A High Precision Measurement of the Neutron Electric Form Factor, G_E^n at High Q^2

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Abstract. In the first half of 2006, Jefferson Lab experiment E02-013 successfully collected data to measure the neutron elastic form factor G_E^n at the four four-momentum transfer values $Q^2 = 1.2, 1.8, 2.6$, and $3.5(\mathrm{GeV}/c)^2$. This quasi-elastic semi-exclusive $^3\vec{H}e(\vec{e}, e'n)$ reaction used the polarized CEBAF beam ($P_b > 80\%$) and a highly polarized ^{3}He target ($P_t > 50\%$). Neutrons were detected by an array of scintillators, which has a measured neutron efficiency of 35-40%. The electrons were detected by the newly commissioned BigBite spectrometer with a momentum resolution of 1-1.5%. The transverse asymmetry of the cross section A_T will be measured from which G_E^n may be extracted. A statistical accuracy of $\Delta G_E^n / G_E^n \approx 0.14$ is expected.

An overview of the experiment and the experimental motivation will be discussed. Analysis progress, especially as related to the many new systems, will also be presented.

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INTRODUCTION

Knowledge of the neutron electric form factor G_E^n is essential for an understanding of nucleon structure. In simplest terms, the Fourier transform (in the Breit or "brick wall" frame) of G_E^n is the charge density of the neutron. Recent measurements of G_E^p show that the ratio (G_E^p/G_M^p) declines sharply as Q^2 increases. Therefore the electric and magnetic form factors (of the proton) behave differently starting at $Q^2 \approx 1(\mathrm{GeV}/c)^2$. At this time, there is scant data on the behavior of G_E^n as we move beyond this Q^2 value. In addition, the form factors constrain the Genralized Parton Distributions (GPDs) via integrals over the variable x[1]. The electrical form factor in particular constains the GPD $\mathrm{E^d}$. Factorization for the hard excluisive reactions allows descriptions of many such reactions in terms of GPDs. As universal functions, they offer insight into otherwise inaccessible structure. Form factors results are used as parameters in determining the GPDs[2]. The largest uncertainty on $\mathrm{E^d}$ is the experimental measurement of G_E^n in the region where the quark model dominates[3].

EXPERIMENTAL METHOD

The standard method of measuring form factors, the Rosenbluth separation, is not possible with G_E^n. The magetic form factor dominates the cross-section ($\tau G_M^n \gg G_E^n$);

these experiments must be performed on light nuclei (mostly ^{2}H); and to extract the nuetron information, the wave functions have to be known – and relativistic effects taken into account. The results of for G_E^n from elastic $e-d$ scattering are large, and consistent with both $G_E^n = 0$ and the Galster parameterization.

Another method of measuring the form factor is the method of double polarization. In this method, a polarized electron beam interacts with a neutron target. Either the polarization of the recoiling neutron is measured, or a polarized neutron target is used. Experiment E02-013 used the latter method. A polarized ^{3}He target was used in place of a free polarized neutron target. Free neutron targets do not exist, so this is a reasonable substitution [4][5]. More is said on this topic in a later section.

The double polarized spin asymmetry used to extract the ratio G_E^n/G_M^n:

$$\begin{aligned} A_{phys} = & - \frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2) G_E^n G_M^n \sin\theta^* \cos\phi^*}{(G_E^n)^2 + (G_M^n)^2(\tau + 2\tau(1+\tau)\tan^2(\theta/2))} \\ & - \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)(G_M^n)^2\cos\theta^*}{(G_E^n)^2 + (G_M^n)^2(\tau + 2\tau(1+\tau)\tan^2(\theta/2))} \end{aligned} \tag{1}$$

In this experiment, the target spin was aligned perpendicular to the momentum transfer. This separates the perpendicular from the longitudinal asymmetries. Specifi cally, what is measured is the perpendicular asymmetry:

$$A_\perp = -\frac{G_E^n}{G_M^n} \cdot \frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2)}. \tag{2}$$

In our kinematics, $(G_E^n/G_M^n)^2$ is small compared to the second term of the denominator. Therefore, G_E^n/G_M^n is nearly proportional to $A_\perp$. Due to the large acceptance of BigBite, no separation into perpendicular kinematics can be the completley acheicved. Small contributions from the longitudinal asymmetry will be taken into account:

$$A_\parallel = -\frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2)} \tag{3}$$

EXPERIMENTAL OVERVIEW

The experiment is a measurement of the exclusive quasi-elastic reaction $^3\vec{H}e(\vec{e},e'n)$. This particular measurement has specifi c challenges. This experiment was designed with those challenges in mind.

In order to measure scattering from a neutron, a neutron target is required. No free neutron targets exist, so a $^3\vec{H}e$ target was used. More is said about this target in a later section. Second, G_E^n is very small, this lead the experiment away from the Rosenbluth method, as described in the physics overview section.

Third, our luminosity was limited due to the high background rates. This was overcome by using the large acceptance spectrometer, BigBite. The acceptance was 76 msr over a 35cm target. The detector stack consisted of 15 planes of wire chambers, a scintillator plane and a lead glass calorimeter. The wire chambers operatored at a very high background rate of 200 MHz per plane. The calorimeter was used to trigger above 750 MeV to reach an acceptable trigger rate of 2KHz.

Fourth, neutrons are diffi cult to detect, and characterize. This experiment used a time of flight method to characterize the neutrons. In order both use the time of flight method and match the acceptance of BigBite, the neutron detector was built very large. The active area of 8m^2 was made up of 200 neutron bars and 180 veto counters. A time of flight resolution of better than 0.5ns was acheived in this experiment.

ADVANCES IN $^3\vec{He}$ TARGETS

Spin Exhange Optical Pumping and the Jefferson Lab Target

Experiment E02-013 was the seventh experiment in Jefferson Lab's Hall A to use a spin-exchange optically pumped ^{3}He target as a neutron target. The principle of spin exchange optical pumping is straightforward: circularly polarized lasre light of a specifi c wavelength interacts with an alkali metal in a magnetic fi eld. In this manner all of the atoms of the alkali metal are quickly polarized[6]. Polarization is transfered from the alkali metal atoms to the noble gas nuclei by means of a hyperfi ne interaction between the outer electron of the alkali metal and the noble gas nucleus.

Advances in Target Technology

All that is required to produce a polarized noble gas in this manner is a homogenous magnetic fi eld, a supply of alkali vapor, and cicularly polarized laser light. This laser light has, in the past required up to 8 optical paths per polarization direction as well as a separate building in the experimental hall. This is due to the high power requirements. Successful experiments have used up to 100W of narrow band circularly polarized light.

This experiment was the fi rst to use a 5–1 laser combiner to reduce the total number of laser paths to 2 per polarization direction. This improvement immediately made the experimental design much more flexible and reduced the error associated with the degree of polarization of the light.

The light was brought to the optics near the target by way of optical fi bers. This experiment used 75m optical fi bers to bring 150W of laser light to the target (by using 5 fi bers, each transporting 30W). The use of these high powered fi bers eliminated the need for a separate structure in the experimental hall and will, in the future allow for even more flexible designs.

Polarization – A Giant Step Forward

This experiment was the fi rst to take advantage in the biggest recent advance in the fi eld of spin exhange optical pumping. The alkali metal described in the paragraphs above has traditionally been a pure alkali (typically Rb). For this experiment a mixture of Rb and K was used. Using this mixture, this experiment benefitted from faster time to polarization, and overall continuously pumped, in-beam, polarization of over 50%. To put this in perspective, previous experiments were content to with in-beam polarizations of 40%. The figure of merit for these experiments increases as the square of the polarization. This increase in polarization was equivalent to recieving over 50% more beamtime.

The spin-exchange efficiency for ^{3}HeK is much greater than that for ^{3}HeRb. Under idealized conditions, it is an order of magnitude larger [7]. However, there remain technical difficulties to pumping K directly for these $^3\vec{He}$ targets. Instead the mixture of Rb and K are used. In this case, the Rb is directly optically pumped. The spin exchange cross section for Rb and K is extremely large and as a result, the K and Rb have equal spin polarizations [6]. The combination of the higher spin efficiency between K and ^{3}He and the very large spin transfer cross section results in a very fast time to polarization("spin-up" time) [8]. This fast spin-up time also provides an overall higher polarization[9].

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