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Effective Neutron Targets

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Because of the lack of a free neutron target, deuterium targets have been used extensively in studying the neutron structure. The unique spin structure of the ^3He ground state wave function and the recent developments in laser technologies made polarized ^3He targets widely used in many experiments from neutron electromagnetic form factor studies to nucleon spin structure function measurements at all major electron accelerator facilities. In this talk, the current status of the polarized ^3He targets will be reviewed. I will focus on neutron electromagnetic form factor studies using polarized ^3He targets. The polarized nucleon spin structure function measurements using polarized ^3He targets will also be discussed.

1. Introduction

Electromagnetic form factors and spin structure functions are of fundamental importance for an understanding of the underlying structure of nucleons. Knowledge of the distribution of charge, magnetization and spin within the nucleons provides a sensitive test of models based on Quantum Chromodynamics (QCD), as well as a basis for calculations of processes involving the electromagnetic interaction with complex nuclei. The understanding of the nucleon structure in terms of quark and gluon degrees of freedom in QCD will provide basis to understand strong interacting matter at the level of quarks and gluons.

Electron scattering has been proven to be a very useful tool in probing the structure of nucleon and nuclei. The leptonic part of the vertex is well understood from Quantum Electrodynamics (QED), thus it is a clean probe for hadronic structure. Furthermore, the electromagnetic coupling constant is relatively weak, higher order diagrams are suppressed compared to the lowest order one-photon-exchange diagram. Proton electromagnetic form factors have been well studied over the years using the technique of Rosenbluth separation from elastic electron-proton scattering.

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Lacking of a free neutron target, the neutron electromagnetic form factors are known with less precision than the proton electric and magnetic form factors. They have been deduced in the past from elastic or quasielastic electron-deuteron scattering. This procedure involves considerable model dependence. The other complication arises from the fact that the net charge of the neutron is zero. Thus, the neutron electric form factor G_E^n is much smaller than its magnetic form factor G_M^n at low Q^2 . Furthermore, the magnetic part of the contribution dominates the cross section, making it very difficult to extract G_E^n from unpolarized cross section measurement using deuterium targets.

The development of polarized targets and beams has allowed more complete studies of electromagnetic structure than has been possible with unpolarized reactions. In quasielastic scattering, the spin degrees of freedom introduce new response functions into the inclusive cross section, thus providing additional information on nuclear structure [1]. ^3He is an interesting nucleus for polarization studies because its ground state wave function is predominantly a spatially symmetric S state in which the spin of the nucleus is carried mainly by an unpaired neutron. Therefore, inelastic scattering of polarized electrons from polarized ^3He in the vicinity of the quasielastic peak should be useful for studying the neutron electromagnetic form factors, as well as the neutron spin structure function from deep inelastic scattering of polarized leptons from polarized ^3He targets.

The idea of using polarized ^3He nuclear target as an effective neutron target was first investigated by Blankleider and Woloshyn in closure approximation [2]. Friar *et al.* [3] have studied the model dependence in the spin structure of the ^3He wave function and its effect on the quasielastic asymmetry. The plane wave impulse approximation (PWIA) calculations performed independently by two groups [4] [5] using spin-dependent spectral functions show that the spin-dependent asymmetries are very sensitive to the neutron electric or magnetic form factors at certain kinematics near the top of the quasielastic peak. Recently, Ishikawa *et al.* [6] performed a new calculation of the ^3He inclusive spin-dependent quasielastic asymmetries in which final state interactions (FSI) were included. Calculations which include FSI and meson-exchange currents (MEC) are currently underway [7].

The first experiments [8] [9] which investigated the feasibility of using polarized ^3He targets to study the neutron electromagnetic structure were performed at MIT-Bates Linear Accelerator Center. Following these two experiments, the first measurement of G_E^n from $^3\vec{H}e(\vec{e}, e'n)$ was reported by Meyerhoff *et al.* [10], and the neutron magnetic form factor at low Q^2 was extracted for the first time [11] from inclusive measurement of the quasielastic transverse asymmetry, A_T . At SLAC and HERA, the neutron spin structure functions were extracted from deep inelastic scattering experiments using polarized ^3He targets [12] [13] [14].

2. Polarized ^3He Targets

Optical pumping technique is widely used to polarize a sample of atoms by transferring angular momentum from a pump light beam, typically a laser beam, to the sample atoms. In the case of ^3He , direct optical pumping between its ground state and the first excited state is not possible because of the energy difference involved. Metastability-exchange optical pumping and spin-exchange optical pumping are two indirect optical pumping techniques commonly used. In this section, I will review both these two techniques.

2.1. Metastability-Exchange Optical Pumping

The metastability-exchange optical pumping technique was developed in the early 1960s at Rice university [15] to polarize ground state ^3He or ^4He atoms through metastability-exchange collisions with optically pumped ^3He or ^4He metastable atoms. This method involves optical pumping of 2^3S_1 metastable state atoms, then transferring the polarization to ^3He ground state atoms through metastability-exchange collisions, in which the excitation of the electronic cloud is exchanged leaving the ground state polarized after the collision.

Metastability-exchange optical pumping of ^3He works as following: metastable 2^3S_1 atoms are produced by an electrodeless weak radio frequency (RF) discharge in a glass cell filled to a pressure of order 1 torr of pure ^3He . The ratio of the ground state atoms to the 2^3S_1 atoms is about $10^6 : 1$; the exact number depends on discharge characteristics such as intensity, uniformity and the discharge frequency. The sample is placed in a weak uniform magnetic field which defines the spin direction of the sample. Right-handed or left-handed circularly polarized light (defined by the right-hand rule used in atomic physics) at $\lambda = 1083.4 \text{ nm}$ corresponding to the transition of $2^3S_1 \rightarrow 2^3P_0$ excites transitions between the 2^3S_1 and 2^3P_0 states with the selection rule $\Delta m = \pm 1$ depending on the helicity of the incident light (+ for the right-handed circularly polarized light and - for the left-handed case). The pumping light excites atoms from the $m_F = -\frac{1}{2}$ and $m_F = -\frac{3}{2}$ sublevels of the metastable state to the 2^3P_0 level which then decay back to all sublevels of 2^3S_1 through spontaneous emission. The result is that atoms from lower magnetic sublevels of the 2^3S_1 level ($m_F = -\frac{1}{2}$, $m_F = -\frac{3}{2}$) are transferred to higher sublevels of the 2^3S_1 level ($m_F = \frac{1}{2}$, $m_F = \frac{3}{2}$), hence the metastable atoms become polarized. In metastable state, hyperfine interaction mixes electronic polarization into nuclear polarization. The polarization of the metastable atoms is then transferred to the ground state through metastability-exchange collisions in which only the excitation of the electronic cloud is exchanged. If the ground state of ^3He is polarized, then the nucleus is polarized because the atom is in a $J = 0$ state. This process can be expressed schematically as:

where * denotes the 2^3S_1 metastable state and the vector notation indicates that the nucleus is polarized.

This optical pumping technique only works for relatively low pressure conditions (0.1 torr to 10 torr). Destruction of metastables at the wall of the container dominates the relaxation at pressures below about 0.1 torr and at high pressures the lifetime of the metastable state atoms limits the optical pumping efficiency. It is also experimentally difficult to maintain a uniform discharge under high pressure conditions. Furthermore, it is necessary to operate optical pumping around room temperature to achieve efficient optical pumping because metastability exchange cross-section, σ_e , which is very temperature dependent for the case of ^3He atoms [16] [17]. σ_e decreases roughly two orders of magnitude between 300 K and 4.2 K. To make a relatively dense target for nuclear physics experiments, the compression and low temperature techniques have been used.

People have tried successfully to make a dense nuclear physics target by mechanically compressing the polarized gas. At Toronto, Timsit *et al.* in the early 1970s [18] constructed a dense target and achieved a density of $0.7 \times 10^{19} \text{cm}^{-3}$ with 3% polarization by compressing the gas with liquid mercury. However, the performance of these targets was severely limited by the absence of laser sources for optical pumping. Recently, at Mainz

Otten *et al.* have designed and built a new type of dense polarized ^3He target using the compression method [19] [20] and have achieved pressures around 1 bar with 38% of polarization. Currently, this target is operated in the pressure range of 1.0 to 10.0 bar with a target polarization of $\sim 50\%$ [21].

Low temperature is another approach to take to construct a dense polarized ^3He target. A double-cell system consisting of a pumping cell and a target cell is a practical design for a polarized ^3He nuclear target. The pumping cell is at room temperature where metastability-exchange optical pumping can be performed efficiently and the target cell is cooled to low temperature where a practical luminosity can be achieved for a nuclear physics experiment. This idea was first explored at Rice University [22]. The ^3He nuclei in the target cell become polarized because the polarized ^3He atoms diffuse between the pumping cell and the target cell, reaching an equilibrium polarization state. External polarized ^3He targets based on this technique were employed in the MIT-Bates experiments [8] [11]. Optical measurement of the atomic polarization in the pumping cell provides a good monitor of the target nuclear polarization during the experiment. The atomic polarization and the nuclear polarization are related because of the hyperfine coupling and this indirect optical measurement of the ^3He nuclear polarization was calibrated carefully with the NMR technique at Caltech [23]. The metastability-exchange optical pumping technique has the unique features of pure atomic species and fast pumping rate for constructing an internal polarized ^3He target. The internal polarized ^3He targets based on this technique have been used successfully at IUCF, DESY and NIKHEF.

2.2. Spin-Exchange Optical Pumping

In spin-exchange optical pumping, circularly polarized resonance light is absorbed by a saturated vapor of alkali-atoms contained in a glass cell. The cell also included a

much larger quantity of noble-gas atoms. The spin angular momentum is transferred to the alkali-metal atoms, thereby spin-polarizing the valence electrons of the alkali-metal atoms. Subsequent spin-exchange collisions between the alkali-metal atoms and noble gas atoms transfer some of the electron-spin polarization to the nuclei of the noble gas.

Rubidium has been commonly used in polarized ^3He targets based on spin-exchange optical pumping technique. The high vapor pressure of rubidium allows operation at modest temperatures where chemical attack on the glass container is not a problem. The resonance line (794.7 nm corresponding to the transition between $5S_{1/2}$ and $5P_{1/2}$ levels) lies in a spectrum region where intense laser light is available from sources such as dye lasers, Ti:sapphire lasers, and more recently diode laser arrays.

A central feature of the target will be sealed glass target cells, which will contain a ^3He pressure of about 10 atmospheres. The cells will have two chambers, an upper chamber in which the spin exchange takes place, and a lower chamber, through which the electron beam will pass. In order to maintain the appropriate number density of alkali-metal (Rb) the upper chamber will be kept at a temperature of 170–200°C using an oven constructed of the high temperature plastic Torlon. A small amount of nitrogen gas is typically used in this type of target to quench the $P_{1/2}$ states, thus reducing the radiation trapping effect in order to reach high optical pumping efficiency. Radiation trapping occurs when the mean free path for the unpolarized photons is much shorter than the dimensions of the pumping vessel. The incident photons can be reemitted, i.e. resonantly scattered, and depolarized. Thus, additional dilution factor comes from the nitrogen present in the target. The dilution factor from the amount of rubidium in the target is typically negligible ($n_{\text{Rb}}/n_{\text{He}} \sim 10^{-4}$). Although the spin-exchange optical pumping technique is capable of producing a dense target (10 amagat), slow pumping time resulting from small spin-exchange cross section of ^3He atom and the Rb atom makes this technique only suitable for external polarized ^3He targets. NMR technique is typically used to measure the target polarization for this type of the targets. External polarized ^3He targets based on this technique have been used in experiments at MIT-Bates, SLAC and TRIUMF.

3. Quasielastic Scattering of Polarized Electrons from Polarized ^3He Targets

3.1. $^3\vec{H}e(\vec{e}, e')$

The inclusive spin-dependent asymmetry for longitudinally polarized electrons scattered from a polarized spin- $\frac{1}{2}$ nuclear target can be written [1] as

$$A = -\frac{\cos \theta^* v_T R_{T'} + 2 \sin \theta^* \cos \phi^* v_{TL'} R_{TL'}}{v_L R_L + v_T R_T}, \quad (2)$$

where the v_K are kinematic factors, and θ^* and ϕ^* are the polar and azimuthal angles of the target spin with respect to the 3-momentum transfer vector $\mathbf{q}$. $R_L(Q^2, \omega)$ and $R_T(Q^2, \omega)$ are the longitudinal and transverse nuclear response functions associated with

the unpolarized cross section and are functions of the square of the 4-momentum transfer, Q^2 , and the electron energy loss ω . $R_{T'}$ and $R_{TL'}$ are the two response functions arising from the polarization degrees of freedom. $R_{T'}$ is a transverse response function and $R_{TL'}$ represents the interference between the transverse and the longitudinal multipoles. By orienting the target spin at $\theta^* = 0^\circ$ or $\theta^* = 90^\circ$, corresponding to the spin direction either along the 3-momentum transfer vector $\mathbf{q}$ or normal to it, one can select the transverse asymmetry $A_{T'}$ (proportional to $R_{T'}$) or the transverse-longitudinal asymmetry $A_{TL'}$ (proportional to $R_{TL'}$).

Figure 1. Transverse asymmetry $A_{T'}$ from MIT-Bates experiment [11] as a function of electron energy loss ω . The data are shown with statistical uncertainties only. The solid line is the calculation by Ishikawa *et al.* [6] The dashed line is the calculation by Salme *et al.* [24] and the dash-dotted line is the calculation by Schulze *et al.* [25]

For inclusive quasielastic ${}^3\vec{H}e(\vec{e}, e')$ process, the transverse asymmetry $A_{T'}$ can be written within PWIA as:

$$A_{T'} \sim \frac{\sigma_n G_M^{n^2}}{\sigma_n + 2\sigma_p} \quad (3)$$

PWIA calculations [2-5] of $A_{T'}$ from quasielastic ${}^3\vec{H}e(\vec{e}, e')$ process neglecting FSI and MEC, as well as the recent calculation by Ishikawa *et al.* [6] including FSI, indicate that the transverse asymmetry $A_{T'}$ is very sensitive to the square of the neutron magnetic

form factor, $G_M^{n,2}$. Thus, one can extract information on G_M^n by measuring the quasielastic transverse asymmetry $A_{T'}$ from ${}^3\bar{H}e(\vec{e}, e')$ process.

Fig. 1 shows the measured ${}^3\text{He}$ inclusive spin-dependent quasielastic transverse asymmetry $A_{T'}$ [11], as a function of the electron energy transfer, ω , together with the two PWIA calculations and the calculation by Ishikawa *et al.* [6]. The deviation of the result by Ishikawa *et al.* [6] from those of PWIA calculations [24] [25] is significant away from the quasielastic peak. The agreement between the data on $A_{T'}(\omega)$ and the calculation by Ishikawa *et al.* is excellent in terms of the magnitude of the asymmetry and also the shape. Unfortunately, because of the large errors associated with the measured $A_{T'}(\omega)$ as shown in Fig. 1, it is not possible to put constraints on the theoretical calculations of the ${}^3\text{He}$ inclusive spin-dependent quasielastic asymmetry.

Because of the limitation of the statistics of the MIT-Bates measurement [11], the measured quasielastic asymmetry, $A_{T'}(\omega)$, averaged over the experimental ω acceptance was used in extracting $G_M^{n,2}$ together with the calculation of Ishikawa *et al.* [6]. Fig. 2 shows G_M^n extracted from the Bates experiment, together with the world data in the low Q^2 region. The standard dipole form factor parametrization [36] gives

$$\frac{G_M^n}{\mu_n} = \frac{G_M^p}{\mu_p} = G_E^p = G_D = \left[1 + \frac{Q^2}{0.71} \right]^{-2}, \quad (4)$$

where Q^2 is in $(\text{GeV}/c)^2$. The total uncertainty of the MIT-Bates measurement is shown, which is dominated by the statistical uncertainty.

On the other hand, $A_{TL'}$ from quasielastic ${}^3\bar{H}e(\vec{e}, e')$ at low Q^2 is ($Q^2 \leq 0.3(\text{GeV}/c)^2$) is dominated by the proton contribution largely because of the smallness of $G_E^{n,2}$ and the small non- S state part of the ${}^3\text{He}$ ground state wave function. Thus, it is questionable to extract information on G_E^n at low Q^2 from ${}^3\bar{H}e(\vec{e}, e')$. It is possible to go to higher Q^2 ($Q^2 \geq 0.3(\text{GeV}/c)^2$) to extract $G_E^{n,2}$ with respectable accuracy from quasielastic ${}^3\bar{H}e(\vec{e}, e')$ measurement where the proton contribution to $A_{TL'}$ is under better control. Fig. 3 shows $A_{TL'}$ from the MIT-Bates experiment [11] as a function of ω together with the PWIA calculations [24-25] and the calculation by Golak *et al.* [7] which included FSI. The PWIA calculations are consistently higher than the measured asymmetry. The calculation from Golak *et al.* is in better agreement with the data.

To extract precise information on G_M^n from inclusive quasielastic $A_{T'}$ measurement, it is important to measure $A_{T'}$ with high precision across the ${}^3\text{He}$ quasielastic peak. As away from the quasielastic peak, predictions from different models deviate. Thus, one can constrain theoretical model using high precision data on $A_{T'}$ at the wing of the QE peak. To extract precise information on G_M^n , one then use the measured $A_{T'}$ right on top of the quasielastic peak, this is a procedure much less sensitive to model dependence than the procedure used previously in analyzing the MIT-Bates measurement [11]. Experiments are planned at TJNAF and MIT-Bates.

Figure 2. The square of the neutron magnetic form factor $G_M^n^2$, in units of the standard dipole parametrization, $(\mu_n G_D)^2$, in the low Q^2 region. The open squares are from Hughes *et al.* [26], the open diamonds are from the analysis by Kramer *et al.* [27] of the data from Grossetête *et al.* [28], the asterisks are from Braess *et al.* [27], the crosses are from Hanson *et al.* [29], the open circles are from Budnitz *et al.* [30], the open star is from Bartel *et al.* [31], the open triangle is from Stein *et al.* [32], and the solid diamonds are from Markowitz *et al.* [33] with the inner (outer) error bars being the statistical (total) uncertainties. The solid triangle shows the result from Anklin *et al.* [34] with the total error being the quadratic sum of the statistical and systematic errors, the solid stars are from Bruins *et al.* [35] with error bars being the quadratic sum of the statistical and systematic uncertainties. The solid circle is from Gao *et al.* [11] shown with the total uncertainty dominated by the statistical error. The data of Markowitz *et al.*, Hughes *et al.*, and Stein *et al.* have been displaced slightly to improve readability.

Figure 3. Longitudinal-transverse asymmetry A_{LT} from MIT-Bates experiment [11] as a function of electron energy loss ω . The data are shown with statistical uncertainties only. The solid line is the calculation by Golak *et al.* [7]. The dashed line is the calculation by Salme *et al.* [24] and the dash-dotted line is the calculation by Schulze *et al.* [25]

Figure 4. The square of the neutron magnetic form factor G_M^n , in units of the standard dipole parametrization, $(\mu_n G_D)^2$, in the low Q^2 region. The anticipated $(G_M^n)^2$ values from this proposal are shown as solid squares with the total errors being the quadrature sum of the statistical, systematic, and model-dependent uncertainties.

The TJNAF experiment [37] will employ a longitudinally polarized electron beam, a spin-exchange polarized ^3He target, and the Hall A High Resolution Spectrometers (HRS). The Hall A electron-arm HRS spectrometer will be used to detect the quasielastically scattered electrons. The Hall A hadron-arm HRS spectrometer will be dedicated to measuring the ^3He elastic asymmetry to serve as a beam and target polarization monitor. Incident electron beam energies of 0.8 and 1.6 GeV are chosen to cover a Q^2 region from 0.1 to 0.5 $(\text{GeV}/c)^2$ in steps of 0.1 $(\text{GeV}/c)^2$. The target spin direction will be aligned along the three-momentum transfer vector $\mathbf{q}$, and the ^3He inclusive spin-dependent quasielastic transverse asymmetry, $A_T(\omega)$, will be formed by varying the helicity of the polarized electron beam. Fig. 4 shows the proposed measurement of G_M^n as solid squares with overall uncertainties of 2%, together with the recently published measurements of G_M^n . There are new data in this Q^2 region from Mainz by measuring the ratio of $D(e, e'n)/D(e, e'p)$, the analysis is not finalized yet.

3.2. $^3\vec{H}e(\vec{e}, e'n)$

The measured asymmetry for the quasielastic reaction $^3\vec{H}e(\vec{e}, e'n)$ can be expressed as follows in PWIA:

$$A = -P_e P_n D \frac{2\sqrt{\tau(\tau+1)}\tan(\vartheta_e/2)G_E^n G_M^n \sin(\theta^*)\cos(\phi^*)}{G_E^{n2} + G_M^{n2}(\tau + 2\tau(1+\tau)\tan^2(\vartheta_e/2))} - P_e P_n D \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\vartheta_e/2)}\tan(\vartheta_e/2)G_M^{n2}\cos(\theta^*)}{G_E^{n2} + G_M^{n2}(\tau + 2\tau(1+\tau)\tan^2(\vartheta_e/2))} \quad (5)$$

Here P_e is the electron polarization, P_n is the neutron polarization, D is an overall dilution factor which contains dilution from (possible) unpolarized neutrons in the target and dilution from background neutrons generated in (p, n) reactions, e.g. in shielding walls. $\tau = (Q^2/4 m_n^2)$, ϑ_e is the electron scattering angle, G_E^n and G_M^n are the neutron electric and magnetic form factors, respectively, θ^* is the polar angle of the ^3He spin vector relative to the $\mathbf{q}$ vector, and ϕ^* is the azimuthal angle of the target spin vector relative to the scattering plane. Eqn. 5 shows the obvious sensitivity to G_E^n in the longitudinal-transversal interference term. Therefore, by aligning the target spin perpendicular to $\mathbf{q}$, i.e. choosing θ^* equals 90° , and ϕ^* equals 0° the above equation can be rewritten in the following form:

$$G_E^n = -\frac{A_{\text{perp}}}{P_e P_n D} \cdot \frac{G_M^n(\tau + 2\tau(1+\tau)\tan^2(\vartheta_e/2))}{2\sqrt{\tau(1+\tau)}\tan(\vartheta_e/2)} \quad (6)$$

Aligning the target spin parallel to $\vec{q}$ reduces Eqn. 5 to ($G_E^{n2} \approx 0$):

$$A_{\text{long}} = -P_e P_n D \frac{2\sqrt{1+\tau+(1+\tau)^2\tan^2(\vartheta_e/2)}\tan(\vartheta_e/2)}{1+2(1+\tau)\tan^2(\vartheta_e/2)} \quad (7)$$

This equation is completely independent of the neutron form factors and serves as an excellent calibration reaction. Thus, one can combine the above two equations and obtain

$$G_E^n = \sqrt{\tau + \tau(1 + \tau)\tan^2(\theta_e/2)} \frac{A_{perp}}{A_{long}} G_M^n. \quad (8)$$

Figure 5. Neutron electric form factor G_E^n as a function of Q^2 in inverse fermi square. The solid triangle is the published Mainz ${}^3\text{He}$ measurement with inner and outer error bars being the statistical and overall uncertainties, respectively. The open triangle and the open diamond are the preliminary Mainz data from ${}^3\vec{H}e(\vec{e}, e'n)$ and $D(\vec{e}, e'\vec{n})$ respectively, with the inner and outer errors being the statistical and overall uncertainties.

In extracting the neutron electric form factor, ${}^3\vec{H}e(\vec{e}, e'n)$ is advantageous compared to the inclusive measurement by minimizing the proton contribution to the asymmetry. However, it is not possible to extract information on G_M^n using ${}^3\vec{H}e(\vec{e}, e'n)$ as indicated by Eqn. 7. ${}^3\vec{H}e(\vec{e}, e'n)$ is more sensitive to FSI than the inclusive measurements. Laget [39] concluded that the FSI and the MEC effects can be neglected in collinear kinematics at $Q^2 > 0.3(\text{GeV}/c)^2$ for ${}^3\vec{H}e(\vec{e}, e'n)$ reaction. There is also technical difficulty involved with detecting knockout neutrons. The first measurement on G_E^n from ${}^3\vec{H}e(\vec{e}, e'n)$ was reported by Meyerhoff *et al.* [10] in which a high pressure polarized ${}^3\text{He}$ target achieved by the metastability-exchange optical pumping technique and the compression method was employed. Fig. 5 shows the world data on G_E^n , together with the preliminary Mainz data from ${}^3\vec{H}e(\vec{e}, e'n)$ and $D(\vec{e}, e'\vec{n})$ [38]. The experiment is planned at TJNAF [40] to measure G_E^n with high precision at large Q^2 using ${}^3\vec{H}e(\vec{e}, e'n)$ reaction and a high pressure

polarized ^3He target based on the spin-exchange optical pumping technique. The proposed measurement together with the measurement by Lung *et al.* [41] is shown in Fig. 6. Fig. 7 shows the projected G_E^n as a function of Q^2 by combining the ^3He inclusive and exclusive ($\vec{e}, e'n$) measurements with BLAST [42] and a polarized ^3He internal gas target based on the metastability-exchange optical pumping technique.

Figure 6. G_E^n as a function of Q^2 . The solid curve corresponds to the Galster parametrization. Shown are the projected error bars of the proposed experiment by Korsch and McKeown [40] as well as the data point from Lung *et al.* [41].

Figure 7. The solid boxes are the projected G_E^n as function of Q^2 by combining the inclusive and exclusive ($\vec{e}, e'n$) measurements. The statistical error for 1000 hours of running is shown. The X and solid diamond are the Mainz data on the polarized ^3He target and ^2H target with neutron recoil polarimeter measurement, respectively [43]. The + are the projected data from Bates experiment E89-05. [44]

4. Deep-in-Elastic Scattering of Polarized Electrons from Polarized ^3He Targets

Deep inelastic scattering (DIS) of polarized leptons by polarized nucleons has been the cornerstone in probing the spin structure of the proton and neutron. For inclusive DIS, the differential cross section can be written by the following general form

$$\frac{d^3\sigma}{dx dy d\phi} = \frac{\alpha^2}{Q^4} y L^{\mu\nu} W_{\mu\nu}, \quad (9)$$

where $x = Q^2/(2p \cdot q)$ and $y = p \cdot q/(p \cdot k)$. p and k are the four-momenta of the initial state nucleon and the incident lepton, respectively. q is the four-momentum transfer vector. The unpolarized part can be written as

$$\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[xy^2 F_1(x, Q^2) + F_2(x, Q^2) \left(1 - y - \frac{y^2\gamma^2}{4} \right) \right], \quad (10)$$

where $\gamma^2 = Q^2/\nu^2$, F_1 and F_2 are the unpolarized structure functions. The spin-dependent part of the polarized deep inelastic cross section is then given by the following formula:

$$\begin{aligned} \frac{d^3\sigma(\alpha) - d^3\sigma(\alpha + \pi)}{dx dQ^2 d\phi} &= \frac{4\alpha^2 y}{Q^4} \cos \alpha \left(\kappa^2 g_1(x, Q^2) - \frac{y}{2} \gamma^2 g_2(x, Q^2) \right) \\ &\quad - \frac{4\alpha^2 y}{Q^4} \sin \alpha \cos \phi \gamma \kappa \left(\frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right), \end{aligned} \quad (11)$$

with $\kappa^2 = 1 - y/2 - y^2\gamma^2/4$. The difference $\sigma(\alpha) - \sigma(\pi + \alpha)$ describes the cross section difference which is achieved by reversing the target polarization. $g_1(x, Q^2)$ and $g_2(x, Q^2)$ are the spin-dependent structure functions. In the simple quark parton model (QPM), all structure functions are independent of Q^2 . $g_1(x)$ is determined by the spin distribution of the quarks and $g_2(x)$ is zero in this simple model (QPM) which neglects masses and intrinsic momenta of the quarks inside the nucleon.

Experimentally, the spin structure functions $g_1(x)$ and $g_2(x)$ can be determined by combined asymmetry measurements off a longitudinally ($\alpha = 0^\circ, 180^\circ$) and a transversely ($\alpha = 90^\circ, 270^\circ$) polarized target. Because of the mixing of g_1 and g_2 a precise determination of g_1 from a longitudinally polarized target alone is not possible. Experimentally, the following two asymmetries $A_{\parallel}$ (longitudinal asymmetry) and $A_{\perp}$ (transverse asymmetry)

$$A_{\parallel} = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} \quad (12)$$

$$A_{\perp} = \frac{d\sigma^{\uparrow\leftarrow} - d\sigma^{\uparrow\Rightarrow}}{d\sigma^{\uparrow\leftarrow} + d\sigma^{\uparrow\Rightarrow}} \quad (13)$$

are obtained by spin flip of a longitudinally and transversely polarized target. The virtual photon asymmetries A_1 and A_2 are independent of the kinematics of the lepton and are directly related to the photon absorption cross section of the nucleon for a given x and Q^2 . A_1 and A_2 are related to the structure functions and $A_{\parallel}$ and $A_{\perp}$ as following:

$$\begin{aligned} A_1 &= \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - (Q^2/\nu^2)g_2}{F_1} = \\ &= \frac{A_{\parallel}}{D(1 + \zeta\eta)} - \frac{\eta A_{\perp}}{d(1 + \zeta\eta)} \end{aligned} \quad (14)$$

$$\begin{aligned}
A_2 &= \frac{2\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{(g_1 + g_2)\sqrt{Q^2}/\nu}{F_1} = \\
&= \frac{\zeta A_{\parallel}}{D(1 + \zeta\eta)} - \frac{A_{\perp}}{d(1 + \zeta\eta)},
\end{aligned} \tag{15}$$

where $\sigma_{1/2}$ and $\sigma_{3/2}$ are the virtual photo-absorption cross section when the projection of the total angular momentum of the photon-nucleon system along the incident photon direction is 1/2 or 3/2 respectively. g_2 is predicted to be small, thus $g_1 \approx A_1 F_1 \approx A_{\parallel} F_1 / D$.

The first experiment to measure the neutron spin structure function using a polarized ^3He target was performed at SLAC by the E142 collaboration [12]. A high-density ^3He target polarized by spin exchange with optically pumped rubidium vapor was employed. More recently the SLAC E154 collaboration [13] reported the precision determination of the neutron spin structure function g_1^n measurement. Longitudinally polarized electron beam at beam energy of 48.3 GeV, a high-density polarized ^3He target, and two new single-arm spectrometers at central scattering angles of 2.75° and 5.5° were employed. Radiative and nuclear corrections need to be applied to extract information on neutron from measurement using a polarized ^3He target. Fig. 8 shows the results of g_1^n versus x together with the E142 results.

The HERMES collaboration reported [14] the measurement of the neutron spin structure function g_1^n using the polarized positron beam from HERA storage ring and an internal polarized ^3He target based on the metastability-exchange optical pumping technique. The 27.5 GeV positrons from the HERA storage ring become transversely polarized due to the Sokolov-Ternov effect [45]. Longitudinal polarization of the positron beam is achieved with spin rotators. Fig. 9 shows an example of the build-up of the longitudinal polarization of the HERA positron beam at the HERMES experiment. The HERMES spectrometer is designed to detect scattered positrons from the target over a large kinematics range. Both HERA storage ring beam lines traverse the HERMES spectrometer. The detectors are each split into two symmetric parts mounted above and below the storage ring plane. The internal polarized ^3He target was used in the first year of the HERMES running. This target is based on the metastability-exchange optical pumping technique with a target thickness of $\sim 10^{15}$ nucleons/cm² and a nuclear polarization of $\sim 50\%$. Fig. 10 shows the HERMES A_1^n and g_1^n results [14].

The experiment is planned at TJNAF [46] to measure the neutron spin structure function at low Q^2 with a high-density polarized ^3He target based on the spin-exchange optical pumping technique. The Q^2 evolution of the first moments of the spin structure functions g_1^n and g_1^p are investigated using the well known result of the Drell-Hearn-Gerassimov (DHG) sum rule [47]. It was recently pointed out [48] that in the real photon limit, the first moment of the spin structure function of the nucleon $g_1(x, Q^2)$ is related to the anomalous magnetic moment of the nucleon and therefore by exploring the Q^2 variation

Figure 8. Results for g_1^n versus x from SLAC experiment E154 compared to experiment E142 evaluated at $Q^2 = 5(\text{GeV}/c)^2$. Shaded region corresponds to 1σ systematic uncertainties.

between this low energy limit and the well known scaling limit one can gain insight into the structure of QCD. Fig. 11 shows the expected results on the Q^2 dependence of the extended Drell-Hearn-Gerasimov sum rule for the neutron. The curves shown are from the program AO (based on an analysis of electromagnetic transition amplitudes in the resonance region) [49], with different assumptions on the structure on the Roper resonance). The Chiral perturbation theory [50] prediction is also reported along with the $Q^2 = 0$ predicted values for DHG and the pion photoproduction data by Workman *et al.* [51].

5. Summary

Significant progress has been made in the last decade or so in the polarized ^3He target technologies. Polarized ^3He targets have been proven very effective in studying the neutron electromagnetic and spin structure. Future experiments with polarized ^3He targets are planned at many major electron accelerator facilities to study the neutron structure. At MIT-Bates, an extensive program [42] to carry out complete studies of spin-dependent responses in the few-body system with the South Hall Ring, Bates Large Acceptance Spectrometer Toroid (BLAST), and internal polarized targets (H/D, ^3He) are planned.

Figure 9. Longitudinal polarization build-up of the HERA positron beam at the HERMES experiment.

Figure 10. HERMES 1995 result for A_1^n and g_1^n as a function of x . The HERMES data are shown as solid dots with statistical uncertainties only, the systematic uncertainties are shown as shaded band. The SLAC E142 data are shown as solid triangles with statistical uncertainties.

This study will reduce model dependence in extract information on the neutron structure with polarized ^3He targets.

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Figure 11. Expected results on the Q^2 dependence of the extended Drell-Hearn-Gerasimov sum rule for the neutron.

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