SINGLE SPIN ASYMMETRIES IN INCLUSIVE HIGH ENERGY HADRON-HADRON COLLISION PROCESSES

Liang Zuo-tang

Institut für theoretische Physik der Freien Universität Berlin
Arnimallee 14, 14195 Berlin, Germany

ABSTRACT

Characteristics of the available data are briefly summarized. Different theoretical approaches are reviewed with special attention to a non-perturbative model which explicitly takes the orbital motion of the valence quarks into account. The connection between such asymmetries and hyperon polarization in unpolarized reactions is discussed.

1. Introduction

Single spin hadron-hadron collision experiments, in which one of the colliding hadrons is transversely polarized, are of particular interests for the following reasons:

(A) The experiments are conceptually very simple.
(B) The observed effects are very striking.
(C) Theoretical expectations based on pQCD deviate drastically from the data.
(D) Information on transverse spin distribution and that on its flavor dependence can be obtained from such experiments.

A large amount of data is now available [1-8]. Besides the well known analyzing power in $pp$-elastic scattering [1], we have now data [2-8] on left-right asymmetry $A_N$ in single-spin inclusive processes for the production of different kinds of mesons, Λ hyperon or direct photon in collisions using transversely polarized proton as well as antiproton beams. It has been observed that $A_N$ is up to 40% in the beam fragmentation region, whereas the theoretical expectation [9] were $A_N \approx 0$.

In this talk, I will concentrate on inclusive hadron production and arrange the talk as follows: After this introduction, I will briefly summarize the characteristics of the existing data, the pQCD based hard scattering models, and the main ideas and results for $A_N$ of a non-perturbative approach of the Berliner group. They are given in section 2, 3 and 4 respectively [10]. In section 5, I will discuss the connection of $A_N$ to hyperon polarization in unpolarized reactions.

2. Characteristics of the data

Data on $A_N$ for hadron production at high energies is now available for $p(\uparrow) +$
\( p(0) \rightarrow \pi \) (or \( \eta \), or \( K \), or \( \Lambda \)) + \( X \) \[3-7\], \( \bar{p}(\uparrow) + p(0) \rightarrow \pi \) (or \( K \)) + \( X \) \[5,7\], and \( \pi + p(\uparrow) \rightarrow \pi \) (or \( \eta \)) + \( X \) \[8\]. These data show the following characteristics:

1. \( A_N \) is significant in, and only in, the fragmentation region of the polarized colliding object and for moderate transverse momenta.
2. \( A_N \) depends on the flavor quantum number of the produced hadrons.
3. \( A_N \) depends also on the flavor quantum number of the polarized projectile.
4. \( A_N \approx 0 \) in the beam fragmentation region in \( \pi^- + p(\uparrow) \rightarrow \pi^0 \) or \( \eta + X \).

3. PQCD based hard scattering models

A number of mechanisms [9-21] have been proposed recently which can give non-zero \( A_N \)'s in the framework of QCD and quark or quark-parton models. They can approximately be divided into two categories: (1) perturbative QCD based hard scattering models [9,11-15] and (2) non-perturbative quark-fusion models [16-21].

In the pQCD based hard scattering models [9,11-15], the cross section for inclusive hadron production in hadron-hadron collision is expressed as convolution of the following three factors: the momentum distribution functions of the constituents (quarks, antiquarks or gluons) in the colliding hadrons; the cross section for the elementary hard scattering between a constituent of one of the colliding hadrons with one of the other; and the fragmentation function of the scattered constituent. The cross section for the elementary hard scattering can be and has been calculated [9] using pQCD. The obtained result [9] shows that, to the leading order, the asymmetry for the elementary process is proportional to \( m_q/\sqrt{s} \) (where \( m_q \) is the quark mass and \( \sqrt{s} \) is the total c.m. energy of the colliding hadron system), which is negligibly small at high energies. Hence, to describe the observed \( A_N \)'s in terms of such models, one can make use one or more of the following three possibilities: (i) Look for higher order and/or higher twist effects in the elementary processes which lead to larger asymmetries; (ii) Introduce asymmetric intrinsic transverse momentum distributions for the transversely polarized quarks in a transversely polarized nucleon; (iii) Introduce asymmetric transverse momentum distributions in the fragmentation functions for the transversely polarized quarks. All three possibilities have been discussed in the literature [11-15]. We note that the question whether (or which one of) these possible effects indeed exist(s) is not yet settled. It is clear that under the condition that pQCD is indeed applicable for the description of such processes, it should (at least in principle) be possible to find out how significantly the effects mentioned in (i) contribute to \( A_N \) by performing the necessary calculations. But, in contrast to this, the asymmetric momentum distributions mentioned in (ii) and (iii) have to be introduced by hand. Whether such asymmetries indeed exist, and how large they are if they exist, are questions which can only be answered by performing suitable
4. A non-perturbative phenomenological approach

In this section, I discuss a non-perturbative phenomenological approach. This section is based on the work done with C. Boros and T. Meng [16-21].

4.1. $A_N$ for $\pi$ production

To understand the observed asymmetries, we took a close look at the data and noted the following.

First, $A_N$ is significant only in the fragmentation region. This is a region where soft processes dominate. It is therefore clear that non-perturbative effects should contribute significantly; and it is not surprising to see that the expectations based on pQCD deviate so drastically from the data.

Second, the fact that $A_N$ has been observed mainly in the fragmentation region, that it depends on the flavor quantum numbers of the produced hadrons and on that of the projectile explicitly shows that the valence quarks play the dominating role. We recall that valence quarks should be treated as Dirac particles and orbital angular momentum is not a good quantum number in Dirac theory. Hence, orbital motion is always involved for the valence quarks even when they are in their ground states. The direction of the orbital motion is determined uniquely by the polarization of the quarks. The polarization of the valence quarks is determined by the wave function of the nucleon. This implies that, for proton, 5/3 of the 2 $u$ valence quarks are polarized in the same, and 1/3 in the opposite, direction as the proton. For $d$, they are 1/3 and 2/3 respectively.

Third, from unpolarized experiments we learned that mesons in the fragmentation region are predominately produced through the direct formation (fusion) of the valence quarks of the projectile $q_P^v$ with suitable antiseaquarks $\bar{q}_T^s$ associated with the target. (See [17-21] and the references cited therein for detailed discussions).

Fourth, since hadron are extended objects, geometrical effects should play a significant role also in single-spin processes. We expect a significant surface effect, which implies that only the mesons directly formed near the front surface of the projectile keep the information of polarization.

Having these four points in mind, we obtain a correlation between the polarization of the valence quarks and the direction of transverse motion of the produced mesons. More precisely, we obtain that mesons produced through the direct formation of upwards transversely polarized valence quarks of the projectile with suitable antiseaquarks associated with the target have large probability to go left. Hence, once we know the polarization of the projectile, we can use the baryon wave function to determine the polarization of its valence quarks and then $A_N$ for the produced
hadron. E.g., for \( p(\uparrow) + p(0) \rightarrow \pi + X \), we obtain:

- \( A_N[p(\uparrow) + p(0) \rightarrow \pi^+ + X] > 0 \), \( A_N[p(\uparrow) + p(0) \rightarrow \pi^- + X] < 0 \),
- \( 0 < A_N[p(\uparrow) + p(0) \rightarrow \pi^0 + X] < A_N[p(\uparrow) + p(0) \rightarrow \pi^+ + X] \),
- The magnitudes of all these \( A_N \)'s increase with increasing \( x_F \). (Here \( x_F \equiv 2p_\parallel/\sqrt{s} \), \( p_\parallel \) is the longitudinal momentum of the pion.)

All these qualitative features are in good agreement with the data!

Quantitatively, \( A_N \) can be expressed \([18]\) in terms of the spin-dependent quark distributions \( q^\pm(x|s, tr) \) in transversely polarized nucleon and other quantities which can be measured in unpolarized experiments. A rough estimation of \( A_N \) was made by assuming \( q^\pm(x|s, tr) \propto q_v(x|s) \). The result is shown in Fig.1.

Fig.1: \( A_N \) as a function of \( x_F \) for \( p(\uparrow)+p(0) \rightarrow \pi+X \), \( p(\uparrow)+p(0) \rightarrow \bar{\nu} \bar{\nu}+X \) and \( \bar{p}(\uparrow)+p(0) \rightarrow \bar{\nu} \bar{\nu}+X \) at 200 GeV/c. The data for pions are taken from \([4]\). For lepton pairs, the solid and dash-dotted curves correspond to \( Q = 4 \) and \( 9 \) GeV/c, respectively.

It has also been found that there exist many simple relations between the \( A_N \)'s for hadron production in reactions using different projectile-target combinations. E.g., comparing \( \bar{p}(\uparrow)+p(0) \) with \( p(\uparrow)+p(0) \), we predicted \([16]\) that there should be change of sign for \( \pi^+ \) and \( \pi^- \) productions, which is confirmed by the E704 data \([5,7]\). Predictions for processes using polarized neutron or deuteron targets have also been made \([18]\). They can be tested by future experiments.

4.2. \( A_N \) for \( K \) production

The above-mentioned analysis can be extended to \( K \)-mesons in a straightforward manner. The results are summarized in \([18,21]\). Together with \( K^0_s \approx \frac{1}{\sqrt{2}}(K^0+\bar{K}^0) \), the results there imply in particular that \( A_N[\bar{p}(\uparrow)+p(0) \rightarrow K^0_s+X] \approx A_N[p(\uparrow)+p(0) \rightarrow K^0_s+X] \), and they should be negative. This prediction in \([18]\) has also been confirmed by the E704 data \([7]\).

4.3. \( A_N \) for lepton-pair production

Not only mesons but also lepton pairs should exhibit left-right asymmetry in
single-spin processes. Here, since the production mechanism — the well known Drell-Yan mechanism — is very clear, and there is no fragmentation, measurement of such asymmetry provide a crucial test of the model and is also very helpful to distinguish the origin of the observed $A_N$.

The calculation for $A_N$ for lepton-pair is straightforward [18]. Here I just include the results for $p(\uparrow) + p(0)$ and $\bar{p}(\uparrow) + p(0)$ collisions at 200 GeV/c in Fig.1.

4.4. $A_N$ for hyperon production

$A_N$ for $\Lambda$ production [6,7] is of particular interest for the following reason: $\Lambda$ in the large $x_F$ region comes predominately from the hadronization of a spin-zero diquark. The fragmentation function has to be symmetric w.r.t. the moving direction of this diquark. The existence of $A_N$ can only be understood in terms of other effects, in particular, the picture described above. Here, we have the following three possibilities for direct formations: (a) $(u_v d_v)^P + s_s^T \rightarrow \Lambda$; (b) $u_v^P + (d_s s_s)^T \rightarrow \Lambda$; and (c) $d_v^P + (u_s s_s)^T \rightarrow \Lambda$; where $v$ stands for valence, $s$ for sea, $P$ and $T$ for projectile and target respectively. According to the proposed picture, $\Lambda$’s produced from (b) should have large probabilities to go left and thus give positive contributions to $A_N$, while those from (c) contribute negatively to it. (a) should be associated with the production of a meson directly formed through fusion of the $u$ valence quark of the projectile with an anti-sea-quark of the target. This meson should have a large probability to obtain an extra transverse momentum to the left. Thus, due to momentum conservation, the $\Lambda$ from (a) should have a large probability to obtain an extra transverse momentum to the right. This implies that (a) contributes negatively to $A_N$, opposite to that of the associatively produced meson ($\pi^+$ or $K^+$ or other). It has been shown that (a) plays the dominating role in the large, (b) and (c) in the middle and non-direct formation in the small, $x_F$ region. The interplay of these different contributions leads exactly to the observed $x_F$ dependence of $A_N$. A quantitative estimation has been made and is shown in Fig.2. Similar analysis have also been made for other hyperons. The results can be found in [20].

Fig.2: $A_N$ as a function of $x_F$ for $p(\uparrow) + p(0) \rightarrow \Lambda + X$ at 200 GeV/c. The data are taken from [6,7].
Before I end this section, I would like to emphasize that the asymmetries are expected to have the following in common: 

\( (\alpha) \) \( A_N \) for hadron is expected to be significant only in the fragmentation region of the polarized colliding object. It should be zero in the fragmentation region of the unpolarized one. 

\( (\beta) \) \( A_N \) for hadron in the fragmentation regions of the polarized colliding objects depends little on what kinds of unpolarized colliding objects are used. 

\( (\gamma) \) In contrast, \( A_N \) for lepton-pair production depends not only on the polarized colliding object but also on the unpolarized one. 

Point\((\alpha)\) implies in particular that \( A_N = 0 \) in the beam fragmentation region in \( \pi^- + p(\uparrow) \rightarrow \pi^0 \) or \( \eta + X \). This is predicted in [16-18] and has been confirmed by the experiment [8].

5. Hyperon polarization in unpolarized hadron-hadron collisions

Another kind of striking spin effect in inclusive hadron production at high energies is hyperon polarization \( P_H \). It has been observed that hyperons produced in high hadron-hadron or hadron-nucleus collisions are polarized transversely to the production plane although neither the projectile nor the target were polarized before the collisions. Data are available for the production of different kinds of hyperons in \( pp \) and \( p \)-nucleus collisions [23] and also in \( K^- \)-nucleus [24] or \( \Sigma^- \)-nucleus collisions [25].

They show the following characteristics:

1. \( P_H \) is significant in and only in the fragmentation region.
2. \( P_H \) depends on the flavor quantum number of the produced hyperon.
3. \( P_H \) depends on the flavor quantum number of the projectile.
4. \( P_H \) in the beam fragmentation region depends little on the targets.

Not only the similarities between these characteristics of the data with those for \( A_N \) but also the following seem to suggest that these two kinds of phenomena are closely related to each other. First of all, we note: \( A_N \neq 0 \) means that there is a correlation between the direction of transverse motion of the produced hadron and the polarization of the projectile. \( P_H \neq 0 \) shows that there is a correlation between the direction of transverse motion of the produced hyperon and the polarization of this hyperon. Both of them describe the correlation between transverse motion and transverse polarization. It can easily be imagined that the polarization of the hyperons observed in the fragmentation region should be closely related to that of the projectile. (This is true even for \( \Lambda \), a fact observed by E704 collaboration recently [7].) Hence, there should also be a close relation between \( A_N \) and \( P_H \). Second, crossing symmetry tell us the following: If hadron \( C \) in reaction \( A(\uparrow) + B(0) \rightarrow C + X \) has large probability to go left, \( \bar{A} \) in reaction \( \bar{C}(0) + B(0) \rightarrow \bar{A} + X \) should be polarized upwards.

In the picture we have discussed in last section, there is a relation between the transverse moving direction of the produced hadrons and the polarizations of the valence quarks. More precisely, we have: (I) Hadron produced through \( q_v(\uparrow)^P + \)
\( \bar{q}_s^T [\text{or } (q_s q_s)^T] \rightarrow M \) [or \( B \)] has large probability to go left. (II) Baryon produced through \((q_v q_v)^P + q_s^T \rightarrow B\) is associated with \((q_v^a)^P + \bar{q}_s \rightarrow M\) and has large probability to move in the opposite direction as \( M \) does. We have seen that these relations describe \( A_N \) very well. Now we show \[26\] that they describe also \( P_H \).

We take \( \Lambda \) as an example. As described in section 4.4, for large \( x_F \), the direct formation process (a), \((u_d d_u)^P + s_s^T \rightarrow \Lambda\), dominate. This process is associated with \((u_u^a)^P + s_s^T \rightarrow K^+\). If \( \Lambda \) is going left, the associatively produced \( K^+ \) should have large probability to go right. According to (I), this implies that \((u_u^a)^P\) has large probability to be downwards polarized. Since \( K \) has spin zero, \( s_s^T \) should be upwards polarized. Thus the \( s_s^T \) should downwards polarized if sea is not polarized. This implies that \( \Lambda \) should have large probability to be downwards polarized, i.e. \( P_\Lambda < 0 \). Taking the contributions from other kinds of direct formation and non-direct-formation processes into account, we calculated \[26\] \( P_\Lambda \) as a function of \( x_F \) without any new parameters. The result is shown is Fig.3.

Fig.3: Lambda polarization \( P_\Lambda \) as a function of \( x_F \). The data are taken from \[23\] or the papers cited therein.

Similar analysis can be made for other hyperons. All the qualitative results are consistent with the available data. We have also considered the processes using \( K^-\)- or \( \Sigma^-\)-beams, and we obtained that \( P_\Lambda \) in \( K^- + A \rightarrow \Lambda + X \) should be large and positive whereas that in \( \Sigma^- + A \rightarrow \Lambda + X \) should be small and negative. These are also consistent with the recent experimental observations \[24,25\].

It should also be mentioned that, with this picture in mind, it is not surprising to see that there is \[7\] a correlation between the polarization of the projectile and the produced \( \Lambda \). Although the \( ud\)-diquark is in a spin-zero state thus does not carry any information about polarization, the left \( u \)-valence quark in proton determines the polarization of the proton. Because of the mechanism of associated production described above, the polarization of this \( u \) valence quarks determines the polarization of the \( s_s \) quark which combine with the \( ud\)-diquark to form the \( \Lambda \). Thus we get a close relation between the polarization of the proton and the produced \( \Lambda \). This is consistent with the E704 data \[7\].

Last but not least, I would like to mention that the existence of these striking \( A_N \) and \( P_H \) in hadron-hadron collisions can be used to study the hadronic behavior.
of particles in other processes. It has been suggested [27] that they can be used as sensors to test whether the virtual photon in deep inelastic scattering behaves like a hadron. Details can be found in [27].

1. See, e.g., P.R. Cameron et al., Phys. Rev. D32, 3070 (1985); A.D. Krisch, in High-Energy Spin Phys., Proc. of the 9th Inter. Symp., 1990, Bonn, ed. K.H. Althoff and W. Meyer, Springer Verlag (1991), p. 20; and the references cited therein.

2. S. Saroff et al., Phys. Rev. Lett. 64, 995 (1990).

3. FNAL E581/704 Collab., D.L. Adams et al., Phys. Lett. B261, 201 (1991).

4. FNAL E704 Collab., D.L. Adams et al., Phys. Lett. B264, 462 (1991); B276, 531 (1992); Z. Phys. C56, 181 (1992).

5. A. Yokosawa, in Frontiers of High Energy Spin Physics, Proc. of the 10th Inter. Symp., Nagoya, Japan 1992, edited by T. Hasegawa et al. 6. FNAL E704 Collab., A.Bravar et al., Phys. Rev. Lett. 75, 3073 (1995).

7. A. Bravar, these Proceedings; and the references given there.

8. V.D. Apokin et al., Phys. Lett. B243, 461 (1990); and “$x_F$-dependence of the asymmetry in inclusive $\pi^0$ and $\eta^0$ production in beam fragmentation region”, Serpuhkov-Preprint (1991).

9. G. Kane, J. Pumplin and W. Repko, Phys. Rev. Lett. 41, 1689 (1978).

10. A review of these aspects can also be found in, Meng Ta-chung, in Proc. of the Workshop on the Prospects of Spin Physics at HERA, August 28-31, 1995, DESY Zeuthen. edited by J. Blümlein and W.D. Nowak, p. 121.

11. D. Sivers, Phys. Rev. D41, 83 (1990); D41, 261 (1991).

12. J. Qiu and G. Sterman, Phys. Rev. Lett. 67, 2264 (1991).

13. J. Collins, Nucl. Phys. 396, 161 (1993); J. Collins, S.F. Hepplelmann and G.A. Ladinsky, Nucl. Phys. B420, 565 (1994).

14. A.Efremov, V.Korotkiyan, O.Teryaev, Phys. Lett. B 348, 577 (1995).

15. M. Anselmino; these proceedings; and the references given there.

16. Meng Ta-chung, in Proc. of the 4th Workshop on High Energy Spin Physics, Protvino, Russia, Sept. 1991, ed. S.B. Nurushev, p. 121 (1991).

17. Liang Zuo-tang and Meng Ta-chung, Z. Phys. A344, 171 (1992).

18. C. Boros, Liang Zuo-tang and Meng Ta-chung, Phys. Rev. Lett. 70, 1751 (1993); Phys. Rev. D51, 4698 (1995).

19. Liang Zuo-tang and Meng Ta-chung, Phys. Rev. D49, 3759 (1994).

20. C. Boros and Liang Zuo-tang, Phys. Rev. D53, R2279 (1996).

21. C. Boros, Liang Zuo-tang and Meng Ta-chung, FUB-HEP/96-1.

22. C. Boros, Liang Zuo-tang, Meng Ta-chung and R. Rittel, FUB-HEP/96-4.

23. For a review of the data before 1990, see, e.g., K. Heller, in High Energy Spin Physics, Proc. of the 9th Inter. Symp., Bonn, Germany, 1990, edited by K.H. Althoff, W. Meyer (Springer-Verlag, 1991); More recent data can be found, e.g., in FNAL E761 Collab., A. Morelos et al., Phys. Rev. D52, 3777 (1995);
and the references given there.

24. S.A. Goulay et al., Phys. Rev. Lett. 56, 2244 (1986); and the references given there.

25. CERN WA89 Collab., M.I. Adamovich et al., Z. Phys. A350, 379 (1995).

26. C. Boros, Liang Zuo-tang and Meng Ta-chung, in preparation.

27. C. Boros, Liang Zuo-tang and Meng Ta-chung, FUB-HEP/95-21.