SPIN EFFECTS IN HIGH ENERGY FRAGMENTATION PROCESSES

LIANG Zuo-tang

Department of physics, Shandong University, Jinan, Shandong 250100, China

Recent measurements, in particular those on $\Lambda$ polarization and spin alignment of vector mesons in $e^+e^-$ annihilation at LEP, and those on the azimuthal asymmetry at HERA, have attracted much attention on the spin effects in high energy fragmentation processes. In this talk, we make a brief introduction to the different topics studied in this connection and a short summary of the available data. After that, we present a short summary of the main theoretical results that we obtained in studying these different topics. The talk was mainly based on the publications [5-9] which have been finished in collaboration with C.Boros, Liu Chun-xiu and Xu Qing-hua.

1. Introduction

Spin effect is a powerful tool to study the properties of the hadronic interactions and hadron structures. Since the deep understanding of different aspects in spin physics of strong interaction almost always involves hadron production, spin effects in high energy fragmentation processes have attracted much attention recently, both experimentally and theoretically (see e.g.Refs.[1-14] and the references given there). There are two main aspects in this connection, i.e., the dependence of the polarization and the momentum distribution of the produced hadron on the spin of the fragmenting quark. The former is usually referred as the spin transfer in the fragmentation process. For the latter, if the fragmenting quark is transversely polarized, we study the azimuthal angle dependence of the produced hadrons, and if the fragmenting quark is longitudinally polarized, we study a quantity which is called “jet handedness”. The first two problems are closely related to the studies of the hyperon polarization in unpolarized hadron-hadron collisions and the left-right asymmetries in singly polarized hadron-hadron collisions[14]. I will concentrate on these two problems in my talk.

2. Spin transfer in high energy fragmentation processes

Spin transfer in high energy fragmentation process is defined as the probability for the polarization of the fragmenting quark to be transferred to the produced hadron. Here, we consider $q_0 \rightarrow h(q_0...) + X$. We suppose that the $q_0$ was polarized before the fragmentation, and ask the following questions: (1) Will the $q_0$ keep its polarization? (2) How is the relation between the polarization of $q_0$ and that of the
produced $h$ which contains the $q_0$? Clearly, the answers to these questions depend on the hadronization mechanism and on the spin structure of hadrons. The study can provide useful information for both aspects. In particular, there exist now two distinctively different pictures for the spin contents of the baryons: the static quark model using the SU(6) symmetric wave function [referred as the SU(6) picture], and the picture drawn from the data for polarized deeply inelastic lepton-nucleon scattering (DIS) and SU(3) flavor symmetry in hyperon decay [referred as the DIS picture]. It is natural to ask which picture is suitable to describe the question (2) mentioned above. Obviously, the answers to these questions are also essential in the description of the puzzling hyperon transverse polarization observed already in the 1970s in unpolarized hadron-hadron reactions.

2.1. Hyperon polarization in high energy reactions as a tool to study the spin transfer in fragmentation processes

It has been pointed out that measurements of the longitudinal $\Lambda$ polarization in $e^+e^-$ annihilations at the $Z^0$ pole provide a very special check to the validity of the SU(6) picture in connecting the spin of the constituent to the polarization of the hadron produced in the fragmentation processes. This is because the $\Lambda$ polarization in this reaction obtained from the SU(6) picture should be the maximum among different models. Data are now available from both ALEPH and OPAL Collaborations. The results show that the SU(6) picture seems to agree better with the data compared with the DIS picture. (See Fig.1). This is rather surprising: the energy at LEP is very high hence the initial quarks and anti-quarks produced at the $e^+e^-$ annihilation vertices are certainly current quarks and current anti-quarks. They cannot be the constituent quarks used in describing the static properties of hadrons using SU(6) symmetric wave functions. It is thus interesting and instructive to have further checks by making complementary measurements.

We note that, to study the spin transfer in fragmentation, we need to know the polarization of $q_0$ and measure the polarization of the produced $h$. Hence, hyperon productions in lepton-induced reactions are ideal to study this problem. Here, the polarization of quark can easily be calculated using the standard model for electroweak interaction and the hyperon polarization can easily be determined by measuring the angular distribution of its decay products. We have thus made a systematic study of hyperon polarizations in different lepton-induced reactions. The obtained results can be used as further checks of the different pictures. Now we give a brief summary of the calculation method and the obtained results.

2.1.1. The calculation method

The calculation method has been formulated in different literature. Here, we summarize the main points in order to show the different inputs we need and what kinds of uncertainties we may have in the calculations.
We consider \( q_f^0 \rightarrow H_i + X \) and divide the produced \( H_i \)'s into the following groups: (a) directly produced and contain the \( q_f^0 \)'s; (b) decay products of heavier hyperons which were polarized before their decays; (c) directly produced but do not contain the \( q_f^0 \); (d) decay products of heavier hyperons which were unpolarized before their decays. Obviously, hyperons from (a) and (b) can be polarized while those from (c) and (d) are not. We obtain,

\[
P_{H_i} = \frac{\sum_j t_{H_i,j}^P P_f \langle n_{H_i,j} \rangle + \sum_j t_{H_i,H_j}^D P_{H_j} \langle n_{H_j} \rangle}{\langle n_{H_i} \rangle + \langle n_{H_i} \rangle + \langle n_{H_i} \rangle + \langle n_{H_i} \rangle}.
\]

The different quantities here are defined and obtained in the following way:

(i) \( P_f \) is the polarization of \( q_f^0 \) which is determined by the electroweak vertex.

(ii) \( \langle n_{H_i,j} \rangle \) is the average number of \( H_i \)'s which are directly produced and contain \( q_f^0 \) of flavor \( f \), and \( \langle n_{H_i,H_j} \rangle \) is that from the decay of \( H_j \)'s which were polarized; \( P_{H_j} \) is the polarization of \( H_j \); \( \langle n_{H_i} \rangle \), \( \langle n_{H_i} \rangle \), \( \langle n_{H_i} \rangle \) and \( \langle n_{H_i} \rangle \) are average numbers of \( H_i \)'s in group (a), (b), (c) and (d) respectively. These average numbers of the hyperons of different origins are determined by the hadronization mechanisms and should be independent of the polarization of the initial quarks. Hence, we can calculate them using a hadronization model which give a good description of the unpolarized data. We used Lund model implemented by JETSET or LEPTO in our calculations.

(iii) \( t_{H_i,f}^P \) is the probability for the polarization of \( q_f^0 \) to be transferred to \( H_i \) in group (a) and is called the polarization transfer factor, where the superscript \( F \) stands for fragmentation. It equals to the fraction of spin carried by the \( f \)-flavor-quark divided by the average number of quark of flavor \( f \) in \( H_i \), which is different...
in the SU(6) or the DIS picture.

(iv) $t_{H_i,H_j}^D$ is the probability for the polarization of $H_j$ to be transferred to $H_i$ in the decay process $H_j \rightarrow H_i + X$ and is called decay polarization transfer factor, where the superscript $D$ stands for decay. It is determined by the decay process and is independent of the process in which $H_j$ is produced. For the octet hyperon decays, they are extracted from the materials in Review of Particle Properties. But for the decuplet hyperons, we have to use an estimation based on the static quark model. This is a major source of the theoretical uncertainties in our calculations of the final $P_{H_i}$'s in different reactions.

We applied the method to $e^+e^- \rightarrow H_i X$, $\mu^- p \rightarrow \mu^- H_i X$ and $\nu_{\mu} p \rightarrow \mu^- H_i X$ at high energies and calculated the polarization of different octet hyperons in these reactions. We now summarize the main results as follows.

2.1.2. The results for $e^+e^-$ annihilation

For $e^+e^- \rightarrow H_i X$, we made the calculations at LEP I and LEP II energies. The results show that, all the octet hyperons should be significantly polarized and the polarizations are different in the SU(6) or the DIS picture. We also tried to make flavor separation. We found that it is impossible to separate only contribution from $u$ or $d$ to $\Lambda$. But we can enhance the contribution from $s$ fragmentation by giving some criteria to the selected events. For details, see Ref.[6].

2.1.3. The results for deeply inelastic scattering at high energies

In deeply inelastic lepton-nucleon scatterings, at sufficiently high $Q^2$ and hadronic energy $W$, hadrons in the current fragmentation region can be considered as the pure results of the fragmentation of the struck quarks. There are two advantages to study hyperon polarization in $\mu^- p \rightarrow \mu^- H_i X$: Here, flavor separation can be achieved by selecting events in certain kinematic regions; and we can study the spin transfer both in longitudinally and in transversely polarized cases. We made the calculations for different combinations of beam and target polarizations. The results show the following characteristics:

(A) hyperons are polarized quite significantly if the beam is polarized but $\Lambda$ polarization is quite small in the case of unpolarized beam and polarized target.

(B) there is significant contribution from heavier hyperon decay to $\Lambda$, it is even higher than the directly produced in most kinematic regions.

(C) for $\Sigma^+$, the decay contribution is very small and the polarization is higher than that for $\Lambda$ and the differences from the different pictures are also larger.

(D) the transverse polarization of the outgoing struck quark is obtained only in the case of using transversely polarized target. But the resulted $\Lambda$ transverse polarization is very small and the decay influence is large. In contrast, the $\Sigma^+$ polarization is larger and there is almost no decay contribution.

We made similar calculations for $\nu_{\mu} p \rightarrow \mu^- H_i X$. We found that there is a com-
plete flavor separation for $\Sigma^+$ production. It comes almost completely from $u$ quark fragmentation. This leads to a quite high $\Sigma^+$ polarization. (See Fig. 2.) However, for $\Lambda$ production, contribution from charmed baryon decay is very significant. It can completely destroy even the qualitative feature of the $\Lambda$ polarization. We thus reached the conclusion that, in deeply inelastic lepton-nucleon scattering, $\Sigma^+$ production is much more suitable to study the spin transfer in fragmentation processes. For details, see Ref. [7].

Fig. 2. $\Sigma^+$ polarization in $\nu_{\mu}p \to \mu^-\Sigma^+X$ at high energies. Here the solid and dashed lines are respectively the results obtained using the SU(6) and the DIS pictures.

2.1.4. Hyperon polarization in $\nu_{\mu} \to \mu^-HX$ at the NOMAD energies

We note that there are also measurements on $\Lambda$ polarization in $\nu_{\mu}N \to \mu^-\Lambda X$ by NOMAD collaboration at CERN. Compared the NOMAD data (See Fig. 3) with the above-mentioned theoretical results, we see a distinct difference: While the theoretical results go to zero when $x_F$ goes to zero, the data show that $|P_{\Lambda}|$ rises monotonically when $x_F$ decreases from positive $x_F$ to negative $x_F$. It does not go to zero when $x_F$ goes to zero. Does this imply that none of the pictures discussed above is suitable for $\nu_{\mu}N \to \mu^-\Lambda X$?

A more detailed analysis shows that the answer to the question should be “No!” This is because, in the above mentioned calculations, we took only the struck quark fragmentation into account and neglected the influence from the remnant of the scattered nucleon. This is a good approximation only at high energies, or more precisely, at high $Q^2$ and $W$. But, in the NOMAD experiments, the incident energies of the $\nu_{\mu}$ is $10 \sim 50$ GeV and $W$ is only of several GeV. In this case, no separation between the fragmentation products of the struck quark and those of the nucleon remnant is possible. In particular, in the region of $x_F$ around zero, the contributions from the nucleon remnant can be very important. We studied this problem numerically using the event generator LEPTO. The results show that the contributions
from the nucleon remnant indeed play an important role even at $x_F \sim 0.5$. We have to take it into account in such energy regions.

Using a valence quark model to calculate the polarization of the nucleon remnant, we made a very rough estimation of $P_\Lambda$ in $\nu\mu N \rightarrow \mu^- \Lambda X$ at the NOMAD energies by taking both the fragmentation of the struck quark and that of the nucleon remnant into account. A qualitative agreement with the data is obtained (See Fig.3 or Ref.[7] for details).

![Fig. 3. Λ polarization in $\nu\mu N \rightarrow \mu^- \Lambda X$ at the NOMAD energies. Here, the upper and lower solid curves are respectively the results obtained using the SU(6) picture when the fragmentation of the nucleon remnant is neglected or taken into account. Those dotted lines are the corresponding results using the DIS picture.]

2.1.5. Longitudinal hyperon polarization in high $p_\perp$ jets in polarized $pp$ collisions

Last but not least, we emphasize that the spin effects in fragmentation processes can also be studied in polarized $pp$ collisions (e.g. at RHIC) by measuring the hadrons in high $p_\perp$ jets. Here, it is envisaged that these hadrons are pure products of the fragmentation of the scattered quark (antiquark or gluon). Since we have many different hard subprocesses (e.g. $qq \rightarrow qq, qg \rightarrow qg$, or $gg \rightarrow gg$) which contribute to high $p_\perp$ jets, the situation here is much more complicated than that in the lepton induced reactions discussed above. We have in particular the contribution from gluon fragmentation. This, on the one hand, make the study more difficult since we know much less about gluon polarization and fragmentation. On the other, it makes the study also more interesting since we can use it to study not only quark but also gluon fragmentation.

A simple Monte-Carlo study shows that, for moderately high $p_\perp$ (e.g. $3 \sim 5$ GeV), gluon fragmentation dominates. This is a kinematic region which is suitable for studying gluon fragmentation. But, for very high $p_\perp$ and large $\eta$, quark fragmentation dominates. Here, we can apply the above-mentioned the method to
calculate the longitudinal hyperon polarizations. Such calculations have also been carried out. An example of the obtained results is given in Fig.4.

Fig. 4. $\Sigma^+$ polarization in high $p_\perp$ jets in $pp$ collisions at $\sqrt{s} = 500\text{GeV}$ and $p_\perp > 13\text{GeV}$.

2.2. Spin alignment of vector mesons in high energy reactions

Another aspect which is related to the problem of spin transfer in fragmentation is the spin alignment of vector meson in high energy reactions. It is clear that the polarization of the fragmenting quark can also be transferred to the vector meson $V$. This effect can be studied by measuring $\rho_{00}^V$, the 00 component of the helicity density matrix of $V$, which is just the probability for $V$ to be in the helicity zero state. Data are available for $e^+e^-$ annihilation at the $Z^0$-pole at LEP. It shows that, for vector mesons with high momentum fraction, $\rho_{00}^V$ is much larger than $1/3$, the result expected in the unpolarized case.

A simple calculation shows that these data imply a significant polarization of the $\bar{q}$ that is created in the fragmentation and combines with the polarized $q_f^0$ to form the vector meson. The polarization has a simple relation to that of the $q_f^0$, i.e., $P(\bar{q}) = -\alpha P(q_f^0)$, where $\alpha \approx 0.5$ is a constant. Using this we got a good fit to the data. It should be interesting to see whether this relation is also true in other processes where polarized $q_f^0$ is produced. We thus apply it to other reactions and made predictions for the spin alignments of vector mesons in these processes. They can be checked by future experiments. For details, see Ref.[8].

3. Azimuthal asymmetry in the fragmentation of a transversely polarized quark

In the fragmentation of a transversely polarized quark, the products can have an azimuthal asymmetry. The first measurement in this connection has been carried out by HERMES, and the results show that such an effect indeed exists at that energy. What we would like to point out here is the following: The existence of such
an azimuthal asymmetry is a direct consequence of Lund string fragmentation model due to conservation of energy-momentum and angular momentum. The model was first used to spin effects in 1979 to explain the unexpected Λ polarization in unpolarized pp collisions. By applying it to the fragmentation of a transversely polarized quark, we obtain a significant azimuthal asymmetry. We are now working on the numerical calculations along this line in collaboration with the Lund group. Predictions for semi-inclusive deeply inelastic lepton-nucleon scattering and hadrons in high $p_T$ jets in transversely polarized pp collisions will be available soon.

Acknowledgements

It is a great pleasure for me to thank the organizer for inviting me to give the talk. This work was supported in part by the Natural National Science Foundation (NSFC) and the Education Ministry of China.

References

1. ALEPH Collab., D. Buskulic et al., Phys. Lett. B374, 319 (1996); OPAL Collab., K. Ackerstaff et al., Euro. Phys. J. C2, 49 (1998).
2. OPAL Collab., K. Ackerstaff et al., Phys. Lett. B412, 210 (1997).
3. NOMAD Collab., P. Astier et al., Nucl. Phys. B558, 3 (2000).
4. HERMES Collab., A. Airapetian et al., Phys. Rev. Lett. 84, 4047 (2000); Phys. Rev. D64, 097101 (2001).
5. C. Boros, and Liang Zuo-tang, Phys. Rev. D57, 4491 (1998).
6. Liu Chun-xiu and Liang Zuo-tang, Phys. Rev. D62, 094001 (2000).
7. Liu Chun-xiu, Xu Qing-hua and Liang Zuo-tang, Phys. Rev. D64, 073004 (2001); talk by Liu in this conference and paper in preparation.
8. Xu Qing-hua, Liu Chun-xiu and Liang Zuo-tang, Phys. Rev. D63, 111301(R) (2001); talk by Xu in this conference and paper in preparation.
9. Xu Qing-hua and Liang Zuo-tang, Chin. Phys. Lett. 18, 1021 (2001).
10. R.L. Jaffe, and Ji Xiangdong, Phys. Rev. Lett. 67, 552 (1991); Nucl. Phys. B 375, 527 (1992); and talks in this conference.
11. G. Gustafson and J. H"akkinen, Phys. Lett. B303, 350 (1993).
12. A. Kotzian, A. Bravar, D. Harrach, Eur. Phys. J. C2, 329 (1998).
13. B.Q. Ma, I. Schmidt, and J.J. Yang, Phys. Rev. D61, 034017 (2000); B.Q. Ma, I. Schmidt, J. Soffer, and J.J. Yang, Phys. Rev. D62, 114009 (2000); 63, 037501 (2001); talks by Ma and Soffer in the conferences and references given there.
14. M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B481, 253 (2000); M. Anselmino, D. Boer, U. D’Alesio, F. Murgia, Euro. Phys. J. C21, 501 (2001); hep-ph/0109186 and talks by Anselmino and D’Alesio in this conference.
15. Ma Jian-ping, hep-ph/0111237 and talk in this conference.
16. For a review dedicated to this topic, see e.g., Liang Zuo-tang and C. Boros, Inter. J. Mod. Phys. A15, 927 (2000).
17. B. Andersson, G. Gustafson, G. Ingelman, Phys. Lett. B85, 417 (1979).