SINGLE SPIN ASYMMETRY OF VECTOR MESON PRODUCTION IN THE STRING MODEL

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Dedicated to Andrzej Białas in honour of his 60th birthday

Azimuthal asymmetry of vector-meson production in single-transversely polarized proton-proton collisions ($p\uparrow p$) is calculated in a model based on the string fragmentation. The string is spanned by a valence quark of the projectile scattered on the target. The asymmetry is generated only during fragmentation of the scattered quark into hadrons. The obtained asymmetry of the ρ mesons is opposite in sign to that of pions. On the other hand, if the asymmetry were generated during the quark scattering then the asymmetries of the vector and of the pseudoscalar mesons would be close to each other.

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Measurement of single transverse-spin azimuthal asymmetries of particle production in $p\uparrow p$ collisions can provide information about transversely polarized quark distributions in the proton [1]. However, to extract information about the latter from the experimental data, one has to know the mechanism generating the asymmetry. It has been shown recently [2] that one can obtain large asymmetries with their signs and x_F dependence similar to those measured by the E704 experiment [3] while assuming that the asymmetry is generated only during the fragmentation of polarized quarks produced in the collision. Such an effect was originally proposed by Collins [4]. In Ref. [2] the string model was used to describe the fragmentation, and the polarization effects were parametrized as prescribed by the Lund

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model [5]. Positive asymmetry was obtained for π^+ and π^0 production and negative for π^-, resulting from upward (downward) polarizations of the u (d) valence qark in the proton polarized upwards.

However, different mechanisms leading to the azimuthal asymmetry are possible. Szwed has shown [6, 7] that the asymmetry appears in scattering of a quark on an external strong field due to multiple gluon exchange. This asymmetry vanishes at a sufficiently high energy due to chiral symmetry and the resulting helicity conservation. Nevertheless, it can be measurable at finite energies.

In this note we show that comparing the asymmetries of vector and pseudoscalar mesons can provide information on the magnitude of the asymmetry of quark scattering. We calculate the asymmetry of ρ mesons along the lines of Ref. [2]. This asymmetry is opposite in sign to that of pions. On the contrary, if the asymmetry of the quark scattering were the dominating one, then the asymmetries of pseudoscalar (PS) and vector (V) mesons would not differ much.

We consider the reaction:

$$p\uparrow + p \to h + X\,, \tag{1}$$

where $\uparrow$ refers to the projectile proton polarized vertically upwards (parallel to the $\hat{y}$ axis) if the beam momentum points in the $\hat{z}$ direction. The produced hadron h carries the fraction $x_F = 2p_z/\sqrt{s}$ of the center-of-mass longitudinal momentum and the transverse momentum $\vec{p}_\perp$. In measurements of the asymmetry, the polarized cross-section $d\sigma_\uparrow$ is assumed to behave as

$$d\sigma_\uparrow(x_F, \vec{p}_\perp) = d\sigma(x_F, p_\perp)[1 + A_N(x_F, p_\perp)\cos(\phi)]\,, \tag{2}$$

where $d\sigma$ denotes the unpolarized cross-section. This defines the asymmetry A_N. ϕ is the azimuthal angle of the transverse momentum $\vec{p}_\perp$ of the hadron, measured with respect to the $\hat{x}$ axis.

If one assumes factorization, the cross-section for the reaction (1) is a convolution of the parton distribution $q(x)$, the cross-section $d\hat{\sigma}$ for the parton scattering and the fragmentation function $D_{h/q}(z)$ of the scattered quark q into the hadron h.

When the projectile proton is transversely polarized then the quark acquires also transverse polarization $\vec{\mathcal{P}}_q$, its magnitude being defined by the transversity distribution [8]

$$\mathcal{P}_q(x) = \frac{\Delta_\perp q(x)}{q(x)} \tag{3}$$

depending on the quark momentum fraction x. After scattering this polarization can be diminished by a depolarization factor D_{NN}. However, D_{NN}

is close to unity at typical small scattering angles [4] and the polarization is conserved during scattering. Moreover, the transverse momentum $\vec{p}_\perp$ of the produced hadron is the sum of its part $z\vec{q}_\perp$ inherited from the transverse momentum $\vec{q}_\perp$ of the scattered quark and some additional transverse momentum $\vec{h}_\perp$ coming from the fragmentation.

Hence, the spin effects can be included by the dependence of the fragmentation function $D_{h/q}$ on the quark polarization $\vec{\mathcal{P}}_q$ (Collins effect). They manifest themselves in an asymmetry of production of the hadrons in the azimuth of the transverse momentum $\vec{h}_\perp$ of the hadron with respect to the axis of the scattered quark.

Another source of asymmetry can appear at the parton level *i.e.* when $d\hat{\sigma}$ depends on the azimuth $\hat{\varphi}$ of the transverse momentum $\vec{q}_\perp$ of the scattered quark (Szwed effect [6, 7]).

Hypothetically, two extreme cases could be defined:

a) the asymmetry appears only in the fragmentation function as calculated in [2]. In this case it can depend on whether the produced hadron is a PS or V meson. This is the case of the high-energy limit since at a sufficiently high energy any asymmetry appearing at the parton level (in $d\hat{\sigma}$) must vanish due to chiral symmetry.

b) The asymmetry appears only at the parton scattering. It has been shown by Szwed in [7] that this mechanism can lead to significant asymmetries at the beam energy of the order of $10 - 20$ GeV. Here, the final asymmetry is defined before fragmentation and it does not depend on whether h is a PS or a V meson. It can depend, however, on the flavour of the scattered quark.

In reality, one can expect a mixture of the two effects with the second one vanishing at a sufficiently high energy. We shall concentrate on the case *a)* and calculate the asymmetry of vector mesons therein.

In reference [2] it was argued that the polarized cross-section for the reaction (1) at large positive x_F can be written as:

$$\frac{d\sigma}{dx_F d^2\vec{p}_\perp} = \sum_{q=u,d} \int dx q(x) \int d^2\vec{q}_\perp \frac{d\hat{\sigma}}{d^2\vec{q}_\perp} \int dz d^2\vec{h}_\perp D_{h/q}(z, \vec{h}_\perp) \times \delta\left(x_F - \sqrt{z^2x^2 - \frac{4p_\perp^2}{s}}\right) \delta^2(\vec{p}_\perp - z\vec{q}_\perp - \vec{h}_\perp) . \quad (4)$$

The fragmentation function $D_{h/q}$ was calculated there in the framework of the string model [5] of particle production. In order to include the spin effects, it was divided into two parts:

$$D_{h/q} = D_{h/q}^{\mathbf{rank}=1} + D_{h/q}^{\mathbf{rank}\geq 2}, \quad (5)$$

where $D_{h/q}^{\mathrm{rank}=1}$ corresponds to the first-rank (leading) hadron containing the original fragmenting quark. Only this part is azimuthally asymmetric.

Two factors determine the spin asymmetry of fragmentation:

a) Correlation of the polarization of the quark and the antiquark $\vec{\mathcal{P}}_q = \vec{\mathcal{P}}_{\bar{q}}$ of a pair produced in the string and their orbital angular momentum $L = 2k_\perp^2/\kappa$, where $k_\perp$ and $-k_\perp$ are the transverse momenta of q and $\bar{q}$ and κ is the string tension. This correlation is parametrized in the Lund model [5] according to the formula: $\mathcal{P}_q = L/(\beta + L)$ with β being a parameter determined to be between 1 and 2. In this paper, following Ref. [2], we use $\beta = 1$.

b) Probability that the leading quark having the polarization $\mathcal{P}_q$ and the first subleading one with polarization $\mathcal{P}_{\bar{q}}$ form a particular meson. This probability for the PS mesons (in the nonrelativistic quark model) is

$$\tfrac{1}{4}\,(1 - \vec{\mathcal{P}}_q \cdot \vec{\mathcal{P}}_{\bar{q}})\,, \tag{6}$$

while for the V mesons it is

$$\tfrac{1}{4}\,(3 + \vec{\mathcal{P}}_q \cdot \vec{\mathcal{P}}_{\bar{q}})\,. \tag{7}$$

This makes the asymmetry of the fragmentation into the ρ mesons opposite in sign and 3 times smaller than for pions.

In the numerical calculations we used the same parameters as those in Ref. [2] in which one can find the detailed description of the model. The only difference between the present calculation an that of Ref. [2] is in the splitting function determinig the fragmentation of the string. The heavier resonances have a harder spectrum. For the ρ mesons, we used the Standard Lund splitting function $f(z) = (1+C)(1-z)^C$ with the parameter $C = -0.2$, while for the pions $C = 0.5$ was used. This accounts reasonably well for the measured inclusive spectra [9, 10] of the ρ mesons as shown in Fig. 1. The x_F dependence of the inclusive cross-section is very well reproduced by the model. The obtained p_T spectrum is slightly steeper than the experimental one but the agreement is satisfactory in view of the simplicity of the model. One could probably get a better agreement using the symmetric splitting function instead of the Standard-Lund one quoted above. Unfortunately one cannot get analytical results neither for the spectra nor for the asymmetry with the symmetric splitting function.

In Figs 2 and 3 we show the results obtained for the asymmetry A_N of the ρ meson production, at 200 GeV beam momentum, compared to that of the charged pions. As already argued, the ratio of the asymmetries is

$$R_{\rho/\pi} = \frac{A_N^\rho}{A_N^\pi} \approx -\frac{1}{3}\,. \tag{8}$$

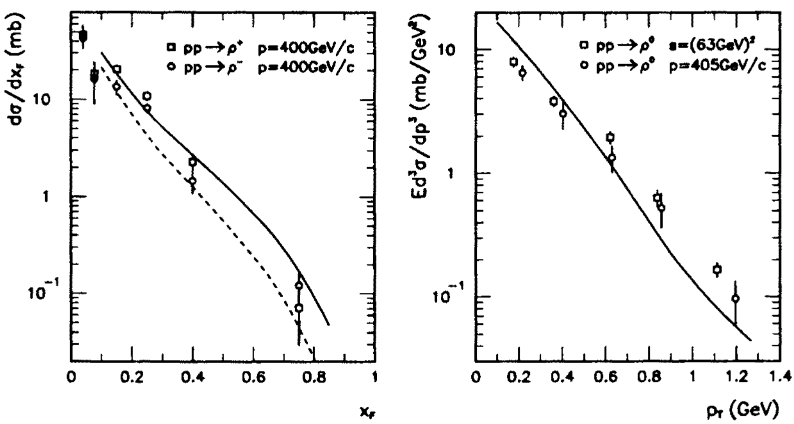

Fig. 1. Inclusive cross sections for ρ production as calculated according to the formula (4) compared to data of Ref. [9] (x_F dependence) and Ref. [10] ($p_\perp$ spectrum).

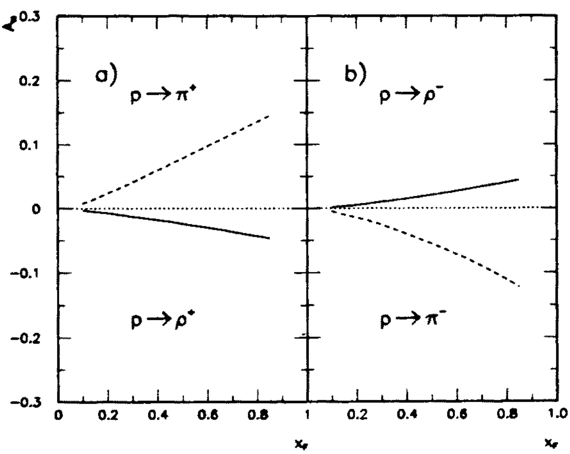

Fig. 2. The single-spin asymmetry of the charged ρ mesons (full lines) and the charged π mesons (dashed lines) plotted versus x_F. For all the plots the beam energy of 200GeV was taken and the particle yields used to calculate the asymmetry was integrated over $0.5 < p_\perp < 2$GeV.

It would be of great interest to verify this prediction experimentally. The formula (8) is exact at the level of the fragmentation but the slight difference in between $R_{\rho/\pi}$ and $-1/3$ is caused by the different parameter C used for fragmentation into the pions and into the ρ mesons.

Violating the rule (8) can be an indication of appearing of the Szwed effect [7, 6] *i.e.* significant asymmetry in parton scattering. In that model,

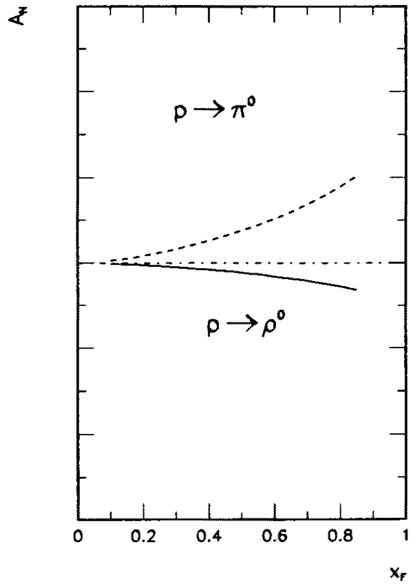

Fig. 3. The single-spin asymmetry of the neutral ρ mesons (full line) and the neutral π mesons (dashed line). All parameters are as in Fig. 2.

originally constructed to describe the polarization of hyperons Λ [6], the asymmetry of a transversely polarized quark scattered on a Coulomb-like strong field is given by:

$$\mathcal{A}_{q\to q'} = 2C_S\alpha_S \frac{mq\sin^3(\theta/2)\ln[\sin(\theta/2)]}{[m^2+q^2\cos^2(\theta/2)]\cos(\theta/2)}\,\frac{\vec{q}\times\vec{q}\,'}{|\vec{q}\times\vec{q}\,'|} \tag{9}$$

where m, $\vec{q}$ and $\vec{q}\,'$ are the mass, the initial and the final momentum of the scattered quark and $q = |\vec{q}|$. θ is the scattering angle in the frame where $|\vec{q}| = |\vec{q}\,'|$. C_S is the constant characterizing the external strong field. The sign of the asymmetry depends on the sign of the constant C_S in (9) or on whether the field source is "quark-like" or "antiquark-like". In the first case C_S is positive and the asymmetry $\mathcal{A}_{q\to q'}$ negative, in the latter C_S is negative and $\mathcal{A}_{q\to q'}$ positive. It would be interesting to check what the asymmetry is in quark–gluon scattering.

Hence, if the asymmetry of quark scattering is treated as a correction to that of fragmentation, $R_{\rho/\pi} < -\frac{1}{3}$ will mean negative $\mathcal{A}_{q\to q'}$ or scattering off a "quark-like" field and $-\frac{1}{3} < R_{\rho/\pi}$ will mean positive $\mathcal{A}_{q\to q'}$ and "antiquark-like" field. As explicitly seen from Eq. (9), at sufficiently high energy ($k \gg m$) the asymmetry of quark scattering vanishes. The energy scale where it appears can be an interesting hint about the scale of the masses of partons being scattered in a pp collision.

$R_{\rho/\pi} \neq -\frac{1}{3}$ could also mean a violation of the nonrelativistic quark model, which was assumed in the calculation of the asymmetry. If this were the case, then the high-energy limit of $R_{\rho/\pi}$ could be taken as the reference value, instead of $-\frac{1}{3}$ and the above analysis could be also made.

To summarize, we have calculated the single spin asymmetry of ρ meson production in $p\uparrow p$ collisions in the framework of Ref. [2], where the asymmetry of pions has been obtained. These results are valid for large positive x_F. The asymmetry was generated only in the fragmentation function using the string model of particle production. The two asymmetries are found to be opposite in sign, the ratio of that of ρ to that of π being approximately -1/3. Violating this rule can indicate to a significant contribution from the azimuthal asymmetry of the transversely polarized parton subprocess.

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REFERENCES

[1] See *e.g.* J.C. Collins, in Proceedings of PANIC XIII — Particles and Nuclei International Conference at Perugia, Italy, 28th June - 2nd July 1993, World Scientific, Singapore 1993 and references quoted therein.

[2] X. Artru, J. Czyżewski, H. Yabuki, Cracow JU preprint TPJU 13/95, hep-ph/9508239, to be published in *Z. Phys.* **C**.

[3] E-704 collaboration, D.L. Adams *et al.*, *Phys. Lett.* **B264**, 462 (1991); *Phys. Lett.* **B261**, 201 (1991); *Z. Phys.* **C56**, 181 (1992).

[4] J.C. Collins, *Nucl. Phys.***B396**, 161 (1993); J.C. Collins, S.F. Heppelmann, G.A. Ladinsky, *Nucl. Phys.***B420**, 565 (1994).

[5] B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, *Phys. Rep.* **97** 31 (1983).

[6] J. Szwed, *Phys. Lett.***B105**, 403 (1981).

[7] J. Szwed, Proceedings of the 9th International Symposium "High Energy Spin Physics" held at Bonn, 6–15 Sep. 1990, Springer Verlag 1991.

[8] J.P. Ralston and D.E. Soper, *Nucl. Phys.***B152**, 109 (1979); X. Artru, M. Mekhfi, *Z. Phys.***C45**, 669 (1990); J.L. Cortes, B. Pire, J.P. Ralston, *Z. Phys.***C55**, 409 (1992); R.L. Jaffe, Xiangdong Ji, *Nucl. Phys.***B375**, 527 (1992).
[9] M. Aguillar-Benitez *et al.*, *Z. Phys.***C50**, 405 (1991).
[10] T. Akesson *et al.*, *Nucl. Phys.***B203**, 27 (1982); A. Suzuki *et al.*, *Nuovo Cim.* **24**, 449 (1979).