Nathaly Santiesteban

1. **Theory Summary: Summary after the meeting with Wim Cosyn and Jerry Miller**

2. **Image update**

1. Summary based on:

Tensor-polarized structure function b_1 in the standard convolution description of the deuteron

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Tensor-polarized structure functions of a spin-1 hadron are additional observables, which do not exist for the spin-1/2 nucleon. They could probe novel aspects of the internal hadron structure. Twist-2 tensor-polarized structure functions are b_1 and b_2, and they are related by the Callan-Gross-like relation in the Bjorken scaling limit. In this work, we theoretically calculate b_1 in the standard convolution description for the deuteron. Two different theoretical models, a basic convolution description and a virtual nucleon approximation, are used for calculating b_1, and their results are compared with the HERMES measurement. We found large differences between our theoretical results and the data. Although there is still room to improve by considering higher-twist effects and in the experimental extraction of b_1 from the spin asymmetry A_{zz}, there is a possibility that the large differences require physics beyond the standard deuteron model for their interpretation. Future b_1 studies could shed light on a new field of hadron physics. In particular, detailed experimental studies of b_1 will start soon at the Thomas Jefferson National Accelerator Facility. In addition, there are possibilities to investigate tensor-polarized parton distribution functions and b_1 at Fermi National Accelerator Laboratory and a future electron-ion collider. Therefore, further theoretical studies are needed for understanding the tensor structure of the spin-1 deuteron, including a new mechanism to explain the large differences between the current data and our theoretical results.

The inclusive cross section of a charged-lepton deep inelastic scattering from a spin-1 target is generally expressed as

$$\frac{d\sigma}{dx dQ^2} = \frac{\pi y^2 \alpha^2}{Q^4(1-\epsilon)} \Big[F_{UU,T} + \epsilon F_{UU,L} + T_{\parallel\parallel}(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}) + T_{\parallel\perp} \cos\phi_{T_\parallel} \sqrt{2\epsilon(1+\epsilon)} F_{UT_{LT}}^{\cos\phi_{T_\parallel}} + T_{\perp\perp} \cos(2\phi_{T_\perp}) \epsilon F_{UT_{TT}}^{\cos(2\phi_{T_\perp})} \Big],$$

the polarization factors $T_{\parallel\parallel}$, $T_{\parallel\perp}$, and $T_{\perp\perp}$ are related to T_{ij} by the relations $T_{\parallel\parallel} = T_{zz}$, $T_{\parallel\perp}\cos\phi_{T_\parallel} = T_{xz}$, and $T_{\perp\perp}\cos(2\phi_{T_\perp}) = T_{xx} - T_{yy}$ by assigning the angles $\phi_{T_\parallel}$ and $\phi_{T_\perp}$.

$$F_{UT_{LL},L} = \frac{1}{x_D}\sqrt{\frac{2}{3}}\Big[2(1+\gamma^2)x_D b_1 - (1+\gamma^2)^2\left(\frac{1}{3}b_2 + b_3 + b_4\right) - (1+\gamma^2)\left(\frac{1}{3}b_2 - b_4\right) - \left(\frac{1}{3}b_2 - b_3\right)\Big],$$

$$F_{UT_{LL},T} = -\frac{1}{x_D}\sqrt{\frac{2}{3}}\Big[2(1+\gamma^2)x_D b_1 - \gamma^2\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right)\Big],$$

$$F_{UT_{LT}}^{\cos\phi_{T_\parallel}} = -\sqrt{\frac{2}{3}}\frac{\gamma}{2x_D}\Big[(1+\gamma^2)\left(\frac{1}{3}b_2 - b_4\right) + \left(\frac{2}{3}b_2 - 2b_3\right)\Big],$$

$$F_{UT_{TT}}^{\cos(2\phi_{T_\perp})} = -\sqrt{\frac{2}{3}}\frac{\gamma^2}{3x_D}\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right).$$

If the deuteron is polarized along the virtual photon direction, only $T_{\parallel\parallel}$ is nonzero and given by Eq. (26). If the deuteron is polarized along the lepton-

$$\widetilde{T}_{\parallel\parallel} = \frac{1}{\sqrt{6}}(1 - 3p^0)$$

The degrees of vector and tensor polarizations are given by $\mathcal{P} = \sqrt{\vec{\mathcal{P}}^2}$ and $T = \sqrt{\sum_{i,j}(T_{i,j})^2}$. If the probabilities of spin states +1, 0, and −1 are denoted as p^{+1}, p^0, and p^{-1}.

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$$\frac{d\sigma}{dx\,dQ^2} = \frac{\pi y^2\alpha^2}{Q^4(1-\epsilon)}\Big[F_{UU,T} + \epsilon F_{UU,L} + T_{\parallel\parallel}\left(F_{UT_{LL},T} + \epsilon F_{UT_{LL},L}\right) + T_{\parallel\perp}\cos\phi_{T_\parallel}\sqrt{2\epsilon(1+\epsilon)}F_{UT_{LT}}^{\cos\phi_{T_\parallel}} + T_{\perp\perp}\cos(2\phi_{T_\perp})\epsilon F_{UT_{TT}}^{\cos(2\phi_{T_\perp})}\Big],$$

the polarization factors $T_{\parallel\parallel}$, $T_{\parallel\perp}$, and $T_{\perp\perp}$ are related to T_{ij} by the relations $T_{\parallel\parallel} = T_{zz}$, $T_{\parallel\perp}\cos\phi_{T_\parallel} = T_{xz}$, and $T_{\perp\perp}\cos(2\phi_{T_\perp}) = T_{xx} - T_{yy}$ by assigning the angles $\phi_{T_\parallel}$ and $\phi_{T_\perp}$.

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$$F_{UT_{LL},T} = -\frac{1}{x_D}\sqrt{\frac{2}{3}}\Big[2(1+\gamma^2)x_D b_1 - \gamma^2\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right)\Big],$$

$$F_{UT_{LT}}^{\cos\phi_{T_\parallel}} = -\sqrt{\frac{2}{3}}\frac{\gamma}{2x_D}\Big[(1+\gamma^2)\left(\frac{1}{3}b_2 - b_4\right) + \left(\frac{2}{3}b_2 - 2b_3\right)\Big],$$

$$F_{UT_{TT}}^{\cos(2\phi_{T_\perp})} = -\sqrt{\frac{2}{3}}\frac{\gamma^2}{x_D}\left(\frac{1}{6}b_2 - \frac{1}{2}b_3\right).$$

Eq. (26). If the deuteron is polarized along the lepton-beam axis, we have $\phi_{T_\parallel} = \phi_{T_\perp} = 0$, and the remaining polarization factors in Eq. (27) can be related to $\widetilde{T}_{\parallel\parallel}$ of Eq. (26) through the transformation properties of the density matrix under rotations as follows:

$$T_{\parallel\parallel} = \frac{1}{4}\,[1 + 3\cos(2\theta_q)]\,\widetilde{T}_{\parallel\parallel}, \quad T_{\parallel\perp} = \frac{3}{4}\sin(2\theta_q)\,\widetilde{T}_{\parallel\parallel},$$
$$T_{\perp\perp} = \frac{3}{4}\,[1 - \cos(2\theta_q)]\,\widetilde{T}_{\parallel\parallel},$$

Theory results:

TABLE I. Theory-2 calculations of the four tensor-polarized structure functions for kinematics of the HERMES b_1 data [20]

x	Q^2 (GeV^2)	$b_1(10^{-4})$	$b_2(10^{-5})$	$b_3(10^{-3})$	$b_4(10^{-3})$	$b_2/(2x_D b_1)$	γ
0.012	0.51	2.81	0.264	-1.34	5.06	0.783	0.0315
0.032	1.06	6.92	1.97	-1.87	7.51	0.890	0.0583
0.063	1.65	3.50	0.265	-2.02	7.96	0.120	0.0920
0.128	2.33	-1.80	-7.38	-2.13	7.49	3.20	0.157
0.248	3.11	-8.39	-28.1	-2.09	4.58	1.35	0.264
0.452	4.69	-6.18	-21.7	-1.11	-0.58	0.777	0.392

In the virtual nucleon approximation

In the HERMES analysis, b_1 was then extracted from A_{zz} using

$$A_{zz} = -\frac{2}{3}\frac{b_1}{F_1}. \tag{48}$$

This equation is correct as an equality if the following two conditions are satisfied.

(1) The deuteron is polarized along the photon direction, namely $\theta_q = 0$.

(2) The Bjorken scaling limit ($Q^2 \to \infty, x \,\text{finite}, \gamma \to 0$) is taken. It implies the Callan-Gross relations for the structure functions ($2x_D F_1 = F_2$, $2x_D b_1 = b_2$) and neglect of the higher-twist structure functions $b_{3,4}$.

HERMES results:

TABLE II: Measured values (in 10^{-2} units) of the tensor asymmetry A^{d}_{zz} and the tensor structure function b^{d}_1. Both the corresponding statistical and systematic uncertainties are listed as well.

$\langle x \rangle$	$\langle Q^2 \rangle$ [GeV^2]	A^{d}_{zz} [10^{-2}]	$\pm\delta\mathcal{A}^{\mathrm{stat}}_{zz}$ [10^{-2}]	$\pm\delta\mathcal{A}^{\mathrm{sys}}_{zz}$ [10^{-2}]	b^{d}_1 [10^{-2}]	$\pm\delta b_1^{\mathrm{stat}}$ [10^{-2}]	$\pm\delta b_1^{\mathrm{sys}}$ [10^{-2}]
0.012	0.51	-1.06	0.52	0.26	11.20	5.51	2.77
0.032	1.06	-1.07	0.49	0.36	5.50	2.53	1.84
0.063	1.65	-1.32	0.38	0.21	3.82	1.11	0.60
0.128	2.33	-0.19	0.34	0.29	0.29	0.53	0.44
0.248	3.11	-0.39	0.39	0.32	0.29	0.28	0.24
0.452	4.69	1.57	0.68	0.13	-0.38	0.16	0.03

Can we really neglect b3 and b4 for all the kinematics of Azz and b1?

Next:

* Wim will estimate the effects of $b_{3,4}$ in his framework for both longitudinal and q-vector polarizations.
  Time estimate of the calculations: Last week of July
* From the paper we can estimate the effects using his calculations for HERMES data.

2. Image test