EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/84-63
May 17th, 1984

Quark Charge Retention in Final State Hadrons
from Deep Inelastic Muon Scattering

The European Muon Collaboration

Aachen¹, CERN², DESY (Hamburg)³, Freiburg⁴, Hamburg (University)⁵, Kiel⁶, LAL (Orsay)⁷, Lancaster⁸, LAPP (Annecy)⁹, Liverpool¹⁰, Marseille¹¹, Mons¹², MPI (München)¹³, Oxford¹⁴, RAL (Chilton)¹⁵, Sheffield¹⁶, Torino¹⁷, Uppsala¹⁸ and Wuppertal¹⁹.

J.P. Albanese¹¹, M. Arneodo¹⁷, A. Arvidson¹⁸, J.J. Aubert¹¹, K.H. Becks¹⁸, C. Bee⁸, C. Benchouk¹¹, I. Bird⁸, D. Blum⁷, E. Böhm⁶, X. de Bouard⁹, F.W. Brasse³, H. Braun¹⁹, C. Broll⁹, S. Brown¹⁰, H. Brück¹⁹, H. Calen¹⁸, D. Callebaut¹², J. Carr^{15a)}, J.S. Chima¹⁵, R. Clift¹⁵, J.H. Cobb^{8b)}, G. Coignet⁹, F. Combley¹⁶, J. Coughlan⁸, G.R. Court¹⁰, G. D'Agostini¹¹, S. Dahlgren¹⁸, J.K. Davies^{14c)}, W.D. Dau⁸, F. Dengler¹³, I. Derado¹³, R.W. Dobinson², U. Dosselli^{2d)}, T. Dreyer⁴, J. Drees¹⁹, J.J. Dumont¹, M. Düren¹, V. Eckardt¹³, A. Edwards¹⁹, M. Edwards¹⁵, T. Ernst⁴, G. Eszes^{9e)}, J. Favier⁹, M.I. Ferrero^{17f)}, J. Figiel^{5g)}, W. Flauger³, J. Foster¹⁶, E. Gabathuler^{2h)}, R. Gamet¹⁰, J. Gayler³, N. Geddes¹⁴, P. Giubellino¹⁷, C. Gössling³ⁱ⁾, P. Grafström¹⁸, F. Grard¹², L. Gustafsson¹⁸, J. Haas⁴, E. Hagberg¹⁸, F.J. Hasert¹, P. Hayman¹⁰, P. Heusse⁷, C. Hoppe⁵, M. Jaffré⁷, A. Jacholkowska⁷, F. Janata⁵, G. Jancso^{9e)}, A.S. Johnson¹⁴, E.M. Kabuss⁴, G. Kellner², V. Korbel³, J. Krüger¹⁸, S. Kullander¹⁸, D. Lanske¹, J. Loken¹⁴, K. Long¹⁴, M. Maire⁹, A. Manz¹³, W. Mohr⁴, F. Montanet¹¹, H.E. Montgomery^{2j)}, R.P. Mount^{14k)}, E. Nagy^{9e)}, J. Nassalski³, P.R. Norton¹⁵, F.G. Oakham¹⁵, A.M. Osborne², C. Pascaud⁷, L. Paul¹⁹, P. Payre¹¹, C. Peroni¹⁷, H. Pessard⁹, J. Pettingale¹⁰, B. Pönsgen³, M. Pötsch¹⁹, H. Preißner^{5l)}, P. Renton¹⁴, P. Ribarics^{9e)}, K. Rith⁴, E. Rondio^{5m)}, A. Schlagböhmer⁴, N. Schmitz¹³, M. Schneegans⁹, T. Schröder⁴, K. Schultze¹, J. Shiers¹³ⁿ⁾, T. Sloan⁸, H.E. Stier⁴, W. Stockhausen¹⁹, M. Studt⁵, G. Taylor¹⁴, J.M. Thénard⁹, J.C. Thompson¹⁵, A. de la Torre⁵, J. Toth⁹, L. Urban^{9e)}, H. Wahlen¹⁹, W. Wallucks⁴, M. Whalley¹⁶ⁿ⁾, W.S.C. Williams¹⁴, S. Wheeler¹⁶, S. Wimpenny¹⁰, R. Windmolders¹², G. Wolf¹³, P. Zank³

(Submitted to Physics Letters)

-
- a) Now at Berkeley Laboratory, Berkeley, California, USA.
b) Now at University of Oxford, England.
c) Now at Plessey Defence System, Farnham, England.
d) Now at INFN, Sez. Padova, Italy.

- e) Now at Central Research Institute for Physics of the Hungarian Academy of Science, Budapest, Hungary.
- f) Now also at Istituto di Fisica, Università di Lecce, Italy.
- g) Now at Institute of Nuclear Physics, Krakow, Poland.
- h) Now at University of Liverpool, England.
- i) Now at CERN, Genève, Switzerland.
- j) Now at FNAL, Batavia, Illinois, USA.
- k) Now at California Institute of Technology, Pasadena, California, USA.
- l) Now at DESY, Hamburg, W. Germany.
- m) Now at University of Warsaw, Poland.
- n) Now at University of Durham, England.

Abstract

The net charge of final state hadrons in both the current and target fragmentation regions has been measured in a 280 GeV/c muon-proton scattering experiment. A clean kinematic separation of the two regions in the centre-of-mass rapidity is demonstrated. The dependence on x_{Bj} of the mean net charges is found to be consistent with a large contribution of sea quarks at small x_{Bj} and with the dominance of valence quarks at large x_{Bj} thus giving clear confirmation of the quark-parton model. It is also shown that the leading forward hadron has a high probability of containing the struck quark.

Introduction

The generally accepted framework in which to interpret hadron production in deep inelastic lepton nucleon scattering is the quark-parton model (QPM). In this picture, the final state hadrons are interpreted as being fragments of either the struck quark or antiquark or else fragments of the remnant target system. This latter system, in the case of scattering from a valence quark, is a diquark configuration. It is expected [1] that the hadrons produced in a fragmentation process will retain some of the quantum numbers, e.g. the electric charge, of their parent partons. Further, the leading (fastest) hadron will most likely contain the parent quark as a constituent [2]. Convincing experimental evidence for these expectations is still missing. The results [3-10] available so far have been obtained at rather low energies and suffer therefore from insufficient separation between quark and diquark fragmentation.

In this paper results are presented, from an experiment performed at CERN on deep inelastic muon-proton scattering, on the net charge of hadrons in both the current and the target fragmentation regions. It is investigated to what extent a clean separation of these two hemispheres is possible at the values of W (centre-of-mass energy of the virtual photon-proton system) reached in this experiment, which are significantly higher than in previous studies. It is further investigated as to whether the net charge of all forward going hadrons and also the mean charge of the leading hadron show a characteristic dependence on $x_{Bj} = Q^2/2m\nu$ ($-Q^2$ and ν being the mass squared and the lab. energy of the virtual photon, m is the proton mass). Such a dependence is expected as the relative proportions of the different quark flavours vary with x_{Bj} .

A detailed account of the apparatus and subsequent analysis can be found in ref. [11]. A beam of 280 GeV/c μ^+ is incident on a 1 metre long liquid hydrogen target which is positioned inside the vertex magnet. The scattered muon and fast hadrons pass through a second (forward spectrometer) magnet with roughly equal but opposite bending power. The data described below were taken by triggering on muons with a scattering angle of greater than $\frac{1}{2}^\circ$, using scintillation counter hodoscopes. The streamer chamber, which is inside the vertex magnet, is pulsed when a trigger occurs. The combination of tracks measured in the streamer chamber, the vertex system detectors and the forward spectrometer system gives essentially complete coverage in solid angle for tracks with momentum greater than about 100 MeV/c.

Results

In order to restrict the event sample used in this analysis to regions where the corrections for acceptance, smearing effects from resolution and radiative corrections are relatively small ($\leq 20\%$) the following selection criteria are required:

$$\begin{array}{ll} Q^2 > 4 \text{ GeV}^2 & \\ 16 \text{ GeV}^2 < W^2 < 400 \text{ GeV}^2 & \\ y < 0.9 & (y = \nu/E_{\text{beam}}) \\ \nu < 260 \text{ GeV} & \\ E_{\mu'} > 20 \text{ GeV} & (\text{energy of scattered muon}) \\ \Theta_{\mu'} > 0.5^\circ & (\text{muon scattering angle}) \end{array}$$

The number of events remaining after these cuts is about 14,100.

As the primary vertex is not visible in the streamer chamber it is determined by fitting the incident and scattered muons and any compatible charged hadrons. A search is also made amongst the charged hadron tracks for any vertices consistent with a V^0 (including γ conversion) or a secondary interaction of a hadron. In the present analysis only hadrons arising from the primary vertex are taken into account.

All the distributions presented below have been corrected for the effects of acceptance, smearing introduced by the resolution of the apparatus, radiative effects and the efficiency of the various off-line pattern recognition, fitting and vertex finding algorithms. These corrections are determined using a detailed Monte Carlo simulation of the experiment in which events were generated using the Lund string model [12] and imposing the kinematic selection criteria given above. A simulation of the raw data was made including the effects of film measurement, chamber efficiencies and the production of tracks by γ conversions and secondary interactions of hadrons in the target. These simulated events were passed through the same analysis chain as the real events. For a particular distribution the correction function is then computed by comparing the generated Monte Carlo distribution with that obtained after the experimental simulation. The errors arising from the finite statistics in the Monte Carlo are added to the statistical errors of the data. The errors shown in the figures are statistical only; possible systematic errors on the net charge are estimated to be $\pm 15\%$.

There are several difficulties in drawing conclusions from the net charge distributions of hadrons on the charge of the fragmenting quark. These problems are connected with the procedure used to select the hadrons belonging to the two different fragmentation hemispheres. Studies in previous lepton-nucleon scattering experiments [3-10] have

shown that in order to achieve a clean separation between the forward and backward regions the following criteria are of great importance: high values of W , correct mass assignment and precisely determined 4-momenta of the virtual photon (boson). All of these requirements are fulfilled to a large extent by this experiment.

The results presented below are given in terms of the hadronic centre-of-mass variables and are given for all charged particles. The transformation from the laboratory system to the centre-of-mass system requires knowledge of the particle's mass. In this experiment identification of charged particles is possible in Cerenkov and time-of-flight counters over a large fraction of the full acceptance [11]. Thus, about 45% of all charged hadrons can be identified, much more than in previous deep inelastic scattering experiments. Nevertheless, in the present analysis a restriction to directly identified hadrons is not adequate since it is intended to investigate the charge flow over the complete phase space.

Therefore the following approach is adopted: All negative particles are assigned the pion mass. Positive particles with $x_F(\pi) > -0.2$ ($x_F(\pi)$ is the value of $x_F = p_{\parallel}^{\text{cm}}/0.5 \cdot W$ computed using the pion mass) are also assigned the pion mass. Particles with $x_F(\pi) < -0.2$ are assigned the proton mass unless $x_F(p) < -0.9$ in which case the pion mass is used. Based on studies using identified particles [13] and also Monte Carlo simulated events, it is estimated that throughout the whole x_F range $\geq 75\%$ of the hadrons are correctly classified in this way. The same procedure is used in the Monte Carlo simulation of the experiment. By comparing the results of this simulation with the original Monte Carlo distributions a correction function is obtained which takes into account not only effects like acceptance losses and smearing but also the influence of residual wrong mass assignments (see also ref. [14]).

In order to test the validity of this procedure the distribution of the net charge as a function of cms rapidity ($y_{\text{cms}} = 0.5 \cdot \log[(E+p_{\parallel})/(E-p_{\parallel})]$) is determined in two different ways. Only hadrons which can be identified in Cerenkov or time-of-flight counters are considered for the experimental and Monte Carlo simulated events. In the first method the mass determined by particle identification measurements is assigned whereas in the second method a particle is given a mass according to the prescription explained in the previous paragraph. The experimental distributions are corrected as outlined above. If the particle yields of different flavours as generated by the Monte Carlo program do not strongly deviate from the corresponding ones found in the experiment [13] the net charge distributions determined in the two ways are expected to agree. Based on identifiable hadrons, the comparison between the two methods is shown in fig. 1. It demonstrates that, independent of x_{Bj} , both procedures lead to essentially the same results. It is assumed that the validity of this conclu-

sion can be extended to the complete final state. Therefore in what follows the second method is used to perform mass assignments and to obtain the corresponding corrections.

In fig. 2 the distribution of net charge is shown as a function of cms rapidity for different x_{Bj} regions. A rather clean separation (net charge almost zero at $y_{cms} \approx 0$) is achieved for $x_{Bj} \lesssim 0.2$, this being the region where the mean W values are largest. Some overlap occurs at higher x_{Bj} (lower W) but a minimum at $y_{cms} \approx 0$ is still observed. One can conclude that in the forward hemisphere ($y_{cms} > 0$) the increase of the net charge with increasing x_{Bj} occurs also at higher values of y_{cms} and is not simply due to the spill-over of target remnants [4,8] which gets more important at low W (high x_{Bj}). Such an increase of the forward net charge with increasing x_{Bj} is expected since scattering from u quarks becomes dominant at higher values of x_{Bj} .

In the QPM the mean net charge of hadrons in the quark fragmentation region is given by [2]

$$\langle Q \rangle = \frac{1}{N_{\mu}} \int_0^1 \left(\frac{dN_h^+}{dx_F} - \frac{dN_h^-}{dx_F} \right) dx_F = \sum_i (e_i - \eta_i) \cdot \varepsilon_i(x_{Bj}) \quad (1)$$

with

$$\varepsilon_i(x_{Bj}) = e_i^2 q_i(x_{Bj}) / \sum_j e_j^2 q_j(x_{Bj}), \quad (2)$$

where e_i and $q_i(x_{Bj})$ are the charge and density distribution of the quark with flavour i ($i = u, d, \dots, \bar{u}, \bar{d}, \dots$). η_i takes into account that in addition to the charge e_i of the parent quark, other charges in the fragmentation process can be transmitted to the forward going hadrons. In chain fragmentation models where only $q\bar{q}$ pairs are produced [2], the 'charge leakage' η_i for a fragmenting quark (antiquark) is related to the mean charge of the quarks (antiquarks) in the following way:

$$\begin{aligned} \eta_i &= \langle Q_q \rangle & i=u,d,\dots \\ \eta_i &= \langle Q_{\bar{q}} \rangle = -\langle Q_q \rangle & i=\bar{u},\bar{d},\dots \end{aligned}$$

with

$$\langle Q_q \rangle = \frac{1}{3} (\gamma_u - \gamma_s). \quad (3)$$

In this formula γ_u (γ_s) is the relative fraction of $u\bar{u}$ ($s\bar{s}$) quark-antiquark pairs created in the fragmentation process. It is assumed that $\gamma_u = \gamma_d$ and $c\bar{c}$ production is neglected. This leads to the normalisation condition $2\gamma_u + \gamma_s = 1$. Further, assuming that $\gamma_s/\gamma_u \approx 0.3$ [12], one gets $\langle Q_q \rangle \approx 0.1$.

The average forward and backward multiplicity of positive and negative hadrons and the difference are plotted in fig. 3 as a function of x_{Bj} . It can be seen that the mean forward charge increases with x_{Bj} whereas the backward charge decreases correspondingly. Since in terms of the QPM one would expect a value of $\langle Q \rangle = 0$ for sea quarks, the rise of $\langle Q \rangle$ observed in fig. 3a is consistent with a strong decrease in the sea contribution as x_{Bj} increases. Assuming $q_u(x_{Bj}) \approx 2 \cdot q_d(x_{Bj})$ in the region $x_{Bj} \gtrsim 0.2$, where the effect of sea-quarks is small, equation (1) yields

$$\langle Q \rangle \approx (2/3 - 0.1) \cdot 8/9 + (-1/3 - 0.1) \cdot 1/9 = 0.45, \quad (4)$$

a value which lies slightly above the data. It should be noted that the increase of the forward going mean net charge with x_{Bj} is not trivially due to an increase of the hadron multiplicity; on the contrary $\langle Q \rangle$ rises while N_h^+ and N_h^- decrease.

In reality this naive picture is complicated by the production of baryons in the fragmentation process, the arbitrariness in the choice of the cut at $y_{cms} = 0$ and the leakage from one hemisphere to another. The Lund model [12] contains prescriptions which take into account all these points. The predictions from this model are also shown in fig. 3 and they agree quite well with the data.

To test the extent to which the parent quark is a constituent of the leading hadron the charge asymmetry of the fastest hadrons has been studied as a function of x_{Bj} . The charge asymmetry is evaluated by

$$A_{\text{leading}} = \frac{N^+ - N^-}{N^+ + N^-}, \quad (5)$$

where N^+ (N^-) is the number of events in which the fastest charged hadron is positive (negative) and its value of x_F lies above the chosen cut.

The charge asymmetry is shown as a function of x_{Bj} in fig. 4 for $x_F > 0$ and $x_F > 0.5$. The data points for $x_F > 0.5$ were obtained as a weighted mean of the results from this and a previous phase of the experiment [15]. In both experiments the fast hadrons were detected using the same forward spectrometer system. Therefore the systematic errors are expected to be similar. The cuts on the kinematical variables which have been applied to these data are the same as those defined above. The statistical weights of the results from the two data samples are roughly equal.

If one assumes that the fragmenting quark (mainly u) is preferentially contained in the fastest hadron then for some fixed value of x_{Bj} , above the sea region, A_{leading} should increase with an increasing cut in x_F . Further,

since the relative proportion of u quarks in the proton increases with x_{BJ} a rise of A_{leading} with x_{BJ} is expected. Both the increase of A_{leading} with an increasing cut in x_F and with x_{BJ} can be seen in fig. 4.

In a simple model in which only scattering from u and d quarks is considered and resonance decay and the fragmentation into baryons are neglected, A_{leading} can be approximated by

$$A(x_{BJ}, p)_{\text{leading}} \approx \frac{p - p'}{p + p'} A(x_{BJ}, p=1)_{\text{leading}}. \quad (6)$$

In this formula p denotes the probability that the leading hadron contains a quark of the same flavour as the scattered quark whereas p' is the probability that the leading hadron contains a d quark if a u quark was struck and vice versa. If the scattered quark is always a constituent of the fastest hadron ($p = 1$) one obtains

$$A(x_{BJ}, p=1)_{\text{leading}} = \frac{4 \cdot q_u(x_{BJ}) \cdot (\gamma_u + \gamma_s) - q_d(x_{BJ}) \cdot \gamma_u}{4 \cdot q_u(x_{BJ}) \cdot (\gamma_u + \gamma_s) + q_d(x_{BJ}) \cdot \gamma_u} \quad (7)$$

for the charge asymmetry of the fastest charged hadrons.

Taking into account equations (6) and (7) together with the normalisation condition

$$p + p' \cdot (1 + \gamma_s/\gamma_u) = 1 \quad (8)$$

an estimate of p can be obtained from the experimental results shown in fig. 4. For this purpose A_{leading} is determined from the data at $x_{BJ} > 0.3$, well above the sea region. $A(x_{BJ}, p=1)_{\text{leading}}$ is evaluated using the parametrisations of the quark density distributions given in ref. [16]; γ_s/γ_u is assumed to be 0.3. This procedure leads to the following result:

$$x_F > 0.5: \quad A_{\text{leading}} = 0.49 \pm 0.08 \quad p = 0.73 \pm 0.05$$

This value of p is strictly speaking only correct for first rank products of the fragmentation. Neglecting the influence of resonance decays however seems to be a reasonable approximation since one can conclude, from the Lund model for example, that 70% of the leading charged hadrons of $x_F > 0.5$ are produced directly. But when drawing conclusions from the value of p given above one should keep in mind that resonance decays diminish A_{leading} somewhat (by about 10% in the framework of the Lund model). Therefore the value of p obtained in this way represents a lower limit.

With this simple model one can also estimate to what extent a selection on the charge of the fastest hadron can be used as a tag on the flavour of the scattered quark. At $x_{Bj} \approx 0.4$ the ratio of the number of events with scattering from u quarks to the number of events with scattering from d quarks is determined to be roughly 12 : 1 when using the parametrisations of the quark density distributions given in ref. [16]. By selecting events with a positive leading hadron of $x_F > 0.5$ this ratio is changed to about 43 : 1 whereas by selecting events with a negative leading hadron of $x_F > 0.5$ this u to d ratio is found to be about 4 : 1. From this it becomes obvious that one can rather easily obtain an almost clean sample of events with scattering from u quarks; in the case of scattering from d quarks only some enrichment can be achieved.

Summary

In conclusion, the data presented in this paper provide further confirmation of the QPM. The charge flow in the forward direction becomes more positive with increasing x_{Bj} , as expected. The net charge of the hadrons in the central region is almost zero thus indicating that the fragmenting quark (or antiquark or remnant target system) is preferentially contained in fast hadrons (both in the forward and backward direction). In the region where scattering from valence quarks is dominant the probability is estimated to be greater than 70% that the fastest forward going charged hadron with $x_F > 0.5$ contains a quark of the same flavour as the scattered quark.

Acknowledgements

We would like to thank all the people in the various laboratories who have contributed to the construction, operation and analysis of this experiment. The support of the CERN staff in operating the SPS, muon beam and computer facilities is gratefully acknowledged.

References

- [1] R. P. Feynman, Photon-hadron interactions (Benjamin Inc., Reading, MA, 1972).
- [2] R. D. Field and R. P. Feynman, Nucl. Phys. B136 (1978) 1.
- [3] R. Erickson et al., Phys. Rev. Lett. 42 (1979) 822.
- [4] J. P. Berge et al., Phys. Lett. 91B (1980) 311.
- [5] M. Derrick et al., Phys Lett. 91B (1980) 470.
- [6] H. Deden et al., Nucl. Phys. B181 (1981) 375.
- [7] P. Allen et al., Nucl. Phys. B181 (1981) 385.
- [8] J. P. Berge et al., Nucl. Phys. B184 (1981) 13.
- [9] S. Barlag et al., Z. Phys. C11 (1982) 283.
- [10] P. Allen et al., Phys. Lett. 112B (1982) 88.
- [11] EMC, J. P. Albanese et al., Nucl. Instr. and Meth. 212 (1983) 111.
- [12] G. Ingelman et al., Nucl. Phys. B206 (1982) 239.
- [13] EMC, J. P. Albanese et al., to be published.
- [14] P. Allen et al., Nucl. Phys. B214 (1983) 369.
- [15] EMC, J. J. Aubert et al., Phys. Lett. 119B (1982) 233.
- [16] M. Glück, E. Hoffmann and E. Reya, Z. Phys. C13 (1982) 119.

Figure Captions

- Fig. 1: Comparison between the distributions of the hadronic net charge $(1/N_\mu \cdot (dN_{h^+}/dy - dN_{h^-}/dy))$ determined by two different methods (see text) as a function of the cms rapidity. Only hadrons detected in Cerenkov or time-of-flight counters are included in this plot. The histograms with error bars correspond to data where particle identification is used whereas the hatched histograms represent results in which Monte Carlo corrections account for mass assignments.
- Fig. 2: Distribution of the hadronic net charge $(1/N_\mu \cdot (dN_{h^+}/dy - dN_{h^-}/dy))$ as a function of the cms rapidity in three different x_{BJ} regions. The corresponding mean values of W are given as well.
- Fig. 3: Average a) forward and b) backward multiplicity as a function of x_{BJ} for h^+ and h^- and the difference between h^+ and h^- (net charge). The latter is compared with results from the Lund Monte Carlo model [12] (dashed curve).
- Fig. 4: Charge asymmetry of the leading charged particle as a function of x_{BJ} . The full symbols correspond to $x_F > 0$, the crosses to $x_F > 0.5$ of the fastest charged hadron. The latter were obtained from results of this and a previous experiment [15] of the EMC.

FIG. 1

FIG. 2

FIG. 3

FIG. 4