Nitrogen dilution effect for small angle GDH experiment in JLab Hall-A *

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Abstract In the GDH sum rule measurement in JLab Hall-A, to obtain the cross section of electron scattering on polarized ^{3}He and its asymmetry in different helicity states, the dilution effect from unpolarized nitrogen mixed in the polarized ^{3}He target were calculated at different kinematic settings.

Key words GDH sum rule, dilution factor, correction, cross section, asymmetry

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1 Introduction

The polarized ^{3}He targets are widely used at SLAC, HERMES, MAINZ, MIT-Bates and JLab to study the electromagnetic structure and the spin structure of the neutron. The method to obtain such target in JLab is based on spin exchange optical pumping[1]. An alkali metal vapor (rubidium, Rb) is optical pumped and then the rubidium polarization is transferred from the valence electron to the ^{3}He nuclei through the spin exchange mechanism during ^{3}He-Rb collisions. The reason to select rubidium is that the D_1 line, which represents the energy splitting between the ground state $S_{1/2}$ and $P_{1/2}$ levels, lies in the near infrared and can be easily pumped with commercially available laser sources. This polarization method was developed at SLAC[2] and has been used in JLab Hall-A since 1998.

There is a single electron in the outer shell of Rb, whose interaction Hamiltonian with a magnetic field $\boldsymbol{B}$ is given by[3, 4]

$$\hat{H}=A_{\rm g}\boldsymbol{I}\cdot\boldsymbol{S}+g_{\rm e}\mu_{\rm B}S_zB_z-\frac{\mu_I}{I}I_zB_z\ , \qquad (1)$$

where $A_{\rm g}\boldsymbol{I}\cdot\boldsymbol{S}$ describes the coupling of the nuclear spin I to the electron spin S. $A_{\rm g}$ = 0.59327 is the isotropic magnetic-dipole coupling coefficient. The magnetic moment $\mu_{\rm B}$ = 0.57884×10^{-11} MeV/T, $g_{\rm e}$ = 2.00232, the nuclear magnetic moment μ_I = 4.26426×10^{-12} MeV/T for ^{85}Rb. In a magnetic field the quantum number $F(=I\pm S)$ state splits into $2F+1$ sublevels labeled by $m_F=m_I+m_s$, where $m_I=-I,-I+1,...,I-1,I$ and $m_S=-S,-S+1,...,S-1,S$, $m_F=-F,-F+1,...,F-1,F$. Because the S, m_S and m_J are 1/2, ±1/2 and ±1/2, respectively, the total angular momentum of the electron $\boldsymbol{J}$ equals to $\boldsymbol{S}$.

The electrons excited from Rb vapor which are exposed to the circularly polarized laser will go from the $m_F=m_I-1/2$ to the $m_F=m_I+1/2$ state. Since the excited procedure exists for each m_I, finally all electrons will be accumulated in the $F=m_F=3$ sublevel if the photon helicity is in the same direction as the magnetic field[4].

When those excited electrons decay to the $m_J=-1/2$ sublevel of the ground state they emit photons which have the same D_1 wavelength as the pumping lasers. These photons are not polarized and can excite the electrons from the m_F = 3 sublevel of the ground state. To minimize this depolarization effect, Nitrogen(N_2) buffer gas is introduced to provide a channel for the excited electrons to decay to the

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ground state without emitting photons. In the presence of N_2, the electrons decay through the collisions between the Rb atoms and N_2 molecules, usually referred to as non-radiative quenching[4]. The amount of N_2 is chosen to be about two orders of magnitude less in density than that of ^{3}He but a few orders of magnitude higher than that of Rb vapor. In this condition, only about 5% of the excited electrons decay by emitting photons. Since these N_2 molecules are unpolarized, they lead to a dilution effect, which is called nitrogen dilution.

2 Nitrogen dilution

The small angle GDH[5] experiment in JLab Hall-A represents a precise inclusive polarized cross section measurement at low momentum transfer and scattering angle in the threshold, quasi-elastic and resonance regions. Since the acceptance solid angle is about 6 msr[6], the scattering electron momentum with a small spread was selected with the magnet field power. To measure those events in different momentum range, the magnet field must be adjusted. Those scattering events in different momentum range at different incoming beam energies were measured, which was called different kinematic setting.

In this experiment, the longitudinally polarized electrons were scattered from a high pressure polarized ^{3}He target. The scattering cross section and the cross section asymmetry in different beam helicity states were measured. Since there was unpolarized N_2 in the target, the cross section of electron scattering from N_2 should be subtracted. But it was hard to separate the N_2 from polarized ^{3}He directly, so a dilution factor was introduced below to do the effect correction.

2.1 Nitrogen dilution factor

To calculate the dilution effect caused by those unpolarized N_2 in the target, the good scattering electron event was selected and some data were taken on a reference cell filled with N_2 at different pressure for each kinematic settings. The good scattering electron event referred that the outgoing particle should be identified as electron by the cherenkov detector and shower[7], and should come from the good data set in which no HV trip was found. The N_2 dilution factor f could be defined by

$$f = 1 - \frac{N_{\mathrm{N}_2}}{N_{^3\mathrm{He}}} \ , \tag{2}$$

where $N_{\mathrm{N}_2}(N_{^3\mathrm{He}})$ was the yield on $\mathrm{N}_2(^3\mathrm{He})$ from good data with the same particle identification(PID) and geometry cuts[7] under running condition.

To obtain N_{N_2} in a good data set, the same cuts were applied to the reference N_2 cell target data at the same kinematic setting. Then N_{N_2} could be calculated with the yield on the reference N_2 cell data Y_{N_2}.

$$N_{\mathrm{N}_2} = Y_{\mathrm{N}_2} \cdot \rho_{\mathrm{target}} / \rho_{\mathrm{ref}} \ , \tag{3}$$

$$\rho_{\mathrm{ref}} = \frac{273.15}{T} \cdot \left(\frac{P}{14.7} + 1 \right), \tag{4}$$

where ρ_{target} and ρ_{ref} were the density of N_2 in the polarized ^{3}He target and reference N_2 cell target, respectively. T was the reference cell temperature in Kelvin and P was the pressure in psig, which is the pressure relative to atmospheric pressure (14.7 psi at STP). T was 303.15±5 in Kelvin in this experiment and P could be read from the data. The uncertainty of T caused about 2% uncertainty for the density and this became about 0.2% for the dilution factor. ρ_{target} should be corrected with the temperature.

$$\rho_{\mathrm{target}} = \rho_{\mathrm{fill}} \cdot T_{\mathrm{run}} / T_{\mathrm{fill}} \ . \tag{5}$$

In the small angle GDH experiment , $T_{\mathrm{run}} = 303.15 \pm 5$ K was the temperature in Kelvin during the data taking, $\rho_{\mathrm{fill}} = 0.1094 \pm 0.0002$ amg and $T_{\mathrm{fill}} = 293.15 \pm 1$ K were the N_2 density and temperature while the polarized ^{3}He target cell was made, respectively. Thus the $\rho_{\mathrm{target}} = 0.1131 \pm 0.0018$ amg.

So the N_2 dilution factor f could be obtained from the yield on N_2 and ^{3}He with the same PID and geometry cuts for those good kinematic setting data.

Table 1 shows the factor f at 2 kinematic settings while the beam energy is 1.1 GeV.

The first column of Table 1 is the central scattering momentum in GeV, the second column P is the pressure in psig read from the data, ρ_{ref} was obtained from P with Eq. (4), $N_{^3\mathrm{He}}$ and Y_{N_2} are the yield on ^{3}He and reference N_2 cell target with the same cuts, respectively, the yield on N_2 in ^{3}He target N_{N_2} could be obtained with Eq. (3), then the dilution factor f could be extracted with Eq. (2).

Table 1. Dilution factor f at different momentum region, beam energy $E_{\mathrm{beam}} = 1.1$ GeV.

P_0	P	ρ_{ref}	$N_{^3\mathrm{He}}$	Y_{N_2}	N_{N_2}	f
0.907	48	3.8432	1263953	4320751	127153	0.8994±0.0020
0.728	73	5.5993	1063491	5702081	115176	0.8917±0.0021

2.2 Nitrogen dilution correction

In the small angle GDH experiment, the cross section of nucleon scattering on the polarized ^{3}He target and its asymmetry in different helicity states should be measured. Since there was a small amount unpolarized N_2 in the polarized ^{3}He target, what one measured was the mixed cross section $\sigma_{^3\mathrm{He}}$ and the asymmetry $A_{^3\mathrm{He}}$ in different helicity states.

The unpolarized experimental cross section was given by:

$$\sigma = \frac{\mathrm{d}\sigma}{\mathrm{d}E'd\Omega} = \frac{N^*_{\mathrm{f}}}{N_{\mathrm{i}}} \times \frac{1}{\Delta\Omega\Delta E'} = k \cdot N^*_{\mathrm{f}} \ , \tag{6}$$

where N^*_{f} was the number of scattered electrons detected which had been corrected for detector and software efficiencies, prescaler and lifetime, N_{i} was the number of incident electrons which was determined from the total charge measured by the beam charge monitor. $\Delta\Omega$ was the angular acceptance, $\Delta E'$ was the energy spread of the scattered electrons and k was a constant for each kinematic setting.

Then the predicted yield $N^0_{^3\mathrm{He}}$ and the cross section $\sigma^0_{^3\mathrm{He}}$ could be obtained from the measured one as:

$$\begin{aligned} N^0_{^3\mathrm{He}} &= N_{^3\mathrm{He}} \cdot \left(1 - \frac{N_{\mathrm{N}_2}}{N_{^3\mathrm{He}}}\right) = f \cdot N_{^3\mathrm{He}} \ , \\ \sigma^0_{^3\mathrm{He}} &= k \cdot N^0_{^3\mathrm{He}} = f \cdot k \cdot N_{^3\mathrm{He}} = f \cdot \sigma_{^3\mathrm{He}} \ . \end{aligned} \tag{7}$$

To calculate the GDH sum rule, the cross section asymmetry in parallel and unparallel was measured. Which was defined as:

$$A_{^3\mathrm{He}} = \frac{1}{P_{\mathrm{t}}P_{\mathrm{b}}} \frac{\sigma^+_{^3\mathrm{He}} - \sigma^-_{^3\mathrm{He}}}{\sigma^+_{^3\mathrm{He}} + \sigma^-_{^3\mathrm{He}}} \ , \tag{8}$$

where + and − represented that the beam helicity was parallel and unparallel to the target helicity, respectively. P_{t} and P_{b} were the target and beam polarizations respectively.

Since the N_2 was unpolarized, the cross section asymmetry on pure ^{3}He target $A^0_{^3\mathrm{He}}$ in different helicity states could be corrected with the asymmetry on ^{3}He target $A_{^3\mathrm{He}}$ and its dilution factor f:

$$\begin{aligned} \sigma^+_{^3\mathrm{He}} &= \sigma^{+^0}_{^3\mathrm{He}} + \sigma^+_{\mathrm{N}_2}, \\ \sigma^-_{^3\mathrm{He}} &= \sigma^{-^0}_{^3\mathrm{He}} + \sigma^-_{\mathrm{N}_2}, \\ \sigma^+_{\mathrm{N}_2} &= \sigma^-_{\mathrm{N}_2} = \frac{1}{2} \cdot \sigma_{\mathrm{N}_2}. \end{aligned} \tag{9}$$

$$\begin{aligned} A_{^3\mathrm{He}} &= \frac{1}{P_{\mathrm{t}}P_{\mathrm{b}}} \frac{\sigma^+_{^3\mathrm{He}} - \sigma^-_{^3\mathrm{He}}}{\sigma^+_{^3\mathrm{He}} + \sigma^-_{^3\mathrm{He}}} = \\ & \frac{1}{P_{\mathrm{t}}P_{\mathrm{b}}} \frac{\sigma^{+^0}_{^3\mathrm{He}} - \sigma^{-^0}_{^3\mathrm{He}}}{\sigma^0_{^3\mathrm{He}}/f} = f \cdot A^0_{^3\mathrm{He}} \ . \end{aligned} \tag{10}$$

So

$$A^0_{^3\mathrm{He}} = \frac{1}{f} \cdot A_{^3\mathrm{He}} \ . \tag{11}$$

Since one couldn't count the event number of electron scattered at pure polarized or unpolarized ^{3}He target, the cross section and the cross section asymmetry in different helicity configurations one measured were not the predicted ones. But Eqs. (7) and (11) showed that the predicted cross section $\sigma^0_{^3\mathrm{He}}$ and the cross section asymmetry in different helicity configurations $A^0_{^3\mathrm{He}}$ could be corrected with the dilution factor f and $1/f$ from the measured ones $\sigma_{^3\mathrm{He}}$ and $A_{^3\mathrm{He}}$.

3 Summary

Because the dilution factor f was obtained from the cross section on ^{3}He and N_2, which depended on the kinematic settings such as beam energy and momentum. It was necessary to do the dilution correction for all kinematic settings during the data taking. The beam energies were set to 1.1 GeV, 2.2 GeV, 3.3 GeV, 3.8 GeV and 4.4 GeV respectively. About ten scattering momentum regions were selected at each beam energy. In each momentum region at one given beam energy, which was called kinematic setting, one could calculate the corresponding dilution factor f from Eqs. (2)—(5). Then one could find the dependence of f on the kinematic settings.

Figure 1 shows the dilution factor f at different kinematic settings.

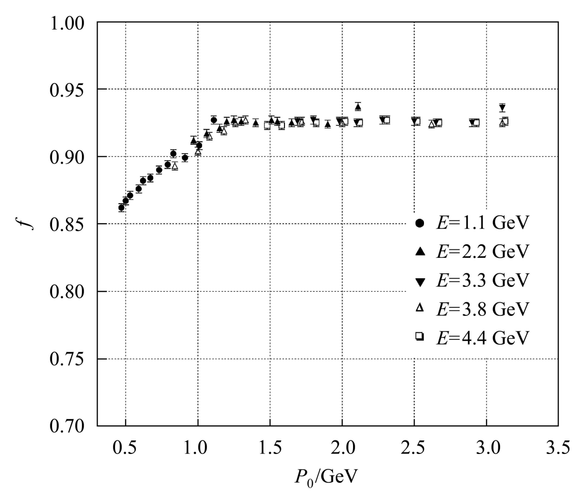

Fig. 1. N_2 dilution factors at different kinematic settings, E is the beam energy and P_0 is the central scattering momentum.

From Fig. 1, one can see that the dilution factors depend on the scattering momentum only. They have some variations in high scattering momentum region. But the factors have a significant increase with the central momentum due to the larger background induced by radiation from the cell in lower momentum region.

The expected cross section on pure polarized ^{3}He target and its asymmetry in different helicity states can be corrected with the corresponding dilution factor.

Because the GDH sum rule measured the integration of the cross section of electron scattered at ^{3}He target, the measured results without dilution factor correction might lead to an excursion. Fig. 1 shows the excursion is crucial at low scattering momentum region.

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