PARTIAL SCREENING OF QUARK CHARGE*

BY W. KRÓLIKOWSKI**

Department of Physics, Kaiserslautern University***

(*Received March 18, 1975*)

To the memory of Włodzimierz Zonn

The hypothesis of vector-gluon dominance over the coloured part of the photon, if true, implies a phenomenon of partial screening of quark charge, which may be responsible for non-integer values of quark charges as "observed" at present in deep inelastic electron scattering. An average rise of R-ratio in e^-e^+ annihilation is a necessary condition for our hypothesis. This hypothesis also implies that (besides strong decays) the first-order radiative decays of coloured states into non-coloured states are forbidden if strong interactions are colour symmetric.

The recent exciting discoveries of narrow resonances $\psi(3105)$ [1, 2] and $\psi(3695)$ [3] as well as the broad structure on e^-e^+ total cross-section around 4.15 GeV [4] changed much the picture of the rising ratio $R = \sigma(e^-e^+ \to \text{hadrons})/\sigma(e^-e^+ \to \mu^-\mu^+)$ from $R = 2-3$ at $q^2 \simeq 9\ \text{GeV}^2$ to $R = 4-7$ at $q^2 \simeq 25\ \text{GeV}^2$ which we got formerly [5]. However, an intriguing possibility still remains that the local resonances corresponding to new mesons are superposed on an average *rise* of R.

Such a picture would be consistent with a dynamical mechanism proposed in a paper [6] written before the recent discoveries. This mechanism based on an idea of "vector-gluon dominance" over the coloured part of the photon can be called the *colour brightening*. It gives a rise of R from the Gell-Mann value $R = 2$ at small q^2 to values which are *higher* than the Han-Nambu figure $R = 4$. For instance, one gets $R = 4-7$ at $q^2 \simeq 25\ \text{GeV}^2$ if the vector-gluon mass in $m_X^2 = 50-40\ \text{GeV}^2$. Subsequently, this mechanism predicts a further rise of R to a maximum at $q^2 \simeq m_X^2$ and then its fall-off to an asymptotic

* This work has been supported in part by the U.S. National Science Foundation under Grant GF-42060 coucerning the Joint Research Project in Elementary Particle and High Energy Physics between the University of Texas, Austin, and the University of Warsaw.

** On leave of absence from the Institute of Theoretical Physics, Warsaw University, Warsaw, Poland.

*** Address: Department of Physics, Kaiserslautern University, Pfaffenbergstrasse, 6750 Kaiserslautern, W. Germany.

value which is $R = 4$ if the vector-gluon-pair production does not increase this figure (in fact, such increase is implied by our mechanism).

Clearly, the colour brightening must cause deviations from scaling also in electroproduction [6]. They are negligible in the SLAC region $-q^2 \ll m_X^2$, where in fact "precocious scaling" is observed. For increasing $-q^2$ they grow up to a limit in the region $-q^2 \gg m_X^2$, where "true scaling" sets in. In the structure function $\nu W_2(\nu, q^2)$, the deviations from precocious scaling are positive and amount to 2%, 50%, and 90% at $-q^2 \simeq 5\,\text{GeV}^2$, $50\,\text{GeV}^2$ and $100\,\text{GeV}^2$, respectively (if we put $m_X^2 \simeq 50\,\text{GeV}^2$; for larger m_X^2 they are smaller). These figures relate to the case, where vector gluons are 50% of all partons in the nucleon. If in the nucleon there are practically no vector gluons (i.e. there are coloured quarks only), these numbers should be diminished by a factor 1/3. Notice that the sign of these deviations is in conflict with recent analyses for electron [7] and muon scattering [8]. One can expect, however, that a quark structure of the type suggested by Chanowitz and Drell [9], if superposed on the vector-gluon-dominance structure considered in Ref. [6], works toward a slow fall-off (with increasing $-q^2$) in the electroproduction structure functions and an additional rise (with increasing q^2) in the R ratio.

In the present note we give an interpretation of the colour brightening which may help us to understand why quark charges as "observed" ar present in deep inelastic electron scattering are noninteger, 2/3, −1/3, −1/3, while lepton charges are always integer.

Let us consider three-triplet quarks $q_{\alpha A}$ ($\alpha = 1, 2, 3$ of SU(3); $A = 1, 2, 3$ of colour SU(3) = SU′(3)) and assume that the coloured part of the photon is dominated by coloured vector gluons $X_{\mu 3}$ and $X_{\mu 8}$ transforming as components 3 and 8 of an SU′(3) octet of neutral vector gluons $X_{\mu i}$ ($i = 1, 2, \ldots, 8$). This hypothesis, which we call the "vector--gluon dominance", leads to the following formula for the electromagnetic current of quarks q and gluons X:

$$\begin{aligned} J_\mu &= \bar{q}\gamma_\mu \tfrac{1}{2}\left(\lambda_3 + \frac{1}{\sqrt{3}}\lambda_8\right) q + f\Box\left(X_{\mu 3} + \frac{1}{\sqrt{3}} X_{\mu 8}\right) \\ &= \bar{q}\gamma_\mu \tfrac{1}{2}\left(\lambda_3 + \frac{1}{\sqrt{3}}\lambda_8\right) q - fg\frac{\Box}{\Box - m_x^2}\bar{q}\gamma_\mu \tfrac{1}{2}\left(\lambda_3' + \frac{1}{\sqrt{3}}\lambda_8'\right) q \\ &\quad - fg\frac{\Box}{\Box - m_x^2}\, i\left(f_{3jk} + \frac{1}{\sqrt{3}} f_{8jk}\right) X_j^\nu \overleftrightarrow{\partial}_\mu X_{\nu k} + f m_x^2\left(X_{\mu 3}^{\text{free}} + \frac{1}{\sqrt{3}} X_{\mu 8}^{\text{free}}\right), \end{aligned} \tag{1}$$

where

$$\begin{gathered} \partial_\mu X_{\mu i} = 0, \\ (\Box - m_x^2) X_{\mu i} = -g(\bar{q}\gamma_\mu \tfrac{1}{2}\lambda_i' q + i f_{ijk} X_j^\nu \overleftrightarrow{\partial}_\mu X_{\nu k}) \\ (i = 1, 2, \ldots, 8) \end{gathered} \tag{2}$$

and

$$\Box A_\mu = -e(J_\mu + \text{el.-mag. current of leptons}), \tag{3}$$

λ's and λ''s being Gell-Mann matrices acting on SU(3) and SU′(3) indices of q, respectively. Due to (1) and (3) the coloured part of the photon is dominated by the field

$-ef\left(X_{\mu 3}+\frac{1}{\sqrt{3}}X_{\mu 8}\right)$. In analogy with the vector-meson dominance hypothesis [10] we put tentatively

$$f=\frac{1}{g}. \tag{4}$$

The difference between both dominance hypothesis is that the latter concerns the non-coloured part of the electromagnetic current of hadrons and does not involve any additional d'Alembertian $\Box$ in the numerator. The reason why such a d'Alembertian appears in (1) is that the vector-gluon dominance concerns the coloured part of the photon rather than the coloured part of the electromagnetic current. This assumption implies that the hadron constituents, coloured quarks q and coloured gluons X, have no *global* electric charges connected with their colour degrees of freedom. Indeed, we obtain from (1)

$$\begin{aligned}\langle p|Q|p+q\rangle &= \langle p|\int d_3xJ_0(x)\,|p+q\rangle = (2\pi)^3\delta_3(\vec{q})\,\langle p|J_0(0)\,|p\rangle \\ &= (2\pi)^3\delta_3(\vec{q})\,\langle p|q^+(0)\,\tfrac{1}{2}\left(\lambda_3+\frac{1}{\sqrt{3}}\lambda_8\right)q(0)\,|p\rangle\end{aligned} \tag{5}$$

for energy-momentum eigenstates $|p\rangle$.

As it is seen from (1), quarks q and gluons X get, due to the vector-gluon dominance, "effective charges" which vary with momentum transfer q^2. They are given by the matrix

$$Q^{\text{eff}}(q^2) = \tfrac{1}{2}\left(\lambda_3+\frac{1}{\sqrt{3}}\lambda_8\right) - fg\,\frac{q^2}{q^2-m_X^2}\,\tfrac{1}{2}\left(\lambda_3'+\frac{1}{\sqrt{3}}\lambda_8'\right) \tag{6}$$

for quarks and by the matrix

$$Q^{\text{eff}}(q^2) = -fg\,\frac{q^2}{q^2-m_X^2}\left\|f_{3jk}+\frac{1}{\sqrt{3}}f_{8jk}\right\| \tag{7}$$

for gluons. Thus, in the case of quarks, the effective charges take for $q^2=0$ (practically for small $|q^2|/m_X^2$) the Gell-Mann [11] values (2/3, −1/3, −1/3), which are values of the global charge (cf. (5)), and if $f=1/g$ tend for $|q^2|\to\infty$ (practically for large $|q^2|/m_X^2$) to the Han and Nambu [12] values (0, −1, −1), (1, 0, 0) and (1, 0, 0). In between, in the region $|q^2|\simeq m_X^2$, they vary violently if $q^2>0$. Similarly, in the case of gluons, the effective charges take for $q^2=0$ zero values, which are values of the global charge (cf. (5)), and if $f=1/g$ tend for $|q^2|\to\infty$ to the values (−1, 0; 0; −1, 0,|; 0, 1), In the region $|q^2|\simeq m_X^2$, they change dramatically if $q^2>0$. Of course, in the region $|q^2|\simeq m_X^2$ if $q^2>0$ the life-times of X_3 and X_8 should be taken into account. Evidently, in the present SLAC region of deep inelastic electron scattering, $|q^2|/m_X^2$ must be small since we "observe" there the quarks with non-integer charges 2/3, −1/3, −1/3.

We can see that for very large momentum transfers (or very small distances) quarks and gluons behave as particles with integer charges (if $f=1/g$). These effective charges transit for very small momentum transfers (or very large distances) into the global charges which are non-integer for quarks and zero for gluons. So, we can interpret this phenomenon as partial screening of quark and gluon charge with increasing distance from the particle. It is actually a total screening of the coloured part of quark and gluon charge with increasing distance. This screening is evidently caused by the vector-gluon dominance over the coloured part of the photon and by strong coupling of gluons to quarks and gluons. One can speculate that integer charges, as always observed in the case of leptons, are related to the fact that leptons do not interact strongly with gluons X.

The phenomenon of partial screening of quark and gluon charge can be neatly visualized in the position space, if we consider electrostatic fields created by point-like quarks and gluons at rest. From (1) and (2) we get in this case:

$$A_0(r) = \frac{eQ^{\text{eff}}(r)}{4\pi r}, \tag{8}$$

where

$$Q^{\text{eff}}(r) = \tfrac{1}{2}\left(\lambda_3 + \frac{1}{\sqrt{3}}\lambda_8\right) - fg\,\tfrac{1}{2}\left(\lambda'_3 + \frac{1}{\sqrt{3}}\lambda'_8\right)e^{-m_X r} \tag{9}$$

for quarks and

$$Q^{\text{eff}}(r) = -fg\left\|f_{3jk} + \frac{1}{\sqrt{3}}f_{8jk}\right\|e^{-m_X r} \tag{10}$$

for gluons. From (9) we obtain the charges $(2/3, -1/3, -1/3)$ for $r \to \infty$ and $(0, -1, -1)$, $(1, 0, 0)$ and $(1, 0, 0)$ for $r = 0$ (if $f = 1/g$). From (10) we get zero charges for $r \to \infty$ and $(-1, 0; 0; -1, 0, 1; 0, 1)$ for $r = 0$ (if $f = 1/g$).

Let us notice that the electromagnetic current of quarks and gluons given by (1) can be rewritten in the form of sum of the Han–Nambu current corresponding to integral charges of quarks and gluons (if $f = 1/g$) and a vector-gluon-dominance term with a conventional coefficient fm_X^2:

$$\begin{aligned} J_\mu = {} & \bar{q}\gamma_\mu\left[\tfrac{1}{2}\left(\lambda_3 + \frac{1}{\sqrt{3}}\lambda_8\right) - fg\,\tfrac{1}{2}\left(\lambda'_3 + \frac{1}{\sqrt{3}}\lambda'_8\right)\right]q \\ & - ifg\left(f_{3jk} + \frac{1}{\sqrt{3}}f_{8jk}\right)X_j^\nu \overleftrightarrow{\partial}_\mu X_{\nu k} + fm_X^2\left(X_{\mu 3} + \frac{1}{\sqrt{3}}X_{\mu 8}\right). \end{aligned} \tag{11}$$

The last term is responsible for the phenomenon of screening discussed in this note.

If we take $-eJ_\mu A^\mu$ as the electromagnetic interaction Lagrangian of quarks and gluons and use the first part of (1) for J_μ, we get (2) and (3) as the equations of motion, with electromagnetic correction terms $-ef\Box A_\mu$ and $-\frac{1}{\sqrt{3}}ef\Box A_\mu$ added to the right-hand side of the second equation (2) for $i = 3$ and 8, respectively. Then we obtain formula (11) corrected by the factor $(1-\frac{4}{3}e^2f^2)^{-1}$. Similarly, instead of the second part of (1) we get a form differing by terms $O(e^2f^2)$ which, however, has the unchanged asymptotic behaviours for $q^2 \to 0$ and $|q^2| \to \infty$ (the latter with the correction factor $(1-\frac{4}{3}e^2f^2)^{-1}$. In fact, this second part of (1) acquires at front the correcting operator

$$\frac{1}{1-\frac{4}{3}e^2f^2}(\Box - m_X^2)\left(\Box - \frac{m_X^2}{1-\frac{4}{3}e^2f^2}\right)^{-1}.$$

Notice that our f_{ijk} is usually denoted by $-if_{ijk}$.

Finally, let us remark that in the case of electromagnetic current J_μ proposed in this note the first-order radiative decays of coloured states into non-coloured states (plus a real γ) are forbidden (as, of course, strong decays) as far as strong interactions are SU′(3) symmetric. It is due to the d'Alembertian $\Box$ appearing in the numerator in (1) which makes that the coloured part of *real* photon is decoupled from quarks and gluons [13] (since then $q^2 = 0$). This remark may be relevant for providing long life-times of $\psi(3105)$ and $\psi(3695)$ if these narrow resonances are coloured vector mesons.

The author expresses his gratitude to CERN's Theoretical Division for its hospitality extended to him during his visit at CERN in February 1975, where this note has been completed.

REFERENCES

[1] J. J. Aubert et al., *Phys. Rev. Lett.* **33**, 1404 (1974).
[2] J.-E. Augustin et al., *Phys. Rev. Lett.* **33**, 1406 (1974).
[3] G. S. Abrams et al., *Phys. Rev. Lett.* **33**, 1453 (1974).
[4] J.-E. Augustin et al., SLAC-PUB-1520 (1975).
[5] J. Ellis, in *Rapporteur's Talk*, *Proc. of the XVII International Conference on High Energy Physics*, London 1974.
[6] W. Królikowski, *Vector-Gluon Dominance and Rising Drell Ratio for e^-e^+ Annihilation*, Trier--Kaiserslautern University preprint, November 1974 (to be published in Nuovo Cimento A).
[7] A. Bodek et al., SLAC-PUB-1442 (1974).
[8] D. J. Fox et al., *Phys. Rev. Lett.* **33**, 1504 (1974).
[9] M. Chanowitz, S. Drell, *Phys. Rev. Lett.* **30**, 807 (1973).
[10] M. Gell-Mann, F. Zachariasen, *Phys. Rev.* **124**, 965 (1961); M. Gell-Mann, D. H. Sharp, W. G. Wagner, *Phys. Rev. Lett.* **8**, 261 (1962); cf. also W. Królikowski, *Nuovo Cimento* **44A**, 745 (1966); *Nucl. Phys.* **87**, 650 (1967).
[11] M. Gell-Mann, *Acta Phys. Austriaca*, Sup. IX, 733 (1972); cf. also W. Królikowski, *Bull. Acad. Pol. Sci., Sér. Sci. Math. Astr. Phys.* **15**, 363 (1967).
[12] M. Y. Han, Y. Nambu, *Phys. Rev.* **139B**, 1006 (1965); Y. Nambu, M. Y. Han, *Phys. Rev.* **D10**, 674 (1974).
[13] This consequence of Ref. [6] was not noticed there.