Pramāṇa – J. Phys., Vol. 25, No. 2, August 1985, pp. 149–156. © Printed in India.

Electromagnetic mass splittings of heavier hadrons in quantum chromodynamics

C P SINGH, C P S VERMA and R L SINGH*

Department of Physics, V.S.S.D. College, Kanpur 208 002, India

*Department of Physics, Awadesh Pratap Singh University, Rewa 486 003, India

MS received 16 October 1984; revised 10 June 1985

Abstract. The electromagnetic mass splittings of heavier hadrons are estimated in the framework of gauge theory model where lighter quarks are taken to behave relativistically and the spatial wave functions are described by the spin-spin interaction affected relative distances between quarks. The predictions for $(\Xi^- - \Xi^0)$, $(\Sigma^{*0} - \Sigma^{*+})$, $(\Xi^{*-} - \Xi^{*0})$, $(D_c^+ - D_c^0)$ and $(D_c^{*+} - D_c^{*0})$ are in fair agreement with the experimental data available whereas those for $(D_b^- - D_b^0)$ and $(D_b^{*-} - D_b^{*0})$ are in qualitative agreement with other theoretical estimates.

Keywords. Electromagnetic mass difference; heavier hadrons; gauge theory model; quantum chromodynamics.

PACS No. 13·40

1. Introduction

Uptil now all the ground state charmed mesons and a few of the charmed baryons have been experimentally observed (Rubia 1984) and the rest of the experiments are in progress. The narrow upsilon resonances (Herb *et al* 1977; Andrew *et al* 1980) have been interpreted as bound states of a new heavy quark ($b\bar{b}$) and the existence of b-quark meson D_b has been experimentally confirmed (Behrends *et al* 1983). Recent experiments (Rubia 1984) have also given the signal for one more heavy quark t which has already been theoretically demanded on the basis of quark-lepton symmetry (Harari 1975). With these c, b and t quarks one can expect a large family of heavier hadrons. In recent past, properties of these hadrons have been investigated using symmetry schemes (Pandit *et al* 1981; Singh 1981a); non-relativistic quark model (Singh *et al* 1981; Singh 1981b; Kim and Sinha 1984), and bag model (Ponce 1979; Singh 1980; Izatt *et al* 1982; Chatley 1983). It appears that QCD-inspired hyperfine interaction within the premises of photon and gluon exchange provides a satisfactory dynamical understanding of many of the finer features of hadron spectroscopy. In particular, it has been applied with striking success to the mass splittings (De Rujula *et al* 1975; Isgur 1978; Isgur and Karl 1978, 1979) and electromagnetic mass splittings (De Rujula *et al* 1975; Itoh *et al* 1979; Isgur 1980; Singh *et al* 1981; Chan 1983; Kim and Sinha 1984) in the case of ground state hadrons where Fermi-Breit interaction potential appears to be operative. Taking the relativistic form $(m^2 + p^2)^{1/2}$ for the free energy of the quarks and assuming that the hadron wave functions are gaussian, Itoh *et al* (1979) discussed the electromagnetic mass splittings of low-lying hadrons quite successfully. They have also investigated how the spin-spin interaction affected inter-quark distances influence the EM mass splittings.

Hoping that heavier hadrons will be observed very soon and following Itoh *et al* (1979) we discuss the EM mass differences of these hadrons. We use the Fermi-Breit type interaction potential between the quarks in the hadrons where spin-spin interactions are repulsive between spin triplet quarks and attractive between spin singlet quarks giving larger distances between spin-triplet quarks than between spin-singlet quarks. The effect of the differences in the relative distances between quarks in a baryon is introduced into the wave functions. In § 2 we discuss the interaction Hamiltonian while the remaining sections deal with the EM mass differences, their estimation and conclusions respectively.

2. Interaction Hamiltonian

In the non-relativistic approximation the strong and electromagnetic parts of the Hamiltonian that describe the internal structure of hadrons are given by (De Rujula *et al* 1975)

$$H = L(r_1 r_2 \ldots) + \sum_i \left(m_i + \frac{p_i^2}{2m_i} + \ldots \right)$$

$$+ \sum_{i>j} (\alpha Q_i Q_j + K\alpha) S_{ij}, \tag{1}$$

where L is the universal interaction binding the quark whose position, masses and momenta are respectively r_i, m_i and p_i. The two-body interaction S_{ij} has the form

$$S_{ij} = \frac{1}{|r_{ij}|} \qquad \text{[Coulomb terms]}$$

$$-\frac{1}{2m_i m_j}\left\{ \frac{\bar{p}_i \cdot \bar{p}_j}{|r_{ij}|} + \frac{\bar{r}_{ij}(\bar{r}_{ij}\bar{p}_i)\bar{p}_j}{|r_{ij}|^3} \right. \qquad \text{[Darwin-Breit term]}$$

$$-\frac{\pi}{2}\delta^3(r_{ij})\left(\frac{1}{m_i^2} + \frac{1}{m_j^2}\right) \qquad \text{[Zitterbewegung term]}$$

$$-\frac{\pi}{2}\frac{16}{3}\frac{\bar{S}_i \cdot \bar{S}_j}{m_i \cdot m_j}\delta^3(r_{ij}) \qquad \text{[Fermi-contact term]}$$

$$\left. -\frac{1}{m_i m_j}\left[\frac{1}{2|r_{ij}|^3}[-2\bar{S}_i \cdot \bar{S}_j] + \frac{6(\bar{S}_i \cdot \bar{r}_{ij})(\bar{S}_j \cdot \bar{r}_{ij})}{|r_{ij}|^2}\right]\right\} \qquad \text{[tensor term]}$$

$$-\frac{1}{2|r_{ij}|^3}\left[\frac{1}{m_i^2} \cdot \bar{r}_{ij} X \bar{p}_i \cdot \bar{S}_i - \frac{1}{m_j^2}\bar{r}_{ij} X \bar{p}_j \cdot \bar{S}_j \right.$$

$$\left. + \frac{1}{m_i m_j}(2\bar{r}_{ij} X \bar{p}_i \bar{S}_j - 2\bar{r}_{ij} X \bar{p}_j \cdot \bar{S}_i)\right] \qquad \text{[spin-orbit term]}. \tag{2}$$

Here $r_{ij}\,(=\bar{r}_i - \bar{r}_j)$ is the relative position vector between ith and jth quarks. The fermi contact term operates when the pair (ij) has zero-orbital angular momentum whereas the tensor force part is operative only when the pair has non-zero angular momentum.

So, for S-wave states the tensor interaction and spin-orbit interaction give no contribution.

3. Electromagnetic mass differences

The spacial wave functions of the baryon and meson are

$$\psi_{(r_1 r_2 r_3)} = N \exp[-ar_{12}^2 - br_{23}^2 - cr_{31}^2], \tag{3}$$

and

$$\psi_{(r_1 r_2)} = N' \exp[-a' r_{12}^2], \tag{4}$$

respectively, where N and N' are normalization factors. The parameters a, b, c and a' are related to the distances between quarks or quark-antiquark.

3.1 *Baryons*

3.1*a* $J^P = 1/2^+$ *baryons*: The expectation value of any relevant function $f(r_1 r_2 r_3)$ is given by

$$\langle f \rangle = \int \psi^*_{(r_1 r_2 r_3)} f_{(r_1 r_2 r_3)} \psi_{(r_1 r_2 r_3)} \mathrm{d}r_1 \, \mathrm{d}r_2 \, \mathrm{d}r_3. \tag{5}$$

Using this expression and (3), one can easily deduce the following results

$$\left\langle \frac{1}{r_{12}} \right\rangle = 2\left(\frac{2(ab+bc+ca)}{\pi(b+c)}\right)^{1/2} = 1/r_{12}, \tag{6a}$$

$$\langle r_{12}^2 \rangle = \frac{6}{\pi} r_{12}^2, \tag{6b}$$

$$\langle \delta^3(r_{12}) \rangle = 1/8\, r_{12}^3, \tag{6c}$$

$$\left\langle \frac{\bar{p}_1 \cdot \bar{p}_2}{|r_{12}|} + \frac{\bar{r}_{12}(\bar{r}_{12} \cdot \bar{p}_1)\bar{p}_2}{|r_{12}|^3} \right\rangle = -4a/r_{12}, \tag{6d}$$

and analogous relations for the permutation of the three quarks. The relative mean square distance of each pair of quarks can be written as

$$\langle r_{12}^2 \rangle = \frac{3}{4}\left(\frac{b+c}{ab+bc+ca}\right), \tag{7a}$$

$$\langle r_{23}^2 \rangle = \frac{3}{4}\left(\frac{a+c}{ab+bc+ca}\right), \tag{7b}$$

$$\langle r_{31}^2 \rangle = \frac{3}{4}\left(\frac{a+b}{ab+bc+ca}\right). \tag{7c}$$

In the case of $1/2^+$ baryons, it is assumed that one pair of quarks (same quarks or two lighter quarks) is in spin-triplet state while the other two pairs are in mixed states of spin-singlet and spin-triplet with the same relative probabilities. So if $r_t = r_{12}$ then $r_{23} = r_{31} = r_m$. Using the expectation values given in (6) and spin and unitary spin wave functions for $1/2^+$ baryons one can easily calculate the various contributions to EM mass differences (table 1).

Table 1. Electromagnetic mass differences of hadrons in MeV.

Various contributions to EM mass splittings are

$$\text{Coul} = \sum_{i<j} (\alpha Q_i Q_j + K\alpha_s) \left\langle \frac{1}{|\bar{r}_{ij}|} \right\rangle$$

$$\text{Rel 1} = -\sum_{i<j} (\alpha Q_i Q_j + K\alpha_s) \frac{1}{2m_i m_j} \left\langle \frac{\bar{p}_i \cdot \bar{p}_j}{|r_{ij}|} + \frac{\bar{r}_{ij} \cdot (\bar{r}_{ij} \cdot \bar{p}_i) \bar{p}_j}{|r_{ij}|^3} \right\rangle$$

$$\text{Rel 2} = -\frac{\pi}{2} \sum_{i<j} (\alpha Q_i Q_j + K\alpha_s) \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} \right) \langle \delta^3(\bar{r}_{ij}) \rangle .$$

$$\text{Mag} = -\frac{\pi}{2} \sum_{i<j} (\alpha Q_i Q_j + K\alpha_s) \frac{16}{3 m_i m_j} \langle \bar{S}_i \cdot \bar{S}_j \delta^3(r_{ij}) \rangle .$$

$$E_f = \sum_i \langle (m_i^2 + p_i^2)^{1/2} \rangle ,$$

which can be evaluated in terms of

$$C_t = \alpha/3r_t, C_m = \alpha/3r_m, C_D = \alpha/3r_D, C_p = \alpha/3r_p, C_v = \alpha/3r_v,$$

$$M_t = \frac{\pi\alpha}{144\, m_u^2 r_t^3},\ M_m = \frac{\pi\alpha}{144\, m_u^2 r_m^3},\ M_D = \frac{\pi\alpha}{144\, m_u^2 r_D^3},$$

$$M_p = \frac{\pi\alpha}{48\, m_u^2 r_p^3},\ M_v = \frac{\pi\alpha}{48\, m_u^2 r_v^3},\ G_t = \frac{\pi\alpha_s\varepsilon}{36\, m_u^2 r_t^3},\ G_m = \frac{\pi\alpha_s\varepsilon}{36\, m_u^2 r_m^3},$$

$$G_D = \frac{\pi\alpha_s\varepsilon}{36\, m_u^3 r_D^3},\ G_p = \frac{\pi\alpha_s\varepsilon}{6\, m_u^3 r_p^3},\ G_v = \frac{\pi\alpha_s\varepsilon}{6\, m_u^3 r_v^3},\ \omega = a/b = 2(r_m/r_t)^2 - 1$$

$$f = \frac{3\omega}{1+2\omega},\ g = \frac{3(1+\omega)}{2(1+2\omega)},\ Z_0 = m_u r_t \left(\frac{1+2\omega}{3} \right)^{1/2},\ Z_1 = m_u r_t (1/g)^{1/2}$$

$$Z_D = m_u r_D,\ Z_p = \frac{2}{(3)^{1/2}} m_u r_p,\ Z_v = \frac{2}{(3)^{1/2}} m_u r_v,$$

$$x = \frac{m_u}{m_s} = 0{\cdot}62,\ y = \frac{m_u}{m_c} = 0{\cdot}22,\ z = \frac{m_u}{m_b} = 0{\cdot}08.$$

The subscripts t, m, D, p and v denote spin-triplet, mixed state of spin triplet and singlet, decuplet, pseudoscalar, and vector mesons, respectively.
The sum of all contributions to various EM mass differences are as follows:

Mass difference	Present analysis	Experimental value	Mass difference	Present analysis	Experimental value
			Baryons		
$(n-p)$	1·29	1·29	$(\Delta^+ - \Delta^{++})$	0·28	
$(\Sigma^0 - \Sigma^+)$	3·10	3·1 ± 0·1	$(\Delta^0 - \Delta^+)$	0·29	
$(\Sigma^- - \Sigma^0)$	4·88	4·88 ± 0·06	$(\Delta^0 - \Delta^{++})$	2·58	2·6 ± 0·4
			$(\Delta^- - \Delta^0)$	4·26	
$(\Xi^- - \Xi^0)$	6·69	6·4 ± 0·6	$(\Sigma^{*0} - \Sigma^{*+})$	2·15	3·0 ± 2·6
$(\Sigma_c^+ - \Sigma_c^{++})$	0·45		$(\Sigma^{*-} - \Sigma^{*0})$	4·13	5·5 ± 2·5
$(\Sigma_c^0 - \Sigma_c^+)$	0·35		$(\Xi^{*-} - \Xi^{*0})$	3·96	3·2 ± 0·6
$(\Xi_c^0 - \Xi_c^+)$	0·45		$(\Sigma_c^{*+} - \Sigma_c^{*++})$	0·05	
$(\Xi_{cc}^+ - \Xi_{cc}^{++})$	−2·36		$(\Sigma_c^{*0} - \Sigma_c^{*+})$	2·08	
$(\Xi_c'^0 - \Xi_c'^+)$	1·93		$(\Xi_c^{*0} - \Xi_c^{*+})$	1·97	

Table 1. (*Contd.*)

Mass difference	Present analysis	Experimental value	Mass difference	Present analysis	Experimental value
$(\Sigma_b^0 - \Sigma_b^+)$	1·56		$(\Xi_{cc}^{*+} - \Xi_{cc}^{*++})$	−0·16	
$(\Xi_{bb}^- - \Xi_{bb}^0)$	3·2		$(\Sigma_b^{*0} - \Sigma_b^{*+})$	2·23	
$(\Sigma_b^- - \Sigma_b^0)$	3·34		$(\Sigma_b^{*-} - \Sigma_b^{*0})$	4·2	
$(\Xi_b^- - \Xi_b^0)$	3·33		$(\Xi_b^{*-} - \Xi_b^{*0})$	4·17	
$(\Xi_b'^- - \Xi_b'^0)$	4·23		$(\Xi_{cb}^{*0} - \Xi_{cb}^{*+})$	2·14	
$(\Xi_{cb}^0 - \Xi_{cb}^+)$	1·34		$(\Xi_{bb}^{*-} - \Xi_{bb}^{+0})$	3·85	
$(\Xi_{cb}'^0 - \Xi_{cb}^{+\prime})$	1·04				
			Mesons		
$(\pi^+ - \pi^0)$	4·6	4·59	$(\rho^+ - \rho^0)$	1·44	−2·4 ± 1·1
					−0·3 ± 2·2
$(K^- - K^0)$	−3·96	−4·0 ± 0·13	$(K^{*-} - K^{*0})$	−1·85	−6·7 ± 1·2
					−4·1 ± 0·6
$(D_c^+ - D_c^0)$	4·72	4·72 ± 0·26	$(D_c^{*+} - D_c^{*0})$	3·92	3·1 ± 1·4
$(D_b^- - D_b^0)$	−0·32	−3·4 ± 3·0	$(D_b^{*-} - D_b^{*0})$	−1·65	

3.1*b* $J^P = 3/2^+$ *baryons*: In case of $3/2^+$ baryons, where all the three quarks have their spin-up, the distance between the different pairs of quarks remains the same *i.e.*

$$r_{12} = r_{23} = r_{31} = r_D, \tag{8}$$

or

$$a = b = c = a_D.$$

Hence

$$\left\langle \frac{1}{r_{ij}} \right\rangle = 1/r_D, \tag{9a}$$

$$\langle r_{ij}^2 \rangle = \frac{6}{\pi} r_D^2, \tag{9b}$$

$$\langle \delta^3(r_{ij}) \rangle = 1/8\, r_D^3, \tag{9c}$$

$$\left\langle \frac{\bar{p}_i \cdot \bar{p}_j}{|r_{ij}|} + \frac{\bar{r}_{ij}(\bar{r}_{ij} \cdot \bar{p}_i)}{|r_{ij}|^3}\, \bar{p}_j \right\rangle = -4\, a_D / r_D. \tag{9d}$$

Using these expressions and the spin and unitary spin wave functions for $3/2^+$ baryons various contributions to EM mass splittings are calculated (table 1).

The uncertainty principle requires several hundred MeV of quark momenta in hadrons and therefore its effect cannot be ignored. The expectation value of free energy term $(m^2 + p^2)^{1/2}$, which can be conveniently carried out, in the momentum space, comes out to be

$$\langle (m_1^2 + p_1^2)^{1/2} \rangle = \frac{4}{\sqrt{\pi D}} \int_0^{\alpha} (m_1^2 D + p^2)^{1/2} \cdot \exp(-p^2)\, p^2\, \mathrm{d}p, \tag{10}$$

where $D = [2(a + c)]^{-1}$ and the analogous relations for

$$\langle (m_2^2 + p_2^2) \rangle^{1/2} \text{ and } \langle (m_3^2 + p_3^2) \rangle^{1/2}$$

can be written. The differences of free energy can be expanded in terms of ε/m_u *i.e.*

$$E_F = [\langle (m_d^2+p^2)^{1/2}\rangle - \langle (m_u^2+p^2)^{1/2}\rangle]$$
$$= \varepsilon I(z) + \theta((\varepsilon/m_u)^2], \tag{11}$$

$$I(z) = \frac{4\sqrt{3}}{\pi} z \int_0^\infty \left(p^2 + \frac{3}{\pi} z^2\right)^{-1/2} e^{-p^2} p^2 \, dp, \tag{12}$$

where $z = \left(\frac{\pi}{3} m_u^2 D\right)^{1/2}.$

3.2 *Mesons*

3.2*a* *Pseudoscalar mesons*: The expectation value of a function $f(r_1 r_2)$ is given by

$$\langle f \rangle = \int \phi^*(r_1 r_2) f(r_1 r_2) \phi(r_1 r_2) dr_1 \, dr_2 \tag{13}$$

Using the expression of (4) one can obtain

$$\langle 1/|r_{12}| \rangle = 2(2a_p/\pi)^{1/2} = 1/r_p, \tag{14a}$$

$$\langle r_{12}^2 \rangle = \frac{6}{\pi} r_p^2, \tag{14b}$$

$$\langle \delta^3(r_{12}) \rangle = 1/8 r_p^3, \tag{14c}$$

$$\left\langle \frac{\bar{p}_1 \cdot \bar{p}_2}{|r_{12}|} + \frac{\bar{r}_{12} \cdot (r_{12} \cdot \bar{p}_1)\bar{p}_2}{|r_{12}|^3} \right\rangle = \frac{\pi}{2 r_p^3}. \tag{14d}$$

Using these expressions and the wave functions, various contributions to EM mass differences are calculated and given in table 1.

3.2*b* *Vector mesons:* The expectation values of the various terms can simply be obtained by replacing r_p and a_p by r_v and a_v, respectively in (14). The calculated EM mass splittings are given in table 1.

The free energy of quarks in mesons is given by

$$\langle (m^2+p^2)^{1/2} \rangle = \frac{4}{\sqrt{\pi D'}} \cdot \int_0^\alpha (m^2 D' + p^2)^{1/2} e^{-p^2} p^2 \, dp, \tag{15}$$

where $D' = (2a')^{-1}$. The change in free energy will be

$$E_F = [\langle (m_d^2+p^2)^{1/2}\rangle - \langle (m_u^2+p^2)^{1/2}\rangle]$$
$$= \varepsilon I(z') + \theta[(\varepsilon/m_u)^2], \tag{16}$$

where $z' = \left(\frac{\pi}{3} m_u^2 D'\right)^{1/2}.$

4. Estimation of EM mass differences

Taking the following experimental values in (MeV)

$$(n-p) = 1{\cdot}29,\ (\Sigma^- - \Sigma^0) = 4{\cdot}88,\ (\Sigma^0 - \Sigma^+) = 3{\cdot}10$$
$$(\pi^+ - \pi^0) = 4{\cdot}60,\ (\rho^+ - \rho^0) = 1{\cdot}4,\ (K^- - K^0) = -4{\cdot}0,$$
$$(\Delta^0 - \Delta^{++}) = 2{\cdot}6 \tag{17}$$

as input one can obtain the numerical values of the various parameters as

$$\begin{aligned}
&[\alpha_s]_{\text{strange}} = 0{\cdot}60,\ w = a/b = 0{\cdot}473,\\
&r_t = 3{\cdot}00\ \text{GeV}^{-1} = 0{\cdot}59\ \text{f},\\
&r_m = 2{\cdot}58\ \text{GeV}^{-1} = 0{\cdot}51\ \text{f},\\
&r_p = 2{\cdot}33\ \text{GeV}^{-1} = 0{\cdot}46\ \text{f},\\
&r_v = 2{\cdot}9\ \ \text{GeV}^{-1} = 0{\cdot}57\ \text{f},\\
&r_D = 3{\cdot}3\ \ \text{GeV}^{-1} = 0{\cdot}65\ \text{f},\\
&\varepsilon = (m_d - m_u) = 3{\cdot}82\ \text{MeV}.
\end{aligned} \tag{18}$$

The value of the gluon coupling constant α_s goes on decreasing as we go to the heavier quark sectors. Its value for the c-quark and b-quark sectors can be calculated from the expression (Isgur 1978)

$$\alpha_s(q^2) = \frac{12\pi}{(33 - 2N_f)\log\dfrac{q^2}{\Lambda^2}}, \tag{19}$$

where N_f is the number of flavours and Λ is QCD parameter. These come out to be

$$[\alpha_s]_{\text{charm}} = 0{\cdot}58, \tag{20}$$

$$[\alpha_s]_{\text{beauty}} = 0{\cdot}30. \tag{21}$$

Using these numerical values of the parameters, the various contributions to the EM mass differences are estimated and given in table 1.

5. Discussion and conclusions

We have studied the electromagnetic mass differences of heavier hadrons taking one photon and one gluon exchange Fermi-Breit type interaction between quark-quark/anti-quark of De Rujula *et al* (1975). The additional effects which are taken, are the relativistic form $(m^2 + p^2)^{1/2}$ for free energy of the quarks and the spin-spin interaction to be repulsive between spin-triplet quarks and attractive between spin-singlet quarks. From our analysis we draw the following conclusions.

(i) The values for $(\Xi^- - \Xi^0)$, $(\Delta^{++} - \Delta)$ $(\Sigma^{*0} - \Sigma^{*+})$, $(\Xi^{*-} - \Xi^{*0})$ and $(D_c^+ - D_c^0)$ are in fair agreement with available experimental data (Rubia 1984).
(ii) In the case of vector mesons, the value for $(D_c^{*+} - D_c^{*0})$ is within experimental limit but the prediction for $(K^{*-} - K^{*0})$ is not in close agreement. This may be because the experimental situation for $(\rho^+ + \rho^0)$ mass difference is not very clear and we have taken only the average value as input.
(iii) Our predictions $(D_b^- - D_b^0) = -0{\cdot}32$ MeV and $(D_b^* - D_b^{*0}) = -1{\cdot}65$ MeV are in qualitative agreement with other theoretical estimates *viz* Singh (1979, 1980), Khare

(1980), Chan (1983), Kim and Sinha (1984), Tewari *et al* (1985) and also consistent with the CLEO measurement (Behrends *et al* 1983).
(iv) In our analysis we have not considered the flavour dependence of the inter-quark distance; however, we feel that the results may be further improved by including such dependence. This suggests that strong interaction effects have significant influence on the electro-magnetic mass differences of strongly interacting hadrons.

Acknowledgements

CPS is thankful to Dr M P Khanna for useful suggestions. Partial financial assistance from UGC, New Delhi is gratefully acknowledged.

References

Andrew D *et al* 1980 *Phys. Rev. Lett.* **44** 1108
Andrew D *et al* 1980 *Phys. Rev. Lett.* **45** 219
Behrends S *et al* 1983 *Phys. Rev. Lett.* **50** 881
Chatley P K 1983 *Pramana* **20** 143
Chan L H 1983 *Phys. Rev. Lett.* **51** 253
De Rujula A, Georgi H and Glashow S L 1975 *Phys. Rev.* **D12** 147
Harari H 1975 *Lepton and photon interaction, Proc. Int. Symp., Stanford*
Herb S W *et al* 1977 *Phys. Rev. Lett.* **39** 252
Isgur N 1978 Soft QCD, Lectures presented at the Sixteenth Int. School of Subnuclear Physics, Erice
Isgur N 1980 *Phys. Rev.* **D21** 779
Isgur N and Karl G 1978 *Phys. Rev.* **D18** 4187
Isgur N and Karl G 1979 *Phys. Rev.* **D19** 2653
Isgur N and Karl G 1979b *Phys. Rev.* **D20** 1191
Itoh C *et al* 1979 *Progr. Theor. Phys.* **61** 548
Izatt D, DeTar C and Stephenson M 1982 *Nucl. Phys.* **B199** 269
Khare A 1980 *Nucl. Phys.* **B163** 269
Kim D Y and Sinha S N 1984 *Phys. Rev.* **D30** 1944
Pandit P N, Singh C P and Khanna M P 1981 *Acta Phys. Austriaca* **53** 211
Ponce W A 1979 *Phys. Rev.* **D19** 2197
Rubia C 1984 *Rev. Mod. Phys.* 56
Singh C P 1981a *Pramana* **16** 493
Singh C P 1981b *Phys. Rev.* **D24** 2431
Singh L P 1979 *Lett. Nuovo Cimento* **25** 463
Singh L P 1980 *Phys. Rev.* **D22** 773, 2224
Singh C P, Sharma A and Khanna M P 1981a *Phys. Rev.* **D23** 793
Singh C P, Sharma A and Khanna M P 1981b *Phys. Rev.* **D24** 788
Tewari K P, Singh C P and Khanna M P 1985 *Phys. Rev.* D