THE GENERALIZED GERASIMOV-DRELL-HEARN SUM OF THE NEUTRON AT LOW Q^2 USING A POLARIZED ^{3}HE TARGET

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A recently finished experiment to evaluate the generalized Gerasimov-Drell-Hearn sum on ^{3}He and the neutron in a Q^2 range between 0.03 GeV^2/c^2 and 1.2 GeV^2/c^2 will be discussed. The experiment was conducted in Hall A at Jefferson Lab using a polarized ^{3}He target in combination with a highly polarized electron beam.

1 Introduction

More than 30 years ago Gerasimov [1] and independently Drell and Hearn [2] (GDH) derived a fundamental sum rule that relates the spin-dependent forward Compton scattering amplitude to the difference of the spin-dependent total cross sections in real photon (γ) – nucleon (N) scattering. On general grounds the forward scattering amplitude of this process can be expressed in the following form:

$$f(\nu) = f_1(\nu)\vec{e}\,' \cdot \vec{e} + \nu f_2(\nu) i\vec{\sigma} \cdot \vec{e}\,' \times \vec{e}\ . \tag{1}$$

ν is the real photon energy, $\vec{e}$ and $\vec{e}\,'$ are the transverse polarization vectors of the incident and scattered photon, respectively; $\vec{\sigma}$ is the spin vector of the nucleon, f_1 denotes the non-spin-flip part of the amplitude and f_2 is the spin-flip contribution. GDH were able to relate $Ref_2(\nu)$ to the spin dependent γ-N cross section by means of an unsubtracted dispersion relation:

$$Ref_2(\nu) = \frac{1}{4\pi^2}\int_{\nu_{thresh}}^{\infty} \frac{\sigma_a(\nu') - \sigma_p(\nu')d\nu'^2}{\nu'^2 - \nu^2} \quad . \tag{2}$$

σ_a and σ_p are the cross sections for absorption of circularly polarized photons with the nucleon spin polarized anti-parallel and parallel to the photon spin vector. The lower limit of the integral corresponds to the inelastic threshold of the reaction which, in the case of nucleons, is the pion photo-production threshold .

About ten years earlier Low [3] and Gell-Mann and Goldberger [4] were able to relate the zero energy limit of the spin-flip amplitude to the square of the anomalous magnetic moment of the nucleon:

$$f_2(0) = -\frac{1}{2}(\alpha/M_N^2)\kappa_N^2. \tag{3}$$

Taking the limit of $\nu \to 0$ ($Q^2 = 0$) in Eqn. 1 allows us to write down the GDH sum rule for real photons:

$$I = \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu}(\sigma_a(\nu) - \sigma_p(\nu)) = -\frac{2\pi^2\alpha}{M_N}\kappa_N^2 \ . \tag{4}$$

Therefore, the value of the integral should be -204.5 μb for the proton and -232.8 μb for the neutron. This raises the question of convergence of the integral. The integrand contains a factor $1/\nu$ which enhances the contributions of low lying nucleon resonances. In order to guarantee convergence $(\sigma_a - \sigma_p)$ has to fall off faster than $1/ln(\nu)$ at high energies. Experimentally this has not been tested yet. However, Regge behaviour and commonly used multi-gluon exchange models in high energy diffractive scattering are commensurate with this assumption [5].
The sum rule can easily be extended to electron – nucleon, or equivalently virtual photon $\gamma^\star$–N, scattering. The so called *generalized sum* has the form:

$$I(Q^2) = \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu}(\sigma_a^T(\nu, Q^2) - \sigma_p^T(\nu, Q^2)) \ . \tag{5}$$

The superscript T refers to the transverse part of the $\gamma^\star$-N cross-section. We can rewrite the generalized GDH integral in terms of the two nucleon spin structure functions $G_1(\nu, Q^2)$ and $G_2(\nu, Q^2)$:

$$\begin{aligned} I(Q^2) &= 8\pi^2\alpha \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu} \frac{(M_N\nu G_1(\nu, Q^2) - Q^2 G_2(\nu, Q^2))}{K(\nu, Q^2)} \\ &= 8\pi^2\alpha \int_{\nu_{thresh}}^{\infty} \frac{d\nu}{\nu} \frac{(W_1(\nu, Q^2)A_1(\nu, Q^2))}{K(\nu, Q^2)} \ , \end{aligned} \tag{6}$$

$K(\nu, Q^2)$ is a virtual photon flux factor which introduces some ambiguity to the definition of the integral, since the virtual photon flux has no unique definition. Commonly, $K(\nu, Q^2) = \sqrt{\nu^2 + Q^2}$ is used. In the second part we used the unpolarized structure function $W_1(\nu, Q^2)$ multiplied by the virtual photon asymmetry, $A_1(\nu, Q^2)$.
We note that the contribution of $G_2(\nu, Q^2)$ to the integral vanishes as Q^2 goes to zero and in the limit of deep inelastic scattering (DIS, $Q^2 \to \infty, \nu \to \infty, Q^2/\nu$ fixed). Anselmino *et al.* [6] pointed out that the generalized GDH sum can be expressed by the first moment of the spin structure function $g_1(x, Q^2)$ in the DIS limit:

$$I(Q^2 \to \infty) = \int_0^1 dx g_1^n(x, Q^2) = \frac{-18.5\mu b}{Q^2} \ . \tag{7}$$

The value -18.5 μb is the asymptotic value of the first moment of $g_1^n(x, Q^2)$ of the neutron as extracted from a fit to the world data of g_1^n. However, this is just the Q^2 dependence in the large Q^2 limit. Fig. 1 shows the complete Q^2 evolution of the integral for the neutron as predicted by a model of Burkert and Li [7]. Recently Ji

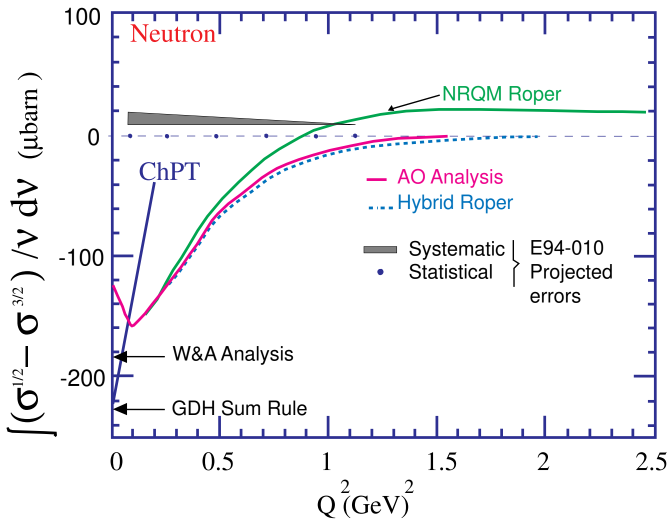

Fig. 1. The GDH sum for the neutron as calculated by Burkert and Li (solid and dashed curves) [7]. The low Q^2 χPT prediction [8] and the result of an analysis by Workman and Arndt (W&A) [9] are also shown. The points and the shaded band indicate the precision anticipated in the experiment presented here.

and Osborne investigated the GDH sum in terms of higher order chiral perturbation theory (χPT) and the operator product expansion (OPE) [10]. The conclusion of their paper was that the generalized GDH sum is calculable in χPT up to Q^2 values of about 0.2 GeV^2/c^2 and down to Q^2 values of about 0.5 GeV^2/c^2 using OPE. The experiment described here covers a Q^2 range from about 0.03 GeV^2/c^2 to 1.2 GeV^2/c^2. This will allow us the test OPE predictions and also give us precision data in the transition regime down to Q^2 values accessible by χPT. The low Q^2 regime ($0.02 < Q^2 < 0.5$ GeV^2/c^2) will be studied to higher precision in the follow-up experiment E97-110 [11].

2 The GDH Experiment in Hall-A at Jefferson Lab

Experiment E94-010 was the first of a whole series of experiments that utilizes a newly developed high pressure polarized ^{3}He ($^3\vec{\mathrm{He}}$) target. The inclusive $^3\vec{\mathrm{He}}(\vec{e},e')X$ reaction was used to study the generalized GDH sum for ^{3}He and neutrons in the quasi-elastic and resonance region at beam energies between 0.8 GeV and 5.1 GeV. Fig. 2 shows a schematic view of the experimental setup.

Polarized electrons were extracted from a strained GaAs crystal and the helicity of the electrons was reversed with a frequency of 1 Hz. The polarization was measured using a Mott polarimeter just in front of the accelerator and with a Møller polarimeter in the experimental hall. The polarization was 72% ± 3% averaged

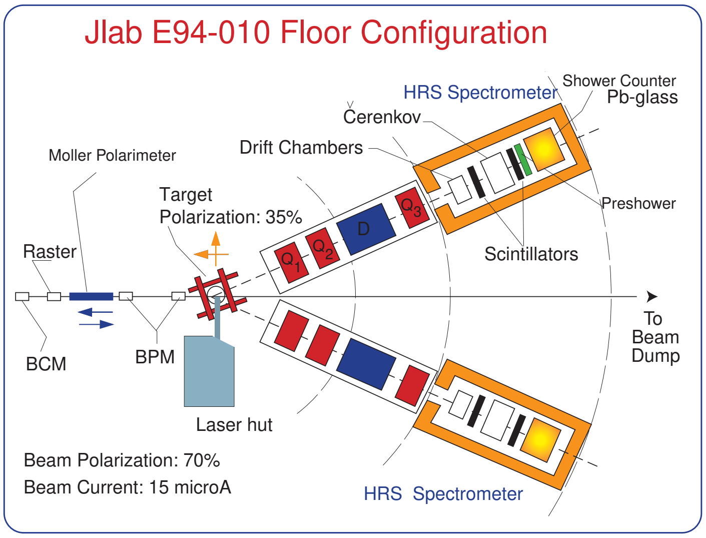

Fig. 2. Schematic floorplan of experiment E94-010.

over the total running period. The results of both polarimeters agreed very well. Due to the small radial dimension of the CEBAF beam, $\sigma \lesssim 0.1$ mm, the beam had to be rastered, i.e. deflected in radial direction with a frequency of 20 kHz, in order to avoid damage of the target caused by the high energy density. The x- and y-amplitudes of the raster were adjusted in such a way that the beam was circular with a diameter of about 3 mm at the target. The beam currents varied between 3 μA and 5 μA so that the data acquisition dead-time was kept at a tolerable level ($< 20\%$). Both High Resolution Spectrometers (HRS) in Hall A were used to detect the electrons. The spectrometers were positioned at $\pm 15.5^\circ$ with respect to the beam direction. Each HRS covered a solid angle of about 5 msr with a momentum acceptance of ± 4 %.
This allowed us to cover the kinematical range of (0.03–1.2) GeV^2/c^2 in Q^2 and (0.02–3.1) GeV in ν.

2.1 The Polarized ^{3}He Target

The polarized ^{3}He target was a high pressure double cell glass system very similar to the target used in the E154 experiment at SLAC [12]. A schematic layout of the target is shown in Fig. 3. The coupled cells contained between 8 atms and 10 atms of ^{3}He gas with a target length of about 40 cm. The ^{3}He atoms were polarized in the pumping cell by means of spin exchange with highly polarized rubidium atoms. The Rb gas was optically pumped using a diode array system which consisted of seven separate laser units. Each unit produced 30 W of laser power at 795 nm with a spectral width of about 2 nm. Typically three lasers where run at a time for longitudinally or transverse pumping, i.e. the target had to withstand laser powers

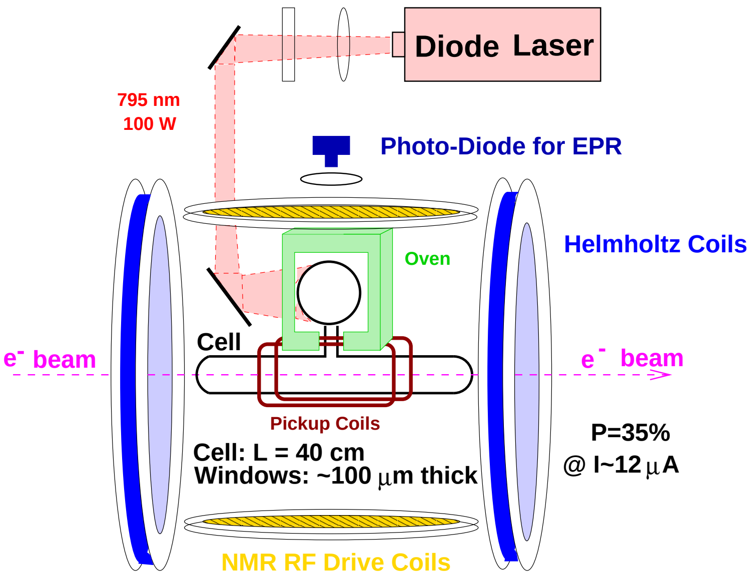

Fig. 3. Schematic view of the polarized ^{3}He target.

of about 90 W. The entrance and exit windows of the target were about 100 μm in thickness.

The target polarization varied between 30% and 37% at a magnetic holding field of 25.12 G and was limited by the beam current. Without electron beam, target polarizations in excess of 40% were achieved. We monitored the target cell polarization every few hours using NMR. In addition we tried for the first time to use the technique of Electron-Paramagnetic-Resonance (EPR) throughout the whole experiment. The basic idea of this technique is to monitor the effect of the polarized ^{3}He atoms on the hyperfine splitting of Rb. Since the hyperfine splitting is in first order proportional to the sum of all external magnetic fields, it is possible to distinguish between the splitting induced by the external holding field and the field generated by the $^3\vec{\mathrm{He}}$ atoms, if the ^{3}He spins are flipped. The change in the hyperfine transition frequency $\Delta\nu_{EPR}$ due to spin flips can be written as follows:

$$\Delta\nu_{EPR} = 2\frac{8\pi}{3}\frac{\mu_0}{4\pi}\frac{d\nu_{EPR}}{dB}\kappa_0\mu_{^3He}n_{^3He}P_{^3He}\ . \qquad (8)$$

Besides constant factors which are defined as per Ref. [13] the above equation contains the density $n_{^3He}$ and the polarization $P_{^3He}$ of the ^{3}He atoms. If the density is known, the polarization can be extracted. Fig. 4 shows a typical EPR spectrum.

This method can only be applied in the pumping cell and served as a polarization monitor. Diffusion models have to be applied to extract the polarization in the target cell. The analysis of the target polarimetry data is in progress. Since neither

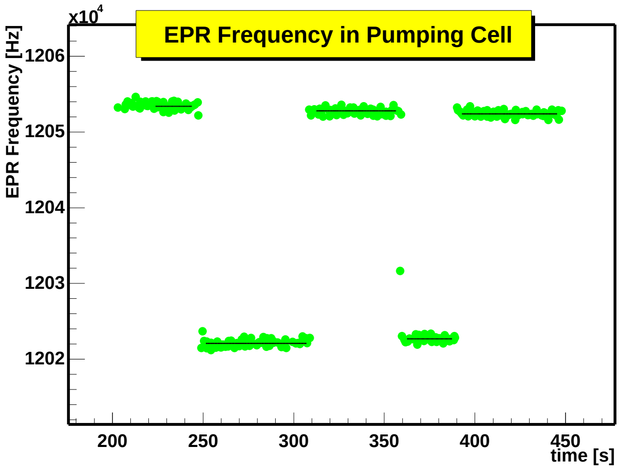

Fig. 4. EPR signal taken during the experiment.

the NMR nor EPR measurements allow us to determine the target polarization on the beam axis where the interaction takes place, we were able to take some elastic $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}')^3\mathrm{He}$ data. The asymmetries for this reaction can be calculated very precisely, since the elastic ^{3}He form factors are well known. The preliminary analysis of these data shows reasonable agreement with the NMR results.

3 Data Analysis

In order to evaluate the generalized GDH sum the spin structure functions have to be extracted from our data (see Eqn. 6). The relation between the virtual photon asymmetries and the spin structure functions is given by:

$$A_1 = \frac{1}{W_1(\nu,Q^2)}\left[M_n\nu G_1(\nu,Q^2) - Q^2 G_2(\nu,Q^2)\right] , \tag{9}$$

$$A_2 = \frac{1}{W_1(\nu,Q^2)}\sqrt{Q^2}\left[M_N G_1(\nu,Q^2) + \nu G_2(\nu,Q^2)\right] . \tag{10}$$

A_1 and A_2 are linear combinations of the count rate asymmetries $A_\parallel$ and $A_\perp$ with target polarization parallel(perpendicular) to the electron polarization. The measured asymmetries can be written as:

$$A^m_{\parallel,\perp} = \frac{N^-L^+ - N^+L^-}{N^-L^+ + N^+L^-} = f P_B P_T A^{phys}_{\parallel,\perp} , \tag{11}$$

$\mathrm{N}^\pm$ is the total number of events and $\mathrm{L}^\pm$ is the total integrated luminosity (dead-time-corrected). Since we had a sealed target cell, the luminosity correction reduces to a beam charge correction. f is a target dilution factor, P_B and P_T refer to the beam and target polarizations, respectively. The unpolarized structure function

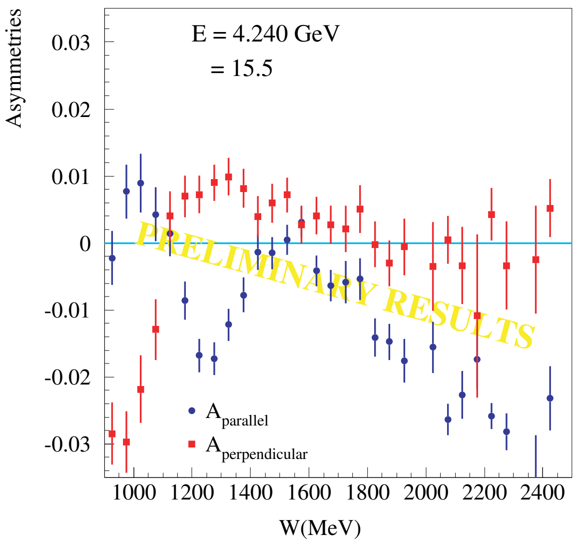

Fig. 5. Preliminary count rate asymmetries, $A_{\parallel}$ and $A_{\perp}$, as a function of the invariant mass for one out of five different energies. *Note:* several corrections, e.g. radiative, acceptance, and dilution, have not been applied.

$W_1(\nu, Q^2)$ will be extracted from our own cross-section measurements, i.e. our data allow us to determine $W_2(\nu, Q^2)$, and $R = \sigma_L/\sigma_T$ which will be taken from previously measured data.
In order to extract the GDH sum for the neutron nuclear corrections due to S′- and D-wave contributions in the ^{3}He function have to be applied. These corrections are well known in the DIS regime. Here the asymmetry can be expressed as a linear combination of the proton and neutron contributions:

$$A_{^3He} = (2 f_p P_p A_p + f_n P_n A_n) P_B P_T \ , \tag{12}$$

$f_p \approx 0.28$ and $f_n \approx 0.23$ are target dilution factors for protons and neutrons, respectively. $P_p = -0.028 \pm 0.004$ and $P_n = 0.86 \pm 0.02$ are the proton and neutron polarizations inside the ^{3}He nucleus [14, 15]. The situation changes in the quasi-elastic and resonance region. Nuclear binding effects and Fermi motion can play an important role. Recently, Ciofi degli Atti and Scopetta [16] studied the extraction of the neutron asymmetries and the generalized GDH sum from a polarized ^{3}He target. Although in the resonance region at low Q^2, the extracted neutron spin structure function G_1 could differ significantly from G_1 of the free neutron, the extracted neutron GDH sum is hardly effected. The reason is that the Fermi motion, being the main effect, does not affect the integrated results. Other theory groups [17] will also study this problem in the future. A preliminary result for one kinematic setting is shown in Fig. 5. The figure indicates the precision of our data.

4 Outlook and Summary

Spin structure and the GDH sum rule studies are major efforts at Jefferson Lab. Experiments on the proton[18] and the deuteron[19] have been partially completed. An extension of this ^{3}He experiment to very low Q^2 [11] and higher energy (6 GeV) is planned. It will enable us to extrapolate to the real photon point and also study the convergence of the sum rule.

In summary, the spin structure and the generalized GDH sum rule of the nucleon and few-body nuclei are one important area of research at Jefferson Lab. JLab E94-010 is the first completed experiment measuring the spin structure and the generalized GDH sum rule for ^{3}He and the neutron at low Q^2. Preliminary results were shown. Other future polarized ^{3}He experiments will focus on precision studies of $g_2(x, Q^2)$ at low Q^2 to search for higher twist effects [20] and $A_1^n(x, Q^2)$ at large x [21].

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