ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2004. Т. 35. ВЫП. 7

УДК 539.12: 539.171

COLLINS EFFECT AND PREDICTIONS OF SSA FOR HERMES AND COMPASS*

*A. V. Efremov***

Joint Institute for Nuclear Research, Dubna

Predictions are made for single-spin azimuthal asymmetries (SSA) due to the Collins effect in pion production from semi-inclusive deep-inelastic scattering off transversely and longitudinally polarized targets for the HERMES and COMPASS experiments. The SSA A_{UT} from the transversely polarized proton target are found to be about 20% for positive and neutral pions both at HERMES and COMPASS. For a longitudinally polarized target for COMPASS $A_{UL}^{\sin\phi} \sim 1\%$ and $A_{UL}^{\sin 2\phi} \sim 3\%$.

Даны предсказания для обусловленных эффектом Коллинза одиночных азимутальных асимметрий в полуинклюзивном рождении пиона в процессе глубоконеупругого рассеяния на поперечно- и продольно-поляризованной мишени в экспериментах HERMES и COMPASS. Асимметрия A_{UT} на поперечно-поляризованной протонной мишени для положительных и нейтральных пионов, как оказалось, и в HERMES, и в COMPASS достигает примерно $20\,\%$. Для продольно-поляризованной мишени на установке COMPASS асимметрии $A_{UL}^{\sin\phi} \sim 1\%$ и $A_{UL}^{\sin 2\phi} \sim 3\,\%$.

INTRODUCTION

Noticeable SSA*** $A_{UL}^{\sin\phi}$ have been observed by the HERMES collaboration in pion and kaon electroproduction in semi-inclusive deep-inelastic scattering (SIDIS) of an unpolarized lepton beam off a longitudinally polarized proton or deuteron target [2–5]. Assuming factorization these single-spin asymmetries can be explained by the Collins and Sivers effect in terms of so far unexplored distribution and fragmentation functions, namely the nucleon chirally odd twist-2 transversity distribution h_1^a and twist-3 distribution functions h_L^a and the Collins parton fragmentation function (PFF) $H_1^{\perp a}$ or the chirally even Sivers parton distribution function (PDF) $f_{1T}^{\perp a}$.

*This work was done in collaboration with K. Goeke and P. Schweitzer, Institut für Theoretische Physik II, Ruhr-Universität Bochum, Germany. More details and complete references can be found in [1].

**E-mail: efremov@thsun1.jinr.ru

***U denotes the unpolarized beam. L (below also T) denotes the longitudinal (and transverse) target polarization with respect to the beam. The superscript $\sin\phi$ characterizes the azimuthal distribution of the produced hadrons with respect to the direction of the exchanged virtual photon.

Reasonable descriptions of the HERMES data using different assumptions and models were given in Refs. 6–8 in terms of the Collins effect only. In this talk I will give predictions of the SSA due to the Collins effect from a transversely polarized target for the kinematics of the HERMES and COMPASS experiments.

COLLINS EFFECT CONTRIBUTION TO A_{UT}

In the HERMES and COMPASS experiments the cross sections $\sigma_N^{\uparrow\downarrow}$ for the process $lN^{\uparrow\downarrow} \to l'hX$ will be measured at the transversely with respect to the beam polarized target. With ϕ (ϕ_S) denoting the azimuthal angles (see Fig. 1) around virtual photon momentum between the lepton scattering plane and the hadron production plane (the nucleon spin) and the observables of interest are defined as

$$A_{UT}^{\sin(\phi+\phi_S)}(x) = \frac{2}{|S_T|}\frac{\langle\sin(\phi+\phi_s)\rangle^{\uparrow} - \langle\sin(\phi+\phi_s)\rangle^{\downarrow}}{\langle 1\rangle^{\uparrow} + \langle 1\rangle^{\downarrow}}. \tag{1}$$

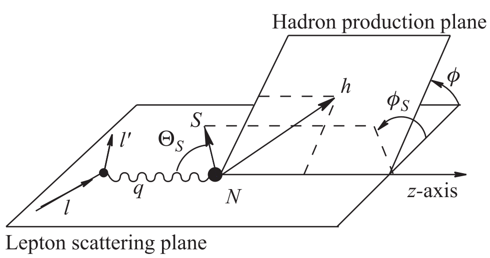

Fig. 1. Kinematics of the process $lN^{\uparrow} \to l'hX$ in the lab. frame

The expressions for the differential cross sections entering the asymmetry in Eq. (1) were derived in [9, 10] assuming factorization. In order to deconvolve the transverse momenta in $A_{UT}^{\sin(\phi+\phi_S)}$ in Eq. (1) we assume the distributions of transverse momenta in the unintegrated distribution and fragmentation functions to be Gaussian. Under this assumption one obtains*

$$A_{UT}^{\sin(\phi+\phi_s)}(x) = a_G\, B_T(x)\, \frac{\sum_a e_a^2\, x\, h_1^a(x)\,\langle H_1^{\perp a}\rangle}{\sum_b e_b^2\, x\, f_1^b(x)\,\langle D_1^b\rangle}\ , \tag{2}$$

where $B_T(x)$ and a_G are defined as

$$B_T(x) = \frac{2\int dy\,(1-y)\,\sin\Theta_S/Q^4}{\int dy\,(1-y+y^2/2)\,/Q^4},\ a_G = \frac{1}{2\langle z\rangle\sqrt{1+\langle z^2\rangle\langle P_{N\perp}^2\rangle/\langle P_{h\perp}^2\rangle}}, \tag{3}$$

where $\langle P_{N\perp}^2\rangle$ and $\langle P_{h\perp}^2\rangle/\langle z^2\rangle$ are the mean transverse momentum squares characterizing the Gaussian distributions of quark transverse momenta in the unintegrated distribution and fragmentation function.

*We use the notation of [9, 10] with $H_1^{\perp}$ normalized to $\langle P_{h\perp}\rangle$ instead of m_h.

TRANSVERSITY AND COLLINS PFF

In order to estimate the azimuthal asymmetry, Eq. (1), one has to know h_1^a and $H_1^{\perp a}$. For the former we shall use the predictions of the chiral quark-soliton model (χQSM) [11]; and for the latter, our analysis of the HERMES data from Ref. 7*.

The χQSM is an effective relativistic quantum field-theoretical model with explicit quark degrees of freedom, in which twist-2 nucleon distribution functions can unambiguously be defined and evaluated at a low renormalization point of about $600-700$ MeV. The χQSM has been derived from the instanton model of the QCD vacuum [13] and has been shown to describe well numerous static nucleonic observables without adjustable parameters. The field-theoretical nature of the model is crucial to ensure the theoretical consistency of the approach: the quark and antiquark PDF computed in the model satisfy all general QCD requirements.

The results of the model agree for the PDF $f_1^a(x)$, $g_1^a(x)$ and $g_T^a(x)$ within 10–30% with phenomenological information. This encourages confidence that the model describes the nucleon transversity PDF $h_1^a(x)$ [11] with a similar accuracy. Also in this approach one can justifiably approximate $h_L^a(x)$ by its twist-2 («Wandzura–Wilczek»-like) term $h_L^a(x) = 2x \int_x^1 dx'\, h_1^a(x')/x'^2$. Moreover, T-odd distribution functions, in particular Sivers PDF, vanish in the χQSM [14].

In the following we will need also the deuteron transversity distribution. Since the corrections due to the D-state admixture are smaller than other theoretical uncertainties in our approach we shall disregard them here.

For Collins PFF a strong suppression of the unfavoured with respect to the favoured has been assumed. From charge conjugation and isospin symmetry one has then

$$H_1^\perp \equiv H_1^{\perp u/\pi^+} = H_1^{\perp \bar{d}/\pi^+} = H_1^{\perp d/\pi^-} = 2H_1^{\perp u/\pi^0} = \ldots \text{ etc.} \gg \gg H_1^{\perp d/\pi^+} = H_1^{\perp \bar{u}/\pi^+} = \ldots \text{ etc.} \quad (4)$$

In Ref. 7 information on $H_1^\perp$ was gained from the HERMES data on the $A_{UL}^{\sin\phi}$ asymmetry in π^+ and π^0 production [3, 4]. For that the transverse momentum distributions were assumed to be Gaussian and the parton distribution functions h_1^a and h_L^a were taken from the χQSM. For the analyzing power the value was found

$$\frac{H_1^\perp(z)}{D_1(z)} = (0.33 \pm 0.06)z \quad \text{with} \quad \frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle} = (13.8 \pm 2.8)\% \quad (5)$$

*Actually, in that analysis the Sivers function was neglected, which has later been shown to be theoretically consistent and phenomenologically justified [12].

at $\langle z \rangle = 0.4$ and $\langle Q^2 \rangle = 2.5$ GeV^2 [7]. This asymmetry was also measured using the DELPHI data collection and a value $|\langle H_1^\perp \rangle / \langle D_1 \rangle| = (12.5 \pm 1.4)\%$ for $\langle z \rangle \simeq 0.4$ at a scale of M_Z^2 was reported [15]. Remarkably, a result numerically close to Eq. (5) was obtained in the model calculation of Ref. 16.

A_{UT} ASYMMETRIES FOR HERMES

The beam in the HERMES experiment has an energy of $E_{\text{beam}} = 26.7$ GeV. We assume the cuts implicit in the integrations in Eq. (3) to be the same as in the longitudinal target polarization experiments: $1 < Q^2 < 15$ GeV^2, $W > 2$ GeV, $0.2 < y < 0.85$, $0.023 < x < 0.4$ and $0.2 < z < 0.7$ with $\langle z \rangle = 0.4$, and $\langle P_{h\perp} \rangle = 0.4$ GeV. The predictions for $A_{UT}^{\sin(\phi+\phi_S)}$ for the transversely polarized proton and deuteron targets are shown in Fig. 2, *a, b*, respectively.

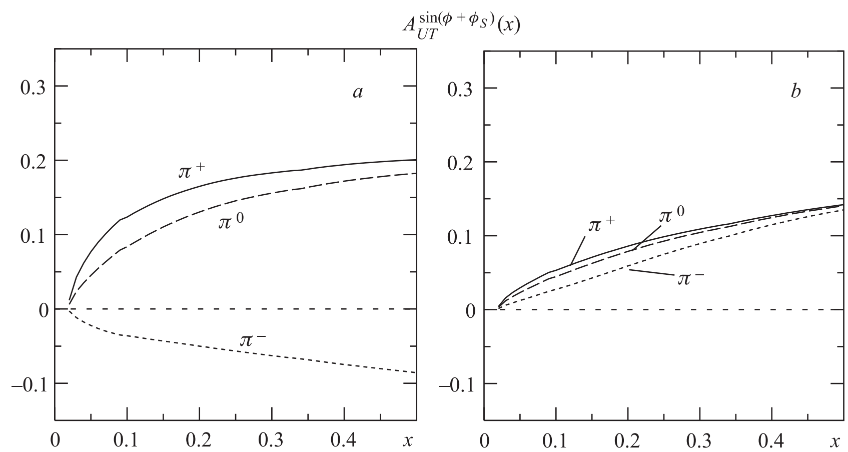

Fig. 2. Predictions for azimuthal asymmetries $A_{UT}^{\sin(\phi+\phi_S)}(x)$ in SIDIS pion productions from transversely polarized proton (*a*) and deuteron (*b*) targets for kinematics of the HERMES experiment

This demonstrates that $A_{UT}^{\sin(\phi+\phi_S)}$ is sizeable, roughly 20% for positive and neutral pions for the proton target and about 10% for all pions for the deuteron target. Comparing this result with the $A_{UL}^{\sin\phi}$ asymmetries $\sim (2-4)\%$ we see that $A_{UT}^{\sin(\phi+\phi_S)}$ asymmetry can clearly be observed.

For negative pions from a proton, however, there might be additional sizeable corrections due to unfavoured flavour fragmentation.

In Ref. 8 $A_{UL}^{\sin\phi}$ asymmetries for kaons have been estimated assuming that the analyzing power for kaons is approximately equal to that of pions*. The predicted asymmetries compare well with the HERMES data within the (admittedly rather large) statistical error [5]. Under this assumption one could expect for the transverse target polarization experiment $A_{UT}^{\sin(\phi+\phi_S)}(K^+) \approx A_{UT}^{\sin(\phi+\phi_S)}(K^0) \approx A_{UT}^{\sin(\phi+\phi_S)}(\pi^+)$ and $A_{UT}^{\sin(\phi+\phi_S)}(\bar{K}^0) \approx A_{UT}^{\sin(\phi+\phi_S)}(K^-) \approx 0$.

COMPASS EXPERIMENT

The beam energy available at COMPASS is $E_{\rm beam} = 160$ GeV. For the kinematic cuts we shall take: $2 < Q^2 < 50$ GeV^2, $15 < W^2 < 300$ GeV^2, $0.05 < y < 0.9$, $x < 0.4$ and evaluate the distribution functions at $Q^2 = 10$ GeV^2. We take $\langle P_{h\perp}\rangle \approx 0.4$ GeV and $\langle z\rangle \approx 0.4$. The latter means that we can use for $\langle H_1^\perp\rangle/\langle D_1\rangle$ the result in Eq. (5) assuming that the ratio $\langle H_1^\perp\rangle/\langle D_1\rangle$ is only weakly scale dependent in the range of scales relevant in the HERMES and COMPASS experiments. The estimate of $A_{UT}^{\sin(\phi+\phi_S)}$ obtained in this way is shown in Fig. 3, *a*.

It shows that $A_{UT}^{\sin(\phi+\phi_S)}$ can be up to $\mathcal{O}(20\%)$ at COMPASS energies, i.e., as large as at HERMES. This is not unexpected since this asymmetry is twist-2 (in the sense that it is not power suppressed).

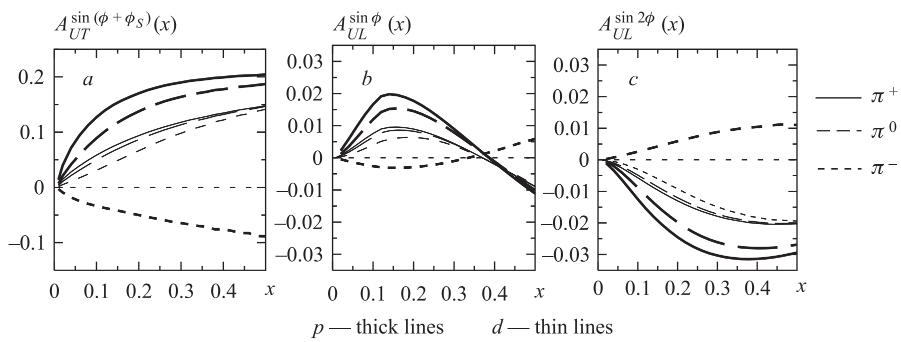

Fig. 3. *a*) Prediction of the SSA $A_{UT}^{\sin(\phi+\phi_S)}(x)$ in SIDIS pion production from a transversely polarized proton and deuteron targets for the kinematics of the COMPASS experiment. Predictions of the SSA $A_{UL}^{\sin\phi}(x)$ (*b*) and $A_{UL}^{\sin 2\phi}(x)$ (*c*) from a longitudinally polarized target for the kinematics of the COMPASS experiment

*This relation would hold exactly in the chiral limit (where pions and kaons would be massless Goldstone bosons).

About 80% of the beam time, the target polarization in the COMPASS experiment will be longitudinal. This will allow one to measure the longitudinal target spin asymmetries $A_{UL}^{\sin\,\phi}$ and $A_{UL}^{\sin\,2\phi}$. The estimates for these asymmetries in our approach are shown in Fig. 3, *b, c*. Clearly, the longitudinal target spin asymmetries are much smaller than the transverse target spin asymmetry $A_{UT}^{\sin\,(\phi+\phi_S)}$, however, the larger statistics could help to resolve them. The $A_{UL}^{\sin\,2\phi}(x)$ asymmetry is of particular interest since it is one of the «independent observables» which could provide further insights on transversity distribution without assuming of Sivers PPF contribution smallness.

SIVERS AZIMUTHAL ASYMMETRIES

Actually, our approach would imply the vanishing of $A_{UT}^{\sin\,(\phi-\phi_S)}(x)$ asymmetry, which is due to the Sivers effect [10] and will be measured at HERMES and COMPASS simultaneously with $A_{UT}^{\sin\,(\phi+\phi_S)}(x)$. However, this cannot be taken literally as a prediction for the following reason. The chiral quark-soliton model was derived from the instanton vacuum model as the leading order in terms of the instanton packing fraction $\rho/R \sim 1/3$ (ρ and R are respectively the average size and separation of instantons in Euclidean space time). In this order the T-odd distribution functions vanish [14].

In higher orders the Sivers function can be well nonzero and all one can conclude at this stage is that the Sivers function is suppressed with respect to the T-even. However, considering that $H_1^{\perp}(z)$ is much smaller than $D_1(z)$, cf. Eq. (5), it is questionable whether such a suppression could be sufficient such that in physical cross sections the Collins effect $\propto h_1^a(x)H_1^{\perp}(z)$ is dominant over the Sivers effect $\propto f_{1T}^{\perp}(x)D_1(z)$.

Acknowledgements. The author is partially supported by INTAS grant 00/587 and RFBR grant 03-02-16816 and DFG-RFBR 03-02-04022.

REFERENCES

1. *Efremov A. V., Goeke K., Schweitzer P.* // Eur. Phys. J. C. 2003. V. 32. P. 337; hep-ph/0309209.
2. *Avakian H. (HERMES Collab.)* // Nucl. Phys. Proc. Suppl. 1999. V. 79. P. 523.
3. *Airapetian A. et al. (HERMES Collab.)* // Phys. Rev. Lett. 2000. V. 84. P. 4047.
4. *Airapetian A. et al. (HERMES Collab.)* // Phys. Rev. D. 2001. V. 64. P. 097101.
5. *Airapetian A. et al. (HERMES Collab.)* // Phys. Lett. B. 2003. V. 562. P. 182.
6. *Efremov A. V. et al.* // Phys. Lett. B. 2000. V. 478. P. 94.
7. *Efremov A. V., Goeke K., Schweitzer P.* // Phys. Lett. B. 2001. V. 522. P. 37; Erratum // Ibid. 2002. V. 544. P. 389.

8. *Efremov A. V., Goeke K., Schweitzer P.* // Eur. Phys. J. C. 2002. V. 24. P. 407; Nucl. Phys. A. 2002. V. 711. P. 84; Acta Phys. Polon. B. 2002. V. 33. P. 3755.

9. *Mulders P. J., Tangerman R. D.* // Nucl. Phys. B. 1996. V. 461. P. 197; Erratum // Nucl. Phys. B. 1997. V. 484. P. 538.

10. *Boer D., Mulders P. J.* // Phys. Rev. D. 1998. V. 57. P. 5780.

11. *Pobylitsa P. V., Polyakov M. V.* // Phys. Lett. B. 1996. V. 389. P. 350;
Schweitzer P. et al. // Phys. Rev. D. 2001. V. 64. P. 034013.

12. *Efremov A. V., Goeke K., Schweitzer P.* // Phys. Lett. B. 2003. V. 568. P. 63.

13. For reviews see: *Diakonov D. I.* // Prog. Part. Nucl. Phys. 2003. V. 51. P. 173.

14. *Pobylitsa P. V.* hep-ph/0212027.

15. *Efremov A. V., Smirnova O. G., Tkachev L. G.* // Nucl. Phys. Proc. Suppl. 1999. V. 74. P. 49; V. 79. P. 554.

16. *Bacchetta A. et al.* // Phys. Rev. D. 2002. V. 65. P. 094021.