Spin alignments of vector mesons in deeply inelastic lepton-nucleon scattering

Xu Qing-hua and Liang Zuo-tang

Department of Physics, Shandong University, Ji'nan, Shandong 250100, China

We extend the calculations of the spin alignments of vector mesons in e^+e^- annihilation in a recent Rapid Communication to deeply inelastic lepton-nucleon scatterings. We present the results for different mesons in the current fragmentation regions of $\mu^- N \to \mu^- VX$ at high energies and $\nu_\mu N \to \mu^- VX$ at both high and low energies. We also present the predictions for $\nu_\mu N \to \mu^- VX$ at NOMAD energies in the target fragmentation region using a valence quark model.

Spin alignments of vector mesons in high-energy reactions have attracted much attention recently [1–8]. Since the influences from the decay of heavier hadrons are relatively small and the production rate is in general higher than that of the hyperon, such studies provide important information for the spin effects in the fragmentation process, in particular, the spin transfer from the fragmenting quark to the produced hadrons. Measurements have been carried out in different reactions [1–4] in particular in e^+e^- annihilation at the CERN e^+e^- collider LEP recently [4]. The data show that the vector mesons produced in e^+e^- annihilation at the Z^0 pole have a large probability to be in the helicity zero state, and the effect is more significant for large momentum fraction region.

In a recent paper [8], we calculated the spin density matrix of vector mesons in e^+e^- annihilation at Z^0 pole by taking the spin of vector meson which contains the fragmenting quark as the sum of the spin of the polarized fragmenting quark (antiquark) and that of the antiquark (quark) created in the fragmentation process. Compared with the data [4], we showed that the experimental results for ρ_{00}, i.e., the probability for vector meson in the helicity zero state, imply a significant polarization for the antiquark (quark) which is created in the fragmentation process and combines with the fragmenting quark to form the vector meson. It should be polarized in the opposite direction as that of the fragmenting quark and the polarization can approximately be written as

$$P_z = -\alpha P_f, \tag{1}$$

where $\alpha \approx 0.5$ is a constant for most of the vector mesons. (Here, P_z is the polarization of the antiquark in the moving direction of the fragmenting quark and P_f is the longitudinal polarization of the fragmenting quark of flavor f.) Using this result, we were able to fit the data of ρ_{00}'s for different vector mesons reasonably. The relation given by Eq. (1) can be considered as a direct implication of the data [4] in e^+e^- annihilation. It should be interesting to extend the studies to other reactions, in particular, to check whether the relation shown in Eq. (1) is also true for the fragmentation of quarks in other processes. In this connection, it is encouraging to see that not only some previous data are available but also new measurements [9] can be made by the NOMAD Collaboration in $\nu_\mu N \to \mu^- VX$.

In this paper, we extend the calculations to deeply inelastic lepton-nucleon scatterings (DIS) and present the results for ρ_{00}'s of different mesons in different cases. We now start our calculations by summarizing the main points of the method in Ref. [8]. To calculate the density matrix of vector mesons which are produced in the fragmentation of a polarized quark q_f^0, we divide them into the following two groups and consider them separately: (a) those which contain the fragmenting quark q_f^0, and (b) those which do not contain the fragmenting quark. The spin density matrix $\rho^V(x_F)$ for the vector meson V is given by

$$\rho^V(x_F) = \sum_f \frac{\langle n(x_F|a,f)\rangle}{\langle n(x_F)\rangle} \rho^V(a,f) + \frac{\langle n(x_F|b)\rangle}{\langle n(x_F)\rangle} \rho^V(b), \tag{2}$$

where $\langle n(x_F|a,f)\rangle$ and $\rho^V(a,f)$ are the average number and spin density matrix of vector mesons from (a), $\langle n(x_F|b)\rangle$ and $\rho^V(b)$ are those from (b), $\langle n(x_F)\rangle = \Sigma_f \langle n(x_F|a,f)\rangle + \langle n(x_F|b)\rangle$ is the total number of vector mesons, and x_F is defined as $x_F \equiv 2p_z^*/W$, p_z^* is the momentum of vector meson in the z direction in the center-of-mass system of total hadronic system, W is the total energy of the hadronic system, and the z axis is taken as the direction of the intermediate boson. The average numbers $\langle n(x_F|a,f)\rangle$ and $\langle n(x_F|b)\rangle$ are determined by the hadronization mechnism and can be calculated using hadronization models [10] as implemented by the Monte Carlo event generators.

The vector mesons from group (b) are taken as unpolarized, thus $\rho^V(b) = 1/3$. For those from group (a) which contain q_f^0 and an antiquark $\bar{q}$ created in the fragmentation [11], the spin density matrix $\rho^V(a,f)$ is calculated from the direct product of the spin density matrix $\rho^{q_f^0}$ for q_f^0 and $\rho^{\bar{q}}$ for $\bar{q}$. Transforming the direct product, $\rho^{q_f^0 \bar{q}} = \rho^{q_f^0} \otimes \rho^{\bar{q}}$, to the coupled basis $|s, s_z\rangle$ (where $\vec{s} = \vec{s}^q + \vec{s}^{\bar{q}}$), we obtain the spin density matrix $\rho^V(a,f)$, and the 00-component as

$$\rho_{00}^V(a,f) = (1 - P_f P_z)/(3 + P_f P_z), \tag{3}$$

where P_f is the longitudinal polarization of q_f^0 and P_z is the polarization of $\bar{q}$ in the z direction. We insert the relation showed by Eq. (1) into Eq. (3) and obtain

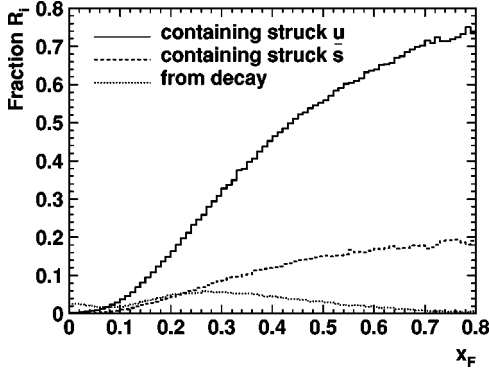$$\rho_{00}^V(a,f) = (1 + \alpha P_f^2)/(3 - \alpha P_f^2). \tag{4}$$

FIG. 1. Different contributions to K^{*+} production in the current region of $\mu^- N \to \mu^- K^{*+} X$ at $E_\mu = 500$ GeV.

Finally, from Eqs. (2) and (4), we have

$$\rho_{00}^V(x_F) = \sum_f \frac{1 + \alpha P_f^2}{3 - \alpha P_f^2} \frac{\langle n(x_F|a,f)\rangle}{\langle n(x_F)\rangle} + \frac{1}{3} \frac{\langle n(x_F|b)\rangle}{\langle n(x_F)\rangle}. \quad (5)$$

Using this result, we obtained [8] a good fit to the data of ρ_{00}^V's in $e^+ e^-$ annihilation. Now, we apply it to the DIS processes.

We first consider the process of $\mu^- p \to \mu^- V X$. For a sufficiently large W, the hadrons produced in the current fragmentation region are mainly from the struck quark's fragmentation. Considering only the leading order subprocess $\mu^- q \to \mu^- q$, the polarization of the outgoing struck quark can be obtained from QED and can be found in different publications (see, e.g., [12]), i.e.,

$$P_f = \frac{P^l D_L(y) q_f(x) + P^N \Delta q_f(x)}{q_f(x) + P^l D_L(y) P^N \Delta q_f(x)}, \quad (6)$$

where $D_L(y)$ is the longitudinal depolarization factor

$$D_L(y) = [1 - (1-y)^2]/[1 + (1-y)^2]$$

and $y \equiv p \cdot (k - k')/p \cdot k$ where p, k, and k' are the four momenta of the incoming q, μ^-, and the outgoing μ^-, respectively. P^l and P^N are the longitudinal polarizations of the incoming lepton and nucleon, respectively, $q_f(x)$ and $\Delta q_f(x)$ are the unpolarized and longitudinally polarized distribution functions. In our calculation, the unpolarized and longitudinal polarized distribution functions are taken as the Glück-Reya-Vogt 1998 (GRV98) leading order (LO) set [13] and the standard LO scenario of Glück-Reya-Stratmann-Vogelsang 2000 (GRSV2000) [14], respectively.

We use the generator LEPTO [15] to calculate the average numbers $\langle n(x_F|a,f)\rangle$ and $\langle n(x_F|b)\rangle$. As an example, we show the different origons of K^{*+} in the current fragmentation region of $\mu^- N \to \mu^- K^{*+} X$ at the beam energy of 500 GeV in Fig. 1. We choose the events for $Q^2 > 5$ (GeV/c)^2, $10^{-4} < x < 0.2$, and $0.5 < y < 0.9$ to ensure a reasonably large W and a reasonably high polarization of the fragmenting quark. We see that, in contrast with hyperon production in the same reaction [12], the decay contribution is indeed very small.
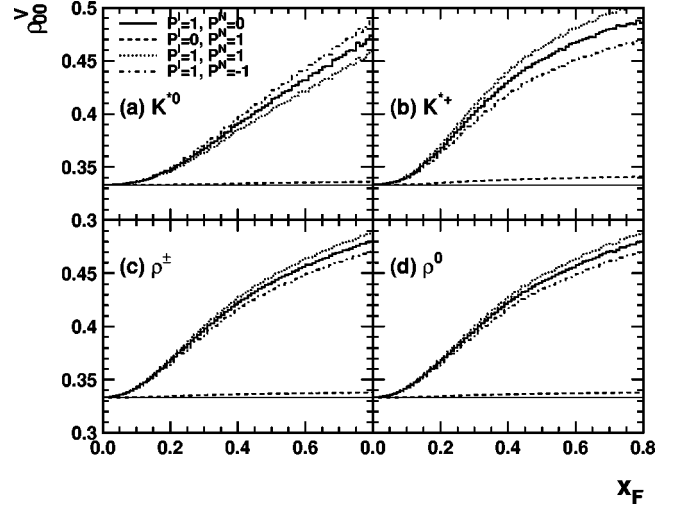

FIG. 2. ρ_{00}^V in the current region of $\mu^- p \to \mu^- V X$ at $E_\mu = 500$ GeV. The straight lines at $\rho_{00} = 1/3$ show the unpolarized cases.

Using Eq. (5) and the average numbers obtained above, we calculate the ρ_{00}^V's for K^{*0}, K^{*+}, $\rho^\pm$, and ρ^0. The results are shown in Fig. 2 for different combinations of P^l and P^N in the same kinematic region as in Fig. 1. We see that ρ_{00}^V's increase with increasing x_F and reach about 0.5 in the cases of polarized lepton beam, which is much larger than 1/3 and can easily be detected in experiments. However, the magnitude of ρ_{00}^V's for $P^l = 0$ and $P^N = 1$ is much smaller than those in other three cases. The reason is that the ratio $\Delta q_f(x)/q_f(x)$ is small in the chosen small x region, so P_f obtained from Eq. (6) is small. In contrast, the $D_L(y)$ is large for the considered large y region; it leads to relatively large P_f in the other three cases. Hence, to get reasonably large ρ_{00}^V, the polarization of the lepton beam is required.

For inclusive meson production in unpolarized ep reactions, the struck quark is unpolarized. Hence, $P_f = 0$ and $\rho_{00}^V = 1/3$ in the current fragmentation region. There have been measurements [1] for ρ^0 with $z > 0.4$ ($z = E_\rho/\nu$ and ν is the energy loss of the lepton beam in the lab frame) in inelastic ep scattering at $E_e = 11.5$ GeV and the result is $\rho_{00} = 0.41 \pm 0.08$, which is in agreement with the theoretical expectation.

For $\nu_\mu N \to \mu^- V X$, the leading subprocess $\nu_\mu q \to \mu^- q$ is a charged current weak interaction with the exchange of a virtual W^+, which selects only left-handed quarks or right-handed antiquarks. We have $P_f = -1$ for struck quarks and $P_f = 1$ for struck antiquarks, whose polarizations reach the maxmum. Hence, we expect larger ρ_{00}^V's in neutrino DIS than in other reactions. We calculate ρ_{00}^V's for different mesons in the current fragmentation region of $\nu_\mu N \to \mu^- V X$ at $E_\nu = 500$ GeV and the results are shown in Fig. 3. We see that, the ρ_{00}^V's for K^{*+}, ρ^+, and ρ^0 increase to about 0.6 with increasing x_F. However, the ρ_{00} for K^{*0} is much smaller. This is because, for K^{*0}, the only contribution of type (a) is from outgoing struck $\bar{s}$ quark which is a result of the absorption of W^+ by a $\bar{c}$ in the nucleon sea. It is very small due to
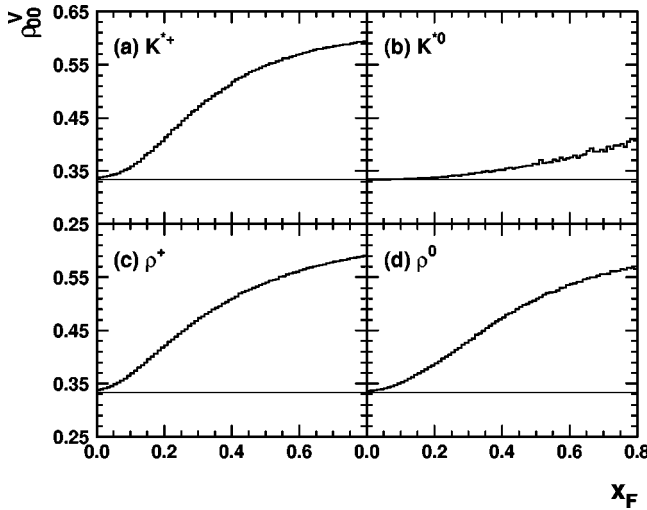
FIG. 3. ρ_{00}^{V} in the current region of $\nu_\mu p \to \mu^- VX$ at $E_\mu = 500$ GeV. The straight lines at $\rho_{00} = 1/3$ show the unpolarized cases.

the rarity of $\bar{c}$ in the nucleon. Other kinds of contributions lead only to 1/3 for ρ_{00}. For other vector mesons, such as K^{*-} and ρ^-, there is no contribution of type (a) at all. Their ρ_{00}'s are just equal to 1/3.

It has been pointed out that [16], at lower energies, such as at the NOMAD energies where $\langle E_\nu \rangle = 43.8$ GeV, the influence of the fragmentation of target remnant to hyperon production is very large, in particular in the small x_F region [16]. It has to be taken into account in calculating the hyperon polarization in such energy region. The characteristic features of the hyperon polarization in this region are determined by this contribution. It is therefore natural to ask whether similar effects also exist for mesons production. To check this we make an analysis using LEPTO and the results for $\nu_\mu p \to \mu^- K^{*+} X$ at $E_\nu = 43.8$ GeV are shown in Fig. 4. We see that, there is indeed a mixture of the contribution from the mesons containing the struck quark and that containing one of the quarks in the target remnant in the region near $x_F \approx 0$, but the effect is much smaller than that for hyperon production. This can be understood easily. We recall that, in the case of hyperon production, the excitation of
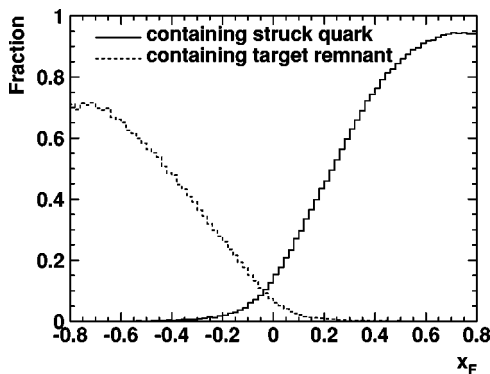

FIG. 4. Different contributions to K^{*+} production both in the current and target fragmentation region of $\nu_\mu p \to \mu^- K^{*+} X$ at $E_\nu = 43.8$ GeV.
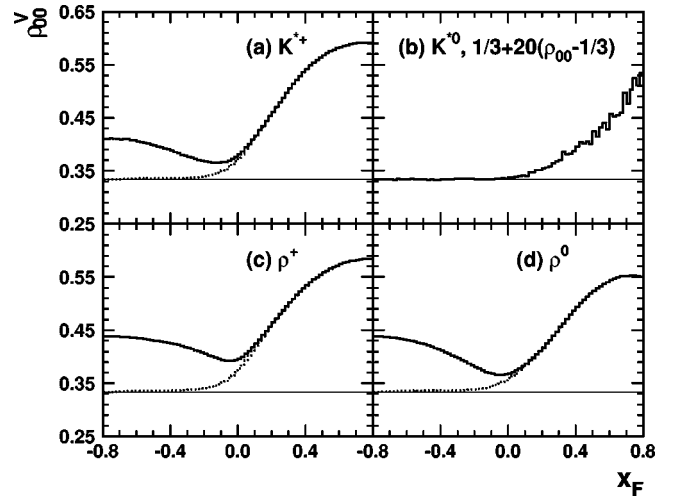

FIG. 5. ρ_{00}^{V} in $\nu_\mu p \to \mu^- VX$ at $E_\nu = 43.8$ GeV. The solid line represents the results where the contribution of target fragmentation is taken into account, the dotted line denotes the results where only the contribution of the current fragmentation is included. The results for K^{*0} are the same.

diquark-antidiquark pair is needed for producing hyperons which contain the struck quark and there should be at least one more baryon and one antibaryon produced. However, the excitation of diquark-antidiquark pair is unnecessary for producing hyperons which contain one quark of the remnant uu diquark. At the NOMAD energies, W is only of several GeV, the probability for the former case should be much smaller than that for the latter. Hence, in the $x_F \sim 0$ region, the contributions from the latter case can dominate. For meson production, to produce mesons containing the struck quark or one u quark of the remnant uu diquark, only quark-antiquark pair excitation is needed. The probability for the mesons containing one quark of uu diquark to move in the opposite direction of the diquark is rather small. Hence, the influences from target remnant fragmentation on the spin alignments of vector mesons in current fragmentation region are small.

Having the abovementioned results for meson production of different origins, we can also calculate their spin align-
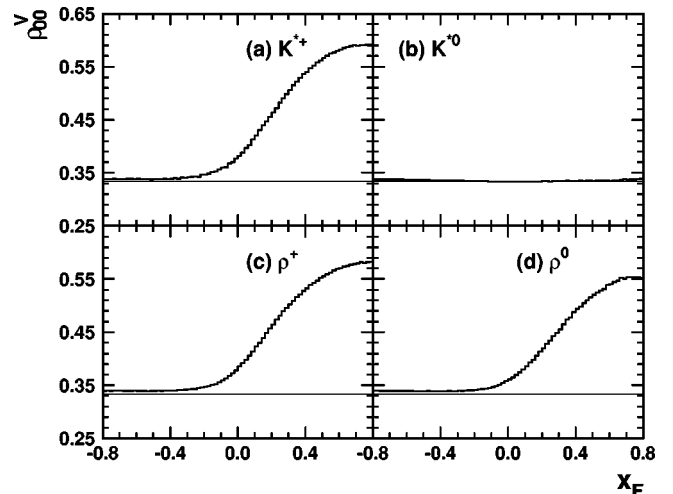

FIG. 6. ρ_{00}^{V} in $\nu_\mu n \to \mu^- VX$ at $E_\nu = 43.8$ GeV.

ments by taking the fragmentation of the nucleon remnant into account. The polarization of the quarks in target remnant is unclear. We calculate it in the same way as in Ref. [16] in studying hyperon polarization, where a valence quark model was used. The results obtained for ρ_{00}^V's in $\nu_\mu p \to \mu^- VX$ at $E_\nu = 43.8$ GeV both in the current and target fragmentation regions are shown in Fig. 5. We see that, for $x_F > 0$, the influence from the target remnant fragmentation is indeed very small. Compared with those obtained at $E_\nu = 500$ GeV, ρ_{00} of K^{*0} is smaller. This is because at such low energy, the probability for the outgoing struck quark to be $\bar{s}$ is very tiny. For the target fragmentation region, the spin alignments are smaller than those in the current region. The results for a neutron target are shown in Fig. 6. The ρ_{00}^V's are much smaller in the target fragmentation region than those in the case of a proton target, because the polarization of the quark in the remnant uu diquark from a proton is larger than that in the remnant ud diquark from a neutron [16]. The difference in the current region is tiny for the two different targets, since the partonic subprocesses are the same and $\nu_\mu d \to \mu^- u$ dominates others for both targets.

There have been measurements [2] for ρ^0 in neutrino DIS and the results are $\rho_{00} = 0.65 \pm 0.18$ and 0.61 ± 0.08 in $\bar{\nu} N_e \to \mu^+ \rho^0 X$ and $\rho_{00} = 0.41 \pm 0.13$ and 0.39 ± 0.08 in νN_e $\to \mu^- \rho^0 X$ at low energies similar to NOMAD. The data are both for ρ^0's with $z > 0.4$ ($z = E_\rho / \nu$). Our results in the same kinematic region are $\rho_{00} = 0.511$ for $\bar{\nu} N_e \to \mu^+ \rho^0 X$ and $\rho_{00} = 0.518$ for $\nu N_e \to \mu^- \rho^0 X$ [17]. They are in agreement with the data and further measurements with high precision are required to give a better check of the model.

In summary, we calculate the spin alignments for different vector mesons in the current fragmentation regions of $\mu^- N \to \mu^- VX$ and $\nu_\mu N \to \mu^- VX$ at high energies by taking the spin of a vector meson as the sum of the spins of the polarized fragmenting quark (antiquark) and that of the antiquark (quark) created in the fragmentation process. We also present the predictions for spin alignments in $\nu_\mu N \to \mu^- VX$ at NOMAD energies both in the current and target fragmentation regions. The results show that there are significant spin alignments for most of the vector mesons in the above reactions. Measurements of them can provide important information for the spin effects in the fragmentation process.

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[17] We note that the quantization axis of the data is chosen along the moving direction of the vector meson (helicity frame), while in our calculations it is chosen as the moving direction of the outgoing struck quark. There is a slight difference between the results in these two frames [8] and the magnitudes of the differences depend on the transverse momentum of the meson with respect to the outgoing struck quark and other related factors. We estimate that, typically, the correction is within 0.05.