Spin content of Λ and its longitudinal polarization in e^+e^- annihilation at high energies

C. Boros
Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany
and Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide, Australia 5005

Liang Zuo-tang
Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany
and Department of Physics, Shandong University, Jinan, Shandong 250100, China
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Longitudinal polarization of Λ produced in e^+e^- annihilation at CERN LEP energies is calculated in a picture for the spin content of Λ which is consistent with the polarized deep inelastic lepton-nucleon scattering data and SU(3) flavor symmetry for hyperon decay, so that the spin of Λ is not completely carried by its s-valence quark. A comparison with the recent ALEPH data and the results of earlier calculations based on the static quark model, in which the spin of Λ is completely determined by the s quark, is given. The result shows that further measurements of such polarization should provide useful information as to the question of which picture is more suitable in describing spin effects in the fragmentation processes. [S0556-2821(98)06205-5]

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There now exist in the literature two completely different pictures for the spin content of baryons: According to the static (or constituent) quark model, the 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. However, according to the data from polarized deep inelastic lepton-nucleon scattering [1] 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 it is natural to ask which picture is suitable to describe the spin effects in the quark fragmentation process. Obviously, the answer to this question is *a priori* unknown, and should be studied in experiments. Polarization of Λ is an ideal place to investigate this problem because of the following: First, the spin structure of Λ in the static quark model is very special: the spin of Λ is completely carried by the s valence quark, while the u and d quarks make no contribution. This picture is completely different from that drawn from the data of deep-inelastic lepton-nucleon scattering [1] 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 [2] the s quark carries only about 60% of the Λ spin, while the u or d quark each carries about -20%. Second, the polarization of the produced Λ can easily be determined in experiments by measuring the angular distribution of the decay products. In addition, striking polarization effects were observed for hyperons produced in unpolarized hadron-hadron collision experiments [3]. Such effects were observed for more than two decades, and remain as a puzzle for theorists. Clearly, the study of the above-mentioned question should be able to provide some useful information about this problem; this makes the study even more interesting and instructive.

The polarization effects for Λ produced in high-energy reactions were studied in different connections [2,4–12]. In some of these discussions [2,4–9], the current quark picture was used; thus the picture for the spin content of Λ drawn from the polarized deep inelastic lepton-nucleon scattering data should be applicable. But in the other [10–12], it is assumed that Λ spin is completely determined by the s quark, thus the picture of the static quark model should be applicable. No discussion has been made yet as 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 polarized [13]. Hence it is expected [13] that the Λ which contains this s quark should also be longitudinally polarized, and such Λ polarization can be measured in experiments. Theoretically, this Λ polarization can be calculated, and the results should be quite different using the above-mentioned two different pictures for the spin contents of Λ. Hence measurements of the polarization should be able to show which picture is more suitable to describe such spin effects. A calculation of the longitudinal Λ polarization in e^+e^- annihilation at the Z pole was made [14] using the picture of the static quark model, but no calculation has yet been made [15] using the picture drawn from the data of deep inelastic scattering.

More recently, longitudinal Λ polarization in e^+e^- annihilation at the Z pole (which is therefore dominated by those from Z decay) was measured [16] by the ALEPH Collaboration at CERN. A comparison of the data [16] with the calculated results of Ref. [14] was made [16], and they are in good agreement with each other. This means the above-mentioned static quark model picture for Λ spin structure is consistent with the data [16]. Does this mean that the static (or constituent) quark model, but not that from deep inelastic lepton-nucleon scattering, should be used in the fragmentation process? To answer this question, calculations have to be carried out using a picture which is consistent with the deep inelastic scattering data, so that a comparison with the ALEPH data [16] can be made.

TABLE I. Fractional contributions ΔU, ΔD, and ΔS 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 Σ, F, and D. The static QM results are obtained by inserting $\Sigma=1$, $F=\frac{2}{3}$, 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 (DIS) experiments [1], and $F+D=g_A/g_V=1.2573$ and $F/D=0.575$ obtained [19,24] from the hyperon decay experiments.

		Λ static QM	DIS data		Σ^0 static QM	DIS data
ΔU	$\frac{1}{3}(\Sigma-D)$	0	-0.17	$\frac{1}{3}(\Sigma+D)$	2/3	0.36
ΔD	$\frac{1}{3}(\Sigma-D)$	0	-0.17	$\frac{1}{3}(\Sigma+D)$	2/3	0.36
ΔS	$\frac{1}{3}(\Sigma+2D)$	1	0.62	$\frac{1}{3}(\Sigma-2D)$	$-1/3$	-0.44
		Ξ^0 static QM	DIS data		Ξ^- static QM	DIS data
ΔU	$\frac{1}{3}(\Sigma-2D)$	$-1/3$	-0.44	$\frac{1}{3}(\Sigma+D)-F$	0	-0.10
ΔD	$\frac{1}{3}(\Sigma+D)-F$	0	-0.10	$\frac{1}{3}(\Sigma-2D)$	$-1/3$	-0.44
ΔS	$\frac{1}{3}(\Sigma+D)+F$	4/3	0.82	$\frac{1}{3}(\Sigma+D)+F$	4/3	0.82

In this Brief Report, we present the results of such a calculation, and compare them with those obtained in [14] and the ALEPH data [16]. The calculations were carried out using the same method as that in Ref. [14]. Here we first consider the contribution of the Λ's 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 latter kind of Λ's, i.e., those which do not contain the initial u, d, or s quark from e^+e^- annihilation, are assumed [14] not to be polarized [17] but the former kind can be polarized since the initial u, d, or s quark is longitudinally polarized. The polarization of such a Λ is different in different pictures for the spin structure of Λ. More precisely, the polarization of such a Λ 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 [13]

$$P_f=-\frac{A_f(1+\cos^2\theta)+B_f\cos\theta}{C_f(1+\cos^2\theta)+D_f\cos\theta}, \tag{1}$$

where θ is the angle between the outgoing quark and the incoming electron, the subscript f denotes the flavor of the quark, and

$$A_f=2a_fb_f(a^2+b^2)-2(1-m_z^2/s)Q_fab_f, \tag{2}$$

$$B_f=4ab(a_f^2+b_f^2)-2(1-m_z^2/s)Q_fa_fb, \tag{3}$$

$$C_f=\frac{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}{s^2}Q_f^2+(a^2+b^2)(a_f^2+b_f^2)$$
$$-2(1-m_z^2/s)Q_faa_f, \tag{4}$$

$$D_f=8aba_fb_f-4(1-m_z^2/s)Q_fbb_f, \tag{5}$$

where m_Z and Γ_Z are the mass and decay width of Z; a, b, a_f, and b_f are the axial and vector coupling constants of the electron and quark to the Z boson, which are functions of the Weinberg angle θ_W. (See Table I in Ref. [13].) Averaging over θ, we obtain $P_f=-0.67$ for $f=u$, c, and t, and $P_f=-0.94$ for $f=d$, s, and b.

The fractional contributions (ΔU_Λ, ΔD_Λ, and ΔS_Λ) of different flavors (u, d, and s) to Λ 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 ΔU_Λ, ΔD_Λ, and ΔS_Λ from the data for Γ_1^p for the proton, and those for F and D, is summarized in the Appendix. The results obtained are given in Table I.

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

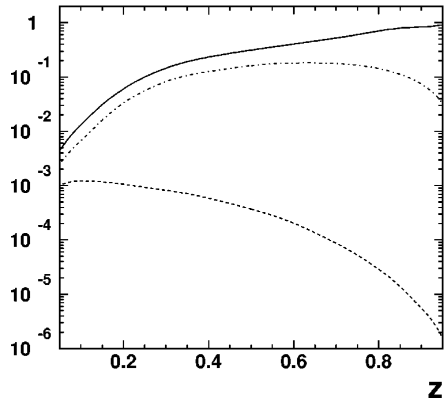

FIG. 1. Fractional contributions to Λ's produced in e^+e^- annihilation at LEP energy from different sources: The solid line denotes those Λ's which are produced directly, and contain the initial u, d, or s quark; the dash-dotted and dashed lines are those from the decay of the octet (Σ^0, Ξ) and decuplet hyperons (Σ^*, Ξ^*) which contain the initial quarks. $z\equiv 2p/\sqrt{s}$, where p is the momentum of the produced Λ, and $\sqrt{s}$ is the total center-of-mass energy of the e^+e^- system.

multiplied by a factor $(1+2\gamma)/3$, where γ can be found in review of particle properties [19] as $\gamma=0.87$.

It is now still impossible to calculate the polarization of the produced hyperons which belong to the baryon decuplet in a way consistent with that for those in the octet. This is because no deep-inelastic scattering data on any one of such baryons is available. It is therefore impossible to calculate the fractional contributions of different flavors to the spin of such a hyperon. Hence it is impossible to estimate the contributions of decays of such hyperons which contain the initial u, d or s quark to the polarization of Λ 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 relatively small, and second, since the mass differences between such hyperons and Λ are relative large, their decays contribute mainly to Λ's in the central region of the e^+e^- annihilation (i.e., those with relatively small momenta). This region is dominated by those Λ's which do not contain the initial quark and are unpolarized.

To make a quantitative estimation, we need a hadronization model to calculate all the different contributions to the Λ's from all the different sources discussed above. For this purpose, we used, as in Ref. [14], the LUND model [20] as implemented by JETSET [21]. We explicitly calculated the different contributions, 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 Λ polarization P_Λ for the following two cases: In the first case, we completely neglected the contribution from decuplet hyperon decay to P_Λ, 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_Λ. We added the results to P_Λ, and obtained the dashed line in Fig. 2. For comparison, we also included in the figure the results from the static quark model without (dotted line) or with (dash-dotted line) contributions from decuplet hyperon decay.

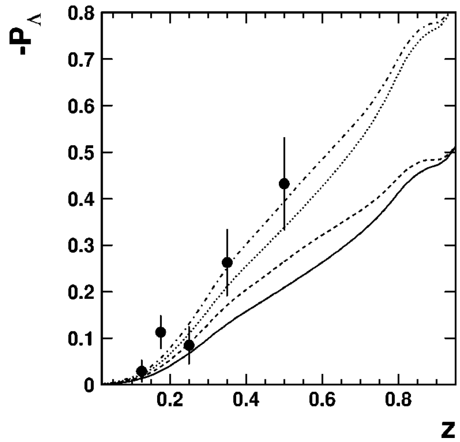

FIG. 2. Longitudinal polarization of Λ, P_Λ, from e^+e^- annihilation at LEP energy as a function of z. (See the text for more details.)

From these results, we see that there is indeed a significant difference between those results obtained in Ref. [14] 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 [1] and SU(3) flavor symmetry for hyperon decay. It seems that the ALEPH data [16] favor the former, but cannot exclude the latter, since the error bars are still too large. We also see that, although the influence from the decuplet is indeed relative small, it is not negligible in particular for moderate z. We can also see that further measurements of P_Λ with higher accuracy are needed 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_Λ 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 Λ's which are not decay products of decuplet hyperons.

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APPENDIX

The way of extracting fractional contributions of quarks of different flavors to the spin of a baryon in the $J^P=\frac{1}{2}^+$ octet from $\Gamma_1^p\equiv\int_0^1 g_1^p(x)dx$ obtained in deep-inelastic lepton-proton scattering experiments and the constants F and D obtained from hyperon decay experiments, is now in fact quite standard [1]. In this appendix we present the main ingredients used in this procedure in order to remind the readers of the assumptions one uses here, and to show how one extends it to obtain the results for other baryons in the same octet as Λ.

According to the quark parton model [22], we have

$$g_1(x)=\tfrac{1}{2}\sum_q e_q^2[\Delta q(x)+\Delta \overline{q}(x)], \qquad \text{(A1)}$$

where $\Delta q(x)=q^{+}(x)-q-(x)$ and $\Delta \overline{q}(x)=\overline{q}^{+}(x)-\overline{q}^{-}(x)$ are the difference between the number density of quarks (antiquarks) of flavor q polarized in the same, and that of those polarized in the opposite, longitudinal direction as the nucleon; e_q is the electric charge of the quark in unit of electron charge. Denoting $\Delta Q\equiv\int_0^1[\Delta q(x)+\Delta \overline{q}(x)]dx$, we obtain

$$\Gamma_1=\int_0^1 g_1(x)dx=2\sqrt{\tfrac{2}{3}}\Delta Q_0+\tfrac{1}{6}\Delta Q_3+\tfrac{1}{6\sqrt{3}}\Delta Q_8, \tag{A2}$$

where $\Delta Q_0\equiv\frac{1}{12}\sqrt{\frac{2}{3}}(\Delta U+\Delta D+\Delta S)$, $\Delta Q_3\equiv\frac{1}{2}(\Delta U-\Delta D)$, and $\Delta Q_8\equiv(\sqrt{3}/6)(\Delta U+\Delta D-2\Delta S)$ are the singlet, triplet, and octet terms. The singlet term ΔQ_0 is proportional to the fraction $\Sigma=\Delta U+\Delta D+\Delta S$ of the spin of the nucleon carried by the light quarks. If SU(3) flavor symmetry is hold, Σ should be the same for baryons in the same SU(3) multiplet. Using the method of operator product expansion, one relates the ΔQ_a's to the matrix elements of local operators $A_a^\mu=\overline{q}\gamma_\mu\gamma_5(\lambda^a/2)q$ by

$$2MS^\mu\Delta Q_a=\langle P,S|A_a^\mu|P,S\rangle, \tag{A3}$$

where $a=0$, 3, or 8; S, P, and M are the spin, momentum, and mass of the baryon B, and λ^a are the usual SU(3) matrices acting in the flavor space. The matrix elements of the local operators are at $Q^2=0$, and can be measured in hyperon decays. Under the assumption that SU(3) flavor symmetry is valid among the baryons, one can use the Wigner-Eckart theorem and obtain [23]

$$\langle\psi_b|A_a^\mu|\psi_c\rangle=2MS^\mu(if_{abc}F+d_{abc}D), \tag{A4}$$

where ψ_b and ψ_c are the basis of the eight-dimensional representation of SU(3) with spin S, f_{abc} and d_{abc} are the totally antisymmetric and symmetric structure constants for the SU(3) group, and the quantities F and D are constants which are independent of the particular states in the same multiplet.

The wave functions of the baryons B's in the baryon octet can be expressed in terms of the basis vectors ψ_a of the eight-dimensional representation of SU(3). For example, $|p\rangle=(1/\sqrt{2})(\psi_4-i\psi_5)$, $|\Lambda\rangle=\psi_8$, $|\Sigma^0\rangle=\psi_3$, $|\Xi^0\rangle=(1/\sqrt{2})(\psi_6+i\psi_7)$, $|\Xi^-\rangle=-(1/\sqrt{2})(\psi_4+i\psi_5)$. Using these wave functions and Eq. (A4) we can calculate the matrix elements of the axial currents between the different baryons in the octet and obtain the ΔQ_3 and ΔQ_8 as functions of F and D. In this way, we obtain $\Delta Q_3^p=\frac{1}{2}(D+F)$ and $\Delta Q_8^p=(1/2\sqrt{3})(3F-D)$. Using the experimental data for F and D, and that for Γ_1^p, we obtain ΔQ_0 from Eq. (A2) and thus Σ for the proton, which should be the same for all the baryons in the octet. We then use this Σ and data for F and D to calculate the ΔU, ΔD, and ΔS for other baryons. The expressions of ΔU, ΔD, and ΔS in terms of Σ, F, and D, and their numerical results obtained using the data, are listed in Table I.

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[17] This is not only true in the popular hadronization models such as the LUND model [18], but is 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., Ref. [3] and references given there.)

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