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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

ЕФИ-592(79)-82

I.G.AZNAURYAN A.A.GRIGORYAN N.L.TER-ISAAKYAN

HOW TO DEAL WITH SPIN IN THE QUARK MODEL AT HIGH ENERGIES

ԵՐԵՎԱՆ 1982 ЕРЕВАН

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КАК РАБОТАТЬ СО СПИНОМ В КВАРКОВОЙ МОДЕЛИ ПРИ ВЫСОКИХ ЭНЕРГИЯХ

Продемонстрирована тесная связь спиновых эффектов в адрон-адронных столкновениях с волновыми функциями кварков в адронах. В рамках аддитивной кварковой модели показано, что корректный подход к построению волновых функций адронов приводит при $S \to \infty$ к взаимодействию, переворачивающему S - канальную спиральность адронов, даже при отсутствии такого взаимодействия на кварковом уровне. В рассмотренных примерах наши предсказания хорошо согласуются с экспериментальными данными.

Ереванский физический институт

Ереван 1982

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The close connection between the spin effects in hadron-hadron collisions and the quark wave functions in hadrons is demonstrated. In the framework of additive quark model it is shown that the correct approach to the hadron wave functions construction at $S \to \infty$ leads to the s-channel helicity flip interaction of hadrons even in the absence of such interaction on the quark level. In the considered examples our predictions agree well with the experiment.

Yerevan Physics Institute

Yerevan 1982

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1. Introduction

During the last years a certain progress has been achieved in the theoretical investigation of the quark-quark or quark-antiquark scattering amplitudes (qq-amplitudes) at high energies. This progress is mainly due to the strong interaction picture, which is based on the dual-topological expansion of the S -matrix and the string and colour tube models. The introduction of the spin in this picture was carried out in [1] . The account of the spin is shown to allow one to explain the position of the secondary Regge-trajectories ρ , A_2 , f ; ω , π , A_1 , B... in the j -plane. As to the spin structure of qq -amplitudes, it turns out that asymptotically the behaviour of their planar part (which corresponds to the rightmost trajectories of vector-tensor group ρ , ω , A_2 , f) is determined by the interaction

$$V = \bar{u}_q(q_3,\lambda_3)\gamma_\mu u_q(q_1,\lambda_1)\,\bar{u}_q(q_4,\lambda_4)\gamma^\mu u_q(q_2,\lambda_2), \qquad (1)$$

which conserves at $S \gg M_N^2$ the S -channel helicity: $V^{s\to\infty} \sim s\,\delta_{\lambda_3\lambda_1}\delta_{\lambda_4\lambda_2}$. In (1) q_i and λ_i are the quark momenta and helicities.

The absence of the spin-flip interaction in qq -amplitudes contradicts at first sight the large diversity of spin effects manifested by the hadron amplitudes (hh -amplitudes) since in the traditional additive quark model (AQM) approach the hadron helicity flip is impossible without the quark one (see, e.g. [2,3]) [1]. This fact made us to revise critically the traditional AQM approach to the construction of hadron spin amplitudes at high energies. In this approach the whole $\vec{K}_\perp$ - dependence of hadron amplitudes ($K = p_3 - p_1 = p_2 - p_4$; p_i are hadron momenta) comes from the qq - amplitudes and overall form-factors $f(\vec{K}_\perp^2)$ [2-4]. We show however that this approach is not correct and contradicts the relativistic invariance. The following simple example clarifies this statement.

Consider the invariant expression of the nucleon electromagnetic current $J_N^\mu = \bar{u}_N(p_3)\left(Q_N\gamma^\mu + \frac{\varkappa_N}{2M_N}\sigma^{\mu\nu}K_\nu\right)u_N(p_1)$. It is well known that the non-relativistic quark model predicts the nonzero anomalous magnetic moment (AMM) of nucleon ($\varkappa_N \neq 0$) even if the quarks have only the normal magnetic moments (i.e. the quark electromagnetic current is $J_q^\mu = Q_q\,\bar{u}_q\,\gamma^\mu u_q$). Project now the invariant expression J_N^μ on the helicity states in the infinite momentum frame (IMF), where the nucleon is moving with the large momentum $|\vec{p}_1| \gg M_N$ along the z axis. We see that the helicity non-flip quark interaction ($\bar{u}_q(\lambda_3)\gamma^{0(3)}u_q(\lambda_1) \xrightarrow{IMF} \sqrt{s}\,\delta_{\lambda_3\lambda_1}$) generates the helicity flip nucleon interaction $\bar{u}_N(\lambda_3)\sigma^{0(3)\nu}K_\nu u(\lambda_1) \xrightarrow{IMF} \sqrt{s}\,|\vec{K}_\perp|\,\delta_{\lambda_3 - \lambda_1}$ in the contradiction with the traditional approach.

As we will show, the solution of this problem is connected with the construction of the final hadron wave functions at $\vec{K}_\perp \neq 0$. In the traditional approach one uses for them the non-relativistic SU(6)-wave functions. We have found however that in these functions the terms of the order

[1] Note that in this work we consider only s-wave hadrons.

of $\frac{|\vec{K}_\perp|}{m_q}$ arise which violate their SU(6)-structure. One can show that just the account of these terms allows one to get in IMF the well-known predictions of quark model for nucleon magnetic moments.[5]

As to the helicity states, the $\frac{|\vec{K}_\perp|}{m_q}$ terms lead to the states of quark systems in hadrons for which the sum of quark helicities does not coincide with the sum of quark helicities in the SU(6) wave function. As a result, the helicity flip hadron amplitudes arise, even if the quark interaction is helicity non-flip.

In the present work we obtain the predictions for the hadron amplitudes, proceeding from the derived in [1] helicity non-flip qq -amplitudes and using the correct wave functions for final hadrons. Those of our predictions which can be compared with the experiment show a good agreement with the data.

2. The Wave Functions in IMF and Spin Flip

Here we show on the nucleon example how to obtain the correct hadron-quarks vertex functions in IMF. For this purpose construct the simplest relativistic-invariant form of the proton $\to 3q$ vertex which reduces in the non-relativistic limit to the SU(6)-wave function:

$$\langle p|3q\rangle = \frac{1}{\sqrt{18}}\Big\{\bar{u}_p\, u_u(q_c)\big[u_u^T(q_a)C\gamma_5 u_d(q_b) - u_d^T(q_a)C\gamma_5 u_u(q_b)\big] + (a\leftrightarrow c) + (b\leftrightarrow c)\Big\}. \qquad (2)$$

In (2) q_a, q_b, q_c are the quark momenta, the lower indices of spinors stand for quark flavour.

Consider the high energy scattering process, where the initial proton is moving along the z -axis with the large momentum $\vec{p}_1=(0,0,p)$. As a result of the interaction, the final proton acquires the transverse momentum $\vec{K}_\perp$: $\vec{p}_3=(\vec{K}_\perp, p)$. Take now the initial proton wave function in the non-relativistic limit $(\vec{q}_a=\vec{q}_b=\vec{q}_c=\vec{p}_1/3)$:

$$\langle p|3q\rangle_{initial} = \Psi^{p}_{SU(6)}. \tag{3}$$

The final proton consists of the two quark-spectators (b, c) and the active quark (a), which carries the transverse momentum $\vec{K}_\perp$ with respect to the spectators. Expanding the transition vertex (2) for the final proton in powers of $\frac{|\vec{K}_\perp|}{m_q}$ and keeping the terms up to $\frac{|\vec{K}_\perp|}{m_q}$, we get

$$\langle p|3q\rangle_{final} = V_{h\to 3q}(\vec{K}_\perp)\cdot\Psi^{p}_{SU(6)}, \tag{4}$$

where

$$V_{h\to 3q}(\vec{K}_\perp) = 1 + \frac{i\varepsilon_{lm}K_l}{6m_q}(\sigma_b+\sigma_c-2\sigma_a)_m. \tag{5}$$

As it is seen from (5), the linear on $\frac{|\vec{K}_\perp|}{m_q}$ terms cause the nonconservation of helicity in the hadron-quarks vertex. As a consequence, the helicity flip hadron amplitudes arise. Note that these $\frac{|\vec{K}_\perp|}{m_q}$ terms are responsible for the nucleon AMM, if the calculations are performed in the IMF [5].

One can show that the transformation matrix $V_{h\to 3q}(\vec{K}_\perp)$ (5), which connects the IMF wave functions with SU(6) ones, is independent of the specific form of the relativistic-invariant generalization of the SU(6)-wave function and is the same for any three-quark state.

The analogous transformation matrix for the $q\bar{q}$ - states has the form

$$V_{h\to q\bar{q}}(\vec{K}_\perp) = 1 + \frac{i\varepsilon_{lm}K_l}{4m_q}(\sigma_b - \sigma_a)_m \cdot \tag{6}$$

3. Some Experimental Consequences

The vector qq - interaction (1) corresponding at $S \gg M_N^2$ to the vector-tensor group reggeons exchange leads to the hh - interaction which has the form of $V_\mu^{13} V^{24\mu}$, where V_μ^{ij} is the hadron vector current of the $h_i \to h_j$ transition. In cases of $N \to N$ and $N \to \Delta$ transitions, the currents are

$$V^\mu_{N_1\to N_3} = \bar{u}_N(p_3)\left(a^I_{NN}\gamma^\mu + \frac{b^I_{NN}}{2M_N}\sigma^{\mu\nu}K_\nu\right)u_N(p_1), \tag{7}$$

$$V^\mu_{N\to\Delta} = i\,\frac{b_{N\Delta}}{2M_N}\varepsilon^{\mu\nu\rho\sigma}K_\nu\,\bar{u}^\Delta_\rho(p_3)\gamma_\sigma u_N(p_1), \tag{8}$$

where I is the isospin of vector current.

Using the nucleon wave functions (4) (5) and the analogous ones for the Δ (1232) isobar, we obtain the following quark model predictions for a^I_{NN}, b^I_{NN}, $b_{N\Delta}$

$$a^0_{pp} = 3a^0_q \;\;,\;\; a^1_{pp} = a^1_q\;; \tag{9}$$

$$b^0_{pp} = 0\,, \quad b^1_{pp} = -4a^1_q\,,$$
$$b_{p\Delta^+} = 4a^1_q/\sqrt{3}. \tag{10}$$

(remind that the quark interaction has the form of $a_q^I \bar{u}_q \gamma^\mu u_q$). Note that these predictions coincide with the well-known non-relativistic quark model results for the charge and magnetic moments of $N \to N$ and $N \to \Delta$ transitions. In Ref. [5] it was shown that the relativistic effects (i.e. the internal motion of quarks in the hadrons) do not change these results considerably.

It is seen from (9) that in $N \to N$ vertices the helicity flip interaction prevails for the isovector reggeons ρ, A_2 and the helicity non-flip interaction dominates for the isoscalar reggeons ω, f . Using now the result of Ref. [1];

$$a_q^0 = a_q^1 , \tag{11}$$

we get that

$$a_{pp}^0 / a_{pp}^1 = 3 . \tag{12}$$

All these results are in agreement with the Regge-pole analysis of experimental data. The predictions (9), (10) for the b_{NN}^1 ; $b_{N\Delta}$ can be tested directly. It follows from (9) and (10) that at high energies the simple relations take place between the helicity flip parts of the $\pi^- p \to \pi^0 n$, $\pi^- p \to \eta n$, $K^- p \to \bar{K}^0 n$ reactions and the Δ -isobar production differential cross sections

$$\frac{d\sigma}{dt}(\pi^+ p \to \pi^0 \Delta^{++}) \Big/ \frac{d\sigma^f}{dt}(\pi^- p \to \pi^0 n) = \frac{3}{2} , \tag{13}$$

$$\frac{d\sigma}{dt}(\pi^+ p \to \eta \Delta^{++}) \Big/ \frac{d\sigma}{dt}(\pi^- p \to \eta n) = \frac{3}{2} , \tag{14}$$

$$\frac{d\sigma}{dt}(K^+p \to K^0\Delta^{++}) \Big/ \frac{d\sigma^f}{dt}(K^-p \to \bar{K}^0 n) = \frac{3}{2}. \qquad (15)$$

Fig.1 shows a good agreement of these predictions with the experimental data.

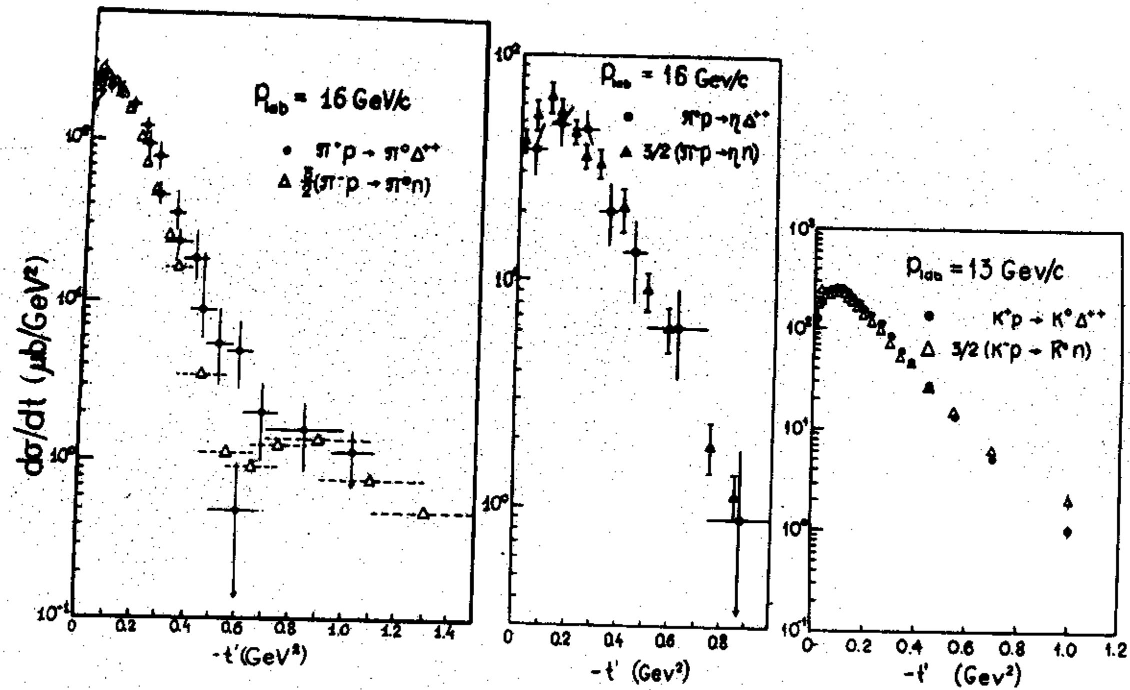
The relations (13)-(15) were obtained earlier in the other theoretical approaches, such as the bootstrap model [6] and the dispersion sum rules for the reggeon-particle scattering amplitudes [7, 8].

Note that the traditional AQM predicts for the relations (13)-(15) the value 24/25 [9] instead of 3/2.

4. Conclusion

Our analysis shows that in the high energy hh -scattering at the non-zero momentum transfer the wave functions of final hadrons differ from the SU(6) non-relativistic functions by the spin rotation. This results in the helicity flip amplitudes even in the absence of the helicity flip on the quark level. This means that the hypothesis of additivity does not hold for the helicity flip hadron amplitudes and the corresponding results of the works [2-4, 9] are not true.

The authors are grateful to S.G.Matinyan for his interest in this work.



Comparison of the additive quark model predictions with the experiment.

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The manuscript was received 26 July 1982

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(на английском языке, перевод З.Н.Асланян)

Редактор Л.П.Мукаян

Техредактор А.С.Абрамян

Заказ 558 | ВФ-01965 | Тираж 299

Препринт | Формат издания 60x84/16

Подписано к печати 23/XI-82 | 1.0 уч-изд.л. Ц. 15 к.

Издано Отделом научно-технической информации
Ереванского физического института, Ереван 36, Маркаряна 2

индекс 3624