A New Proposal to Jefferson Lab PAC48

Measurement of the Two-Photon Exchange contribution to the electron-neutron elastic scattering cross section

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Abstract

We propose make a high precision measurement of the two-photon exchange contribution (TPE) in elastic electron-neutron scattering at a four-momentum transfer $Q^2 = 4.5$ (GeV/c)^2. While significant efforts to study the two-photon-exchange have focused around elastic electron-proton scattering, the impact of TPE on neutron form factors was never examined experimentally. The proposed experiment will provide the very first assessment of the two-photon exchange in electron-neutron scattering, which will be important for understanding of the nucleon form factor physics.

The proposed experiment will be performed in Hall A using the BigBite (BB) spectrometer to detect the scattered electrons and the Super-BigBite (SBS) to detect the protons and neutrons. The experiment should run concurrently with the E12-09-019 G_M^n and E12-17-004 G_E^n-Recoil experiments, which are expected to run in 2021. The experimental setup of the proposed experiment will be identical to that of E12-09-019 experiment.

The "ratio" method will be used to extract the electric form factor of the neutron G_E^n by scattering unpolarized electrons from deuterium quasi-elastically at two beam energies 4.4 and 6.6 GeV and electron scattering angles 41.9 and 23.3 degrees respectively. In the proposed approach, systematic errors are greatly reduced compared to those in the traditional single electron arm configuration. Several experiments at Mainz and JLab have used the ratio method to measure the neutron magnetic form factor in the past years. The method can be extended to extract the neutron electric form factor even with less stringent requirements on the knowledge of the absolute neutron detection efficiency and experimental kinematics.

I. INTRODUCTION

In 1950's, a series of experiments performed by R. Hofstadter [1] revealed that the nucleons have a substructure (would be called later the quarks and gluons). The experiment confirmed M. Rosenbluth's theory [2] based on one-photon exchange approximation. In the Born approximation, where the interaction between the electron and the nucleon occurs *via* an exchange of a one virtual photon (OPE), the unpolarized $e-N$ elastic cross section can be expressed in terms of a nucleon magnetic, $\mathrm{G}_{_M}$, and electric, $\mathrm{G}_{_M}$, form factors. These form factors describe the deviation from a point-like scattering cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{eN\to eN} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\ \left[\tau\cdot G^2_{_M}(Q^2)+\epsilon\cdot G^2_{_E}(Q^2)\right]\ =\ \sigma_{_T}+\epsilon\cdot\sigma_{_L}, \tag{1}$$

where E and E' are the incident and scattered electron energies, respectively, θ is the electron scattering angle, $\tau \equiv -q^2/4M^2$, with $-q^2 \equiv Q^2 = 4EE'\sin(\theta/2)$ being the negative four momentum transfer square, M is the nucleon mass, and $\epsilon = \left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$ is the longitudinal polarization of the virtual photon, $\sigma_{_L}$ and $\sigma_{_T}$ are the cross sections for longitudinally and transversely polarized virtual photons, respectively.

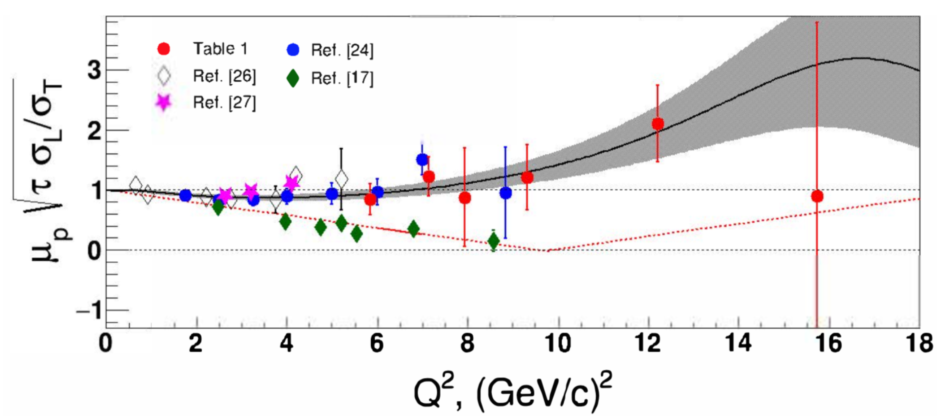

FIG. 1. The square root of Rosenbluth slope, corrected for kinematical factor $\sqrt{\tau}$ and μ_p, observed in elastic electron-proton scattering, adopted from Ref. [3].

The linear ϵ dependence of the cross section is due to $\sigma_{_L}$ term, see Eq. 1. The ratio $\sigma_{_L}/\sigma_{_T}$

is a Rosenbluth slope related to G_E/G_M(in OPE), see Fig. 1. The data show that at Q^2 of 4-5 $(GeV/c)^2$ the Rosenbluth slope is three-four times larger than it suppose to be (in OPE) for the observed values of the G^p_E/G^p_M ratio.

The nucleon electromagnetic form factors can reveal a lot of information about the nucleon internal structure, as well as the quark distribution. The form factors depend only on one variable the negative square of the four-momentum transfer carried by the photon, Q^2. In the limit of large Q^2, pQCD provides well-motivated predictions for the Q^2-dependance of the form factors and their ratio. However, it was never predicted at what Q^2 range the pQCD prediction (scaling) will be valid. Studies of GPDs show that pQCD validity will require a very large Q^2 of 100 $(GeV/c)^2$. It was discovered at JLab, using the double polarization methods, that the proton electric and magnetic form factors behave differently starting at $Q^2 \approx 1$ $(GeV/c)^2$.

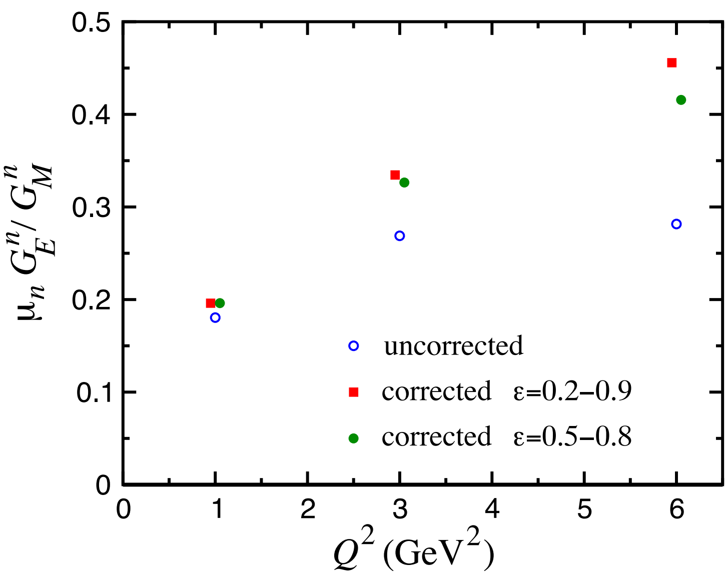

FIG. 2. Projected impact of TPE on G^n_E/G^n_M using LT separation, according to Ref. [4].

Experimentally, the nucleon form factors can be measured using one of two techniques: polarization transfer technique and Rosenbluth technique. The polarization method examines the polarization transfer from longitudinally polarized electron to the recoiling nucleon and determine the resulting azimuthal asymmetry distribution using a polarimeter. Alternatively, one can use the polarized electron beam and a polarized target. While in the Rosenbluth method, the electric and magnetic from factors can be separated by making two or more measurements with different ϵ values (*i.e.* different beam energies and angles), but with same Q^2 value. Rosenbluth technique requires an accurate measurement of the cross section and suffers from large systematic uncertainties arising from several factors. For instance, an accurate knowledge of the neutron detector efficiency is required.

When comparing the values of G^p_E/G^p_M obtained from both techniques, a significant discrepancy was observed (see Fig. 1). Such discrepancy implies a potential problem in our understanding of the nucleon substructure. Many efforts were made in order to provide legitimate explanation, and it is believed that the inconsistency is due to contribution of two-photon exchange in $e - N$ elastic scattering process, see Refs. [5, 6]. Predictions made for the neutron case are shown in Fig. 2, adopted from [4]. The contribution of TPE could reach about 30% of Rosenbluth slope value at 5 $(\mathrm{GeV/c})^2$.

In the following we propose to make precision L/T separation of the elastic electron-neutron cross section and first experimental assessment of the two-photon exchange contribution on the neutron magnetic form factor measurements (see also Ref. [7]). The result of the nTPE experiment will likely add a new component to our understanding of the elastic electron-nucleon process.

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II. PHYSICS MOTIVATION

The nucleon plays the same central role in hadronic physics that the hydrogen atom does in atomic physics and the deuteron in the physics of nuclei. The structure of the nucleon and its general properties, such as (static) charge, magnetic moment, size, mass, and the form factors and structure functions, are of fundamental scientific interest. The nucleon is a laboratory for the study of the quark-gluon interaction and both nucleons, the proton and the neutron, need to be explored. At present the proton has been more thoroughly studied at large Q^2 than the neutron. More data on the neutron is essential if we are to make real progress in obtaining a complete description of the quark structure of the nucleon [8].

Considerable information on the structure of the nucleon has been obtained by using electromagnetic probes via electron scattering. Inclusive deep inelastic scattering (DIS) has been a classical tool with which the partonic structure of the nucleon has been probed. At high Q^2, DIS yields information on the light-cone momentum space distributions of quarks and gluons in the nucleon when viewed through the infinite momentum frame. Many of the experimental foundations of QCD are in fact derived from investigations of various aspects of DIS.

Exclusive processes, on the other hand, such as elastic electron and photon scattering, can provide information on the spatial distribution of the nucleon's constituents, which is parameterized through the elastic nucleon form factors. Experimental studies of elastic electron scattering from both the proton and the neutron were initiated at SLAC and are now being thoroughly performed at Jefferson Lab and other facilities world-wide.

The Dirac form factor, F_1, describes the distribution of the electric charge, while the helicity non-conserving Pauli form factor, F_2, describes the distribution of the magnetic moment; these two form factors are the ingredients of the hadronic current. These currents contain information on the transverse charge distribution for an unpolarized and transversely polarized nucleon, respectively, in the infinite momentum frame [9, 10].

The Sachs form factors, G_E and G_M, the ratio of which will be extracted directly from our data for the neutron, are related to F_1 and F_2 by

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \text{ and } F_2 = \frac{G_M - G_E}{\kappa(1+\tau)}, \tag{2}$$

where κ is the nucleon anomalous magnetic moment.

At asymptotically high Q^2, one can apply perturbative QCD (pQCD) to describe the Q^2 dependence of exclusive electron scattering. Early attempts to determine the scaling behavior for F_1 were performed by using a simple dimensional counting rule justified by the inclusion of two gluon exchange processes [**?** **?**].

A recent calculation by Belitski *et al.* [**?**] was performed where quark orbital angular momentum was included to determine the behavior for the non-helicity conserving form factor F_2. It was found to logarithmic accuracy that the ratio F_2/F_1 should, at high Q^2, follow the form

$$\frac{F_2}{F_1} \propto \frac{\log^2 (Q^2/\Lambda^2)}{Q^2}, \tag{3}$$

This behavior was found to set in surprisingly early for the proton data for $Q^2 > 2.0$ GeV^2 with $\Lambda \approx 300$ MeV. Using preliminary G_E^n data from E02-013 up to 3.5 GeV^2, this scaling had not yet been observed [**?**] suggesting pQCD has not yet set in at this range in Q^2. A calculation from ANL utilizing a Poincare invariant truncated Faddeev equation for a quark-diquark system [**?**] suggests this type of behavior for each of the two nucleons may be expected. For high Q^2, this experiment in conjunction with high Q^2 G_M^n data may be able to observe the onset of this pQCD behavior in the neutron form factors.

Over the years many QCD-inspired models have been developed to describe nucleon electromagnetic form factors at small and intermediate Q^2 values ($Q^2 < 1$–2 GeV^2). While these have provided some insights into the possible origin of the nonperturbative quark structure of the nucleon, ultimately one would like to use experimental form factor data to test the workings of QCD itself.

Recently, important developments in QCD phenomenology has been the exploration of the generalized parton distribution (GPD) formalism [**?** **?** **?**], which provides relations between inclusive and exclusive observables. The nucleon elastic form factors F_1 and F_2 are given by the first moments of the GPDs

$$F_1(t) = \sum_q \int_0^1 H^q(x,\xi,t,\mu)dx \text{ and } F_2(t) = \sum_q \int_0^1 E^q(x,\xi,t,\mu)dx, \tag{4}$$

where H^q and E^q are two of the generalized parton distributions, x is the standard Bjorken x, ξ is is the "skewdness" of the reaction (Fig. **??**), t is the four-momentum transferred by the electron, μ is a scale parameter necessary from the evolution over Q^2, analogous to DIS parton distributions, and the sum is over all quarks and anti-quarks. These may be accessed through processes such as deeply virtual compton scattering, where the interaction is factorized into a hard part with the virtual photon/photon interactions with an individual quark and a soft part of the residual system where the GPD information is contained, Fig. **??**.

Furthermore, as shown earlier by Ji [**?**], the moments of GPDs can yield information, according to the Angular Momentum Sum Rule, on the contribution to the nucleon spin from quarks and gluons, including both the quark spin and orbital angular momentum.

At present, experimental measurements of GPDs are scarce. Until such data becomes available, work has been done to attempt to parameterize these GPDs, which rely heavily on data from electromagnetic form factors and parton distributions from DIS as constraints [**? ? ?**]. Data at high Q^2 for G_E^n would contribute significantly in the development of these models.

The isovector and isoscalar form factors constructed from the proton and neutron form factors have different sensitivity to higher Fock components of the light cone quark wave function. This difference can be an important handle to test the valence quark dominance in exclusive reactions in the few $(GeV/c)^2$ range. Data on F_{1p} and F_{1n} will allow the extraction of information related to the *(u-d)* distribution, which was calculated recently using the GPD approach by K. Goeke, M. Polyakov, and M. Vanderhaeghen [**?**].

Recent theoretical developments also indicate that measurements of the individual elastic form factors of the nucleon up to high Q^2 may shed light on the problem of nucleon spin [**?**].

As an incidental benefit of the proposed experiment, a better determination of the neutron electric form factor will be very important for calculations of nuclear form factors, such as those of the deuteron. Even though $G_E^n \ll G_E^p$ at $Q^2 \approx 0$, at larger Q^2 ($Q^2 \sim 3$ GeV^2) the ratio G_E^n/G_E^p can be as large as ≈ 0.4, so that accurate information on G_E^n at large Q^2 is essential for a reliable description of the deuteron form factors.

III. TECHNIQUE

The neutron form factors are challenging to be determind experimentally especially because there is no free neutron target. However, since the deuterium is a loosely coupled system, it can be viewed as the sum of a proton target and a neutron target. In fact, quasi-elastic scattering from deuterium has been used to extract the neutron magnetic form factor, G^n_M, at modestly high Q^2 for decades [11, 12] in the single arm (e,e') experiments. However, the proton cross section needs to be subtracted by applying a single-arm quasi-elastic electron-proton scattering. This "proton-subtraction" technique suffers from a number systematic uncertainties e.g. contributions from inelastic and secondary scattering processes.

Many year ago, L. Durand [13] proposed the so-called "ratio-method" based on the measurement of both D(e,e'n) and D(e,e'p) reactions. In this method, many of the systematic errors are cancel out. Several experiments [14–16] have applied the ratio-method to determine the neutron magnetic form factor. We propose to use this method to measure Rosenbluth slope and extract (in OPE approximation) the neutron electric form factor, G^n_E.

Data will be collected for quasi-elastic electron scattering from deuteron in process $D(e,e'n)p$. A complementary $D(e,e'p)n$ data will be taken to calibrate the experiment apparatus. The current knowledge of the $e-p$ elastic scattering cross section (obtained in the single arm H(e,e')p and H(e,p)e' experiments) will be also used for precision determination the experiment kinematics.

Applying Rosenbluth technique to measure G^n_E requires accurate measurement of the cross section and suffers from large uncertainties. To overcome this issue, we propose to extract the value of G^n_E from the measured the ratio of quasi-elastic yields, $R_{n/p}$, in scattering from a deuteron target as follows:

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}} \tag{5}$$

$R_{observed}$ needs to be corrected to extract the ratio of e-n/e-p scattering from nucleons:

$$R_{corrected} = f_{corr} \times R_{observed} \quad , \tag{6}$$

where the correction factor $f_{correction}$ takes into account the variation in the hadron efficiencies due to changes of $e-N$ Jacobian, the radiative corrections, and absorption in path from the target to the detector, and small re-scattering correction.

In one-photon approximation, $R_{corrected}$ can be presented as:

$$R_{corrected} = \frac{\sigma^n_{_{Mott}} \cdot (1+\tau_p)}{\sigma^p_{_{Mott}} \cdot (1+\tau_n)} \times \frac{\epsilon\sigma^n_{_L} + \sigma^n_{_T}}{\epsilon\sigma^p_{_L} + \sigma^p_{_T}} \tag{7}$$

It is important that the ratio $R_M = \frac{\sigma^n_{_{Mott}} \cdot (1+\tau_p)}{\sigma^p_{_{Mott}} \cdot (1+\tau_n)}$ could be determine with very high accuracy even with modest precision for the beam energy, electron scattering angle, and detector solid angle.

Now, let us write the $R_{corrected}$ at two values of ϵ using $R^{n(p)}_s = \sigma^{n(p)}_{_L}/\sigma^{n(p)}_{_T}$ as

$$R_{corrected,\epsilon_1} = R_{M,\epsilon_1} \times \frac{\epsilon_1\sigma^n_{_L} + \sigma^n_{_T}}{\epsilon_1\sigma^p_{_L} + \sigma^p_{_T}}$$
$$R_{corrected,\epsilon_2} = R_{M,\epsilon_2} \times \frac{\epsilon_2\sigma^n_{_L} + \sigma^n_{_T}}{\epsilon_2\sigma^p_{_L} + \sigma^p_{_T}}$$

In this two equation there are two unknown variables: $\sigma^n_{_L}$ and $\sigma^n_{_T}$.

The dominant contribution to the uncertainty of $R^n_s = \sigma^n_{_L}/\sigma^n_{_T}$ is coming the uncertainty in R^p_s which is at Q^2=4.5 $(GeV/c)^2$ is of 0.05 according to the global analysis [3].

This resulting in the equation with just one unknown variable R^n_s:

$$A = B \times \frac{\epsilon_1 R^n_s + 1}{\epsilon_2 R^n_s + 1} \approx B \times (1 + \Delta\epsilon \cdot R^n_s)$$

Where the variable $A = R_{corrected,\epsilon_1}/R_{corrected,\epsilon_2}$ will be measured with precision of 0.1% and the variable $B = R_{M,\epsilon_1}/R_{M,\epsilon_2} \times (\epsilon_1\sigma^p_{_L} + \sigma^p_{_T})/(\epsilon_2\sigma^p_{_L} + \sigma^p_{_T}) \approx (1 + \Delta\epsilon \cdot R^p_s)$ which will be determined to precision 0.25×0.05. The final uncertainty of R^n_s is 0.05 which dominated by current knowledge of the same proton parameter 1.91*(sqrt(0.057*2) -sqrt(0.057*2+0.05)).

At Q^2=4.5 $(GeV/c)^2$ the combination $\mu_n G^n_{_E}/G^n_{_M}$ has the value of 0.5 (see the review [17]), so the accuracy of our experiment (assuming the TPE portion of R^n_s as large as for the proton) for will be $\delta(\mu_n\sqrt{\tau\sigma_{_L}/\sigma_{_T}}) = \pm 0.08$.

IV. EXPERIMENTAL SETUP

As illustrated in Fig. 3, this experiment will study electron scattering from a 15 cm long liquid Deuterium target held in a vacuum. The scattered electron will be detected in the BigBite spectrometer with an upgraded electron detector stack. The neutron arm is arranged with a dipole magnet 48D48 (SBS) and a segmented hadron calorimeter HCAL. The whole detector package was designed and is now under assembling for the GMn, E12-09-019, experiment.

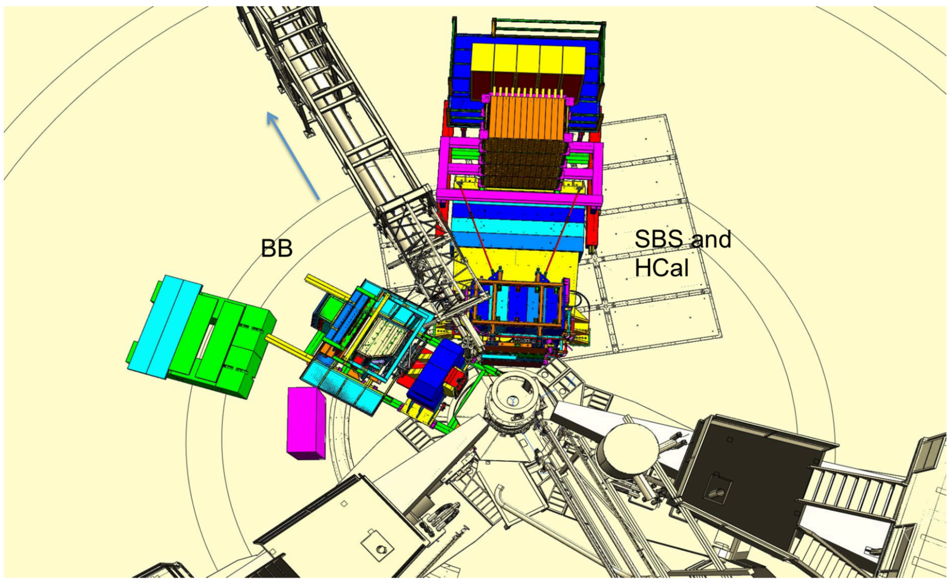

FIG. 3. Layout of the experimental setup in nTPE.

1. Parameters of the SBS

The 48D48 magnet from Brookhaven was acquired as part of the Super Bigbite project and will be available for this experiment. It consists of a large dipole magnet which provides a field integral of about 1.7 $\mathrm{T \cdot m}$, allowing for quasielastic protons to be sufficiently deflected to allow clear differentiation from neutrons. The active field volume has an opening of 46$\times$ 25 vertical $\times$ horizontal), matching the aspect ratio of the neutron arm, and a depth of 48 cm.

The placement of this magnet will be 1.6 m away from the target, which would normally interfere with the beamline. To accommodate this, modifications were made to the iron yoke such that the beamline will pass through the magnet yoke area.

The field configuration will be such that positively charged particles will be deflected upwards away from the hall floor. For a field integral of 1.7 Tesla-m, protons of momentum 2.5 GeV/c will be deflected 250 mrad, which translates to a displacement of xxm. Including expected detector resolution, the $p_{miss,\perp}$ distribution will be similar to what was seen in E02-013, so cuts of < 100 MeV/c will be appropriate. Monte Carlo simulations show a contamination of charged quasielastics to be negligible.

The presence of the magnet also works to sweep low energy charged particles from the target away from the neutron arm. Particles of momentum less than 1.3 GeV/c will be entirely swept outside of the neutron arm acceptance. This greatly reduces the amount of charged low energy background.

A. The BigBite Spectrometer

Scattered electrons will be detected in the BigBite spectrometer. The spectrometer consists of a single dipole magnet (with magnetic field approximately 1.2 Tesla-m and a detection system, see Fig. 4.

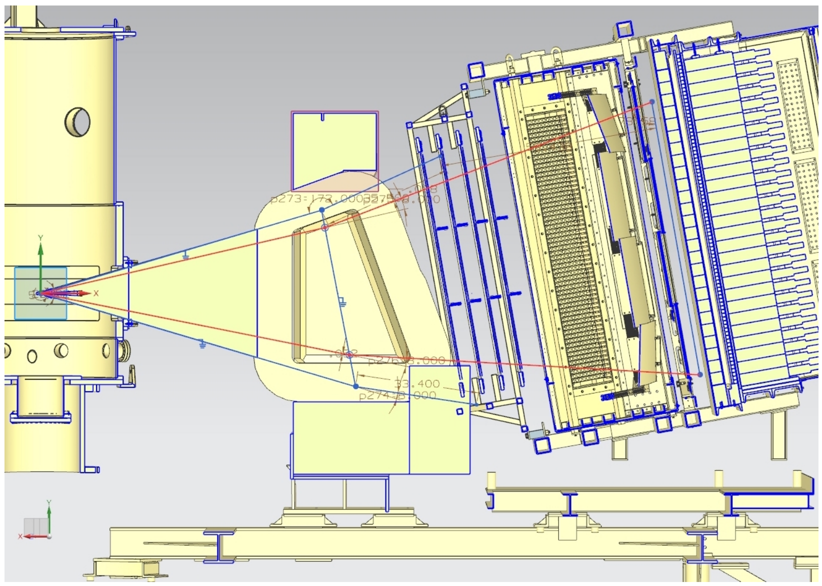

FIG. 4. The BigBite spectrometer with the upgraded detector stack.

1. *Simulation of BigBite*

2. *Detector Package*

a. Background Rate in BigBite

b. Front GEM chambers

c. Gas Cherenkov Counter

d. Rear GEM chamber

e. Shower and Preshower

f. Timing Scintillator Hodoscope

3. Trigger

4. Simulation of BigBite

a. Rates in the detectors

b. Trigger rate and efficiency

B. Neutron Detector

S

1. *Structure of the Neutron Detector*

V. PROPOSED MEASUREMENTS

We propose to use the same experimental setup of E12-09-019 experiment. We will add a kinematic point at $Q^2 = 4.5$ (GeV/c)^2, but with a higher ϵ value. This additional point along with the data point of E12-09-019 experiment will allow us to perform LT separation and obtain (in one-photon approximation) the G_E^n value. Table 1 displays the kinematic setting of the proposed experiment.

Point	Q^2 (GeV/c)^2	E (GeV)	E$'$ (GeV)	θ_{BB} degrees	θ_{SBS} degrees	ϵ	$\Delta\sigma$ (%)	ΔTPE (%)
1	4.5	4.4	2.0	41.88	24.67	0.599		
2	4.5	6.6	4.2	23.23	31.2	0.838		

TABLE I. Kinematic settings of the proposed experiment. The blue row is a kinematic point of E12-09-019 experiment.

VI. BEAM TIME REQUEST

We request 48 hours total time (32 hours of beam-on target) to measure the two-photon effect (and G_E^n in one-photon approximation) at $Q^2 = 4.5$ (GeV/c)^2 through a measurement of the cross sections of the reaction D(e,e'N) at a large value of the virtual photon polarization ϵ=0.84. This experiment will take place in Hall A, utilizing the BigBite spectrometer to detect electrons scattered off the liquid deuterium target, and HCal calorimeter to detect the recoiling neutron and proton.

Data taking (if approved by PAC48) will take place in summer 2021 during the approved and scheduled run of the GMn, E12-09-019, experiment, which is going to measure the $e-n$ elastic scattering cross section at $Q^2 = 4.5$ (GeV/c)^2 at ϵ=0.60.

The set of instrumentation and required beam current for proposed measurement is identical to one in the GMn experiment. The beam energy of 6.6 GeV will be used. One of two data points required for the cross section LT separation is already in the data taking plan of GMn.

There are no other measurements of TPE in the $e-n$ elastic scattering and knowledge of the TPE is essential for the understanding of the elastic electron scattering from neutron (and proton) and hadron structure. Furthermore, it is a necessary input in the analysis and interpretation of a wide range of electron scattering processes.

The kinematics of our measurements emphasize the same Q^2 range where TPE in $e-p$ elastic scattering was observed to dominate in Rosenbluth slope. Measuring at this high momentum transfers will provide unique input for testing TPE calculations [4].

We propose to measure the Rosenbluth slope and extract (in one-photon approximation) $\delta G_E^n/G_M^n$ to an accuracy of 0.15, which would bring its precision to a level comparable with that of the double polarization experiments GEN-RP and GEN-He3 at such value of Q^2. Such precision should be sufficient to detect the TPE contribution to the $e-n$ Rosenbluth slope on the three sigma level.

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