Hadronization mechanisms and longitudinal polarization of Λ in $e^+e^-$ annihilation at high energies

Liang Zuo-tang
Department of Physics, Shandong University,
Jinan, Shandong 250100, CHINA

Abstract

We suggested that longitudinal polarization of Lambda produced in $e^+e^-$ annihilation at LEP energies can provide useful information on hadronization mechanism in general and on testing the validity of different pictures for the spin content of baryon in describing the fragmentation process in particular. We present the results obtained from the calculations based on two very much different pictures. We compare the results with the recent ALEPH data and make suggestions for future measurements.

*Work supported in part by the National Natural Science Foundation of China
In this talk, I would like to discuss a question which we met in our study on spin effects in hadron production processes and the efforts we made toward solving this problem. The work which I will present in the following has been done in collaboration with Dr. Boros. The main ideas and results have already been published in [1].

As you certainly know, there exist now in literature two completely different pictures for the spin contents of the baryons: According to the static (or constituent) quark model, spin of a baryon belonging to the \( J^P = \frac{1}{2}^+ \) octet is completely determined by the three valence quarks. The sum of the spins of these valence quarks is the spin of the baryon. This picture is very successful in describing the static properties of the baryons. But according to the data from polarized deep inelastic lepton-nucleon scattering [2] and SU(3) flavor symmetry in hyperon decay, the sum of the spins of the three valence quarks is only a small fraction of the spin of the nucleon. A large part of the baryon spin originates from the orbital angular momenta of the valence quarks and/or from the sea (i.e. the sea quarks, antiquarks and gluons). Hence, we met a question: Which picture is suitable in describing the spin effects in the fragmentation process? Obviously, the answer to this question can be different in different hadronization models. Hence, study of this question should be able to provide also further test of these models. Usually, we say that, in the hadronization process, a quark and an antiquark combine to form a meson or three quarks combine together to form a baryon. In this way, we consider only the valence quarks of the hadron but neglect the sea. It seems that here the SU(6) wave function based on the static quark model should be suitable. Surely, whether this is indeed true is a priori unknown and should be studied in experiments. We found that polarization of Lambda
is an ideal place to investigate this problem because of the following: First, the spin structure of Lambda in the static quark model is very special: the spin of Lambda is completely carried by the $s$ valence quark while the $u$ and $d$ have completely no contribution. This picture is completely different from that drawn from the data of deep-inelastic lepton-nucleon scattering [2] and SU(3) flavor symmetry in hyperon decay. The deep inelastic scattering data, together with the SU(3) flavor symmetry for hyperon decay, suggest that [3] the $s$ quark carries only about 60% of the Lambda spin, while the $u$ or $d$ quark each carries about $-20\%$. Second, the polarization of the produced Lambda can easily be determined in experiments by measuring the angular distribution of the decay products. Besides, striking polarization effects have been observed for hyperons produced in unpolarized hadron-hadron collisions experiments [4]. Such effects have been observed for more than two decades and remain as a puzzle for the theoretians. Clearly, the study of the above mentioned question should be able to provide some useful information of this problem; and this makes the study even more interesting and instructive.

Polarization effects for Lambda produced in high energy reactions have been studied in different connections [3,5-13]. In some of these discussions [3,5-10], current quark picture has been used thus the picture for the spin content of Lambda drawn from the polarized deep inelastic lepton nucleon scattering data should be applicable. But in the other [11-13], it is assumed that Lambda spin is completely determined by the $s$ quark thus picture of the static quark model should be applicable. No discussion has been made yet to the question of which of them is more suitable.

It is known from the standard model of electroweak interaction that the $s$ quark produced in $e^+e^-$ annihilation at high energies is longitudinally po-
larized [14]. Hence it is expected [14] that the Lambda which contains this s quark should also be longitudinally polarized and such Lambda polarization can be measured in experiments. Theoretically, this Lambda polarization can be calculated and the results should be quite different using the above mentioned two different pictures for the spin contents of Lambda. Hence, measurements of the polarization should be able to show which picture is more suitable in describing such spin effects. Calculations of the longitudinal Lambda polarization in $e^+e^-$ annihilation at the Z-pole has been made [15,1] using the picture of the static quark model, and using the picture drawn from the data of deep inelastic scattering respectively. These calculations are in principle exactly the same. I will therefore briefly summarize the calculations made in [1] and their comparison with those in [15] and the available data [16] in the following.

Here, we first consider the contribution of the Lambdas which are directly produced in the hadronization process. Such hyperons are divided into two groups: those which contain the leading $u$, $d$ or $s$ quark and those which do not. The former kind of Lambdas, i.e. those which contain the initial $u$, $d$ or $s$ quark from $e^+e^-$ annihilation, can be polarized since the initial $u$, $d$ or $s$ quark is longitudinally polarized. But the latter are assumed not to be polarized. This is not only true in the popular hadronization models such as LUND model [17] but also consistent with the experimental observations that both hyperon polarization in unpolarized hadron-hadron collisions and left-right asymmetries in inclusive production processes in single spin hadron-hadron collisions in the central rapidity region are consistent with zero although they are quite large in the fragmentation region. (See e.g. [4] and the references given there). The polarization of former kind of Lambda
is different in different pictures for the spin structure of \( \Lambda \). More precisely, the polarization of such \( \Lambda \) is equal to the fraction of spin carried by the quark which has the flavor of the initial quark multiplied by the polarization of this initial quark. The polarizations of the initial quarks from \( e^+e^- \) annihilations are determined by the standard model for electroweak interactions, and given by [14],

\[
P_f = -\frac{A_f(1 + \cos^2 \theta) + B_f \cos \theta}{C_f(1 + \cos^2 \theta) + D_f \cos \theta}
\]

where \( \theta \) is the angle between the outgoing quark and the incoming electron, the subscript \( f \) denotes the flavor of the quark and

\[
A_f = 2a_fb_f(a_f^2 + b_f^2) - 2(1 - \frac{m_Z^2}{s})Q_{fab_f},
\]

\[
B_f = 4ab(a_f^2 + b_f^2) - 2(1 - \frac{m_Z^2}{s})Q_{faf_b},
\]

\[
C_f = \frac{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}{s^2}Q_f^2 + (a_f^2 + b_f^2)(a_f^2 + b_f^2) - 2(1 - \frac{m_Z^2}{s})Q_{faaf_f},
\]

\[
D_f = 8aba_fb_f - 4(1 - \frac{m_Z^2}{s})Q_fbb_f,
\]

where \( m_Z \) and \( \Gamma_Z \) are the mass and decay width of \( Z \); 

\[
a = \frac{-1 + 4 \sin^2 \theta_W}{2 \sin 2\theta_W},
\]

\[
b = -\frac{1}{2 \sin 2\theta_W},
\]

\[
a_f = \begin{cases} 
\frac{1 - 8 \sin^2 \theta_W/3}{2 \sin 2\theta_W}, & \text{for } f = u, c, t, \\
\frac{1 + 4 \sin^2 \theta_W/3}{2 \sin 2\theta_W}, & \text{for } f = d, s, b,
\end{cases}
\]

\[
b_f = \begin{cases} 
\frac{1}{2 \sin 2\theta_W}, & \text{for } f = u, c, t, \\
-\frac{1}{2 \sin 2\theta_W}, & \text{for } f = d, s, b,
\end{cases}
\]

are the axial and vector coupling constants of electron and quark to \( Z \) boson, which are functions of the Weinberg angle \( \theta_W \). (See also table 1 in [14]).
Table 1: Fractional contributions $\Delta U$, $\Delta D$ and $\Delta S$ of the light flavors to the spin of baryons in the $J^P = \frac{1}{2}^+$ octet calculated using the static quark model (static QM) and those obtained using the data for deep inelastic lepton-nucleon scattering and those for hyperon decay under the assumption that SU(3) flavor symmetry is valid. The first column shows the obtained expressions in terms of $\Sigma$, $F$ and $D$. The static QM results are obtained by inserting $\Sigma = 1$, $F = 2/3$ and $D = 1$ into these expressions and those in the third column are obtained by inserting $\Sigma = 0.28$, obtained from deep inelastic lepton-nucleon scattering experiments [2], and $F + D = g_A/g_V = 1.2573, F/D = 0.575$ obtained [18,19] from the hyperon decay experiments.

|         | $\Lambda$                      | $\Sigma^0$                      |
|---------|---------------------------------|---------------------------------|
|         | static QM | DIS data                      | static QM | DIS data                      |
| $\Delta U$ | $\frac{1}{4}(\Sigma - D)$     | 0                                | $\frac{1}{4}(\Sigma + D)$     | 2/3                                | 0.36          |
| $\Delta D$ | $\frac{1}{4}(\Sigma - D)$     | 0                                | $\frac{1}{4}(\Sigma + D)$     | 2/3                                | 0.36          |
| $\Delta S$ | $\frac{1}{3}(\Sigma + 2D)$    | 1                                | $\frac{1}{3}(\Sigma - 2D)$    | -1/3                               | -0.44         |
|         | $\Xi^0$                      |                                  | $\Xi$                              |
|         | static QM | DIS data                      | static QM | DIS data                      |
| $\Delta U$ | $\frac{1}{4}(\Sigma - 2D)$     | -1/3                             | $\frac{1}{4}(\Sigma + D) - F$   | 0                                  | -0.10         |
| $\Delta D$ | $\frac{1}{4}(\Sigma + D) - F$   | 0                                | $\frac{1}{4}(\Sigma - 2D)$      | -1/3                               | -0.44         |
| $\Delta S$ | $\frac{1}{3}(\Sigma + D) + F$  | 4/3                             | $\frac{1}{3}(\Sigma + D) + F$   | 4/3                                | 0.82          |

Averaging over $\theta$, we obtain $P_f = -0.67$ for $f = u, c, t$ and $P_f = -0.94$ for $f = d, s, b$.

The fractional contributions ($\Delta U_\Lambda$, $\Delta D_\Lambda$, and $\Delta S_\Lambda$) of different flavors ($u$, $d$ and $s$) to Lambda spin are calculated using the deep inelastic lepton-nucleon scattering data on $\Gamma_1 \equiv \int_0^1 g_1(x)dx$ [where $g_1(x)$ is the spin-dependent structure] and those for the constants $F$ and $D$ in hyperon decay. The detailed procedure of extracting the $\Delta U_\Lambda$, $\Delta D_\Lambda$, and $\Delta S_\Lambda$ from the data for $\Gamma_1^p$ for proton, and those for $F$ and $D$ is standard and is summarized in the Appendix of [1]. The obtained results are given in Table 1.

We next consider the contribution of those Lambda’s from the decay of other hyperons in the same octet as Lambda. These hyperons can also be
polarized if they contain the initial $u$, $d$ or $s$ quark, and the polarization can be transferred to Lambda’s in the decay processes. The polarization of such Lambda is thus equal to the polarization of the hyperon multiplied by the probability for the polarization to be transferred to Lambda. Hence, to calculate such contribution, we need to calculate the polarization of the such hyperon before it decays and the probability for the polarization to be transferred to Lambda in the decay process. The polarization of hyperon in the same octet as Lambda can easily be calculated using exactly the same method as that for Lambda. There are three such hyperons, i.e. $\Sigma^0$, $\Xi^0$ and $\Xi^-$ which may decay into $\Lambda$. We calculated the fractional contributions of different flavors of quarks to their spins in the same way as that for Lambda and obtained the results shown in Table 1. These results are as reliable as those for Lambda, and are therefore [3] as reliable as those for the nucleons. $\Sigma^0$ decay into $\Lambda$ by emitting a photon, i.e., $\Sigma^0 \rightarrow \Lambda \gamma$. Whether the polarization of $\Sigma^0$ is transferred to the produced Lambda in this decay process has been discussed in [20]. It has been shown that, on the average, the produced $\Lambda$ is also polarized (in the opposite direction as $\Sigma^0$) if $\Sigma^0$ was polarized before its decay, and the polarization is $-1/3$ of that of the $\Sigma^0$. The hyperon $\Xi$ decays into $\Lambda$ through $\Xi \rightarrow \Lambda \pi$, which is a parity non-conserving decay and is dominated by S-wave. The polarization of the produced $\Lambda$ is equal to that of the $\Xi$ multiplied by a factor $(1 + 2\gamma)/3$, where $\gamma$ can be found in review of particle properties [18] as $\gamma = 0.87$.

Unfortunately, at present, it is only possible to estimate the contribution from the decays of hyperons belongs to the baryon decuplet using the picture of the static quark model. It is however impossible to calculate the polarization of the produced decuplet hyperons in a way consistent with that
for those in the octet using the picture derived from deep-inelastic scat-
ering data [2]. This is because no deep-inelastic scattering data on any one
of such decuplet baryons is available. It is therefore impossible to calculate
the fractional contributions of different flavors to the spin of such hyperon.
Hence, it is impossible to estimate the contributions of decays of such hyper-
ons which contain the initial $u$, $d$ or $s$ quark to the polarization of Lambda
in the final state of $e^+e^-$ annihilations in the same way as that for the octet
hyperons. Qualitative analysis suggests that the influences of such hyperons
should not be very large. This is because, first, their production rates are rel-
atively small, and second, since the mass differences between such hyperons
and Lambda are relative large, their decays contribute mainly to Lambda’s
in the central region of the $e^+e^-$ annihilation (i.e. those with relatively small
momenta). This region is dominated by those Lambda’s which do not contain
the initial quark and are unpolarized.

To make a quantitative estimation, we need a hadronization model to cal-
culate all the different contributions to the Lambda’s from all the different
sources discussed above. For this purpose, we used the LUND model [17] as
implemented by JETSET [21]. We explicitly calculated the different contri-
butions, and obtained the results shown in Fig.1. We see in particular that
the contribution from the decay of the decuplet hyperons is indeed relatively
small. We calculated Lambda polarization $P_\Lambda$ for the following two cases: In
the first case, we completely neglect the contribution from decuplet hyperon
decay to $P_\Lambda$ and obtained the results shown by the solid line in Fig.2. In the
second case, we used the results for the polarization of the decuplet hyperons
obtained from the static quark model as an approximation to estimate the
contribution of such hyperon decay to $P_\Lambda$. We added the results to $P_\Lambda$ and
Figure 1: Fractional contributions to Lambdas produced in $e^+e^-$ annihilation at LEP energy from different sources: The solid line denotes those Lambdas which are produced directly and contain the initial $u$, $d$ or $s$ quark; the dash-dotted and dashed lines are those from decay of octet ($\Sigma^0$, $\Xi$) and decuplet hyperons ($\Sigma^*$, $\Xi^*$) which contain the initial quarks. $z \equiv 2p/\sqrt{s}$, where $p$ is the momentum of the produced Lambda and $\sqrt{s}$ is the total center of mass energy of the $e^+e^-$ system.

obtained the dashed line in Fig.2. For comparison, we included in the figure also the results from the static quark model without (dotted line) or with (dash-dotted line) the contributions from decuplet hyperon decay.

From these results, we see that there is indeed a significant difference between those obtained in [15] based on the picture of the static quark model and those obtained in the present estimation using a picture based on the polarized deep-inelastic lepton-nucleon scattering data [2] and SU(3) flavor symmetry for hyperon decay. It seems that the ALEPH data [16] favors the former but cannot exclude the latter since the error bars are still too large. We see also that, although the influence from the decuplet is indeed relative small, but it is not negligible in particular for moderate $z$. We can also see that further measurements of $P_{\Lambda}$ with higher accuracy are needed.
Figure 2: Longitudinal polarization of Lambda, $P_\Lambda$, from $e^+e^-$ annihilation at LEP energy as a function of $z$. (See text for more details).

to distinguish between these two kinds of models. The large $z$ region is most suitable for such a study since in this region not only the magnitude of $P_\Lambda$ itself is large but also the difference between the prediction of the two different models is large. It will be also particularly helpful to measure the polarization only for those Lambda’s which are not decay products of decuplet hyperons.

References

[1] C. Boros, and Liang Zuo-tang, Phys. Rev. D57, 4491 (1998).

[2] For a review of data, see e.g., G.K. Mallot, in Proc. of the 12th Inter. Symp. on Spin Phys., Amsterdam 1996, edited by de Jager et al., World Scientific (1997), p.44.

[3] R.L. Jaffe, Phys. Rev. D54, R6581 (1996).
[4] For a review of data, see e.g., K. Heller, in Proc. of the 12th Inter. Symp. on Spin Phys., Amsterdam 1996, edited by de Jager et al., World Scientific (1997), p.23.

[5] X. Artru and M. Mekhfi, Z. Phys. C45, 669 (1990); Nucl. Phys. A532, 351 (1991).

[6] J.L. Cortes, B. Pire and J.P. Ralston, Z. Phys. C55, 409 (1992).

[7] R.L. Jaffe, and Ji Xiangdong, Phys. Rev. Lett. 67, 552 (1991); Nucl. Phys. B375, 527 (1992).

[8] M. Burkardt and R.L. Jaffe, Phys. Rev. Lett. 70, 2537 (1993).

[9] J. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. C69, 467 (1996).

[10] Lu Wei, Phys. Lett. B373, 223 (1996); Lu Wei and Ma Bo-qiang, Phys. Lett. B357, 419 (1995).

[11] B. Andersson, G. Gustafson and G. Ingelman, Phys. Lett. 85B, 417 (1979).

[12] T.A. DeGrand and H.I. Miettinen, Phys. Rev. D24, 2419 (1981).

[13] Liang Zuo-tang and C. Boros, Phys. Rev. Lett. 79, 3608 (1997).

[14] J.E. Augustin and F.M. Renard, Nucl. Phys. B162, 341 (1980).

[15] G.Gustafson and J.Häkkinen, Phys. Lett. B303, 350 (1993).

[16] ALEPH-Collaboration; D. Buskalic et al., Phys. Lett. B 374 (1996) 319.
[17] B. Anderson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Phys. Rep. 97, 31 (1983).

[18] R.M. Barnett et al., Phys. Rev. D 54, 1 (1996).

[19] F.E. Close and R. G. Roberts, Phys. Lett. B 316, 165 (1993).

[20] R. Gatto, Phys. Rev. 109, 610 (1958).

[21] T. Sjöstrand, Comp. Phys. Comm. 39, 347 (1986).