by means of a cut on a p-γ angular correlation. Regarding the photon beam intensity, an easy way (mixed e-γ beam) is limited due to the polarized target cooling rate, while a clean photon beam typically leads to a large photon spot size (or low intensity due to collimation). This is why a small photon spot is very important. It defines the width of the out-of-plane photon-proton angular correlation, and contributes to the proton momentum resolution, see figure 7.

A possible work plan to study the WACS process will consist of the following steps:

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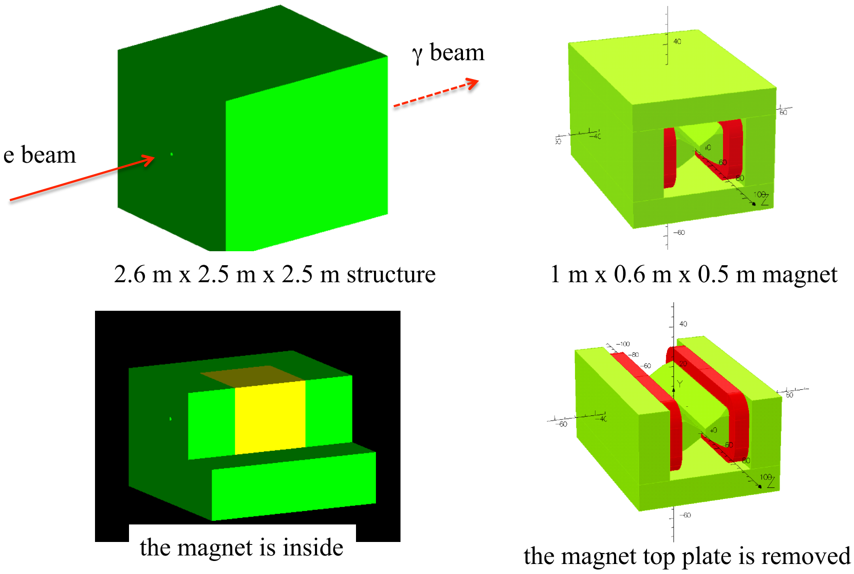

Figure 5: Structure of the CPS used to simulate performance with Geant4 code.

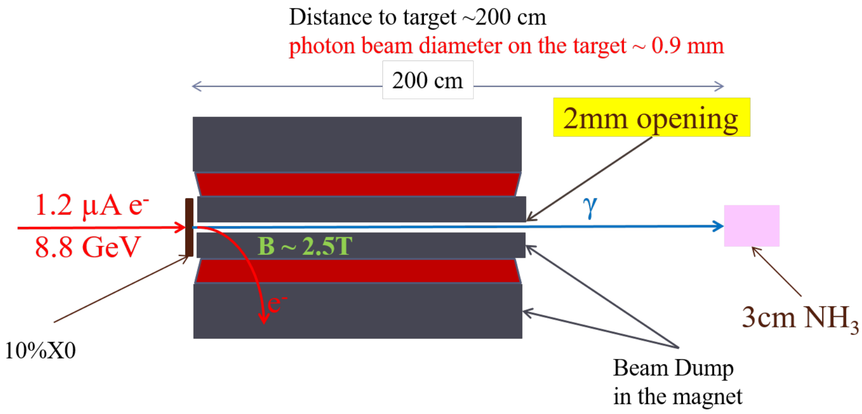

Figure 6: CPS combined magnet-dump conceptual design.

1. A low intensity test of the shielding concept and the detector counting rates using a narrow tilted channel in a CuW80 bar located inside a pile of blocks.
2. Design, mechanical and beam testing of a vibrating CuW80 bar with a set of four narrow channels for the photon beam.
3. Development of monitoring of the force on the target solenoid.
4. Design of a slow raster with fast current control. The existing raster needs synchronization controlled by the bar motion sensor.

4. Summary

Our experiment on WACS would use an 8.8 GeV, 1.2 μA, 80% polarized electron beam and

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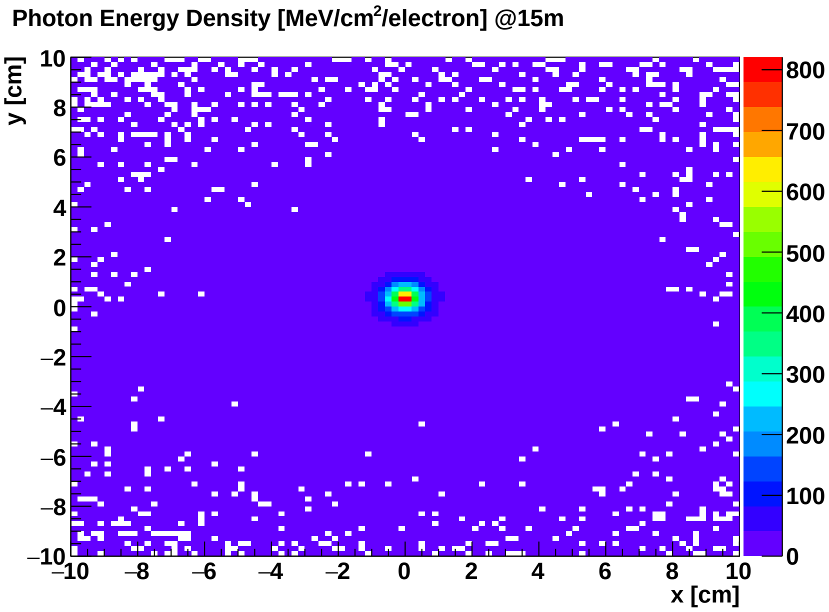

Figure 7: Monte Carlo results for the CPS photon spot.

a longitudinally polarized target. A sweeper-dump magnet combination may be used to produce a narrow photon beam. The scattered photons are detected by the NPS spectrometer while the SBS spectrometer detects protons.

The measures have to be carried out at large s and $-t$ in the wide-angle regime. These are optimal conditions for unambiguously testing the applicability regime of GPDs and will most likely resolve the (apparent) puzzles discovered by recent JLab experiments. Knowledge of the initial state helicity correlation asymmetry $A_{\rm LL}$ in WACS at these kinematics will allow a rigorous test of the reaction mechanism for exclusive reactions at high $-t$, which is crucial for advancing the understanding of nucleon structure, and, moreover, the applicability of the GPD approach.

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