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БИБЛИОТЕКА

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Поляризация в процессах с большим поперечным импульсом и при кумулятивном рождении адронов

В картине жесткого соударения проанализирована причина поляризации адронов в указанных процессах. На основе предположения о скейлинге дано правильное качественное объяснение поведения зависимости поляризации от $p_\perp$ (или угла вылета θ в кумулятивном рождении). Предсказана независимость поляризации от энергии и слабая зависимость от сорта пучка и мишени. Предложен метод измерения поляризации адронных струй.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Polarization in High $p_\perp$ and Cumulative Hadron Production

The final hadron polarization in the high $p_\perp$ processes is analyzed in the parton hard scattering picture. Scaling assumption allows a correct qualitative description to be given for the $p_\perp$-behaviour of polarization (or θ behaviour in cumulative production).

The energy scaling and weak dependence on the beam and target type is predicted. A method is proposed for measuring the polarization of hadron jets.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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I. Introduction

One of the problems of inclusive high $p_\perp$ processes is the polarization of Λ-particles [1,2]. Experiments [3] in the 300 GeV proton beam show that Λ-particles produced at Be target

i) Are polarized perpendicularly to the scattering plane.

ii) The polarization weakly depends on x in the interval 0.3 - 0.7.

iii) The polarization linearly rises with $p_\perp$ up to 28% at $p_\perp \simeq 1.5$ (Fig.1).

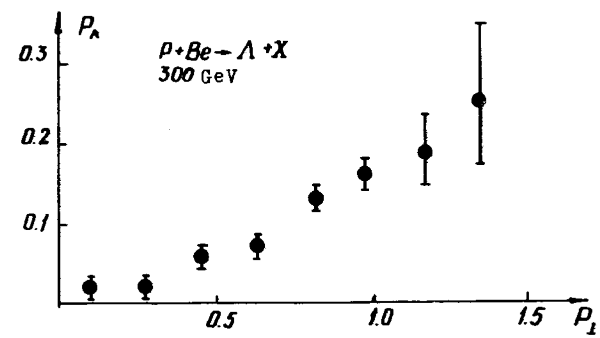

Fig. 1

It should be noted also that this experiment made no distinction between direct Λ's and those from $\Sigma^0 \to \Lambda + \gamma$ decay, which bring the depolarization effect [4]

$$P_{obs} = \frac{1}{r}\left(P_\Lambda - r\,\frac{P_\Sigma}{3}\right),$$

where r is the ratio of Σ^0/Λ yields.
Assuming this ratio is about 1 (as follows from SU_3) and $P_\Sigma \simeq P_\Lambda$ we see that the polarization of direct Λ is $\simeq 80 \div 90\%$!

It is interesting to compare this fact with polarization of "cumulative" Λ [5] produced in $\pi^- + (C + Xe)$ collision at 2.9 GeV/c. The polarization here depends essentially on the angle by which Λ is emitted (θ) with maximum around 90° and decreases at forward and backward directions (Fig.2).

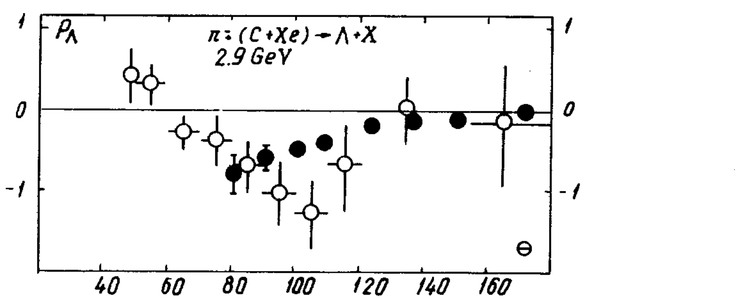

Fig. 2

From our point[6] of view these two different at first sight phenomena are due to the same mechanism of hard scattering of partons. Indeed, both the processes proceed in the region,

where all variables s, u, t and also ut/s are greater than 1. (The similarity of A-dependence in both processes[7,8] is a natural consequence of this hypothesis). As to the larger value of P_{obs} in cumulative production, it is probably due to the threshold suppression of Σ^0-production and to a lesser depolarization effect.

It seems strange that till now we do not see any serious attempt of theoretical explanation of these phenomena, though high $P_\perp$ data were published two years ago and polarization of cumulative protons is known even for 10 years [9].

In this work we try to understand both phenomena on the same footing using the hard scattering parton model and scaling assumption. Sec . II is devoted to high $P_\perp$ polarization, Sec . III to cumulative one. In Sec . IV we discuss the consequences and propose the measurement of the jet's polarization.

II. High $P_\perp$ particle polarization

The available experimental data on high $P_\perp$ production [10] and especially data from MPS of FNAL [11] and also theoretical investigation of QFT[1] strongly support the parton hard scattering origin of these phenomena. Let us see how the scattering of a nonpolarized hadron in this picture can give polarized one. The density matrix of the process fig. 3 can be easily written as (see, for instance, [1])

$$\rho_{\lambda\mu} E_c \frac{d\sigma}{d^3p_c} = \int d\gamma\, d\Delta\, Q_{A/a}(\alpha)\, Q_{B/b}(\beta)\, \frac{1}{\pi}\, \rho_{\lambda\lambda'} \frac{d\sigma}{dt'}(s',t')\, D^{\lambda'\mu}_{c/C}(\gamma), \quad (1)$$

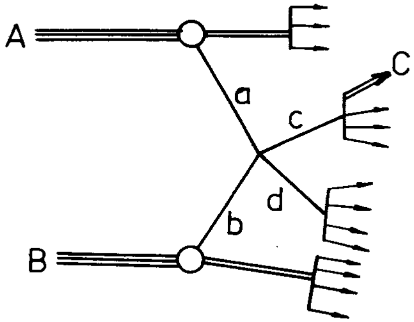

Fig. 3

where $Q(x) = x f(x)$ and $f_{A/a}$, $f_{B/b}$ is the number of partons with a fraction of momentum α, β, $D_{c/c}^{\lambda'\mu}(\gamma)$ is the number of hadrons C of helicity μ in parton c of helicity λ' and fraction of momentum γ,

$$\alpha = \frac{x_1}{\gamma}(1+e^{\Delta}), \quad \beta = \frac{x_2}{\gamma}(1+e^{-\Delta})$$

$$s' = \alpha\beta s, \quad t' = \frac{\alpha}{\gamma} t, \quad u' = \frac{\beta}{\gamma} u,$$

$$s = 2P_A P_B, \quad t = -2P_A P_C, \quad u = -2P_B P_C, \quad x_1 = -\frac{u}{s}, \quad x_2 = -\frac{t}{s}$$

and integration region is

$$-\ln\frac{\gamma - x_1}{x_1} \le \Delta \le \ln\frac{\gamma - x_2}{x_2}, \qquad x_1 + x_2 \le \gamma \le 1 .$$

Consider in more detail the subprocess of parton scattering $a + b \to c + d$ (parton is assumed to be a quarks of spin $1/2$). The amplitude of the process, as is well known, can be developed into the five-tensor structure in u - or t - channel

$$f = \sum_i (\bar{u}(a) T_i u(c))(\bar{u}(b) T_i u(d)) A_i(s', t') =$$
$$= \sum_j (\bar{u}(a) T_j u(d))(\bar{u}(b) T_j u(c)) A_j(s', u'),$$

where a, b and c are the momenta of partons. To calculate the density matrix $\rho_{\lambda\lambda'} \frac{d\sigma}{dt'}$ we have to average the squared amplitude over helicity of a and b and sum over helicity of d . To guarantee $a \leftrightarrow b$ symmetry we will use half of t-channel development of f and u -channel of f^* plus t -channel of f^* and u-channel of f , i.e.,

$$\rho_{\lambda\lambda'} \frac{d\sigma}{dt'} = \frac{1}{2} \bar{u}^{\lambda}(c) \sum_{ij} \left[(T_i \hat{a} T_j \hat{d} T_i \hat{b} T_j) A_i(s', t') A_j^*(s', u') + \right.$$
$$\left. + (T_j \hat{b} T_i \hat{d} T_j \hat{a} T_i) A_j(s', t') A_i^*(s', u') \right] .$$

Using the γ-matrix algebra this can be written in the c -rest frame as

$$\rho_{\lambda\lambda'} \frac{d\sigma}{dt'} = a(s', t') + b(s', t') \sin\varphi \, (\vec{\sigma} \vec{n}), \tag{2}$$

where

$$a = \sum_{ij} \left[\left(\frac{t'}{s'}\right)^2 C_{ij}^{(1)} + \left(\frac{u'}{s'}\right)^2 C_{ji}^{(1)} + \frac{u't'}{s'^2} C_{ij}^{(2)} \right] Re\left(A_i(s', t') A_j^*(s', u')\right)$$

$$b = \sum_{ij} \frac{u't'}{s'^2} C_{ij}^{(3)} \, Im\left(A_i(s', t') A_j^*(s', u')\right), \tag{3}$$

φ is the angle between $\vec{a}$ and $\vec{b}$ and $\vec{n} = \frac{\vec{a} \times \vec{b}}{|\vec{a} \times \vec{b}|}$ is the unit vector normal to the scattering plane and $C^{(1)}$, $C^{(2)}$, $C^{(3)}$ are numerical metrices. It is easy to find

$$\sin\varphi = \frac{2m_c\sqrt{u't'/s' - m_c^2}}{u't'/s'} = \frac{2m_c C_\perp}{C_\perp^2 + m_c^2} . \qquad (4)$$

The polarization of parton c

$$P_c = \frac{\ell(s',t')}{a(s',t')} \cdot \frac{2m_c C_\perp}{C_\perp^2 + m_c^2} \qquad (5)$$

appears to be nonzero only when the scattering amplitude has an imaginary part, i.e., a discontinuity in s' -channel. This clears the difficulty of most of the models used for description of high phenomena (CIM, OGEM, fusion model, etc.), because all they assume an exchange character of interaction of partons which leads to a pure real amplitude and zero polarization.

Consider now the dependence of polarization on $C_\perp$. It is well known, that high $P_\perp$ experimental data are well described by the form /10/

$$\mathcal{E}_c \frac{d\sigma}{d^3p_c} \simeq m_\perp^{-n} f(x_1, x_2)$$

which assumes the scaling of $a(s',t')$ in the hard scattering formula (1). According to this we shall also assume the factorization of invariant amplitudes

$$A_i(s',t') \sim (s')^{-n/4} f_i(s'/t'). \qquad (6)$$

Using this in expression (5) we can obtain for the quark polarization

$$P_c = \frac{\chi_2(\Delta)}{\chi_1(\Delta)} \frac{2m_c C_\perp}{C_\perp^2 + m_c^2} ,$$

i.e., the polarization linearly increases with $C_\perp$ for small values of $C_\perp$ $(< m_c)$ and decreases for larger momenta.

Let us turn now to polarization of hadron C. It is easy to see that the fragmentation function of the polarized parton $D^{\lambda'\mu}_{c/C}$ in the c -rest frame depends on one 3-vector (e.g., $\vec{P}_C$ or $\vec{P}_\perp^{jet}$). So, it is impossible to build up any pseudovector and then

$$D^{\lambda'\mu}(\gamma) = D(\gamma)\delta_{\lambda'\mu} .$$

Using this in the hard scattering formula (1) and also the density matrix (2),(3) and scaling (6) one can obtain the expression for the hadron polarization

$$P_C = I(x_1, x_2) \frac{2m_c P_\perp}{P_\perp^2 + m_c^2}$$

$$I(x_1, x_2) = \frac{\int d\Delta\, d\gamma\, Q_{A/a} Q_{B/\ell} D_{c/C} \gamma^n \chi_2(\Delta)}{\int d\Delta\, d\gamma\, Q_{A/a} Q_{B/\ell} D_{c/C} \gamma^n \chi_1(\Delta)} . \qquad (7)$$

Consider some qualitative features of polarization determined by this expression

i) For fixed x_1, x_2 the hadron polarization follows the quark polarization, i.e., first it increases with $P_\perp$ up to m_C and then decreases when $P_\perp > m_C$.

ii) In the central region the polarization does not depend on x_1, x_2, when the latter become small (< 0.15, i.e., $E \gtrsim 50$ GeV for $P_\perp \simeq 1.5$).

Really, this dependence appears only due to the difference of χ_1 and χ_2 . However, from the θ - dependence of one particle spectrum and also from the away peak position it is known /12/ that $\chi_1(\Delta) \le e^{-|\Delta|}$, when $\Delta \to \infty$ and consequently $\chi_2(\Delta) < e^{-|\Delta|}$, so that the tailes of χ_1 and χ_2 in (7) beyond the boundary $|\Delta| > 1.5 \div 2$ (i.e., $x_1, x_2 < 0.15$ for $\gamma \approx 1$) are negligible and do not change with subsequent decrease of x_1 and x_2 (fig.4).

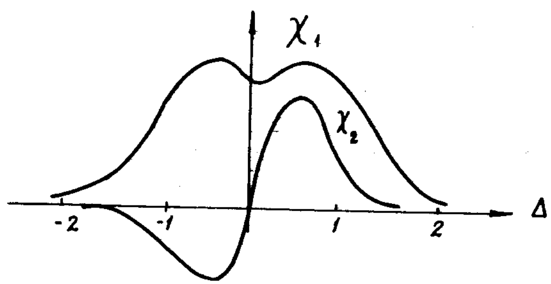

Fig.4.

iii) Similar conclusion can be made in the fragmentation region also, where $x_1 \simeq x_F$ and $x_2 \simeq m_\perp^2 / 2 m_B x_F E$ is small. At fixed x_F and $m_\perp$ the polarization will not change with the incident energy above

$E \gtrsim 4 m_\perp^2 / m_B x_F$ (i.e., $E \gtrsim 20 \div 30$ GeV for $P_\perp \approx 1.5$ and $x_F \approx 0.5$).

iv) The polarization weakly depends on x_F and also on the target and beam kind , because the influence of fragmentation functions in the numerator and denominator of (7) try to compensate each other. Some of these properties were observed in experiment (growth with $P_\perp$ up to 1.5 GeV/c, weak x_F dependence, and by rumor, target independence)

the other can be considered as predictions. More thorough predictions require computations and depend on a detailed behaviour of $\chi_2(\Delta)$.

A few words about estimation of the absolute value of polarization. In the model of hard scattering of quarks polarization arises from interference of the one-gluon and two-gluon s-channel exchange (Fig.5),

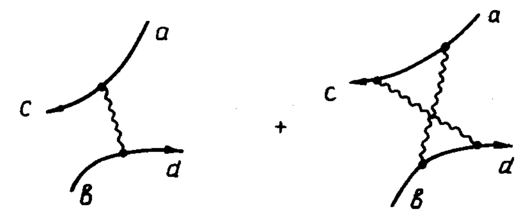

Fig.5.

i.e.,the polarization is proportional to $g^2_{inv}(m_\perp)$. However, to describe one-pion spectra as is known, /12,13/ we have to assume that $d\sigma/dt' = \frac{32\pi^2}{m_\perp^4} g^4_{inv}(m_\perp) \simeq 2300\ mb \cdot GeV^6 / m_\perp^8$,

i.e., $g^2_{inv} \approx (2\ GeV/m_\perp)^2$. Therefore, for estimation of I in (7) we can obtain

$$I \approx \left(\frac{2}{m_\perp}\right)^2 \approx 1.2 \quad \text{at} \quad P_\perp = 1.5 \text{ GeV/c.}$$

So, the polarization can be quite large at those momenta. However, next order corrections seem also to be not small and further investigation is needed.

III. Cumulative production

As was mentioned in Sec. I. this process is due to the same mechanism of hard scattering of partons of incident particle with a parton of a fluctuon in a nucleus. Really, all invariant variables

$$s = 2mE\,, \quad t = -2m\mathcal{E}\,, \quad u = -2E(\mathcal{E} - p\cos\theta)$$

and also $\sqrt{ut/s} = \sqrt{2\mathcal{E}(\mathcal{E} - p\cos\theta)}$ (≈ 3.5) are larger than hadron masses just as in the high $p_\perp$ production. So, we will also use the hard scattering formula (1) with the natural substitution

$$x_1 = -\frac{u}{s} \approx \frac{\mathcal{E} - p\cos\theta}{m} = K \quad \text{(cumulative index)}$$

$$x_2 = -\frac{t}{s} = \frac{\mathcal{E}}{E}$$

$$\sin\varphi = \frac{m_c \sin\theta}{\mathcal{E} - p\cos\theta}$$

$$Q_{A/a}(\alpha) = \sum_{n=1}^{A} \left\{ {n \atop A} \right\} q^n (1-q)^{A-n}\, Q_{nN/a}\left(\frac{\alpha}{n}\right),$$

where $\mathcal{E}, p, \theta$ are the total energy, momentum and production angle of cumulative particle, $Q_{nN/a}$ is an N-nucleon fluctuon fragmentation function and $\left\{ {n \atop A} \right\} q^n (1-q)^{n-A}$ is the probability (binomial) of the fluctuon formation in a nucleus of atomic number A.

For the polarization of cumulative particle it naturally leads to

$$P_c = I_K(x_1, x_2)\, \frac{m_c \sin\theta}{\mathcal{E} - p\cos\theta}$$

and to similar to high $p_\perp$ production qualitative features:

i) Sharp θ-dependence with maximum in the region $90°$ (i.e., $\varphi \approx \theta$ for small momenta);

ii) Energy independence for $E \gtrsim 5 \div 10$ GeV;

iii) Weak K-dependence of $K P_c$ and weak dependence on the kind of beam and target.

Now we can use the weak dependence of I on x_1, x_2 and on the kind of target, equate $I = I_K$ and try to compare experimentally the data on high $p_\perp$ and cumulative Λ-polarization (Figs. 1 and 2) at the same values of $\sin\varphi$. In this comparison we put $P_{obs} \approx \frac{1}{3} P_\Lambda$ for high $p_\perp$ and $P_{obs} \approx P_\Lambda$ for cumulative Λ (due to the threshold suppression of Σ-production at 2.9 GeV). This comparison is shown by black points in fig. 2 and seems to be quite good for this rough approximation.

IV Discussion

As we have seen, the parton hard scattering mechanism gives a simple and reasonable qualitative explanation of polarization phenomena and predicts features which can be checked experimentally. This indicates to importance of spin dependence of parton subprocesses and force to expect, in particular, for the high $p_\perp$ hadron production on a polarized target a noticeable left-right asymmetry in respect to the "beam-polarization" plane. The detailes of this processes will be considered elsewhere.

As for the predictions considered here the most interesting seems to be the energy scaling which distinguishes the hard scattering mechanism from that of Regge-pole exchange and the decrease of polarization with increasing E. In this region polarization can serve as a good tool for better understanding of quark dynamics. For instance, the asymptotics of $g_{inv}(m_\perp)$ can discriminate between different schemes of the charge renormalization

$$m_\perp P_C \sim \begin{cases} \left(\ln \frac{m_\perp}{\Lambda}\right)^{-1} & \text{for asymptotical freadom} \\ g_c^2 + \left(\frac{\Lambda'}{m_\perp}\right)^{\varkappa} & \text{for dilatation invariance (finite bare charge)} \end{cases}$$

It is noteworthy that this conclusion (as well as qualitative features given in Secs. II and III) depend by no means on particularities of the hard scattering subprocess and are the same, for instance, for the subprocess of direct production $(q+q \to B+\bar{q})$ which seems to dominate in the presently available region due to the violent trigger bias. (One of the indications to this statement is a higher power of decrease $(\sim P_\perp^{-12})$ of baryon and antibaryon spectra [10]).

Of a special interest is the possibility to observe the polarization of high $P_\perp$ hadron jets. (An argument in favour of the quark nature of jets).

The idea is as follows.

When we consider the semi-inclusive decay of jet $c \to C_1 + C_2 + X$ in its c.m.s. there appears an additional pseudovector $\vec{n}' = \vec{P}_{C_1} \times \vec{P}_{C_2} / |\vec{P}_{C_1} \times \vec{P}_{C_2}|$. So, the fragmentation function has the form

$$D^{\mu\lambda'}_{c/C_1,C_2} = D_{c/C_1,C_2} \cdot \left(1 + \alpha\,(\vec{\sigma}\vec{n}')\right)_{\mu\lambda'}$$

and the cross-section $A+B \to C_1+C_2+X$ has the correlation term

$$\alpha P_c(\vec{n}\vec{n}') = \alpha P_c \cos\psi ,$$

where

$$\cos\psi = \frac{\cos(\widehat{AC_1})\cos(\widehat{BC_2}) - \cos(\widehat{AC_2})\cos(\widehat{BC_1})}{\sin(\widehat{AB})\,\sin(\widehat{C_1C_2})} .$$

Measuring two-particle distribution over $\cos\psi$ one can determine the polarization of parton c. The coefficient α can be determined by a similar procedure in $e^+ + e^- \to jet + jet$, where the quark polarization is known.

Such measurements could be made probably by using the data of the experiment $E260$ yet finished at MPS.

The polarization experiments seem to be especially valuable in cumulative processes, because these can help to establish the mechanism of these very phenomena. The similarity of Λ-particle polarization in cumulative and high $P_\perp$ productions and also the rumor that in the latter case the same polarization was observed with the hydrogen target give strong arguments in favour of the fluctuon hypothesis proposed 20 years ago [14]. The discovery of such a "dense" formation in nucleus opens a new possibility in the investigation of small distance dynamics. The mentioned analogy of $P_\perp$ and $\sqrt{4t/s} \approx 2\mathcal{E}$ allows in principle, even at Dubna accelerator, probing of the distance equivalent to $P_\perp \simeq 15\ \mathrm{GeV}/c$ (ISR range) and at Serpukhov machine, reaching the fantastic level $P_\perp \simeq 100\ \mathrm{GeV}/c$. Of course the practical possibility to reach such a level depends on the rate of decrease of the cross-section for large cumulativity index about which we can only guess now.

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