Quark Flavor Separation in Λ-Baryon Fragmentation

Bo-Qiang Ma[1] and Jacques Soffer[2]
[1]CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
and Institute of High Energy Physics, Academia Sinica, P.O. Box 918(4), Beijing 100039, China
[2]Centre de Physique Théorique, CNRS, Luminy Case 907, F-13288 Marseille Cedex 9, France
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It is shown that unpolarized and polarized Λ and $\bar{\Lambda}$ production in neutrino and antineutrino deep inelastic scattering, can provide a clean separation of unpolarized and polarized fragmentation functions of a quark into a Λ, for both light-flavor quarks and antiquarks and also for strange quarks. Combining with Λ and $\bar{\Lambda}$ production in polarized electron deep inelastic scattering, one can systematically measure or check the various flavor and spin dependent fragmentation functions. Such measurements can provide crucial tests of different predictions concerning the spin structure of hadrons and the quark-antiquark asymmetry of the nucleon sea. [S0031-9007(99)08684-6]

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Spin physics is currently one of the most active research directions of hadron physics due to the rich phenomena, which are different from the naive theoretical expectations, and the large number of experimental facilities which can provide precision measurements of many physical quantities related to the underlying spin structure of hadrons. Among the various topics, the strange content of the proton is one of the most attractive due to its close connections to the proton spin problem [1] and to the quark-antiquark asymmetry of the nucleon sea [2]. Although there has been much progress and achievement, both theoretically and experimentally, our current knowledge of the strange quark content of the proton is still very poor, since one is still unclear as to whether or not [1,2] strange quarks are highly polarized inside the proton, and it is even more obscure whether or not [2,3] the strange quark-antiquark distributions are symmetric. Thus a precision measurement of the strange-antistrange polarizations of the proton is one of the most challenging and significant tasks for hadron quark structure.

From another point of view, the quark distribution of a quark inside a hadron is related to the fragmentation function of the same flavor quark into the same hadron, by a simple reciprocity relation [4]

$$q_h(x) \propto D_q^h(z)\,, \tag{1}$$

where $z = 2p \cdot q/Q^2$ is the momentum fraction of the produced hadron from the quark jet in the fragmentation process, and $x = Q^2/2p \cdot q$ is the Bjorken scaling variable corresponding to the momentum fraction of the quark from the hadron in the deep inelastic scattering (DIS) process. Although such an approximate relation may be valid only at a specific scale Q^2, which deserves further studies, it could provide reasonable connection between different physical quantities and lead to different predictions about the fragmentations based on our understanding of the quark structure of a hadron [3]. Thus measurements of quark fragmentations into a hadron can also provide new insights into the quark structure of the hadron. Among the various produced hadrons, Λ hyperon is most suitable to study the polarized fragmentation due to its self-analyzing property owing to the characteristic decay mode $\Lambda \rightarrow p\pi^-$ with a large branching ratio of 64%. The technology to disentangle between Λ and $\bar{\Lambda}$, which relies on magnetic spectrometers, is also mature for DIS processes [5]. In fact, there are already some available data on Λ and $\bar{\Lambda}$ productions in different DIS processes, and more to come in the near future [6–9]. Therefore it is meaningful and urgent to exploit a systematic way to extract the various quark contributions to Λ fragmentation functions.

There have been many proposals concerning the measurements of the Λ fragmentation functions in different processes, for different physical goals [2,10–21], and in this Letter we will focus our attention on the longitudinally polarized case. One promising method to obtain a complete set of polarized fragmentation functions for different quark flavors is based on the measurement of the helicity asymmetry for semi-inclusive production of Λ hyperons in e^+e^- annihilation on the Z^0 resonance [12], but the existing data can only provide a poor constraint for different scenarios [19]. Measurements of the light-flavor quark fragmentations into Λ have also been suggested from the polarized electron DIS process [15] and the neutrino DIS process [17], based on the u-quark dominance assumption. There is also a recent interesting suggestion to determine the polarized fragmentation functions by measuring the helicity transfer asymmetry in the process $p\vec{p} \rightarrow \vec{\Lambda} X$ [18]. From its dependence on the rapidity of the Λ, it is possible to discriminate between various parametrizations. In this Letter we will show that the neutrino and antineutrino deep inelastic scattering processes of unpolarized and polarized Λ and $\bar{\Lambda}$ productions can provide a clean separation of unpolarized and polarized fragmentation functions of a light-flavor quark into a Λ, for both quarks and antiquarks, and also for strange quarks. Combining with polarized electron beam DIS processes of unpolarized and polarized Λ and $\bar{\Lambda}$ productions, one can systematically measure or check the various

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flavor and spin dependent fragmentation functions. Thus, in addition to the known process $e^+e^- \to \vec{\Lambda}X$ [12], we have a different method: We measure a complete set of quark to Λ unpolarized and polarized fragmentation functions for different quark flavors by the systematic exploitation of unpolarized and polarized Λ and $\bar{\Lambda}$ productions in neutrino, antineutrino, and polarized electron DIS processes.

Our considerations rely on the fact that neutrinos (antineutrinos) can be regarded as a purely polarized lepton beam, due to the fact that neutrinos are left handed (antineutrinos are right handed), therefore they only interact with quarks of specific helicities and flavors. For example, a neutrino (antineutrino) can only interact with the d, $\bar{u}$, and s (u, $\bar{d}$, and $\bar{s}$) light-flavor quarks with left-handed quarks and with right-handed antiquarks of a hadronic target, regardless if this target is polarized or not, and the scattered quarks will keep the same helicities of their parent quarks before the collision [10]. Thus the scattering of a neutrino (antineutrino) beam on a hadronic target provides a *source of polarized quarks with specific flavor structure*, and this particular property makes the neutrino (antineutrino) DIS process an ideal laboratory to study the flavor-dependence quark fragmentation into hadrons in the current fragmentation region, especially in the polarized case.

From the charged current quark transitions, for neutrino induced reactions,

$$\begin{aligned} \nu d &\to \mu^- u, & \nu d &\to \mu^- c\,, \\ \nu \bar{u} &\to \mu^- \bar{d}, & \nu \bar{u} &\to \mu^- \bar{s}\,, \\ \nu s &\to \mu^- c, & \nu s &\to \mu^- u\,, \end{aligned} \tag{2}$$

and, for antineutrino induced reactions

$$\begin{aligned} \bar{\nu} u &\to \mu^+ d, & \bar{\nu} u &\to \mu^+ s\,, \\ \bar{\nu} \bar{d} &\to \mu^+ \bar{u}, & \bar{\nu} \bar{d} &\to \mu^+ \bar{c}\,, \\ \bar{\nu} \bar{s} &\to \mu^+ \bar{c}, & \bar{\nu} \bar{s} &\to \mu^+ \bar{u}\,, \end{aligned} \tag{3}$$

the expressions for the Λ and $\bar{\Lambda}$ longitudinal polarizations in the beam direction are, for Λ and $\bar{\Lambda}$ produced in the current fragmentation,

$$P_{\nu}^{\Lambda}(x,y,z) = -\frac{d(x)\Delta D_u^{\Lambda}(z) - (1-y)^2\bar{u}(x)\Delta D_{\bar{d}}^{\Lambda}(z)}{d(x)D_u^{\Lambda}(z) + (1-y)^2\bar{u}(x)D_{\bar{d}}^{\Lambda}(z)} \quad \text{for } \nu N \to \mu^- \vec{\Lambda} X\,, \tag{4}$$

$$P_{\bar{\nu}}^{\Lambda}(x,y,z) = -\frac{(1-y)^2u(x)\Delta D_{d}^{\Lambda}(z) - \bar{d}(x)\Delta D_{\bar{u}}^{\Lambda}(z)}{(1-y)^2u(x)D_{d}^{\Lambda}(z) + \bar{d}(x)D_{\bar{u}}^{\Lambda}(z)} \quad \text{for } \bar{\nu} N \to \mu^+ \vec{\Lambda} X\,, \tag{5}$$

$$P_{\nu}^{\bar{\Lambda}}(x,y,z) = -\frac{d(x)\Delta D_u^{\bar{\Lambda}}(z) - (1-y)^2\bar{u}(x)\Delta D_{\bar{d}}^{\bar{\Lambda}}(z)}{d(x)D_u^{\bar{\Lambda}}(z) + (1-y)^2\bar{u}(x)D_{\bar{d}}^{\bar{\Lambda}}(z)} \quad \text{for } \nu N \to \mu^- \vec{\bar{\Lambda}} X\,, \tag{6}$$

$$P_{\bar{\nu}}^{\bar{\Lambda}}(x,y,z) = -\frac{(1-y)^2u(x)\Delta D_{d}^{\bar{\Lambda}}(z) - \bar{d}(x)\Delta D_{\bar{u}}^{\bar{\Lambda}}(z)}{(1-y)^2u(x)D_{d}^{\bar{\Lambda}}(z) + \bar{d}(x)D_{\bar{u}}^{\bar{\Lambda}}(z)} \quad \text{for } \bar{\nu} N \to \mu^+ \vec{\bar{\Lambda}} X\,. \tag{7}$$

Here we have neglected the Cabibbo suppressed processes and the small strange quark distributions inside the hadronic target; $\Delta D_q^h(z) = D_{q\uparrow}^{h\uparrow}(z) - D_{q\uparrow}^{h\downarrow}(z)$ denotes the polarized fragmentation function, $D_{q\uparrow}^{h\uparrow}(z)$ $[D_{q\uparrow}^{h\downarrow}(z)]$ being the probability for finding a hadron with positive (negative) helicity in a quark q with positive helicity, and $y = \nu/E$ is the energy fraction of the incident neutrino carried by the charged intermediate boson $W^{\pm}$ in the laboratory frame. For any value of x and z, we see that the measurement of these four quantities in the region $y \simeq 1$ leads directly to the two fragmentation asymmetries $\Delta D_q^{\Lambda}(z)/D_q^{\Lambda}(z)$, where $q = u$ for processes (4) and (7) and $q = \bar{u}$ for processes (5) and (6). Of course, here we have applied matter and antimatter symmetry, i.e., $D_{q,\bar{q}}^{\Lambda}(z) = D_{\bar{q},q}^{\bar{\Lambda}}(z)$ and similarly for $\Delta D_{q,\bar{q}}^{\Lambda}(z)$. We can also assume the u and d symmetry for the fragmentation functions $D_u^{\Lambda,\bar{\Lambda}}(z) = D_d^{\Lambda,\bar{\Lambda}}(z)$ and $D_{\bar{u}}^{\Lambda,\bar{\Lambda}}(z) = D_{\bar{d}}^{\Lambda,\bar{\Lambda}}(z)$, from the symmetry of u and d inside Λ and $\bar{\Lambda}$. Hence we have, for the unpolarized fragmentation functions,

$$\begin{aligned} D_q^{\Lambda}(z) &= D_u^{\Lambda}(z) = D_d^{\Lambda}(z) = D_{\bar{u}}^{\bar{\Lambda}}(z) = D_{\bar{d}}^{\bar{\Lambda}}(z)\,, \\ D_{\bar{q}}^{\Lambda}(z) &= D_{\bar{u}}^{\Lambda}(z) = D_{\bar{d}}^{\Lambda}(z) = D_{u}^{\bar{\Lambda}}(z) = D_{d}^{\bar{\Lambda}}(z)\,, \end{aligned} \tag{8}$$

and, for the polarized fragmentation functions,

$$\begin{aligned} \Delta D_q^{\Lambda}(z) &= \Delta D_u^{\Lambda}(z) = \Delta D_d^{\Lambda}(z) = \Delta D_{\bar{u}}^{\bar{\Lambda}}(z) = \Delta D_{\bar{d}}^{\bar{\Lambda}}(z)\,, \\ \Delta D_{\bar{q}}^{\Lambda}(z) &= \Delta D_{\bar{u}}^{\Lambda}(z) = \Delta D_{\bar{d}}^{\Lambda}(z) = \Delta D_{u}^{\bar{\Lambda}}(z) = \Delta D_{d}^{\bar{\Lambda}}(z)\,. \end{aligned} \tag{9}$$

Equations (4)–(7) thus reduce to equations of the four fragmentation functions $D_q^{\Lambda}(z)$, $D_{\bar{q}}^{\Lambda}(z)$, $\Delta D_q^{\Lambda}(z)$, and $\Delta D_{\bar{q}}^{\Lambda}(z)$. The cross sections of the corresponding unpolarized Λ and $\bar{\Lambda}$ productions can be written as

$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma}{dz} = \frac{\sum_i [a_i q_i(x) + b_i \bar{q}_i(x)] D_i^{\Lambda,\bar{\Lambda}}(z)}{\sum_i [a_i q_i(x) + b_i \bar{q}_i(x)]}\,, \tag{10}$$

where i implies all quark (antiquark) flavors involved in the corresponding process ($i = d, \bar{u}$ for neutrino beams and $i = u, \bar{d}$ for antineutrino beams, neglecting the Cabibbo mixings and the strange distributions of the target in the formula), and a_i and b_i are two factors with $a_i = 1$ and $b_i = 0$ ($a_i = 1/3$ and $b_i = 0$) for relevant quarks and $a_i = 0$ and $b_i = 1/3$ ($a_i = 0$ and $b_i = 1$) for antiquarks for neutrino (antineutrino) induced processes. [We can replace in the numerator the factor $1/3$ by $(1-y)^2$ for y dependent cross sections, and the factor 1 by $\int_{y_l}^{y_h} dy$ and the factor $1/3$ by $\int_{y_l}^{y_h} dy\,(1-y)^2$ to take into account the experimental cuts for $y_l < y < y_h$.]

In principle, Eqs. (4)–(7) are sufficient to determine all four independent fragmentation functions $D_q^{\Lambda}(z)$, $D_{\bar{q}}^{\Lambda}(z)$,

$\Delta D_q^{\Lambda}(z)$, and $\Delta D_{\bar{q}}^{\Lambda}(z)$, at specified x and y, or integrating both the numerators and denominators over y and/or x within the experimental cuts. However, in practice we must be careful, since the contribution from the Cabibbo suppressed process of $u \to s \to \Lambda$ ($\bar{u} \to \bar{s} \to \bar{\Lambda}$) is by no means negligible in process (5) $\bar{\nu} N \to \mu^+ \Lambda X$ [(6) $\nu N \to \mu^- \bar{\Lambda} X$]. By measuring both the unpolarized and polarized Λ and $\bar{\Lambda}$ productions, using the relatively clean processes (4) and (7), it seems enough to determine the four independent fragmentation functions. Nevertheless, as already mentioned above, by varying y and/or x, if data allow it, one may make a clean flavor separation (even without the assumption of u and d flavor symmetry) by only the polarized processes (4) and (7). The antiquark contribution of the target can be safely neglected only at large y for process (4), not for processes (5) and (7) (where it dominates).

There are many possible ways to obtain the strange fragmentation functions from the neutrino, antineutrino and polarized electron DIS processes. The first way is to use processes (4) and (7), y and/or x dependent (or varying the cuts for x and y), or polarized combined with unpolarized ones within all the cuts, to extract the four light-flavor quark fragmentation functions. Then, by substituting these four quantities in polarized (5) and (6) (or a y and/or x dependent single process), one can determine the strange fragmentation functions D_s^{Λ} and ΔD_s^{Λ}. [The fragmentation process $\bar{s} \to \Lambda$ ($s \to \bar{\Lambda}$) is expected to be much smaller compared to $s \to \Lambda$ ($\bar{s} \to \bar{\Lambda}$), since the former is from the sea $s\bar{s}$ pairs in Λ, whereas the latter is from the dominant valence configuration in which s provides the spin of Λ.] Besides, with an unpolarized Λ production of process (5) one can also, in principle, extract the strange fragmentation function $D_s^{\Lambda}(z)$, provided $D_q^{\Lambda}(z)$ and $D_{\bar{q}}^{\Lambda}(z)$ are known and then check this quantity by using (6). [One can also use the unpolarized processes (4)–(7) to determine D_q^{Λ}, $D_{\bar{q}}^{\Lambda}$, D_s^{Λ}, and $D_{\bar{s}}^{\Lambda}$, if one thinks that $D_{\bar{s}}^{\Lambda}$ is not negligible, and then, by extending the same analysis to the polarized processes, measure ΔD_q^{Λ}, $\Delta D_{\bar{q}}^{\Lambda}$, ΔD_s^{Λ}, and $\Delta D_{\bar{s}}^{\Lambda}$.] Then, by extending the same analysis to the polarized cases, one can also first measure $\Delta D_s^{\Lambda}(z)$ in process (5) and then check this quantity by process (6). Thus the measurements of unpolarized and polarized Λ and $\bar{\Lambda}$ productions in neutrino and antineutrino can, in principle, provide a full determination of the flavor dependent unpolarized and polarized fragmentation functions.

Another way is to combine the polarized Λ and $\bar{\Lambda}$ productions in neutrino and antineutrino DIS processes with those of polarized electron DIS processes [15] and determine the four light-flavor fragmentation functions and two strange fragmentation functions from six independent equations of Λ ($\bar{\Lambda}$) polarizations of the six processes. (New high statistics data are expected soon from several experiments [8,9].) This method has the advantage that one does not need to take care of the magnitudes or the y and/or x dependences of the Λ and $\bar{\Lambda}$ productions, but only their polarizations. Needless to say, the strange (antistrange) quark distributions of the hadronic target in the polarized electron DIS processes must be taken into account due to the large fragmentation process $s \to s \to \Lambda$ ($\bar{s} \to \bar{s} \to \bar{\Lambda}$), as we have mentioned. It is interesting to note that the use of different nuclear targets, with different isospin properties, can also help us to gain additional information on the flavor dependence for the fragmentation functions.

Clearly, the above analysis can also be extended to the production of other hadrons, such as Σ, Ξ, etc., or even to heavier flavor hadrons such as Λ_c. Although such studies might be tedious theoretically and difficult experimentally, they are meaningful not only for their own purpose but also for the physics purpose of this paper. The reason is that the final Λ and $\bar{\Lambda}$ hyperons might come from decays of these hadrons which generate a background to be studied and removed for a precise understanding of the quark to Λ fragmentation. Notice that some progress has already been achieved along this direction [10,11,17,20], as well on the quantum chromodynamics (QCD) evolution of the fragmentation functions [19] and on higher order corrections [16]. It should be pointed out that the presented results in Eqs. (4)–(7) hold only in leading order. In next-to-leading order the x/z factorization does not hold any longer, which complicates the analysis considerably. Also processes induced by gluons and the fragmentation of gluons into Λ and $\bar{\Lambda}$ become relevant. All of these effects, including also the contributions from Cabibbo mixings, will have to be further taken into account with increasing statistical accuracy of the data. (To our knowledge, the highest statistics data on Λ and $\bar{\Lambda}$ production separately comes from the NOMAD neutrino beam experiment [7].)

It is known that the original proposal [13] for measuring the strange quark polarization of a proton $\Delta s(x)$ from the semi-inclusive Λ polarization of an unpolarized electron beam on the polarized proton target DIS process suffers from the contributions of u and d quark fragmentations due to the nonzero $\Delta D_q^{\Lambda}(z)$ [15,17,19]. With a better knowledge of the flavor and spin dependent quark to Λ fragmentation functions, one can try to remove the background from contributions of the polarized u and d quarks of the proton to the polarized Λ, to allow the measurement of $\Delta s(x)$. As also mentioned in Ref. [2], a complementary measurement of $\bar{\Lambda}$ polarization in the same process can also help to pin down the antistrange quark polarization inside the proton. [Remember that the neutrino (antineutrino) DIS process cannot be done on a polarized target and therefore cannot provide any information concerning the spin structure of the nucleon target.] Such measurements can provide crucial tests of different predictions concerning the spin structure of hadrons [1,2] and the quark-antiquark asymmetry of the nucleon sea [2,3]. Besides, the u and d polarizations inside a Λ are closely related to the physical mechanism for the s polarization inside a proton. Measurement of ΔD_q^Λ is also helpful to understand the mechanism for the s polarization of the proton.

We need to point out that the measurement of $\Delta D_{\bar{q}}^\Lambda$ is also related to the quark-antiquark asymmetry discussed in Refs. [2,3]. From the SU(3) symmetry argument of Burkardt-Jaffe [12], we know that the u and d quarks inside a Λ should be negatively polarized. If the valence u and d in a Λ are unpolarized, one may simply expect the u and d polarizations coming from the sea, with the same polarizations for quarks and antiquarks, for the u and d flavors, and therefore $\Delta D_{\bar{q}}^\Lambda \neq 0$. However, this might not be true in general and, in the baryon-meson fluctuation model of the intrinsic sea quarks of a hadron [2], the intrinsic $u\bar{u}$ and $d\bar{d}$ pairs inside a Λ are mainly from the configurations $\Lambda(udsu\bar{u}) = p(uud)K^-(s\bar{u})$ and $\Lambda(udsd\bar{d}) = n(udd)K(s\bar{d})$. From this picture the u and d quarks inside a Λ are negatively polarized, whereas $\bar{u}$ and $\bar{d}$ should be unpolarized or slightly polarized from higher fluctuations. In fact, the predictions [2,22] of a small or zero polarization of the sea antiquarks in the proton are supported by the Spin Muon Collaboration measurement of the u and d antiquark helicity distributions from the semi-inclusive DIS process [23]. Therefore the future measurement of $\Delta D_{\bar{q}}^\Lambda$ can provide another test of different predictions concerning the hadron spin structure. For example, the Λ and $\bar{\Lambda}$ polarizations for processes (4) and (6) at $y \simeq 1$ are predicted to be $P_\nu^\Lambda = 0.14 \pm 0.04$ and $P_\nu^{\bar{\Lambda}} = 0.06 \pm 0.02$ for case I and $P_\nu^\Lambda = 0.09 \pm 0.04$ and $P_\nu^{\bar{\Lambda}} = 0.12 \pm 0.04$ for case II in Ref. [15], whereas they are $P_\nu^\Lambda \approx 0.02$ and $P_\nu^{\bar{\Lambda}} = 0$ in the baryon-meson fluctuation model, assuming an intrinsic $u\bar{u}$ sea fluctuation probability at about 10% and $\Delta u_N + \Delta d_N \approx 0.5$ [2].

In summary, we showed that a complete investigation of Λ and $\bar{\Lambda}$ hyperon productions in neutrino and antineutrino DIS processes can provide an ideal laboratory for a systematic study of the flavor and spin dependence of the quark fragmentations. The flavor and spin separation we propose is based on the particular property that the scattering of neutrinos (antineutrinos) on a hadronic target provides a source of polarized quarks with specific flavor structure. A full determination of unpolarized and polarized quark to Λ fragmentation functions is also helpful, to measure the strange and antistrange polarizations of the proton and to test ideas related to the spin structure of the nucleon and to the quark-antiquark asymmetry of the nucleon sea.

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