Ref.TH.2712-CERN

AN IMPORTANT TEST OF SHORT-DISTANCE BEHAVIOUR :

THE SPIN DEPENDENCE OF LARGE ANGLE NUCLEON-NUCLEON ELASTIC SCATTERING

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A B S T R A C T

We show that contrary to approaches based on perturbative QCD, a theoretical framework where quarks are confined gives a very successful description of the striking spin-dependent effects which have been recently observed in large angle nucleon-nucleon elastic scattering.

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25 July 1979

Another approach is the constituent interchange model (CIM) ⁶⁾, which is compatible with (1) and with the experimentally observed absolute value, but is not able to produce a value of $A_{NN}(90^\circ)$ bigger than $1/3$, which is clearly unacceptable. On the face of what seems to be a real crisis, many excuses based on instantons ⁴⁾, Landshoff diagrams dominated by scalar mesons, etc. ³⁾, have been invented ; but the lesson of all this, we believe, is that the "inessential complications due to spin" have found in large angle pp scattering their long due nemesis.

In this letter we want to show that the further development of the theoretical ideas which led to a realistic description of short-distance phenomena in terms of the massive quark model (MQM)⁷⁾, do provide a very successful and natural description of what is experimentally observed in large angle pp scattering.

The MQM diagrams we must consider for large angle scattering are reported in Fig. 2. In order to evaluate the scattering amplitude we must analyze separately

- A) the nucleon overlap functions ;
- B) the elementary $(qq \rightarrow qq)$ amplitude at large angle.

A) - The nucleon overlap functions

In the nucleon overlap functions we must consider separately the helicity from the energy dependence. Assigning the nucleons their natural SU(6) wave functions in terms of the quark helicities and taking a spin-conserving overlap ^{*)} we readily compute :

$$= F_{B_H, B'_H}; q_h, q'_h =$$

(2)

*) Spin-, and not helicity - conservation seems a natural assumption for "spectator quarks".

Short-distance behaviour plays a very important rôle in our understanding of subnuclear phenomena. The striking experimental discovery of scaling in deep inelastic lepton-nucleon scattering has given many physicists the hope that strong interactions at short distances can be calculated in simple terms.

A very interesting process where short-distance behaviour, according to current ideas ^{*)}, is tested in a real way is large angle nucleon-nucleon elastic scattering. Thus any theory which claims to understand short-distance physics must submit to this very important test. At the level of the differential cross-section many approaches have met with success by deriving the scaling law

$$\frac{d\sigma}{dt} \rightarrow \frac{1}{s^n} F(\theta) \quad (1)$$

which, with the power n close to 10, fits remarkably well the large angle data ¹⁾. Recently experimental results have been published ²⁾ (see Fig. 1) on the spin dependence of large angle pp scattering which show an appalling spin dependence of the 90° pp cross-section. Such a characteristic spin dependence should clearly help decide which of the proposed approaches, if any, can survive.

A very important question is whether perturbative QCD, which is accepted almost universally as an adequate theory of short-distance phenomena, passes these tests. The answer is already in the literature ^{3),4)} and is unequivocally negative, even though this does not seem to have stirred up any great concern. Firstly whilst the scaling law (1) holds with the correct power, it is numerically off by at least five orders of magnitude, secondly its spin dependence is extremely weak contrary to observation ^{**)}. The conclusion is that if perturbative QCD does not work here for some mysterious reason, then it must be equally mysterious why it should work anywhere else, including one-particle inclusive cross-sections at large p_T .

^{*)} These ideas have led to the (unjustified) extension of perturbative methods in QCD much beyond the totally inclusive processes described by light cone physics.

^{***)} The coefficient ⁵⁾

$$A_{NN}(90^\circ) = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$

turns out to be equal to 1/9.

$$G_{h_1 h_2, h_3 h_4}^{(V)} = 4E^2 (1 + \cos^2 \theta/2) (\sigma_0)_{h_3 h_1} (\sigma_0)_{h_4 h_2} + 4E^2 \sin^2 \theta/2 (\sigma_3)_{h_3 h_1} (\sigma_3)_{h_4 h_2} \quad (4a)$$

$$G_{h_1 h_2, h_3 h_4}^{(P)} = 4E^2 \sin^2 \theta/2 (\sigma_1)_{h_3 h_1} (\sigma_1)_{h_4 h_2} \quad (4b)$$

$$G_{h_1 h_2, h_3 h_4}^{(V_L)} = 4E^2 \sin^2 \theta/2 \langle s \rangle (\sigma_2)_{h_3 h_1} (\sigma_2)_{h_4 h_2}, \quad (4c)$$

and $\langle s \rangle$ is given by ($R^2 \approx 2 \text{ GeV}^{-2}$, is related to the slope of Regge trajectories)

$$\langle s \rangle = \frac{4R^2}{\pi} p_1^2. \quad (5)$$

Calculating the diagrams in Fig. 2, it turns out that $p_1^2 = (m_N^2 - k_T^2)$, where k_T^2 is the transverse momentum of the quark inside the nucleons. Taking $k_T^2 \approx 0.1 \text{ GeV}^2$ we obtain

$$\langle s \rangle \approx 2. \quad (5a)$$

Turning to the energy dependence, we must evaluate the large t, u limit of our amplitude ¹⁰⁾

$$G(t, u) = \sum_n \frac{1}{m_n^2} \frac{1}{m_n^2 - t} \sum_{l=0}^{l_{\max}} (2l+1) P_l \left(1 + \frac{2u}{m_n^2}\right) \quad (6)$$

and, using the techniques developed in Ref. 10), we obtain

$$G(t, u) \rightarrow \log \left(-\frac{t}{m_0^2} \right) \frac{1}{(-u)^{3/2}}, \quad (7)$$

where the peculiar u behaviour is to be noticed.

$$\begin{aligned}
& + \left[\delta_{hh'} \delta_{HH'} \cos^2 \frac{\theta}{2} + \epsilon_{hh'} \epsilon_{HH'} \sin^2 \frac{\theta}{2} + (\delta_{hh'} \epsilon_{H'H} + \epsilon_{h'h} \delta_{H'H}) \sin \frac{\theta}{2} \cos \frac{\theta}{2} \right] \times \\
& \quad \times \left[\delta_q^{q'} (\bar{B}B) - (\bar{B}B)_q^{q'} \right] + \\
& + \left[\epsilon_{hh'} \epsilon_{HH'} \cos^2 \frac{\theta}{2} + \delta_{hh'} \delta_{HH'} \sin^2 \frac{\theta}{2} + (\epsilon_{hh'} \delta_{H'H} + \epsilon_{HH'} \delta_{h'h}) \sin \frac{\theta}{2} \cos \frac{\theta}{2} \right] \times \\
& \quad \times \left[(\bar{B}B)_q^{q'} + (\bar{B}B)_q^{q'} - \delta_q^{q'} (\bar{B}B) \right], \tag{2ctd.}
\end{aligned}$$

where θ is the centre-of-mass angle between B' and B , ϵ_{ij} is the two-dimensional Levi-Civita symbol, and B_a^b is the $SU(3)$ wave function of the baryon B .

As for the energy dependence using the wave functions of Ref. 8), we can compute the high energy behaviour for the baryon overlap in the centre-of-mass as (E is the active quark energy in the centre-of-mass frame)

$$F(t; E) \rightarrow \frac{1}{t} \frac{1}{E^2} \tag{3}$$

which leads to the observed asymptotic behaviour of the nucleon form factors.

B) The elementary $(qq \rightarrow qq)$ amplitude at large angle

In the $(qq \rightarrow qq)$ amplitude too we must separate the spin from the energy dependence. According to quark-geometroynamics (QGD) ⁹⁾ the $(qq \rightarrow qq)$ amplitude is given by the sum of contributions in Fig. 3, where the sum runs over the infinite number of mesons belonging to four different meson families (four are in fact the different $q\bar{q}$ spin configurations) : transverse vector (V_T), pseudoscalar (P), longitudinal vectors (V_L). Thus asymptotically we have a very rich spin structure, which is given by :

$$G_{h_1 h_2 h_3 h_4} = G_{h_1 h_2 h_3 h_4}^{(V_T)} + G_{h_1 h_2 h_3 h_4}^{(P)} + G_{h_1 h_2 h_3 h_4}^{(V_L)} \tag{4}$$

Now we have at our disposal all we need to compute the five nucleon-nucleon helicity amplitudes ϕ_i ⁶⁾. After some algebra we obtain

$$\phi_i = \frac{1}{s^{9/2}} \log \left(\frac{s}{m_0^2} \right) \left[\frac{T_i(\theta)}{(1-\cos\theta)^2 (1+\cos\theta)^{3/2}} + \frac{U_i(\theta)}{(1+\cos\theta)^2 (1-\cos\theta)^{3/2}} \right] \quad (8)$$

where

$$\begin{aligned} T_1(\theta) = & \frac{3+\cos\theta}{2} \left([A_{13}(4-\cos\theta) + S_{13}(1+2\cos\theta)][A_{24}(4-\cos\theta) + S_{24}(1+2\cos\theta)] \right) \\ & + \frac{1-\cos\theta}{2} \left\{ ([SA_{13}-S_{13}][SA_{24}-S_{24}]) - \langle s \rangle \sin\theta ([A_{13}-2S_{13}] \times \right. \\ & \left. \times [A_{24}-2S_{24}]) \right\} \end{aligned} \quad (8a)$$

$$\begin{aligned} T_2(\theta) = & -\frac{3+\cos\theta}{2} \sin^2\theta \left([2S_{13}-A_{13}][2S_{24}-A_{24}] \right) + \\ & -\frac{1-\cos\theta}{2} \left\{ ([SA_{13}-S_{13}][SA_{24}-S_{24}]) - \langle s \rangle ([A_{13}(4+\cos\theta) + S_{13}(1-2\cos\theta)] \times \right. \\ & \left. \times [A_{24}(4+\cos\theta) + S_{24}(1-2\cos\theta)]) \right\} \end{aligned} \quad (8b)$$

$$\begin{aligned} T_3(\theta) = & \frac{3+\cos\theta}{2} \left([A_{13}(4-\cos\theta) + S_{13}(1+2\cos\theta)][A_{24}(4-\cos\theta) + S_{24}(1+2\cos\theta)] \right) + \\ & + \frac{\cos\theta-1}{2} \left\{ ([SA_{13}-S_{13}][SA_{24}-S_{24}]) + \langle s \rangle \sin^2\theta ([A_{13}-2S_{13}][A_{24}-2S_{24}]) \right\} \end{aligned} \quad (8c)$$

$$\begin{aligned} T_4(\theta) = & \frac{3+\cos\theta}{2} (+\sin^2\theta) \left([2S_{13}-A_{13}][2S_{24}-A_{24}] \right) + \frac{1-\cos\theta}{2} ([SA_{13}-S_{13}][SA_{24}-S_{24}]) \\ & + \frac{\cos\theta-1}{2} \langle s \rangle ([A_{13}(4+\cos\theta) + S_{13}(1-2\cos\theta)][A_{24}(4+\cos\theta) + S_{24}(1-2\cos\theta)]) \end{aligned} \quad (8d)$$

$$\begin{aligned} T_5(\theta) = & \frac{3+\cos\theta}{2} (-\sin\theta) \left([2S_{13}-A_{13}][A_{24}(4-\cos\theta) + S_{24}(1+2\cos\theta)] \right) \\ & + \frac{1-\cos\theta}{2} (\sin\theta) \langle s \rangle \left([2S_{13}-A_{13}][A_{24}(4+\cos\theta) + S_{24}(1-2\cos\theta)] \right), \end{aligned} \quad (8e)$$

where

$$(S_{ij})_q^{q'} = S_q^{q'} (\bar{B}_i B_j) - (\bar{B}_j B_i)_q^{q'}$$

$$(A_{ij})_q^{q'} = (B_i \bar{B}_j)_q^{q'},$$

and the U_i are given directly by the following substitutions :

$$3 \leftrightarrow 4$$

$$U_{1,2,5}(\theta) = T_{1,2,5}(\theta + \pi)$$

$$U_3(\theta) = T_4(\theta + \pi)$$

$$U_4(\theta) = T_3(\theta + \pi).$$

Setting $\langle s \rangle = 2$ according to (5a), we obtain the following results :

- (i) the scaling law (1) gets modified by log terms, i.e.,

$$\frac{d\sigma}{dt} \rightarrow \frac{\log(\frac{s}{m_0^2})^2}{s^{11}} F_{NN}(\theta); \quad (9)$$

- (ii) the asymptotic functions $F_{pp}(\theta)$ and $F_{pn}(\theta)$ are given by the curves in Fig. 4, along with their ratio as a function of the angle ; in particular we get :

$$\frac{d\sigma^{pn}(90^\circ)}{d\sigma^{pp}(90^\circ)} = 0.305; \quad (10)$$

- (iii) both $A_{NN}^{pp}(\theta)$ and $A_{NN}^{pn}(\theta)$ exhibit impressive spin effects as can be seen by the curves of Fig. 5.

The agreement of our results with experiment is extremely satisfactory. In fact we have :

- (i) the s dependence of (9) from $m_0^2 \simeq 4 \text{ GeV}^2$ is very close to $1/s^{10}$; in the range $20 < s < 90 \text{ GeV}^2$, as can be seen from Fig. 6 where $R(s) = (s^{10} \log^2(s/4)) / s^{11}$ is plotted as a function of s ;

- (ii) the shape of pp scattering appears well reproduced by our curve $F_{pp}(\theta)$; furthermore the ratio (10) is in very good agreement with the recent determination of Stone et al. ¹¹⁾

$$\frac{d\sigma^{pn}(90^\circ)}{d\sigma^{pp}(90^\circ)} = 0.34 \pm 0.05, \quad (11)$$

- (iii) the comparison of our $A_{NN}^{pp}(\theta)$ with the data at $p_{lab} = 11.75 \text{ GeV}/c$ ²⁾ is given in Fig. 7 ; the fact that agreement with experiment gets poor for angles below 60° is an expected consequence of the relatively low values of t , in fact $|t| \leq 2.5 \text{ GeV}^2$, a region where diffractive contributions can still be present ; notice that also the unpolarized differential cross-section requires a substantial diffractive contribution in this angular region.

In conclusion the spin-dependence of nucleon-nucleon elastic scattering at large angles has proved to be too severe a test for the approaches to short-distance behaviour which are now popular. On the other hand, the ideas that are at the basis of a realistic description of the quark degrees of freedom of hadronic matter have found in those impressive experimental results a beautiful confirmation.

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FIGURE CAPTIONS

- Fig. 1 The ratio $(d\sigma/dt)(\uparrow\uparrow) / (d\sigma/dt)(\uparrow\downarrow)$ at large angle according to Ref. 2).
- Fig. 2 The MQM diagrams describing the large angle reaction $N_1(P_1) + N(P_2) \rightarrow N(P_3) + N(P_4)$.
- Fig. 3 The $(qq - qq)$ amplitude in QGD.
- Fig. 4 The asymptotic functions $F_{pp}(\theta)$ and $F_{pn}(\theta)$, and the ratio $r(\theta) = F^{pn}(\theta) / F^{pp}(\theta)$.
- Fig. 5 Theoretical predictions for the asymptotic values of $A_{NN}^{pp}(\theta)$, $A_{LL}^{pp}(\theta)$, $A_{NN}^{pn}(\theta)$ and $A_{LL}^{pn}(\theta)$.
- Fig. 6 How close our prediction (9) is to a scaling law (1) with $n = 10$.
- Fig. 7 Comparison of the predicted asymptotic $A_{NN}^{pp}(\theta)$ with the experimental results of Ref. 2).

- Figure 1 -

- Figure 2 -

- Figure 3 -

- Figure 4 -

- Figure 5 -

- Figure 6 -

- Figure 7 -