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Author
Chanowitz, Michael S.

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Michael S. Chanowitz

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Michael S. Chanowitz

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

Experimental predictions for inelastic Compton scattering, $d\sigma(\gamma N \to \gamma + \text{all})$, are presented which can distinguish between fractional and integral charge quark-parton models at energies above or below the color threshold.

By design the integral charge quark model[1] is usually equivalent to the fractional charge color model[2] in the color singlet sector.[3] Naively we expect dramatic differences to appear above the threshold for production of color nonsinglet states,[4] but the threshold might be at an arbitrarily high energy.[5] On the other hand, in gauge theory realizations of the integral charge model the dramatic differences naively expected above threshold in e^+e^- annihilation and lepton-nucleon scattering are damped for $|q^2|$ much greater than the gluon masses.[6] Thus some authors have even argued that the integral charge model with a low color threshold could be difficult to distinguish experimentally from the fractional charge model with a high (or infinite) color threshold.[7] It is therefore important to find experiments which can cut through this maze of possibilities and can distinguish between the integral and fractional charge models,[8] regardless of the location of the color threshold and regardless of whether (in

the case of the integral charge model) gauge vector gluons are introduced. Here I wish to suggest that inelastic Compton scattering, $\gamma N \to \gamma$ + anything, may provide such experimental information. The predictions I will present are based on the parton model analysis of Bjorken and Paschos.[9]

I will first sketch the line of argument and the results for the "naive version" of the integral charge model (i.e., without gauge gluons). Bjorken and Paschos showed that in the parton model the differential cross sections at large s and $t = -Q^2$ for $eN \to e + \text{all}$ and $\gamma N \to \gamma + \text{all}$ are related by

$$\left.\frac{d^2\sigma}{d\Omega'\,dE'}\right|_{\gamma N} = \frac{\nu^2}{EE'}\left.\frac{d^2\sigma}{d\Omega'\,dE'}\right|_{eN} \frac{\langle \sum_i Q_i^4 \rangle_N}{\langle \sum_i Q_i^2 \rangle_N} \tag{1}$$

where E and E' are the energies of the initial and final electron or photon in the lab frame, $\nu \equiv E - E'$, and $\langle Q_i^n \rangle_N$ is the <u>nth</u> power of the charge Q_i of the <u>ith</u> parton, weighted by the probability to find parton i in the target N at $x = Q^2/2M_N\nu = 2EE' \sin^2(\theta'/2)/M_N(E - E')$. Equation (1) implies a scaling law which must be tested experimentally to test the extension of the parton model to this process.[10] If the scaling law is verified then we may extract a measurement of $\langle \sum Q_i^4\rangle_N/\langle \sum Q_i^2\rangle_N$ as a function of x. In the fractional charge model (with or without color) the ratio is bounded by 1/9 and 4/9 while in the naive integral charge model above the color threshold it is equal to one. I will now show that <u>the ratio is also equal to one in the naive integral charge model for energies below the color threshold</u>, so that we can distinguish between the fractional and naive integral charge models regardless of the location of the color threshold.

The electromagnetic current in the fractional[11] and integral charge models is respectively

$$J^F_{EM} = J_{8,1} = \sum_{c=r,b,y} \frac{2}{3}\,\bar{p}_c p_c - \frac{1}{3}\,\bar{n}_c n_c - \frac{1}{3}\,\bar{\lambda}_c \lambda_c \qquad (2)$$

$$J^I_{EM} = J_{8,1} + J_{1,8} = \bar{p}_r p_r + \bar{p}_b p_b - \bar{n}_y n_y - \bar{\lambda}_y \lambda_y \qquad (3)$$

where

$$J_{1,8} = \sum_{q=p,n,\lambda} -\frac{2}{3}\,\bar{q}_y q_y + \frac{1}{3}\,\bar{q}_r q_r + \frac{1}{3}\,\bar{q}_b q_b \,. \qquad (4)$$

Here c denotes the colors red, blue, and yellow; $J_{8,1}$ transforms as an octet of the ordinary ("flavor") SU(3) and as a singlet of the color SU(3); and $J_{1,8}$ is the opposite. For single photon amplitudes below the color threshold, such as $eN \to e$ + all, the "colored" $J_{1,8}$ term in J^I_{EM} does not contribute and J^I_{EM} and J^F_{EM} have identical matrix elements. Then the quantity $\langle \sum Q_i{}^2 \rangle_N$ in Eq. (1) is given by $\langle \sum_c \frac{4}{9}\,\bar{p}_c p_c + \frac{1}{9}\,\bar{n}_c n_c + \frac{1}{9}\,\bar{\lambda}_c \lambda_c \rangle_N$. But in two photon amplitudes below the color threshold, such as $\gamma N \to \gamma$ + all, the $J_{1,8} \cdot J_{1,8}$ term can contribute since it has a color singlet projection. Since Eq. (1) requires[9] that the two photons couple to the same parton, $J_{1,8} \cdot J_{1,8}$ may be represented by an "effective operator"[12] $\sum_{q=p,n,\lambda} \frac{4}{9}\,\bar{q}_y q_y + \frac{1}{9}\,\bar{q}_r q_r + \frac{1}{9}\,\bar{q}_b q_b$, which is easily decomposed into a singlet of both color and flavor, $\frac{2}{9} \sum_{c=r,b,y} \sum_{q=p,n,\lambda} \bar{q}_c q_c$, and a term proportional to $J_{1,8}$. Combining this singlet projection with $J_{8,1} \cdot J_{8,1}$ we find that the effective operator for $J^I_{EM} \cdot J^I_{EM}$ below the color threshold is $\sum_{c=r,b,y} \frac{2}{3}\,\bar{p}_c p_c + \frac{1}{3}\,\bar{n}_c n_c + \frac{1}{3}\,\bar{\lambda}_c \lambda_c$. To compute $\langle \sum Q_i{}^4 \rangle_N$ we must take the square of this effective operator, yielding

$\langle \sum_c \frac{4}{9}\,\bar{p}_c p_c + \frac{1}{9}\,\bar{n}_c n_c + \frac{1}{9}\,\bar{\lambda}_c \lambda_c \rangle_N$. But this is precisely what we have just computed for $\langle \sum Q_i{}^2 \rangle_N$! <u>Thus in the naive integral charge model we have $\langle \sum Q_i{}^4 \rangle_N / \langle \sum Q_i{}^2 \rangle_N = 1$ both below and above the color threshold</u>.

Although the arithmetic is simple it involves an assumption about the dynamics which needs to be examined. In adding the color singlet projection of $J_{1,8} \cdot J_{1,8}$ I include a piece of the amplitude which might have a color nonsinglet s-channel discontinuity and which might therefore be suppressed. But if this contribution is like a subtraction constant, i.e., has no discontinuity, then it will not be suppressed. In the language of the infinite momentum frame, the question is whether the γ + parton $\to \gamma$ + parton amplitude is dominated by Z-graphs which have no finite energy discontinuities and correspond to instantaneous interactions (roughly analogous to the seagull interaction of a spin 0 theory). Brodsky and Roy[13] have argued that the Bjorken-Paschos treatment can <u>only</u> be given a field theoretical justification in the infinite momentum frame if this is the case. In this sense, if the parton model treatment of $\gamma N \to \gamma$ + all is valid, then it is also valid to include the contribution of the color singlet projection of $J_{1,8} \cdot J_{1,8}$ below the color threshold. I have shown that the parton model treatment can be given such a justification: in a true infinite momentum frame obtained by boosting along the photon axis in the photon brick-wall frame, I have verified that the amplitude at large $s, t = -Q^2, u$ is given by just the instantaneous interactions. Details will be presented elsewhere.[14]

On a more intuitive level and without using an infinite momentum frame, the point is that the quark-partons are in a state of net color only during the short time scale T_s of the high momentum transfer parton-photon interaction. But it is necessary to assume in even the most familiar applications of the quark-parton model below the color threshold that color charges can be freely separated on this time scale. For instance, to get scaling in electroproduction, it is necessary that the struck quark scatters freely away from the remaining fragment quarks during the time T_s of the electron-parton interaction. It is only on a longer time scale $T_L \gg T_s$ that the quarks are conjectured to rearrange themselves into color singlet hadrons.[15] In Eq. (1) we compare eN and γN scattering with equal momentum transfers, so the time scale of the parton-photon amplitude is like the short time scale of the electron-parton process in electroproduction.

Consider now the gauge theory realizations of the integral charge model,[6] in which the effective quark current is $J^I_{EM} = J_{8,1} + (M_G^2/M_G^2 - k^2)\, J_{1,8}$ where k_μ is the four momentum carried by the current. For $\gamma N \to \gamma + \text{all}$ we have $k^2 = 0$ and $J^I_{EM} = J_{8,1} + J_{1,8}$ so that $\langle \sum Q_i^4 \rangle_N$ is evaluated as for the naive model. Below the color threshold only $J_{8,1}$ contributes to electroproduction and $\langle \sum Q_i^2 \rangle_N$ is again as in the naive model. Thus below the color threshold the quark contribution is again $\langle \sum Q_i^4 \rangle_N / \langle \sum Q_i^2 \rangle_N = 1$.

It has been suggested in this context[6,7] that the observed scaling at SLAC, FNAL, and SPEAR may be above the color threshold. Then either $M_G^2 < 1\ \text{GeV}^2$ or $M_G^2 \gg O(20\ \text{GeV}^2)$ so that the factor $M_G^2/M_G^2 - q^2$ does not induce large scaling violations. $M_G^2 \lesssim 1\ \text{GeV}^2$ is then required by the value

$R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) \cong 2$ observed at SPEAR below the new physics threshold. In this case, $M_G^2 < 1\ \text{GeV}^2$, the dominant contribution to J^I_{EM} in deep-inelastic electroproduction is again $J_{8,1}$ but in $\gamma N \to \gamma + \text{all}$ the full current $J^I_{EM} = J_{8,1} + J_{1,8}$ contributes. Thus we have $\langle \sum Q_i^4 \rangle_N = \langle \bar{p}_R p_R + \bar{p}_b p_b + \bar{n}_y n_y + \bar{\lambda}_y \lambda_y \rangle_N = \langle \sum_c \frac{2}{3}\bar{p}_c p_c + \frac{1}{3}\bar{n}_c n_c + \frac{1}{3}\bar{\lambda}_c \lambda_c \rangle_N$, since the nucleon is a color singlet, and we compute $\frac{3}{2} < \langle \sum Q_i^4 \rangle_N / \langle \sum Q_i^2 \rangle_N < 3$. This is farther still from the allowed range of values in the fractional charge model, between $1/9$ and $4/9$. In the unlikely possibility that M_G is large and the color threshold small we return again to $\langle \sum Q_i^4 \rangle_N / \langle \sum Q_i^2 \rangle_N = 1$.

In the gauge theory realizations of the integral charge model four of the color gluons carry electromagnetic charge and may contribute to eN and γN scattering as partons. In $eN \to e + \text{all}$ this contribution scales and gives $\sigma_L/\sigma_T \to \infty$, while the data[16] is more nearly consistent with the spin 1/2 parton result $\sigma_L/\sigma_T \to 0$. Thus the gluon contribution must be small in the region $x > 0.1$ in which σ_L/σ_T is measured. In particular, near $x = 1$ we would expect the nucleon wave function to be dominated by valence quarks, so that Eq. (1) should hold with the values of $\langle \sum Q_i^4 \rangle_N / \langle \sum Q_i^2 \rangle_N$ computed above. This can be tested experimentally because if there are contributions from charged gluons they will induce violations of the scaling predicted in Eq. (1). Thus gluon contributions could not cause us to "misread" the quark charges though they might obscure the validity of the parton model scaling prediction. I have made a detailed calculation of the gluon contributions and will present the results elsewhere[14,17] (in principle the quark and gluon contributions can be disentangled experimentally).

CONCLUSION

Experimentally the first order of business is to test the scaling predicted in Eq. (1), probably[10] at FNAL or SPS energies. If scaling is confirmed then $\langle \sum Q_i^4 \rangle_N / \langle \sum Q_i^2 \rangle_N$ can be measured. In the fractional charge model it bounded by 1/9 and 4/9 while in all the various versions of the integral charge model it is equal to one or larger.

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FOOTNOTES AND REFERENCES

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