GENERALIZED GDH SUM RULE AND SPIN-DEPENDENT ELECTROPRODUCTION IN RESONANCE REGION

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We have measured the spin-parallel and spin-perpendicular asymmetries and cross sections for inclusive $^3\vec{H}e(\vec{e},e')$ reaction from the quasielastic to beyond the resonance region. The Q^2 range covered is from 0.1 to 1 GeV^2. From these data, the ^{3}He and the neutron spin structure and the Q^2 evolution of the generalized Gerasimov-Drell-Hearn (GDH) sum are extracted. Preliminary results are presented. Plans for future studies on this subject is discussed. Also discussed is a new approved experiment in the resonance region at higher Q^2 range to study spin duality.

1 Introduction

The nucleon spin structure has been of central interest ever since the EMC experiment found that at small distances the quarks carry only a fraction of the nucleon spin. Going from shorter to larger distances the quarks are dressed with gluons and $q\bar{q}$ pairs and acquire more and more of the nucleon spin. How is this process evolving with the distance scale (or 4-momentum transfer Q^2)? At the two extreme kinematic regions we have two fundamental sum rules: the Bjorken sum rule[1] at Q^2 of ∞ and the Gerasimov-Drell-Hearn (GDH) sum rule[2,3] at $Q^2 = 0$. A study of the connection between the two sum rules, in particular the evolution of the GDH sum rule in the low Q^2 region, will help us understand the transition from the incoherent processes of deep inelastic scattering (DIS) off the partons (quark-gluon picture) to the resonance dominated coherent processes (hadronic picture).

2 Generalized GDH Sum Rules

2.1 Bjorken Sum Rule

From 20 years of spin structure experiments in the deep inelastic region, one of the most important outcomes is the experimental test of the Bjorken sum rule to better than 10%. The Bjorken sum rule relates the spin structure over the entire energy range to a static property of the nucleon, the axial coupling

**FOR THE JEFFERSON LAB E94-010 COLLABORATION* constant g_A:

$$\int_0^1 (g_1^p - g_1^n)dx = \frac{1}{6}g_A \tag{1}$$

The Bjorken sum rule is based on very general principles (QCD) and is valid at the Bjorken limit: $Q^2 \to \infty, \quad \nu \to \infty$ while $x = Q^2/2m\nu$ is finite. For finite Q^2, there is a QCD correction factor.

2.2 GDH Sum Rule

Another fundamental sum rule, the Gerasimov-Drell-Hearn (GDH) sum rule, holds at the other extreme of the kinematics, $Q^2 = 0$:

$$\int_{thr}^{\infty} (\frac{\sigma_{3/2} - \sigma_{1/2}}{\nu})d\nu = \frac{2\pi^2\alpha}{M^2}\kappa^2 \tag{2}$$

Here again the sum rule relates the helicity (doubly polarized) cross section difference over the whole energy range to a static property of the nucleon, the anomalous magnetic moment of the nucleon, κ.

The GDH sum rule is derived using the dispersion relation (without subtraction) on the forward Compton scattering amplitude, combined with the Optical and the Low Energy Theorems. The input assumptions are very general. The only assumption, which could be open to "reasonable" questions, is the no-subtraction condition in the dispersion relation. Initial partial wave analysis[7] based on unpolarized and singly polarized data, provided an estimate of the double polarization cross section, and therefore the indirect 'experimental' sum, which indicated a discrepancy from the GDH sum rule. The direct experimental test became possible only recently, with the availability of high luminosity polarized beams and polarized targets and advanced detection technology.

The first direct measurement was performed on the proton at MAMI over an energy range from 200 MeV to 800 MeV[5]. Experiments extending the proton measurement to higher energies are on-going at Bonn or planned at several other facilities. An analysis by the Mainz group[6] shows that the GDH sum rule for the proton is reasonably satisfied. However, a similar analysis shows a significant discrepancy exists for the neutron GDH sum rule. Measurements of the GDH sum for the neutron are also planned[7].

2.3 Generalized GDH Sum Rule

A number of models have been proposed to extend the GDH integral for the proton and neutron to finite Q^2 and connect it to the Bjorken sum rule in the deep inelastic regime [8,9]. Recently, Ji and Osborne[10] made a rigorous generalization of the GDH sum rule to the entire region of Q^2. Under the same assumptions as the GDH sum rule, Ji and Osborne derived the generalized GDH sum rule:

$$4\int_{el}^{\infty} \frac{G_1(\nu, Q^2)}{\nu} d\nu = S_1(Q^2)$$

where $S_1(Q^2)$ is the forward virtual Compton Scattering amplitude. The GDH sum rule and Bjorken sum rule are the two limiting cases ($Q^2 = 0$ and $Q^2 = \infty$) of the generalized GDH sum rule. Other than the two limiting cases, $S_1(Q^2)$ can also be calculated at small Q^2, where hadrons are the relevant degree of freedom, with Chiral Perturbation theory and at large Q^2, where quarks and gluons(partons) are the relevant degree of freedom, with a higher order QCD expansion (twist expansion). At small Q^2, it was calculated to leading order[11,10] and to next-to-leading order[12] using the Chiral Perturbation theory in the Heavy Baryon approximation. Efforts are underway to calculate the generalized GDH sum rule to next-to-leading order without the Heavy Baryon approximation[13]. At large Q^2, twist-2 and twist-4 terms have been calculated. Efforts are underway to calculate to higher orders.

An important question in this connection is how low in Q^2 the Bjorken sum rule can be evolved using the high twist expansion. Recent estimates [10] suggest a Q^2 value as low as 0.5 GeV^2. Also at the other end, chiral perturbation theory is applicable at small Q^2, and may allow the evolution of the GDH sum rule to Q^2 up to about 0.2 GeV^2. Theoretical efforts (such as lattice calculations) are needed to bridge the remaining gap.

This would be the first time that hadronic structure is described by a fundamental theory in the entire kinematical regime, from $Q^2 = 0$ to ∞.

3 JLab E94-010 experiment

Experiment JLab E94-010[14], has recently been completed with a polarized ^{3}He target to study the Q^2 evolution of the GDH integral for ^{3}He and the neutron. The experiment covers a range of $Q^2 from 0.1 to 1 GeV^2$ and from the quasi-elastic to beyond the resonance region. Figure 1 shows the kinematic coverage of the experiment.

3.1 The Experimental Setup

The experiment was carried out in Hall A of Jefferson Lab. A highly polarized (> 70%) electron beam with a current of up to 15 was μA scattered off a

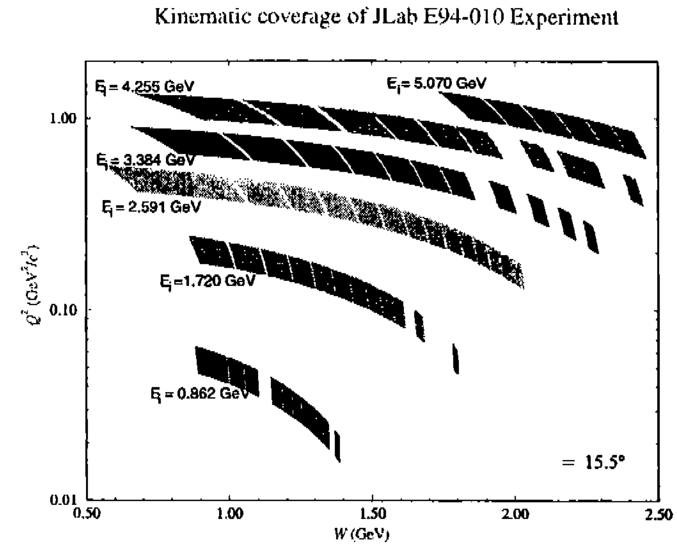

Figure 1. The kinematics of the E94-010 experiment

high density (10 atm gaseous in a 40 cm long glass cell) polarized ^3He target (30-40% polarization in-beam). The polarized ^3He target utilized the spin-exchange principle. Rubidium atoms were polarized by optical pumping, and the polarization was transferred to ^3He nuclei via spin-exchange collisions. The target was polarized either parallel or perpendicular to the beam direction and the polarization was measured with two independent methods: NMR with Adiabatic Fast Passage, and EPR (Electron Paramagnetic Resonance). Both methods have an uncertainty of about 4%, and the two methods agree with each other within the uncertainty. It is additionally checked by measuring the elastic asymmetry, which gives a measurement of the product of the beam and the target polarization.

Two nearly identical spectrometers, set at the same scattering angle of 15.5°, were used to detect the scattered electrons. Both spectrometers were equipped with the standard electron detector packages. The comparison of the data from the two spectrometers provides a check of the data quality and minimizes some systematic uncertainties.

3.2 Preliminary Results

The data analysis has almost been completed. The spectrometer acceptance was carefully studied with a Monte-Carlo simulation compared to elastic data measured on a 7-foil ^{12}C target with sieve slits. Detector efficiencies were throughly studied. The measured ^3He elastic asymmetries were checked against the world elastic data weighted by the beam and target polarizations. The measured ^3He elastic cross section was checked against the world elastic data. Radiative corrections were performed using the formalism of Kuchto, Shumeiko amd Akushevich[15]. The spin structure functions g_1 and g_2 were extracted using the parallel cross section difference and the perpendicular cross section difference. The quantity $\sigma'_{TT} = \frac{1}{2}(\sigma_{1/2} - \sigma_{3/2})$ was extracted from g_1 and g_2:

$$\sigma'_{TT} = \frac{4\pi^2\alpha}{MK}(g_1 - \frac{Q^2}{nu^2}g_2)$$

where $K = \nu - Q^2/2M$ is the virtual photon flux. To compute the generalized GDH sum, σ'_{TT} is needed at constant Q^2 values. We used interpolation to extract σ'_{TT} for 10 constant Q^2 values from 0.1 to 1 GeV^2. The generalized GDH integral was computed using σ'_{TT}, at constant Q^2, integrating from the pion threshold to an invariant mass W at 2 GeV. The results of the ^3He GDH integral are shown in fig. 2 as filled circles. (For the lowest Q^2 of 0.1 GeV^2, the interpolated σ'_{TT} covered only the dominant Δ peak and a little beyond. To reach $W = 2\ GeV$, extrapolation was used).

The neutron GDH integrals were extracted using the PWIA model of Ciofi degli Atti and Scopetta[16]. The extraction of the neutron GDH sum will be discussed in more detail in the next subsection. Also plotted in fig. 2 are the high Q^2 results from HERMES. For comparison, the predictions of Drechsel, Kamalov and Tiator[6] are plotted. Finally, the real photon GDH sum rule prediction for the neutron is also shown.

These data from the first precision measurement of the generalized GDH integral at low Q^2 ($0.1\ GeV^2 < Q^2 < 1\ GeV^2$) show a dramatic change in the value of the integral from what is observed at high Q^2 ($> 1\ GeV^2$). While not unexpected from theoretical models, our data illustrate the large sensitivity of the GDH integral to the transition from incoherent partonic behavior to the coherent hadronic behavior. Understanding the transition region will provide a bridge to connect the quark-gluon picture to the hadronic picture.

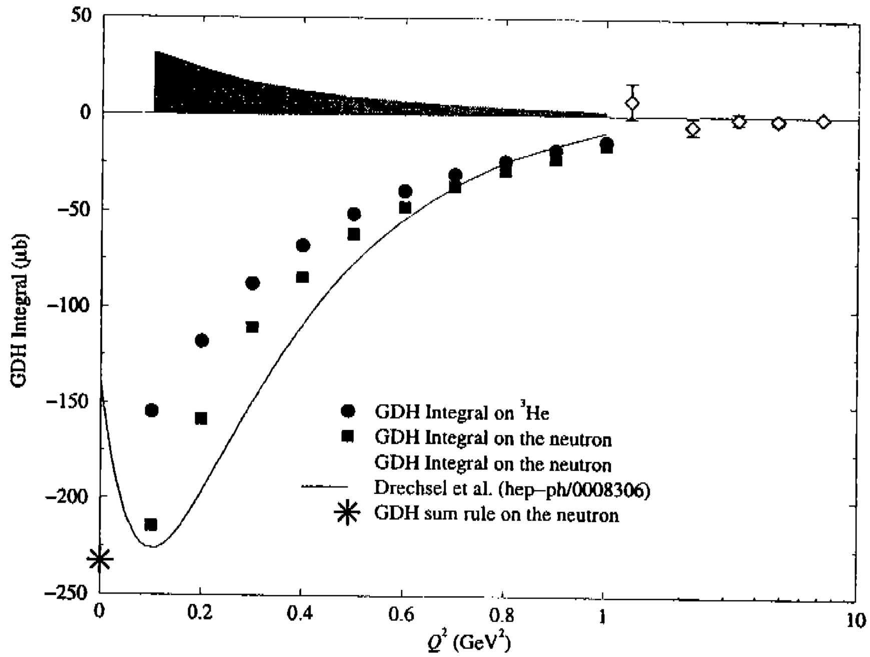

Figure 2. Preliminary results of the GDH integral on ^{3}He and the neutron. The integration was performed from the pion threshold to $W = 2\ GeV$. HERMES results at high Q^2 and the Mainz model predictions are shown for comparison. The real photon GDH sum rule value is also plotted.

3.3 Extraction of the Neutron Results

Due to the small components of S and D waves in the ^{3}He ground state, the polarized ^{3}He target is only approximately a polarized neutron target. J. Friar et al. [17] calculated the effective polarization of the neutron and proton in a polarized ^{3}He target. The results are that the effective neutron polarization is about 87% and the effective proton polarization is about -3%.

Recently, Ciofi degli Atti and Scopetta[16] studied the extraction of the neutron spin structure functions and the generalized GDH sum from a polarized ^{3}He target. Although at 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 does not differ as much from the free neutron GDH sum. The reason is that the Fermi motion, being the main effect, does not affect the integrated results. Other theory groups[18] will also study this problem in the future.

4 GDH with nearly real photons: JLab E97-110

The preliminary results connect well with the high Q^2 data from HERMES. However, at the low Q^2 end, the experiment reached its limit at $Q^2 = 0.1\ GeV^2$, where the uncertainty is relatively large. The region below $Q^2 = 0.2\ GeV^2$ is of special interest, since it is the region where Chiral Perturbation theory calculation is expected to be valid. Moreover, by measuring the slope near $Q^2 = 0$, one could extrapolate to the real photon $Q^2 = 0$ to test the fundamental real photon GDH sum rule.

JLab experiment E97-110[19], which is planned to take data next year, will measure the generalized GDH with polarized ^{3}He in the very low Q^2 region ($0.01\ GeV^2 < Q^2 < 0.5\ GeV^2$) and with higher electron energy (up to 6 GeV). It uses new septum magnets to reach small scattering angle for the Hall A spectrometers to enable us to reach the very low Q^2 region. The experiment will enable us to extrapolate to the real photon point and also study the convergence of the sum rule.

5 Outlook and Summary

The spin structure and the GDH sum rule study are one of the major efforts at Jefferson Lab. Another experiment measuring the resonance spin structure at higher Q^2 ($1\ GeV^2 < Q^2 < 5\ GeV^2$) was recently approved to study quark-hadron duality in the spin structure function[20]. JLab is planning to upgrade the accelerator to 12 GeV, which would allow a test of the high energy (Regge) behavior of the GDH sum rule.

JLab E94-010 is the first completed experiment measuring the spin structure and the generalized GDH sum rule for ^{3}He and the neutron in the low Q^2 region. Preliminary results were shown. A future extension to nearly real photon kinematics and higher energies is planned. A new experiment in the resonance region at higher Q^2 values was recently approved. Future GDH studies will include a high energy test with JLab 12 GeV energy upgrade. Fruitful results from the GDH sum rule and spin structure study are expected in the next few years.

Acknowledgments

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