Pramāṇa - J. Phys., Vol. 33, No. 5, November 1989, pp. 555–571. © Printed in India.

Bounds on non-leading QCD effects in a quark model for inclusive reactions

D K CHOUDHURY and R C GOSWAMI*

Department of Physics, Gauhati University, Guwahati 781 014, India
*Department of Physics, Darrang College, Tezpur 784 001, India.

MS received 14 March 1989

Abstract. We study the possible effect of QCD in the proton wave function in a quark model for inclusive processes $A + B \rightarrow C + X$ pursued by us. The assumption is the validity of the conjecture of Lepage and Brodsky in QCD on such effects. Our results obey the perturbative expectation, $|R_g \tan^2 \phi| < 1$. Symmetric version of the model is, however, found to be at variance with most of the inclusive data as well as with some known phenomenology. If the dynamics of the underlying theory generate Regge-like symmetry breaking approximately, the model is phenomenologically viable, and the non-leading QCD effects become reasonable in size. Phenomenological necessity of the admixtures of $(56, 0^+)^*$, $(70, 0^+)$ and $(56, 2^+)$ in the nucleon wave function is also discussed in the present analysis.

Keywords. quark model; inclusive reactions; gluons.

PACS Nos 12·40; 13·60; 12·38

1. Introduction

We address ourselves to the problem of nonleading QCD effects (Jacob 1982) in inclusive reactions (Collins and Martin 1984) $A + B \rightarrow C + X$. Specifically, we report such results within a quark model pursued by us in recent years (Barkakati and Choudhury 1983; Choudhury 1986; Choudhury and Goswami 1987, 1988). The model is based on the $qq\bar{q}$ model of Mitra (Mitra 1968). The motivation of the present analysis originates from the work of Lepage and Brodsky (Lepage and Brodsky 1981) in perturbative QCD. They find that while the leading term of the baryon wave function is the standard SU(6) symmetric, the next leading term contains a spin-flavour antisymmetric component.

Le Yaouanc *et al* (1975) observed that the nucleon at rest is not a pure $(56, 0^+)$ state, mixing with $(70, 0^+)$ seems to be required with a mixing angle $\phi \sim -20°$. Their conclusion was based on the problem of large x behaviour of the structure function ratio F_2^{en}/F_2^{ep} in deep inelastic scattering. From exhaustive analysis of strong and electromagnetic couplings, Isgur and Karl (Isgur and Karl 1978; Isgur *et al* 1982) and Koniuk and Isgur (Koniuk and Isgur 1980) have also indicated the non $(56, 0^+)$ admixtures. In the present paper, we will investigate whether such admixtures are at all necessary within our model.

In §2 we discuss the formalism and the results, while §3 is devoted to comments and conclusions.

2. Formalism

2.1 *Processes $P+B \to P+X$ ($P \to$ pseudoscalar mesons, $B \to$ baryons)*

This class of processes is controlled by the basic meson-quark amplitude $\pi_\alpha + q \to \pi_\beta + q$ which is given in the model (Mitra 1968; Barkakati and Choudhury 1983; Choudhury 1986; Choudhury and Goswami 1987) as

$$\tilde{O}_{\beta\alpha} = \tilde{A}(\tfrac{1}{2}\delta_{\beta\alpha} + u_{\beta\alpha}^{(+)}) + \tilde{B}u_{\beta\alpha}^{(-)} \tag{1}$$

where

$$u_{\beta\alpha}^{(+)} = (if_{\beta\alpha\gamma} + d_{\beta\alpha\gamma})\lambda_\gamma^{(1)} \tag{2}$$

$$u_{\beta\alpha}^{(-)} = (-if_{\beta\alpha\gamma} + d_{\beta\alpha\gamma})\lambda_\gamma^{(2)} \tag{3}$$

while the superscripts 1, 2 denote the quark indices in the $qq\bar{q}$ amplitude. The operators $\tilde{A}$ and $\tilde{B}$ operate upon the spin-cum-space part of the amplitude and contain the operator

$$P = (\mathbf{k}\cdot\mathbf{p}) + i\bar{\sigma}^{(2)}\cdot(\mathbf{k}\times\mathbf{p}) \tag{4}$$

where $\mathbf{k}$ and $\mathbf{p}$ represent the three momenta of the initial and the final state mesons respectively. The operators $\tilde{A}$ and $\tilde{B}$ are also the functions of the space overlaps defined in terms of two sets of parameters ($D_{s,a}^{(+)}$, $F_{s,a}^{(+)}$, $\bar{D}_{s,a}^{(+)}$, $\bar{F}_{s,a}^{(+)}$, $d_{s,a}^{(+)}$, $f_{s,a}^{(+)}$) and ($D_{s,a}^{(-)}$, $F_{s,a}^{(-)}$, $\bar{D}_{s,a}^{(-)}$, $\bar{F}_{s,a}^{(-)}$, $d_{s,a}^{(-)}$, $f_{s,a}^{(-)}$). Explicitly they are,

$$\tilde{A} = \frac{1}{16\sqrt{2}}[3A^{(+)} + \bar{A}^{(+)} + P(3A^{(-)} + \bar{A}^{(-)})] \tag{5}$$

$$\tilde{B} = \frac{1}{16\sqrt{2}}[3B^{(+)} - \bar{B}^{(+)} + P(3B^{(-)} - \bar{B}^{(-)})] \tag{6}$$

with

$$A^{(\pm)} = \tfrac{2}{3}[5(F_s^{(\pm)} + 2F_a^{(\pm)}) + 3(2D_s^{(\pm)} + D_a^{(\pm)})] \tag{7}$$

$$\bar{A}^{(\pm)} = \tfrac{2}{3}[3(\bar{F}_s^{(\pm)} + 2\bar{F}_a^{(\pm)}) + 5(2\bar{D}_s^{(\pm)} + \bar{D}_a^{(\pm)})] \tag{8}$$

$$B^{(\pm)} = \tfrac{2}{3}[(F_s^{(\pm)} + 2E_a^{(\pm)}) - (2D_s^{(\pm)} + D_a^{(\pm)})] \tag{9}$$

$$\bar{B}^{(\pm)} = \tfrac{2}{3}[(\bar{F}_s^{(\pm)} + 2\bar{F}_a^{(\pm)}) - (2\bar{D}_s^{(\pm)} + \bar{D}_a^{(\pm)})]. \tag{10}$$

Method of application of the model to inclusive processes has been discussed in QM-1 (Choudhury and Goswami 1987). To that end, we need the structure of the baryon wave function as $3q$ composite. Its standard form is (Mitra 1968),

$$\psi = \psi^s \eta^a \left(\frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}}\right). \tag{11}$$

Here ψ^s and η^a respectively denote the symmetric space and antisymmetric colour components. Similarly, (χ', χ'') are the conventional mixed symmetric spin states, while (ϕ', ϕ'') are the similar quantities in flavour space.

Lepage and Brodsky (1981) have shown that in perturbative QCD the leading term of the nucleon wave function expansion has a structure

$$\psi_L(Q^2) \sim \psi^s \left(\ln \frac{Q^2}{\Lambda^2} \right)^{-2/3\beta} \tag{12}$$

while the next leading term is of the form,

$$\psi_{NL}(Q^2) \sim \psi^a \left(\ln \frac{Q^2}{\Lambda^2} \right)^{-2\cdot 6/9\beta} \tag{13}$$

with

$$\frac{1}{\beta} = \frac{3}{33 - 2N_f} \cdot (N_f \rightarrow \text{number of flavours}). \tag{14}$$

In (14) ψ^s and ψ^a are respectively the spatial symmetric and antisymmetric pieces of the wave function, while $\ln(Q^2/\Lambda^2)$ is the standard QCD factor.

Thus keeping the Lepage and Brodsky expansion up to the next leading term, the baryon wave function gets the structure

$$\psi = \psi^s \eta^a \cos\phi \frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}} + \psi^a \eta^a \sin\phi \frac{\chi'\phi'' - \chi''\phi'}{\sqrt{2}} \tag{15}$$

where the angle ϕ measures the strength of the nonleading term of the wave function. Using (1)–(15) one then obtains the following form of the inclusive pseudoscalar meson production cross section:

$$\begin{aligned}\sigma(\bar{\Lambda}_\alpha + B \rightarrow \bar{\Lambda}_\beta + X) = {} & A'_q \cos^2\phi u'_q + A'_g \sin^2\phi u'_g \\ & + A''_q \cos^2\phi u''_q + A''_g \sin^2\phi u''_g \\ & + B'_q \cos^2\phi v'_q + B'_g \sin^2\phi v'_g \\ & + B''_q \cos^2\phi v''_q + B''_g \sin^2\phi v''_g \\ & + C'_q \cos^2\phi w'_q + C'_g \sin^2\phi w'_g \\ & + C''_q \cos^2\phi w''_q + C''_g \sin^2\phi w''_g .\end{aligned} \tag{16}$$

Here (u'_q, u'_g), (u''_q, u''_g), (v'_q, v'_g), (v''_q, v''_g), (w'_q, w'_g) and (w''_q, w''_g) are certain calculable geometrical flavour factors given in table 1.

The six functions $(A'_q, A''_q, B'_q, B''_q, C'_q, C''_q)$ represent the spatial contribution from the leading term of (15) while $(A'_g, A''_g, B'_g, B''_g, C'_g, C''_g)$ that from the non leading one. They have the following structures:

$$\begin{aligned}A'_q = {} & |G_1|^2 + (G_1^\dagger G_2 + G_2^\dagger G_1)(\mathbf{k}\cdot\mathbf{p}) + (G_1^\dagger G_2 - G_2^\dagger G_1) i(\mathbf{k}\times\mathbf{p})\cdot\hat{n} \\ & + |G_2|^2 \{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\}\end{aligned} \tag{17}$$

$$\begin{aligned}A''_q = {} & |G_1|^2 + (G_1^\dagger G_2 + G_2^\dagger G_1)(\mathbf{k}\cdot\mathbf{p}) + (G_1^\dagger G_2 - G_2^\dagger G_1)\{-\tfrac{1}{3} i(\mathbf{k}\times\mathbf{p})\cdot\hat{n}\} \\ & + |G_2|^2 \{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\}\end{aligned} \tag{18}$$

$$\begin{aligned}B'_q = {} & |R_1|^2 + (R_1^\dagger R_2 + R_2^\dagger R_1)(\mathbf{k}\cdot\mathbf{p}) + (R_1^\dagger R_2 - R_2^\dagger R_1) i(\mathbf{k}\times\mathbf{p})\cdot\hat{n} \\ & + |R_2|^2 \{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\}\end{aligned} \tag{19}$$

Table 1. SU(4) flavour coefficient for various processes as occurred in (16) of the text.

Processes	u'_q	u'_g	u''_q	u''_g	v'_q	v'_g	v''_q	v''_g	w'_q	w'_g	w''_q	w''_g
$\pi^- p \to \pi^- X$	61/72	101/72	101/72	61/72	2/9	2/3	2/3	2/9	−5/18	13/18	13/18	−5/18
$K^+ p \to K^+ X$	1/72	1/72	1/72	1/72	1/18	1/18	1/18	1/18	−1/36	−1/36	−1/36	−1/36
$\pi^- p \to \pi^0 X$	1/2	5/6	5/6	1/2	1	1/3	1/3	1	0	1/3	1/3	0
$\pi^+ p \to \pi^0 X$	1/2	1/6	1/6	1/2	0	2/3	2/3	0	0	1/3	1/3	0
$\pi^- p \to K^0 X$	1	5/3	5/3	1	0	0	0	0	0	0	0	0
$\pi^+ p \to \pi^+ X$	61/72	7/24	7/24	61/72	8/9	4/9	4/9	8/9	5/9	2/9	2/9	5/9
$K^- p \to K^- X$	25/72	25/72	25/72	25/72	2/9	2/9	2/9	2/9	−5/18	−5/18	−5/18	−5/18
$K^- p \to \bar{K}^0 X$	1	5/3	5/3	1	0	0	0	0	0	0	0	0
$\pi^+ p \to \eta X$	1/6	1/18	1/18	1/6	0	2/9	2/9	0	0	−1/9	−1/9	0
$\pi^+ p \to \bar{D}^0 X$	1	1/3	1/3	1	0	0	0	0	0	0	0	0
$K^- p \to D_s^- X$	1	5/3	5/3	1	0	0	0	0	0	0	0	0
$\pi^- p \to D^- X$	1	5/3	5/3	1	0	0	0	0	0	0	0	0
$\pi^+ p \to \eta' X$	1/6	1/18	1/18	1/6	0	2/9	2/9	0	0	−1/9	−1/9	0
$\pi^+ p \to K^+ X$	1	1/3	1/3	1	0	0	0	0	0	0	0	0
$\pi^- p \to \eta' X$	1/6	5/8	5/8	1/6	1/3	1/9	1/9	1/3	0	−1/9	−1/9	0
$\pi^- p \to \eta X$	1/6	5/18	5/18	1/6	1/3	1/9	1/9	1/3	0	−1/9	−1/9	0
$K^+ p \to K^0 X$	0	0	0	0	0	4/3	4/3	0	0	0	0	0
$K^- p \to \eta X$	2/3	10/9	10/9	2/3	1/3	1/9	1/9	1/3	0	0	0	0
$K^- p \to \pi^0 X$	0	0	0	0	1	1/3	1/3	1	0	0	0	0
$K^- p \to \pi^- X$	0	0	0	0	0	4/3	4/3	0	0	0	0	0
$K^- p \to \eta' X$	1/6	5/18	5/18	1/6	1/3	1/9	1/9	1/3	0	0	0	0

$$B_q'' = |R_1|^2 + (R_1^\dagger R_2 + R_2^\dagger R_1)(\mathbf{k}\cdot\mathbf{p}) + (R_1^\dagger R_2 - R_2^\dagger R_1)\{-\tfrac{1}{3}i(\mathbf{k}\times\mathbf{p})\cdot\hat{n}\} + |R_2|^2\{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\} \tag{20}$$

$$C_q' = (G_1^\dagger R_1 + R_1^\dagger G_1) + (G_1^\dagger R_2 + G_2^\dagger R_1 + R_1^\dagger G_2 + R_2^\dagger G_1)\cdot(\mathbf{k}\cdot\mathbf{p}) + (G_1^\dagger R_2 - G_2^\dagger R_1 + R_1^\dagger G_2 - R_2^\dagger G_1)i(\mathbf{k}\times\mathbf{p})\cdot\hat{n} + (G_2^\dagger R_2 + R_2^\dagger G_2) \times \{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\} \tag{21}$$

$$C_q'' = (G_1^\dagger R_1 + R_1^\dagger G_1) + (G_1^\dagger R_2 + G_2^\dagger R_1 + R_1^\dagger G_2 + R_2^\dagger G_1)(\mathbf{k}\cdot\mathbf{p}) + (G_1^\dagger R_2 - G_2^\dagger R_1 + R_1^\dagger G_2 - R_2^\dagger G_1)\{-\tfrac{1}{3}i(\mathbf{k}\times\mathbf{p})\cdot\hat{n}\} + (G_2^\dagger R_2 + R_2^\dagger G_2)\{(\mathbf{k}\cdot\mathbf{p})^2 + (\mathbf{k}\times\mathbf{p})\cdot(\mathbf{k}\times\mathbf{p})\}. \tag{22}$$

In these equations $\hat{n}$ represents a unit vector along the z-direction, while G_1, G_2, R_1 and R_2 are defined in terms of $(A^{(\pm)}, \bar{A}^{(\pm)}, B^{(\pm)}, \bar{B}^{(\pm)})$ of (7)–(10) as follows:

$$G_1 = \frac{1}{16\sqrt{2}}(3A^{(+)} + \bar{A}^{(+)}), \quad G_2 = \frac{1}{16\sqrt{2}}(3A^{(-)} + \bar{A}^{(-)}),$$
$$R_1 = \frac{1}{16\sqrt{2}}(3B^{(+)} - \bar{B}^{(+)}), \quad R_2 = \frac{1}{16\sqrt{2}}(3B^{(-)} - \bar{B}^{(-)}). \tag{23}$$

Similar relations can be obtained for $(A_g', A_g'', B_g', B_g'', C_g', C_g'')$ as well with appropriate sets of the space overlaps. We note that each of the functions defined in (17)–(22) is positive definite.

One can obtain also equivalent expressions for these functions in terms of relevant cross sections and the angle ϕ as discussed below:

For the sake of simplicity, we define a parameter R_g such that

$$R_g = \frac{A_g'}{A_q'} = \frac{A_g''}{A_q''} = \frac{B_g'}{B_q'} = \frac{B_g''}{B_q''} = \frac{C_g'}{C_q'} = \frac{C_g''}{C_q''} \tag{24}$$

which represents universally the ratio of the spatial functions of the nonleading to the leading term of (15). One then has,

$$A_q'(\phi) = \frac{1}{\cos^2\phi(1-R_g^2) + R_g^2(1-\tan^2\phi)}[2\sigma(K^-p\to\eta X) - 2\sigma(K^-p\to\eta' X) - \tfrac{5}{4}\{\sigma(\pi^-p\to K^0X) - \sigma(\pi^+p\to K^+X)\} - \tfrac{3}{4}\{\sigma(\pi^-p\to K^0X) - \sigma(\pi^+p\to K^+X)\}R_g\tan^2\phi] \tag{25}$$

$$A_q''(\phi) = \tfrac{3}{4}\{\sigma(\pi^-p\to K^0X) - \sigma(\pi^+p\to K^+X)\} \times (1+\tan^2\phi) - A_q'(\phi)R_g\tan^2\phi \tag{26}$$

$$B_q'(\phi) = \frac{1}{\cos^2\phi(1-R_g^2) + R_g^2(1-\tan^2\phi)}[3\sigma(K^-p\to\eta X) - 2\sigma(K^-p\to\bar{K}^0X) - \tfrac{1}{4}\sigma(K^+p\to K^0X) - \tfrac{3}{4}\sigma(K^+p\to K^0X)R_g\tan^2\phi] \tag{27}$$

$$B_q''(\phi) = \tfrac{3}{4}\sigma(K^+p\to K^0X)(1+\tan^2\phi) - B'q(\phi)R_g\tan^2\phi \tag{28}$$

$$C'_q(\phi)=\frac{1}{\cos^2\phi(1-R_g^2)+R_g^2(1-\tan^2\phi)}$$
$$\times\,[\tfrac{1}{3}\{\sigma(\pi^+p\to\pi^+X)-9\sigma(K^-p\to K^-X)$$
$$-\tfrac{11}{2}\sigma(K^{-p}\to\pi^-X)+\tfrac{51}{8}\sigma(K^-p\to\bar{K}^0X)-\tfrac{7}{4}\sigma(\pi^+p\to K^+X)$$
$$+36\sigma(\pi^+p\to\eta X)\}-\tfrac{3}{2}R_g\{\sigma(\pi^+p\to K^+X)+\sigma(K^+p\to K^0X)$$
$$-6\sigma(\pi^+p\to\eta X)\}\tan^2\phi] \tag{29}$$

$$C''_q(\phi)=\tfrac{3}{2}\{\sigma(\pi^+p\to K^+X)+\sigma(K^+p\to K^0X)-6\sigma(\pi^+p\to\eta X)\}$$
$$\times\,(1+\tan^2\phi)-C'_q(\phi)R_g\tan^2\phi. \tag{30}$$

We note that the singularity on the right hand side of (25)–(30) at $\phi=\pi/4$ for $R_g=1$ is spurious and can be eliminated by the $(1-\tan^2\phi)$ factors occurred in the numerators for all the cases.

$|R_g\tan^2\phi|$ measures the relative strength of the nonleading terms in the inclusive reactions if the nucleon wave function has the structure (15). To investigate if the currently available data (CERN HERA 1972, 1979, 1983) of the inclusive reactions yield any information on it, we observe that $B'_q(\phi)$ and $B''_q(\phi)$ can be obtained phenemenologically at $p_{\rm lab}\sim 16{\cdot}0$ GeV/c and $E_{\rm cm}\sim 5{\cdot}56$ GeV:

$$\frac{B'_q(\phi)}{\sigma(\pi^+p\to\pi^+X)}\sim\frac{16{\cdot}6-4{\cdot}52R_g\tan^2\phi}{\cos^2\phi(1-R_g^2)+R_g^2(1-\tan^2\phi)} \tag{31}$$

$$\frac{B''_q(\phi)}{\sigma(\pi^+p\to\pi^+X)}\sim 4{\cdot}52(1+\tan^2\phi)-\frac{R_g\tan^2\phi(16{\cdot}6-4{\cdot}52R_g\tan^2\phi)}{\cos^2\phi(1-R_g^2)+R_g^2(1-\tan^2\phi)}. \tag{32}$$

While $\cos^2\phi(1-R_g^2)+R_g^2(1-\tan^2\phi)$ is positive definite invariably for $R_g^2<1$, the r.h.s. of (32) will be positive definite if

$$4{\cdot}52(1+\tan^2\phi)\geqslant\frac{R_g\tan^2\phi(16{\cdot}6-4{\cdot}52R_g\tan^2\phi)}{\cos^2\phi(1-R_g^2)+R_g^2(1-\tan^2\phi)} \tag{33}$$

yielding

$$|R_g\tan^2\phi|\lesssim 0{\cdot}27. \tag{34}$$

If the second term of (15) is of perturbative origin, this is expected theoretically too; i.e.,

$$|R_g\tan^2\phi|<1. \tag{35}$$

Problems however arises when one evaluates R_g or ϕ separately.

We note that $|\phi|\lesssim 27°$ if $\psi^s=\psi^a$, or $R_g=1$. Even if $\psi^s\neq\psi^a$, large value of ϕ seems to be unavoidable in the present version of the model. In fact there appears no reason why $\psi^s=\psi^a$, or R_g should be very large. For smaller R_g, on the other hand, the upper limit of $|\phi|$ might exceed 27°! This contradicts known phenemenology in the field of baryon spectroscopy (Isgur and Karl 1978; Isgur *et al* 1982; Koniuk and Isgur 1980) and their static properties (Verma and Khanna 1981).

In the quark models with chromodynamics (De Rujula *et al* 1975; Isgur and Karl 1978; Isgur *et al* 1982; Koniuk and Isgur 1980) a small ϕ comes about because the nucleons are mainly composed of ground state harmonic oscillator wave function with excited states mixed in via the hyperfine terms of one gluon exchange. The antisymmetric admixtures occur as the second order effect, $O(\alpha_s^2)$ and hence a small value of ϕ is expected.

A possible way of overcoming the difficulty envisaged in the present context is to incorporate the breakdown of flavour symmetry in the model.

In QM-1 (Choudhury and Goswami 1987), while comparing the predicted cross section sum rules with data, it was observed that in the model symmetries alone are not sufficient, the dynamics of the underlying theory should generate the following symmetry breaking pattern:

The orbital functions $(D_{s,a}^{(\pm)}, F_{s,a}^{(\pm)}, \bar{D}_{s,a}^{(\pm)}, \bar{F}_{s,a}^{(\pm)}, d_{s,a}^{(\pm)}, f_{s,a}^{(\pm)})$ are not same for all types of quark transitions; instead, they have four distinct classes for (i) diagonal quark transitions ($u \to u$, $d \to d$, $s \to s$), (ii) charge exchange transitions ($u \leftrightarrow d$), (iii) strangeness exchange transitions ($u \to s$, $d \to s$) and (iv) charm transitions ($u, d, s \to c$).

Thus one has the following four sets of orbital functions:

$$O_{\mathbb{P}} \equiv (A'_q, A'_g, A''_q, A''_g, B'_q, B'_g, B''_q, B''_g, C'_q, C'_g, C''_q, C''_g)_{\mathbb{P}}$$
$$O_Q \equiv (A'_q, A'_g, A''_q, A''_g, B'_q, B'_g, B''_q, B''_g, C'_q, C'_g, C''_q, C''_g)_Q$$
$$O_Y \equiv (A'_q, A'_g, A''_q, A''_g, B'_q, B'_g, B''_q, B''_g, C'_q, C'_g, C''_q, C''_g)_Y$$
$$O_C \equiv (A'_q, A'_g, A''_q, A''_g, B'_q, B'_g, B''_q, B''_g, C'_q, C'_g, C''_q, C''_g)_C \tag{36}$$

for these four classes of transitions instead of the single set (A'_q, A'_g, A''_q, A''_g, B'_q, B'_g, B''_q, B''_g, C'_q, C'_g, C''_q, C''_g) of (16). It was also observed that the overall pattern of symmetry breaking within the model can be understood if

$$O_{\mathbb{P}}, O_Q, O_Y \gg O_C. \tag{37}$$

One plausible way to understand (37) is to assume that $(O_{\mathbb{P}}, O_Q, O_Y, O_C)$ are Regge-behaved. In the triple Regge limit, ($s \gg M^2 \gg 1$), inclusive cross sections (Collins and Martin 1984) behave as $\sim (s/M)^{2\alpha(t)-1}$ where $\alpha(t)$ is the linear Regge trajectory for the exchange processes under consideration. It is then possible to understand the relative suppression of charm production cross sections over others due to the conjectured negative intercept of the charm trajectory (Berger and Phillips 1975). Using such a Regge-biased argument even beyond triple Regge limit, we assume,

$$O_{\mathbb{P}} > O_Q \tag{38}$$

and

$$O_Q > O_Y \tag{39}$$

to be true as well. These equations signify qualitatively the relative displacements among the Pomeron ($\alpha_{\mathbb{P}}(0) = 1$), and Reggeons ($\alpha_\rho(0) = 0{\cdot}58$) and ($\alpha_{K^*}(0) = 0{\cdot}3$) respectively.

To study such effects in (34), we define a symmetry breaking parameter

$$\varepsilon = O_Y/O_Q \tag{40}$$

and assume

$$(R_g)_{\mathbb{P}} \approx (R_g)_Q \approx (R_g)_Y \approx (R_g)_C \approx R_g \tag{41}$$

to hold for the sets O_P, O_Q, O_Y and O_C approximately. Then (27) and (28) will have the structures,

$$B'_q(\phi,\varepsilon)=\frac{1}{\cos^2\phi(1-\varepsilon R_g^2)+\varepsilon R_g^2(1-\tan^2\phi)}$$
$$\times[3\sigma(K^-p\to\eta X)-2\sigma(K^-p\to\bar{K}^0X)-\tfrac{1}{4}\sigma(K^+p\to K^0X)$$
$$-\tfrac{3}{4}\varepsilon R_g\sigma(K^+p\to K^0X)\tan^2\phi-f(\phi,\varepsilon)] \quad (42)$$

$$B''_q(\phi,\varepsilon)=\frac{3\sigma(K^+p\to K^0X)(1+\tan^2\phi)}{4\varepsilon}-B'_q(\phi,\varepsilon)R_g\tan^2\phi \quad (43)$$

with

$$f(\phi,\varepsilon)=(1-\varepsilon)[A'_Y(2\cos^2\phi+\tfrac{10}{3}\sin^2\phi)+A''_Y(\tfrac{10}{3}\cos^2\phi+2\sin^2\phi)]. \quad (44)$$

Similar expressions for the other functions as well can be derived by introducing suitable symmetry breaking ratios. Due to lack of phenomenological consequences we, however, desist from recording them here. By setting up equations similar to (31) and (32) one then has,

$$R_g\tan^2\phi\left(18\cdot1-1\cdot51\varepsilon-\frac{f(\phi,\varepsilon)}{\sigma(K^+p\to K^0X)}\right)\leqslant 4\cdot52 \quad (45)$$

instead of (34). Note that in exact flavour symmetry $\varepsilon=1$ and $f(\phi,\varepsilon)=0$. As a consequence, (45) reduces to (34).

To make an order of magnitude estimate, we set $A'_Y\approx A''_Y\sim 1$ mb* and take $\sigma(K^+p\to K^0X)\sim 6$ mb from data (CERN HERA 1972, 1979, 1983) so that

$$\frac{f(\phi,\varepsilon)}{\sigma(K^+p\to K^0X)}\sim\tfrac{8}{9}(1-\varepsilon) \quad (46)$$

and

$$|R_g\tan^2\phi|\lesssim\frac{4\cdot52\varepsilon}{17\cdot22-0\cdot63\varepsilon}. \quad (47)$$

The approximate relation (47) implies that for $\varepsilon<1$, $|R_g\tan^2\phi|$ is smaller than 0·27, cf (34). As illustrations, $|R_g\tan^2\phi|\lesssim 0\cdot106$ and 0·026 for $\varepsilon\sim 0\cdot4$ and 0·1 respectively. This corresponds to $|\phi|\gtrsim 18°$ and 9·33° respectively for $R_g<1$. However, the value of $|R_g\tan^2\phi|$ may further come down if the non-leading QCD effects are shared by the components of the nucleon wave function other than $(56,0^+)$ and $(20,0^+)$ of (15) (to be discussed later in this paper).

It may be noted that $\varepsilon<1$ is consistent with Regge-like condition (39) obtained in QM-1. Thus the flavour symmetry breaking suitably incorporated in the model can reduce anomalously large ϕ.

This feature can be made more quantitative if we choose z-axis as the incident

*In QM-1 we have made the analysis taking z-axis as the incident beam direction. It leads to $A'_Y=A''_Y=A_Y$. With data from CERN HERA (1972, 1979, 1983) we then obtain $A_Y\approx 1\cdot09\pm0\cdot04$ mb. Hence $A'_Y\approx A''_Y\sim 1$ mb seems to be a reasonable assumption for order of magnitude estimation.

beam direction. In this frame the number of parameters is reduced so that

$$A'_q(\phi) = A''_q(\phi) = A_q(\phi)$$
$$B'_q(\phi) = B''_q(\phi) = B_q(\phi)$$
$$C'_q(\phi) = C''_q(\phi) = C_q(\phi) \tag{48}$$

and similarly for A_g's. Then (16) reduces to

$$\sigma(\pi_\alpha + B \to \pi_\beta + X) = (uA_q + vB_q + wC_q)\cos^2\phi + (uA_g + vB_g + wC_g)\sin^2\phi \tag{49}$$

where

$$u = u'_q + u''_q = u'_g + u''_g$$
$$v = v'_q + v''_q = v'_g + v''_g$$
$$w = w'_q + w''_q = w'_g + w''_g. \tag{50}$$

In this case (43) takes the form,

$$B_q(1 + R_g \tan^2\phi) = \frac{3\sigma(K^+ p \to K^0 X)(1 + \tan^2\phi)}{4\varepsilon}. \tag{51}$$

Here all the multiplicative factors are positive definite. Hence it does not yield any bound on $|R_g \tan^2\phi|$ unlike (34) or (47). Instead we can estimate its magnitude directly from data (CERN HERA 1972, 1979, 1983) under certain simplified assumptions discussed below.

(i) *Exact flavour symmetry*: From data at $p_{\text{lab}} \sim 16{\cdot}0\,\text{GeV/c}$ and $E_{\text{cm}} \sim 5{\cdot}56\,\text{GeV}$, we find:

$$A_q\cos^2\phi + A_g\sin^2\phi = 3{\cdot}29 \pm 0{\cdot}1\ \text{mb}$$
$$B_q\cos^2\phi + B_g\sin^2\phi = 19{\cdot}95 \pm 0{\cdot}75\ \text{mb}$$
$$C_q\cos^2\phi + C_g\sin^2\phi = 8{\cdot}17 \pm 0{\cdot}38\ \text{mb} \tag{52}$$

in (49). Let us now define

$$R_\sigma = \sigma_{\text{Experiment}}/\sigma_{\text{Theory}}. \tag{53}$$

In table 2 we record its value for several processes under study. Some of them deviate significantly from unity indicating its incompatibility with data (CERN HERA 1972, 1979, 1983). Such a feature of the model was met earlier too (Choudhury and Goswami 1987) thus suggesting its broken symmetric version.

(ii) *Broken flavour symmetry*: Here we define in brief,

$$A_p = (A_q\cos^2\phi + A_g\sin^2\phi)_p, \tag{54}$$

and similarly for the others. In this case, we find that at $p_{\text{lab}} \sim 16{\cdot}0\,\text{GeV/c}$ and $E_{\text{cm}} \sim 5{\cdot}56\,\text{GeV}$,

Table 2. R_σ, $|R_g \tan^2\phi|$ and ϕ for the processes $P+B\to P+X$.

Processes	R_σ In exact symmetry	R_σ In broken symmetry	$\lvert R_g \tan^2\phi\rvert$ in broken flavour symmetry	ϕ in degrees with $R_g<1$
$\pi^- p\to\pi^- X$	1·248	0·9997	0·0003	0·6
$K^+ p\to K^+ X$	0·367	0·9995	0·0005	1·28
$\pi^- p\to\pi^0 X$	~ 1	~ 1	~ 0	0
$\pi^+ p\to\pi^0 X$	1·971	1·077	0·077	15·5
$\pi^- p\to K^0 X$	0·331	0·997	0·003	2·56
$\pi^+ p\to\pi^+ X$	1·074	1·122	0·122	19·25
$K^- p\to \bar{K}^0 X$	0·849	~ 1	~ 0	0
$\pi^+ p\to\eta X$	0·352	~ 1	~ 0	0
$K^- p\to D_s^- X$	0·034	~ 1	~ 0	0
$K^+ p\to K^0 X$	0·226	~ 1	~ 0	0
$K^- p\to\eta X$	0·313	1·067	0·067	14·5
$K^- p\to\pi^0 X$	0·944	~ 1	~ 0	0
$K^- p\to\pi^- X$	~ 1	1·059	0·059	13·6
$K^- p\to K^- X$	~ 1	0·998	0·001	1·81

$$A_{\mathbb{P}}\approx 7{\cdot}57\pm 0{\cdot}18\,\text{mb};\quad B_{\mathbb{P}}\approx 7{\cdot}33\pm 0{\cdot}03\,\text{mb};\quad C_{\mathbb{P}}\approx 20{\cdot}56\mp 0{\cdot}31\,\text{mb};$$
$$A_Q\approx 2{\cdot}79\pm 0{\cdot}12\,\text{mb};\quad B_Q\approx 4{\cdot}52\pm 0{\cdot}13\,\text{mb};\quad C_Q\approx 85{\cdot}35\pm 3{\cdot}5\,\text{mb};$$
$$A_Y\approx 1{\cdot}09\pm 0{\cdot}08\,\text{mb};\quad B_Y\approx 18{\cdot}83\pm 1{\cdot}2\,\text{mb};$$
$$A_C\approx 0{\cdot}11\pm 0{\cdot}02\,\text{mb} \tag{55}$$

while C_Y, B_C and C_C do not contribute to the processes we consider.*

Using these values we now estimate R_σ of (53) and record them in table 2. For most of the processes it is around unity. This suggests that the broken symmetric version of the model is phenomenologically viable.

(iii) *Evaluation of* $|R_g \tan^2\phi|$: Let us discuss if the relative strength of the non-leading QCD term parametrised through $|R_g \tan^2\phi|$ can be estimated. This can be done only if ϕ is small. To investigate this, let us define

$$\frac{\sigma(\pi_\alpha+B\to\pi_\beta+X)}{\sigma_1}=1+R_g(u,v,w)\tan^2\phi \tag{56}$$

with

$$R_g(u,v,w)=\frac{uA_g+vB_g+wC_g}{uA_q+vB_q+wC_q}. \tag{57}$$

In (56), σ_1 denotes the inclusive cross section with leading QCD effects only. Thus the theoretical evaluation of σ_1 alone can yield the nonleading effect parametrised through the flavour dependent function R_g of (57).

Evaluation of σ_1 would be possible only in explicit QCD potential models so that all the space overlaps are calculated. As the model in the present form falls short of

*The apparent deviation $C_{\mathbb{P}}<C_Q$ and $B_Q<B_Y$ in (55) from the Regge expectation (38) and (39) are due to the experimental observations of the type $\sigma(K^-p\to\bar{K}^0X)<\sigma(K^-p\to\pi^0X)$.

such a facility, we have to take recourse to small ϕ approximation as pointed out earlier. Indeed, we assume ϕ to be so small that we can make bold to write approximately,

$$(A_q\cos^2\phi + A_g\sin^2\phi)_{\mathbb{P}} \sim (A_q)_{\mathbb{P}}$$
$$(B_q\cos^2\phi + B_g\sin^2\phi)_{\mathbb{P}} \sim (B_q)_{\mathbb{P}}$$
$$(C_q\cos^2\phi + C_g\sin^2\phi)_{\mathbb{P}} \sim (C_q)_{\mathbb{P}} \tag{58}$$

and similarly for others. Under such extreme assumption, σ_1 defined in (56) can be estimated and $(R_\sigma - 1)$ from table 2 can be interpreted as $|R_g\tan^2\phi|$ or $|R_g\phi^2|$. One then can estimate ϕ for $R_g < 1$ as is done in the same table. In exact symmetry, small ϕ approximation, (58) breaks down as the value of $(R_\sigma - 1)$ comes out to be as high as 0·971 and $-0{\cdot}966$ for $(\pi^+p\to\pi^0X)$ and $(K^-p\to D_s^-X)$ respectively. Hence non-leading QCD effects cannot be estimated in this approximation.

A study of table 2 shows that in the broken symmetric limit $|R_g\tan^2\phi| \lesssim 0{\cdot}06$ ($E_{\rm cm} \sim 5{\cdot}56$ GeV) for most of the processes. This is expected of a contribution from the $(20,0^+)$ piece of the nucleon wave function. But even in the broken symmetric limit, some of the estimated values of $(R_\sigma - 1)$ remain relatively large; as for example, for the process $(\pi^+p\to\pi^+X)$. So this may demand the components of the nucleon wave function other than $(56,0^+)$ and $(20,0^+)$ of (15) as discussed below:

(*iv*) *Nucleon wave function beyond* $(56, 0^+)$: Le Yaouanc *et al* (1975) suggested the idea that the nucleon at rest is not a pure SU(6) $(56, 0^+)$ state, mixing with $(70, 0^+)$ seems to be required. From exhaustive analysis of strong and the electromagnetic couplings, Isgur and Karl (Isgur and Karl 1978; Isgur *et al* 1982) and Koniuk and Isgur (Koniuk and Isgur 1980) have indicated such admixtures. Specifically, they have obtained the following admixtures of the radically excited $(56, 0^+)^*$, $(70, 0^+)$ and $(56, 2^+)$ states in the nucleon wave function:

$$\begin{aligned}\psi \sim \eta^a\Bigg[&0{\cdot}90\psi^s\left(\frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}}\right) - 0{\cdot}34\psi^{s*}\left(\frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}}\right)\\ &- 0{\cdot}27\times\tfrac{1}{2}\{(\chi'\phi'' + \chi''\phi')\psi' + (\chi'\phi' - \chi''\phi'')\psi''\}\\ &- 0{\cdot}06\times\frac{1}{\sqrt{2}}(\phi'\psi_{ij}'^{L=2} + \phi''\psi_{ij}''^{L=2})\chi_{ij}^s\Bigg].\end{aligned} \tag{59}$$

In (59) ψ^{s*} represents the spatial component of the radially excited $(56,0^+)^*$, while (ψ', ψ'') stand for the spatial wave functions of $(70,0^+)$; $(\psi_{ij}', \psi_{ij}'')$ on the other hand, represent $L=2$ components to be associated with the spin triplet state (χ_{ij}^s) of the nucleon. Features of (59) can be incorporated in the present model by rewriting (15) as,

$$\begin{aligned}\psi \sim\ &\eta^a\cos\phi\left[\psi^s\left(\frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}}\right)\right]\\ &+ \eta^a\sin\phi\Bigg[-\psi^{s*}\left(\frac{\chi'\phi' + \chi''\phi''}{\sqrt{2}}\right) - \tfrac{1}{2}\{(\chi'\phi'' + \chi''\phi')\psi' + (\chi'\phi' - \chi''\phi'')\psi''\}\\ &- \frac{1}{\sqrt{2}}(\phi'\psi_{ij}'^{L=2} + \phi''\psi_{ij}''^{L=2})\chi_{ij}^s + \left(\frac{\chi'\phi'' - \chi''\phi'}{\sqrt{2}}\right)\psi^a\Bigg]\end{aligned} \tag{60}$$

where the numerical coefficients of various terms of (59) are absorbed in the definition of the unknown spatial wave functions:

(49) then assumes the form,

$$\sigma(\pi_\alpha + B \to \pi_\beta + X) \sim \cos^2\phi(uA_q + vB_q + wC_q) + \sin^2\phi(uA_g + vB_g + wC_g) + \sin^2\phi(uA_X + vB_X + wC_X) + \sin\phi\cos\phi\,(uA_M + vB_M + wC_M). \quad (61)$$

In (61) the functions (A_X, B_X, C_X) represent the additional contributions to the inclusive cross sections due to the transitions $(56,0^+)^* \to (56,0^+)^*$, $(70,0^+) \to (70,0^+)$, $(56,0^+)^* \rightleftarrows (70,0^+)_s$ and $(70,0^+)_a \rightleftarrows (20,0^+)$, while the functions (A_M, B_M, C_M) corresponds to the possible transitions $(56,0^+) \rightleftarrows (56,0^+)^*$ and $(56,0^+) \rightleftarrows (70,0^+)_s$. With these additional contributions (56) gets modified to,

$$\frac{\sigma(\pi_\alpha + B \to \pi_\beta + X)}{\sigma_1} = 1 + R_g(u,v,w)\tan^2\phi + R_X(u,v,w)\tan^2\phi + R_M(u,v,w)\tan\phi \quad (62)$$

where

$$R_X(u,v,w) = \frac{uA_X + vB_X + wC_X}{uA_q + vB_q + wC_q} \quad (63)$$

and

$$R_M(u,v,w) = \frac{uA_M + vB_M + wC_M}{uA_q + vB_q + wC_q}. \quad (64)$$

(61) demonstrates that while the contribution of $(20,0^+)$ occurs quadratically in ϕ, those of $(56,0^+)^*$, $(56,2^+)$ and $(70,0^+)$ occur even linearly. Thus the flavour dependent functions $R_M(u,v,w)$ and/or $R_X(u,v,w)$ defined in (63) and (64) might contribute significantly to the value of $R_\sigma - 1$ for some of the processes such as, $\pi^+ p \to \pi^+ X$. In such a generalisation, column 4 of the Table 2 will have the interpretation as $|(R_g + R_X)\tan^2\phi + R_M\tan^2\phi|$ instead of mere $|R_g\tan^2\phi|$.

2.2 *Processes $P + B \to V + X$ ($V \to$ vector meson)*

This class of processes can be described by the parameters (A'_{qv}, A''_{qv}, B'_{qv}, B''_{qv}, C'_{qv}, C''_{qv}) and (A'_{gv}, A''_{gv}, B'_{gv}, B''_{gv}, C'_{gv}, C''_{gv}) similar to (A'_q, A''_q, B'_q, B''_q, C'_q, C''_q) and (A'_g, A''_g, B'_g, B''_g, C'_g, C''_g) of (16). In exact flavour symmetry, ($p_{\text{lab}} \sim 16{\cdot}0$ GeV/c, $E_{\text{cm}} \sim 5{\cdot}56$ GeV),

$$A'_{qv}\cos^2\phi + A'_{gv}\sin^2\phi = 0{\cdot}0625 \pm 0{\cdot}025\,\text{mb}$$
$$A''_{qv}\cos^2\phi + A''_{gv}\sin^2\phi = 1{\cdot}9425 \pm 0{\cdot}225\,\text{mb}$$
$$B'_{qv}\cos^2\phi + B'_{gv}\sin^2\phi = 2{\cdot}3225 \pm 0{\cdot}325\,\text{mb}$$
$$B''_{qv}\cos^2\phi + B''_{gv}\sin^2\phi = 1{\cdot}7325 \pm 0{\cdot}225\,\text{mb}$$
$$C'_{qv}\cos^2\phi + C'_{gv}\sin^2\phi = 1{\cdot}864^{+0{\cdot}074}_{-0{\cdot}269}\,\text{mb}$$
$$C''_{qv}\cos^2\phi + C''_{gv}\sin^2\phi = 0{\cdot}54^{+0{\cdot}12}_{-0{\cdot}23}\,\text{mb}. \quad (65)$$

In table 3 we evaluate R_σ in exact as well as in broken symmetries using these relations. One is easily convinced with the values of R_σ in the exact symmetry that the symmetry breaking is necessary in this case also as was indicated in 2.1. Following the notations

Table 3. R_σ, $|R_g^v \tan^2 \phi|$ and ϕ for the processes $P + B \to V + X$.

Processes	R_σ In exact symmetry	R_σ In broken symmetry	$\lvert R_g^v \tan^2 \phi\rvert$ in broken flavour symmetry	ϕ in degrees with $R_g^v < 1$
$\pi^- p \to \rho^0 X$	~ 1	~ 1	~ 0	0
$\pi^+ p \to \rho^0 X$	2·84	~ 1	~ 0	0
$K^- p \to \bar{K}^{*0} X$	~ 1	~ 1	~ 0	0
$\pi^+ p \to \omega X$	6·015	~ 1	~ 0	0
$\pi^+ p \to K^{*+} X$	~ 1	~ 1	~ 0	0
$K^- p \to \phi X$	0·233	1·018	0·018	7·64
$\pi^- p \to \omega X$	0·148	~ 1	~ 0	0
$K^+ p \to K^{*0} X$	~ 1	~ 1	~ 0	0
$K^- p \to \omega X$	2·52	~ 1	~ 0	0
$K^- p \to \rho^0 X$	~ 1	0·36	0·64	38·66
$K^- p \to \rho^- X$	1·255	~ 1	~ 0	0

similar to those in (54) and (55), we obtain for the vector mesons: ($p_{\text{lab}} \sim 16{\cdot}0\,\text{GeV}/c$, $E_{\text{cm}} \sim 5{\cdot}56\,\text{GeV}$)

$$(A_v)'_Q = 12{\cdot}29 \pm 1{\cdot}9\,\text{mb};\quad (B_v)'_Q = 4{\cdot}1 \pm 0{\cdot}33\,\text{mb};$$

$$(A_v)''_Q = -(5{\cdot}39 \pm 0{\cdot}9)\,\text{mb};\quad (B_v)''_Q = 1{\cdot}73 \pm 0{\cdot}23\,\text{mb};\ (C_v)''_Q = -(4{\cdot}8 \pm 0{\cdot}35)\,\text{mb};$$

$$(A_v)'_Y = 0{\cdot}87 \pm 0{\cdot}03\,\text{mb};\quad (B_v)'_Y = 7{\cdot}34 \pm 1{\cdot}12\,\text{mb};\quad (C_v)'_Y = 22{\cdot}37 \pm 3{\cdot}1\,\text{mb};$$

$$(A_v)''_Y = -0{\cdot}47 \pm 0\,\text{mb};\quad (B_v)''_Y = 2{\cdot}17 \pm 0{\cdot}02\,\text{mb} \tag{66}$$

while $(C_v)'_Q$ and $(C_v)''_Y$ do not contribute to the processes considered.

Due to insufficient data we could not evaluate the parameters $(A_v)'_P$, $(A_v)''_P$, $(B_v)'_P$, $(B_v)''_P$, $(C_v)'_P$ and $(C_v)''_P$ as well as $(A_v)'_C$ $(A_v)''_C$, $(B_v)'_C$, $(B_v)''_C$, $(C_v)'_C$ and $(C_v)''_C$ for vacuum and charm exchanges respectively. Under small ϕ approximation similar to (58), we can interpret $(R_\sigma - 1)$ as $|R_g^v \tan^2 \phi|$ (table 3) where the superscript 'v' stands for vector mesons. The value of $|R_g^v \tan^2 \phi|$ for the process $(K^- p \to \phi X)$ calls for its reinterpretation in terms of $|(R_g^v + R_X^v) \tan^2 \phi + R_M^v \tan \phi|$. However, for the process $(K^- p \to \rho^0 X)$, $(R_\sigma - 1)$ even in the broken flavour symmetry comes out as high as $-0{\cdot}64$. Detailed dynamical models might perhaps be able to resolve such an anomaly.

2.3 *Photoproduction processes*

(a) $\gamma + B \to P + X$. ($P \to$ pseudoscalar mesons)

Here the inclusive cross sections is described by three parameters similar to (49) if the spin-flip amplitudes are assumed to be dominant. Then in exact flavour symmetry, we have ($E_\gamma \sim 6{\cdot}0\,\text{GeV}$):

$$A_q^\gamma \cos^2 \phi + A_g^\gamma \sin^2 \phi \approx 1{\cdot}956 \pm 0{\cdot}05\,\mu\text{b}$$

$$B_q^\gamma \cos^2 \phi + B_g^\gamma \sin^2 \phi \approx 0{\cdot}698 \pm 0{\cdot}02\,\mu\text{b}$$

$$C_q^\gamma \cos^2 \phi + C_g^\gamma \sin^2 \phi \approx 0{\cdot}512 \pm 0{\cdot}01\,\mu\text{b} \tag{67}$$

(the superscript γ denotes photon). In the broken symmetry they are ($E_\gamma \sim 6{\cdot}0\,\mathrm{GeV}$):

$$A_Q^\gamma \approx A_Y^\gamma \approx -0{\cdot}0706 \pm 0{\cdot}002\,\mu\mathrm{b}$$
$$B_Q^\gamma \approx B_Y^\gamma \approx 0{\cdot}4097 \pm 0\,\mu\mathrm{b}$$
$$C_Q^\gamma \approx C_Y^\gamma \approx -8{\cdot}71 \pm 0{\cdot}19\,\mu\mathrm{b}$$
$$A_C^\gamma \approx 0{\cdot}0416 \pm 0{\cdot}01\,\mu\mathrm{b}$$
$$B_C^\gamma \approx 0{\cdot}0116 \pm 0{\cdot}001\,\mu\mathrm{b} \tag{68}$$

while A_{P}^γ, B_{P}^γ, C_{P}^γ and C_C^γ remain undetermined due to insufficient data. Notations are same as used in (54). Data are taken from Burfeindt *et al* (1974), Abe *et al* (1983, 1984) and CERN HERA (1987).

In table 4 we record the values of R_σ in both exact and broken symmetries using (67) and (68). It is clear that in the exact symmetry case, R_σ deviates from unity for many processes, while in the broken symmetry they are all near unity. Hence $R_g^\gamma \tan^2\phi$ have negligible contributions to such processes indicating a very small value of ϕ.

(b) $\gamma + B \to V + X$. ($V \to$ vector mesons)

In this case also the inclusive cross section is expressible in terms of three parameters. Using the subscript 'v' to denote vector mesons, one then has ($E_\gamma \sim 20$–$70\,\mathrm{GeV}$):

$$A_{qv}^\gamma \cos^2\phi + A_{gv}^\gamma \sin^2\phi \approx -(15{\cdot}35 \pm 1{\cdot}07)\,\mu\mathrm{b}$$
$$B_{qv}^\gamma \cos^2\phi + B_{gv}^\gamma \sin^2\phi \approx 83{\cdot}46 \pm 2{\cdot}61\,\mu\mathrm{b}$$
$$C_{qv}^\gamma \cos^2\phi + C_{gv}^\gamma \sin^2\phi \approx 107{\cdot}13 \pm 6{\cdot}35\,\mu\mathrm{b} \tag{69}$$

in exact flavour symmetry. In the broken symmetric limit, using the notations as in (54), we have,

$$(A_v^\gamma)_{\mathrm{P}} \sim -77{\cdot}88 \pm 4{\cdot}11\,\mu\mathrm{b}$$
$$(B_v^\gamma)_{\mathrm{P}} \sim 215{\cdot}86 \pm 8{\cdot}06\,\mu\mathrm{b}$$
$$(C_v^\gamma)_{\mathrm{P}} \sim 140{\cdot}29 \pm 11{\cdot}5\,\mu\mathrm{b}$$
$$(A_v^\gamma)_Q \approx (A_v^\gamma)_Y \sim -(3{\cdot}67 \pm 0{\cdot}14)\,\mu\mathrm{b}$$
$$(B_v^\gamma)_Q \approx (B_v^\gamma)_Y \sim 36{\cdot}72 \pm 2{\cdot}9\,\mu\mathrm{b}$$
$$(C_v^\gamma)_Q \approx (C_v^\gamma)_Y \sim 129{\cdot}06 \pm 3{\cdot}74\,\mu\mathrm{b}$$
$$(A_v^\gamma)_C \sim -0{\cdot}127 \pm 0\,\mu\mathrm{b}$$
$$(B_v^\gamma)_C \sim 0{\cdot}221 \pm 0{\cdot}002\,\mu\mathrm{b} \tag{70}$$

while $(C_v^\gamma)_C$ could not be determined owing to its absence in the processes under consideration. Data are taken from Avery *et al* (1980), Atkinson *et al* (1984) and CERN HERA (1987).

The value of R_σ obtained with the above values of the corresponding parameters are also recorded in table 4 for exact as well as broken symmetries. Here also R_σ deviates from unity in exact symmetry while closely approaches unity in the broken. This implies that the contribution of $|R_g^\gamma \tan^2\phi|$ is insignificant also in the photoproduction of the vector mesons. For $\gamma p \to \rho^- X$, contributions from R_X^γ and R_M^γ seem to be necessary.

Table 4. R_σ, $|R_g'' \tan^2\phi|$ and ϕ in the photoproduction processes, $\gamma + B \to P + X$ and $\gamma + B \to V + X$.

Processes	R_σ In exact symmetry	R_σ In broken symmetry	$\lvert R_g \tan^2\phi\rvert$ in broken flavour symmetry	ϕ in degrees with $R_g'' < 1$
$\gamma p \to \pi^- X$	3·33	~1	~0	0
$\gamma p \to \pi^+ X$	0·89	~1	~0	0
$\gamma p \to K^+ X$	0·13	~1	~0	0
$\gamma p \to \bar{D}^0 X$	0·02	~1	~0	0
$\gamma p \to D^- X$	0·04	~1	~0	0
$\gamma p \to \rho^- X$	0·407	0·68	0·32	29·4
$\gamma p \to \rho^+ X$	~1	~1	~0	0
$\gamma p \to \kappa^{*+} X$	~1	~1	~0	0
$\gamma p \to \rho^0 X$	~1	~1	~0	0
$\gamma p \to \omega X$	2·015	~1	~0	0
$\gamma p \to \phi X$	2·584	~1	~0	0
$\gamma p \to \kappa^{*0} X$	0·472	~1	~0	0
$\gamma p \to \bar{D}^{*0} X$	0·002	~1	~0	0
$\gamma p \to D^{*-} X$	0·003	~1	~0	0

2.4 *Tensor meson production processes*

The inclusive cross sections for such processes have six parameters. Taking data from Bartke *et al* (1976), Kirk *et al* (1976), Cochet *et al* (1979), Chung *et al* (1982) and CERN HERA (1979), and following the notations of the earlier sections we obtain the following values of the parameters: ($p_{\text{lab}} \sim 16{\cdot}0$ GeV/c, $E_{\text{cm}} \sim 5{\cdot}56$ GeV)
Exact flavour symmetry:

$$A'_{qT}\cos^2\phi + A'_{gT}\sin^2\phi \approx -(1{\cdot}4798 \pm 0{\cdot}55)\,\text{mb}$$
$$A''_{qT}\cos^2\phi + A''_{gT}\sin^2\phi \approx 1{\cdot}0859 \pm 0{\cdot}39\,\text{mb}$$
$$B'_{qT}\cos^2\phi + B'_{gT}\sin^2\phi \approx 1{\cdot}1215 \pm 0{\cdot}36\,\text{mb}$$
$$B''_{qT}\cos^2\phi + B''_{gT}\sin^2\phi \approx 0{\cdot}4725 \pm 0{\cdot}19\,\text{mb}$$
$$C'_{qT}\cos^2\phi + C'_{gT}\sin^2\phi \approx 8{\cdot}3283 \pm 0{\cdot}45\,\text{mb}$$
$$C''_{qT}\cos^2\phi + C''_{gT}\sin^2\phi \approx -(6{\cdot}6718 \pm 0{\cdot}85)\,\text{mb}. \tag{71}$$

Broken flavour symmetry:

$$(A_T)'_Q \approx (A_T)' \sim 3{\cdot}1765 \pm 0{\cdot}7\,\text{mb}; \quad (A_T)''_Q \approx (A_T)''_Y \sim -(1{\cdot}7079 \pm 0{\cdot}36)\,\text{mb};$$
$$(B_T)'_Q \approx (B_T)'_Y \sim 1{\cdot}156 \pm 0{\cdot}37\,\text{mb}; \quad (B_T)''_Q \approx (B_T)''_Y \sim 0{\cdot}4725 \pm 0{\cdot}19\,\text{mb};$$
$$(C_T)''_Q \approx (C_T)''_Y \sim -1{\cdot}0842 \pm 0{\cdot}26\,\text{mb};$$
$$(A_T)'_C \sim 2{\cdot}4 \times 10^{-6}\,\text{mb}; \quad (A_T)''_C \sim 0\,\text{mb}. \tag{72}$$

The other parameters could not be detected due to insufficient data. Table 5 shows the quantities R_σ and $|R_g^T \tan^2\phi|$ for these processes. It is observed that when flavour symmetry breaking is taken into account, the nonleading QCD effects parametrised

Table 5. R_σ, $|R_g^T \tan^2\phi|$ and ϕ for the tensor meson production processes.

Processes	R_σ In exact symmetry	R_σ In broken symmetry	$\|R_g^T \tan^2\phi\|$ in broken flavour symmetry	ϕ in degrees with $R_g^T < 1$
$K^+p \to K_2^{*+}(1425)X$	~ 1			
$K^-p \to K_2^{*-}(1425)X$	0·84			
$K^-p \to \bar{K}_2^{*0}(1425)X$	~ 1	~ 1	~ 0	0
$K^+p \to K_2^{*0}(1425)X$	~ 1	~ 1	~ 0	0
$\pi^+p \to f_2(1270)X$	~ 1	~ 1	~ 0	0
$\pi^-p \to f_2(1270)X$	0·503	~ 1	~ 0	0
$K^-p \to f_2(1270)X$	~ 1	~ 1	~ 0	0
$K^-p \to f_2'(1525)X$	0·16	~ 1	~ 0	0
$\pi^-p \to D^{*-}(\sim 2900)X$	0·0001	~ 1	~ 0	0

through $|R_g^T \tan^2\phi|$ or $|(R_g^T + R_X^T)\tan^2\phi + R_M^T \tan\phi|$ are negligible. More experimental information is however needed to ascertain such rapid convergence of the nonleading QCD effects.

3. Conclusions

In this paper we have obtained the nonleading QCD effects in a quark model pursued by us. We observe that the model with exact SU(4)/SU(3) flavour symmetry falls short of most of the inclusive data. This is evident from the sizeable values of $(R_\sigma - 1)$ in the tables 2–5. This aspect of the model was observed earlier too (Choudhury and Goswami 1987) when the inclusive cross section sum rules were compared with data. Taking hint from the pattern of symmetry breaking, it was shown that suitable dynamics should be incorporated in the model so that the relevant space overlaps have Regge-like behaviour. Once this is done, $(R_\sigma - 1)$ becomes reasonably small. In small ϕ approximation, it can then be interpreted as $|R_g \tan^2\phi|$ defined in the text. Some authors believe (Le Yaouanc *et al* 1975; Isgur and Karl 1978, Isgur *et al* 1982 and Koniuk and Isgur 1980) that the nucleon wave function might also contain $(56, 0^+)^*$, $(56, 2^+)$ and $(70, 0^+)$ pieces. $(R_\sigma - 1)$ then assumes the meaning of $|(R_g + R_X)\tan^2\phi + R_M \tan\phi|$ in our work. The flavour dependent functions R_g, R_X and R_M can then well account most of the inclusive data. The situation is found to be similar for the photoproduction of pseudoscalar and vector mesons as well as the tensor meson processes. For these processes the nonleading QCD effects are found to be vanishingly small.

Dynamical evaluation of the model parameters with QCD-inspired potentials are currently under progress (Choudhury and Mallikarjun 1988).

Acknowledgements

One of the authors (DKC) gratefully acknowledges the receipt of the Professor V D Thawani fellowship of the Assam Science Society, while the other (RCG) is thankful to the UGC for financial assistance.

References

Abe K *et al* 1983 SLAC-PUB-3271
Abe K *et al* 1984 *Phys. Rev.* **D29** 1877
Atkinson M *et al* 1984 *Nucl. Phys.* **B245** 189
Avery P *et al* 1980 *Phys. Rev. Lett.* **44** 1309
Barger V and Phillips RJN 1975 *Phys. Rev.* **D12** 2623
Barkakati D K and Choudhury D K 1983 *Phys. Rev.* **D28** 136
Bartke J *et al* 1976 *Nucl. Phys.* **B107** 93
Burfeindt H *et al* 1974 *Nucl. Phys.* **B74** 189
CERN-HERA 1972 72–2
CERN-HERA 1979 79–01
CERN-HERA 1979 79–02
CERN-HERA 1983 83–01
CERN-HERA 1987 87–01
Choudhury D K 1986 Proceedings of the 14th International Colloquium on Group Theoretical Methods in Physics, Seoul, (ed.) Y M Cho (Singapore: World Scientific) p. 602
Choudhury D K and Goswami R C 1987 *Phys. Rev.* **D36** 83 referred to as QM-1 in the text
Choudhury D K and Goswami R C 1988 *Indian J. Phys.* **A62** 73
Choudhury D K and Mallikarjun R 1988 "A Chromodynamic Potential Model for Inclusive Hadron Collisions", contribution to IX High Energy Physics symposium, Madras
Collins P B and Martin A D 1984 in '*Hadron Interactions*' (Adam Hilger)
Chung S U *et al* 1982 *Phys. Rev. Lett.* **48** 785
Cochet C *et al* 1979 *Nucl. Phys.* **B155** 333
De Rujula A, Georgi H and Glashow S L 1975 *Phys. Rev.* **D12** 147
Isgur N and Karl G 1978 *Phys. Rev. Lett.* **41** 1269
Isgur N, Karl G and Koniuk R 1982 *Phys. Rev.* **D25** 2394
Jacob M 1982 *Perturbative quantum chromodynamics* (North Holland)
Koniuk R and Isgur N 1980 *Phys. Rev.* **D21** 1868
Lepage G P and Brodsky S J 1981 *Phys. Rev.* **D22** 2157
Le Yaouanc *et al* 1975 *Phys. Rev.* **D12** 2137
Mitra A N 1968 *Phys. Rev.* **167** 1382
Verma R C and Khanna M P 1981 *Nuovo Cimento Lett.* **32** 429