A COMPARISON OF THE ENERGY DISTRIBUTIONS OF HADRONS PRODUCED IN DEEP
INELASTIC SCATTERING OF MUONS ON HYDROGEN AND DEUTERIUM TARGETS

The European Muon Collaboration (EMC)

CERN¹, DESY (Hamburg)², Freiburg³, Kiel⁴, Lancaster⁵, LAPP (Annecy)⁶, Liverpool⁷,
Marseille⁸, Oxford⁹, Rutherford¹⁰, Sheffield¹¹, Turin¹², and Wuppertal¹³.

J.J. Aubert⁸, G. Bassompierre⁶, K.H. Becks¹³, C. Benchouk⁸, C. Best^{10a},
E. Böhm⁴, X. de Bouard⁶, F.W. Brasse², C. Broll⁶⁺, S. Brown⁷, J. Carr^{10b},
R. Clifft¹⁰, J.H. Cobb^{5c}, G. Coignet⁶, F. Combley¹¹, G.R. Court⁷,
G. D'Agostini⁸, W.D. Dau⁴, J.K. Davies^{9d}, Y. Déclais^{6e}, U. Dosselli^{1f},
J. Drees¹³, A. Edwards^{13a}, M. Edwards¹⁰, G. Eszes^{6l}, J. Favier⁶,
M.I. Ferrero¹², W. Flauger², H. Forsbach¹³, E. Gabathuler⁷, R. Gamet⁷,
J. Gayler², V. Gerhardt^{2g}, C. Gössling^{2s}, J. Haas³, K. Hamacher¹³,
P. Hayman⁷, M. Henckes^{13h}, V. Korbel², B. Korzen¹³, U. Landgraf³,
M. Leenen¹ⁱ, M. Maire⁶, W. Mohr³, H.E. Montgomery^{1j}, K. Moser³,
R.P. Mount^{9k}, E. Nagy^{6l}, J. Nassalski^{2m}, P.R. Norton¹⁰, J. McNicholas⁹ⁿ,
A.M. Osborne^{1,0}, N. Pavel¹³, P. Payre⁸, C. Peroni¹², H. Peschel¹³,
H. Pessard⁶, U. Pietrzyk¹³, P. Ribarics^{6l}, K. Rith³, M. Schneegans⁶,
A. Schneider¹³, T. Sloan⁵, H.E. Stier³, W. Stockhausen¹³, J.M. Thénard⁶,
J.C. Thompson¹⁰, L. Urban^{6l}, M. Villers⁹, H. Wahlen¹³, M. Whalley^{11p},
D. Williams^{7q}, W.S.C. Williams⁹, J. Williamson^{11r}, S.J. Wimpenny^{7s}.

Abstract

The energy distribution of inclusive hadrons produced by 280 GeV muons on hydrogen and deuterium targets are compared. The sum of the scaled energy distributions of the positive and negative hadrons is found to be the same for the two targets. The difference of these distributions is observed to factorise in x and z and the z -dependence is found to be independent of the target type and have a form $(1-z)^{2.1 \pm 0.2}$. The net charge of the hadronic jet is positive at high x even in the case when the scattering takes place on the neutron. These results are in good agreement with the expectations of the Quark Parton Model.

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- a) Now at JET, Joint Undertaking, Abingdon, England.
- b) Now at University of Colorado, Boulder, Colorado, USA.
- c) Now at University of Oxford, England
- d) Now at Plessey Defence Systems, Fareham, England.
- e) Now at Université d'Aix-Marseille II, Luminy, France.
- f) Now at INFN. Sez. Padova, Italy.
- g) Now at Beiersdorf AG, Hamburg, Germany.
- h) Now at ICR-PV, Köln, Germany.
- i) Now at Physikalisches Institut der Universität, Bonn, Germany.
- j) Now at FNAL, Batavia, Illinois, U.S.A.
- k) Now at California Institute of Technology, Pasadena, California, USA.
- l) Now at Central Research Institute for Physics of the Hungarian Academy of Science, Budapest, Hungary.
- m) Now at Institute for Nuclear Studies, Warsaw, Poland.
- n) Now at GEC Computers, Coventry, England.
- o) On leave of absence at FNAL, Batavia, Illinois, U.S.A.
- p) Now at Durham University, Durham, England.
- q) Now at U.K.A.E.A., Winfrith, Dorchester, England.
- r) Now at RAL, Chilton, Didcot, Oxon, England.
- s) Now at CERN, Geneva, Switzerland.
- +) Deceased.

Introduction

In this paper the scaled energy distribution of non-identified forward going charged hadrons produced in deep inelastic scattering of muons on hydrogen and deuterium targets are compared. The spectra of the positive and negative hadrons are predicted by the Quark Parton Model (QPM) to be different in the forward direction due to the different quark composition of the targets. However, such differences are not expected from the fragmentation mechanism or from nuclear effects. In particular, the QPM predicts that the sum of the scaled energy distributions of the positive and negative hadrons are approximately the same for the two targets. It also predicts that the difference of these distributions factorises to a good approximation in the kinematic variables of the muons and hadrons, the dependence on the latter being independent of the target type. The study of these spectra can thus be used to test the QPM.

The standard notation of deep inelastic muon scattering is used. In the one photon exchange approximation Q^2 and ν are the square of the four momentum transferred and the energy transfer in the laboratory frame to the virtual photon, respectively, and $x = Q^2/2M\nu$, where M is the proton mass, is the fraction of the momentum of the nucleon carried by the struck parton; W is the total energy in the virtual photon-proton rest frame. The energy of each hadron in the laboratory frame is E_h and $z = E_h/\nu$.

In the QPM the normalised scaled energy distributions of the positive and negative hadrons can be written as [1]:

$$\frac{1}{N_\mu} \frac{dN^\pm}{dz} = \frac{\sum_i e_i^2 q_i(x) D_i^\pm(z)}{\sum_i e_i^2 q_i(x)} \quad (1)$$

where N_μ is the number of deep inelastic scattering events, e_i^2 are the quark charges squared, $q_i(x)$ are the quark momentum distribution functions of the target and $D_i^\pm(z)$ is the fragmentation function of quark i into positive or negative hadrons. Equation (1) can be split into the sum and the difference of the positive and negative hadrons:

$$\frac{1}{N_u} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right) = \Sigma = \frac{1}{\sum_i e_i^2 q_i(x)} \cdot \sum_j e_j^2 q_j(x) (D_j^+(z) + D_j^-(z)) \quad (2)$$

$$\frac{1}{N_u} \left(\frac{dN^+}{dz} - \frac{dN^-}{dz} \right) = \Delta = \frac{1}{\sum_i e_i^2 q_i(x)} \cdot \sum_{k=u,d} e_k^2 q_k^v(x) (D_k^+(z) - D_k^-(z)) \quad (3)$$

where $q_k^v(x)$ are the distributions of the valence quarks, and the summation over i and j is for quark flavours $u, d, s, \bar{u}, \bar{d}, \bar{s}$. Here it is assumed that the effect of sea quarks cancels in taking the difference.

Σ depends essentially on the variable z and it is practically independent of x and of the type of target. Factoring out the contribution of the u quark in eqn. (2) gives

$$\Sigma = (D_u^+(z) + D_u^-(z)) \cdot (1 + \epsilon(x, z)) \quad (4)$$

It can be shown that $\epsilon(x, z)$ is proportional to the probability that the virtual photon strikes a d or s quark instead of a u quark and also to the relative differences of the u and d or u and s fragmentation functions, $(D_u^+ + D_u^- - D_d^+ - D_d^-) / (D_u^+ + D_u^-)$ and $(D_u^+ + D_u^- - D_s^+ - D_s^-) / (D_u^+ + D_u^-)$. Thus $\epsilon(x, z)$ should be small and is expected to be of the order of a few percent.

Similarly, it can be shown that the differences of the fragmentation functions, $D^+ - D^-$, for the u and d quarks in Δ are roughly proportional to each other, so that eqn. (3) can be written:

$$\Delta = \frac{1}{\sum_i e_i^2 q_i(x)} (e_u^2 q_u^v(x) \alpha - e_d^2 q_d^v(x) \beta) P(z) \quad (5)$$

Thus, according to the QPM the z -dependence of Δ is universal i.e. it is independent of x and of the type of target. This can be seen most easily in the case of charged pions, where from isospin invariance $D_u^{\pi^+} - D_u^{\pi^-} = -(D_d^{\pi^+} - D_d^{\pi^-})$

and therefore eqn. (5) holds with $\alpha = \beta$. In the general case for all charged hadrons α and β are not equal because the isospin partners of the protons and K^+ , i.e. neutrons and K^0 mesons, are not detected. However, in this case eqn. (5) still holds to a good approximation. The function $P(z)$ is the difference between the favoured and the unfavoured fragmentation functions [3] (softened by resonance decays). It is thus related to the primordial fragmentation function in chain fragmentation models [2,13]. In these models the constants α and β are given by

$$\alpha = 1 + \frac{\gamma_s}{\gamma} + \frac{\gamma_{ud}}{\gamma} \quad (6)$$

$$\beta = 1 - \frac{\gamma_{ud}}{2\gamma}$$

where $\gamma_u = \gamma_d = \gamma$, γ_s and $\gamma_{ud} = 2\gamma_{dd} = 2\gamma_{uu}$ are the fractions of $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ quark pairs and $u\bar{d}u\bar{d}$, $d\bar{d}d\bar{d}$ or $u\bar{u}u\bar{u}$ di-quark pairs created in the fragmentation process, respectively.

Integrating $\Delta(x,z)$ over z above a threshold z_t gives the net charge of the forward going hadron-jet:

$$Q(x) = \int_{z_t}^1 \Delta(x,z) dz \quad (7)$$

Since the incident virtual photon is neutral, $Q(x)$ is closely related to the charge distribution of the target. $Q(x)$ is expected to rise monotonically as x increases due to the decreasing contribution of sea quarks, and to be dominated by u quarks.

The experimental verification of relations (4) and (5) allows the predictions of the QPM to be tested and the functional form of $P(z)$ to be determined.

The aim of this paper is to compare the distribution of the hadrons produced in deep inelastic scattering on hydrogen and deuterium targets and thereby to show that

- i) the Σ distribution is independent of the type of the target
- ii) the Δ distribution factorises in the case of both targets as predicted by eqn. (5)
- iii) the z dependence of Δ , represented by the function $P(z)$, is independent of the type of the target.

In earlier charged leptonproduction experiments [16,17] at lower lepton energies some tests of the QPM have already been carried out by comparing the charged hadron distributions on hydrogen and deuterium targets. However, the above mentioned points (i) - (iii) have not yet been verified.

For the above purposes we present here the analysis of non-identified charged hadrons produced on a deuterium target and a reanalysis of a comparable fraction of the hydrogen data which was published earlier to study other physics aspects [4,5,6,7]. We also compare the non-identified hadron distribution with that of the identified pions [3] on the deuterium target, which allows us to estimate a combination of the parameters in eqn. (6).

Data Analysis

The experiment was performed in the M2 muon beam at the CERN SPS. Muons of energy 280 GeV were incident on a 6m long target containing either liquid hydrogen or deuterium. The scattered muons and forward going hadrons were detected and measured in the EMC forward spectrometer which is fully described elsewhere [8]. Events were selected for further analysis if their vertices were reconstructed in the most downstream 2m of the target. This reduced the reinteraction probability of the produced hadrons to $\sim 15\%$ and $\sim 8\%$ for the deuterium and hydrogen data, respectively. The electron contamination in the observed hadrons was estimated to be 5% for the deuterium data and somewhat less for the hydrogen data.

Reconstructed hadron tracks were selected and associated with the vertex, requiring the presence of a hit inside the magnet volume at the predicted junction of the upstream and downstream segments of the track in the bending plane. This criteria improved the quality of the selected tracks, especially in the case of the deuterium target.

Further cuts were applied to the data to avoid regions where the corrections for apparatus acceptance and radiative effects were large or varying rapidly. These cuts are given in table 1.

Table 1

Data Selection Cuts

$Q^2_{\min}$	$\nu_{\min}$	$p'_{\mu, \min}$	$\Theta_{\mu, \min}$	$W^2_{\min}$	$W^2_{\max}$	$E_{h, \min}$	$z_{\min}$
5 GeV ²	70 GeV	40 GeV	10 mrad	30 GeV ²	330 GeV ²	6 GeV	0.15

Here p' and Θ are the laboratory momentum and angle of the scattered muon relative to the beam muon. The total number of events which survived these selection criteria are 11300 and 16800 for the hydrogen and deuterium data, respectively.

The acceptance of the apparatus was determined by a Monte Carlo simulation which included the effects of electromagnetic radiation from the incident and scattered muons and the Fermi-motion of the nucleon inside the deuteron [9]. The effect of the latter was small. The hadrons were generated for the two targets using the Lund model [10] to simulate the fragmentation process with the inclusion of secondary hadron interactions in the target. The complete apparatus was simulated including the effects of chamber and hodoscope efficiencies and smearing due to measurement errors. The efficiency of the detector was calculated by the method described earlier [11]. On one third of the Monte Carlo events a more elaborate simulation was used in which the simulated detector signals were passed through the complete off-line analysis chain. This allowed the corrections made for the losses in the analysis programmes to be checked.

Results

Figure 1 shows the variation of $\Sigma(z)$ with z for the two targets integrated over the muon kinematic variables. No difference can be seen between the hydrogen and deuterium data in agreement with the predictions of the QPM (eqn. 4). Figure 2 shows the same quantity in two different W^2 regions. Again, no target dependence can be seen although the spectra show slight variations with W^2 . This effect which has already been observed for hydrogen data [5] is confirmed here for both hydrogen and deuterium targets.

Figure 3 shows $\Delta(x,z)$ as a function of $(1-z)$ in the x regions $0.04 \leq x \leq 0.15$ and $0.15 \leq x < 1$, for each target separately. In order to verify the factorisation property in eqn. (5) the data were fitted to the ansatz

$$\Delta(x,z) = A(x) \cdot (1-z)^B. \quad (8)$$

The low z points ($z < 0.25$) were omitted from the fit to avoid uncertainties due to the contribution of the remnants from the target diquark. The fitted values of the parameters A and B are shown in the first and second rows of table 2. A good fit to the data is obtained. Furthermore, the slopes B agree well for the hydrogen and deuterium data, showing that the z dependent part of $\Delta(x,z)$ is universal. This is in agreement with the QPM which predicts factorisation in this manner (eqn. 5). The ratios of the $A(x)$ values for the two targets are also in agreement with the QPM and will be shown later using the quantities R (eqn. 10).

An estimate of γ_{ud}/γ (eqn. 6) can be made by comparing the data for all charged hadrons and for identified pions from deuterium. Figure 4 shows the variation of $\Delta(x,z)$ with $(1-z)$ for both identified pions [3] and all charged hadrons in the range $0.15 \leq x \leq 1.0$ using the deuterium data. The z dependence is observed to be similar for the two cases. This is also seen in table 2 (last two rows) from the small value of χ^2 obtained from a fit to each distribution, with a common slope B . Thus the factorisation form in eqn. (8) gives a good representation of the data and $P(z)$ (eqn. 5) is the same for both.

Table 2

Fitted Parameters of Eqn. (8)

Type of Particle	Target	A	B	χ^2/dof
		$0.04 \leq x \leq 0.15$ $0.15 \leq x \leq 1.0$		
Non-identified	H ₂	0.90 ± 0.18 1.42 ± 0.27	2.14 ± 0.21	3.3/5
	D ₂	0.54 ± 0.13 1.31 ± 0.27	2.13 ± 0.23	2.8/5
Identified	D ₂	0.67 ± 0.11	2.13 ± 0.23	2.7/5
Non-identified		1.31 ± 0.27		

For identified pions α and β (eqn. 5) are each unity where α and β are defined in eqn. (6). In taking ratios of the values of A for identified pions and all hadrons observed from a deuterium target, the quark distribution functions cancel assuming from isospin invariance that the u and d valence quark distributions are the same in the deuteron. It follows, taking the u and d quarks to have charges 2/3 and 1/3, that

$$\frac{A^h}{A^\pi} = \frac{4\alpha - \beta}{3} = 1 + \frac{4}{3} \frac{\gamma_s}{\gamma} + \frac{3}{2} \frac{\gamma_{ud}}{\gamma} \quad (9)$$

where A^h and A^π are the values of A for all hadrons and charged pions, respectively. The measured ratio is

$$\frac{A^h}{A^\pi} = 1.96 \pm 0.54$$

from the values given in table 2, where the error is statistical only. A further systematic error of 10% arises from the uncertainty in the

normalisation of the two data samples. From this ratio, using the value $\gamma_s/\gamma = 0.29 \pm .02$ determined experimentally [12] in the same W range as the data presented here, it follows that $\gamma_{ud}/\gamma = 0.38 \pm 0.38$ which is in reasonable agreement with the expectations of [13].

In fig. 5 $Q(x)$ is shown with $z_t = 0.25$ for the hydrogen and the deuterium targets in two x regions: $0.04 < x < 0.15$ and $0.15 < x < 1.0$. As expected from the QPM, $Q(x)$ is observed to increase with x and it tends to be higher for the hydrogen than for the deuterium. The ratios of the values of $Q(x)$ for hydrogen and deuterium are

$$R = \frac{Q_{H_2}}{Q_{D_2}} = 1.62 \pm 0.36, \quad R_{QPM} = 1.30 \quad (0.04 < x < 0.15) \quad (10)$$

$$R = \frac{Q_{H_2}}{Q_{D_2}} = 1.12 \pm 0.17, \quad R_{QPM} = 1.31 \quad (0.15 < x < 1.0)$$

where R_{QPM} is the prediction of eqn. (5) averaged over x using the quark distribution function of Eichten et al. [14] and the values of α and β calculated from γ , γ_s and γ_{ud} given in [13]. The measured values of R are consistent with the values expected from the QPM.

The value of $Q(x)$ for the neutron may be extracted assuming that the scattering on deuterium takes place incoherently from the proton and neutron:

$$Q_n(x) = Q_{D_2}(x) + \frac{F_2^p(x)}{F_2^n(x)} (Q_{D_2}(x) - Q_{H_2}(x)), \quad (11)$$

where $F_2^p(x)$ and $F_2^n(x)$ are the proton and neutron structure functions, respectively, [11,15]. It can be seen from fig. 5 that $Q_n(x)$ is positive at high x which demonstrates the presence of the charged constituents of the neutron. Similar results were obtained earlier [16] at lower values of W and Q^2 .

Conclusions

Measurements of the scaled energy distributions in the forward region of inclusive hadrons on deuterium have been presented and compared with the same distributions from hydrogen. The fragmentation functions for all charged hadrons produced from protons and deuterons are found to be the same. This implies that the summed hadron fragmentation functions from proton and neutron targets are equal. The difference between the scaled energy distributions for positive and negative hadrons was found to factorise in x and z . These results are in good agreement with the expectations of the quark parton model. The z dependence of the difference between the scaled energy distributions for positive and negative hadrons, which is related to the primordial fragmentation function softened by resonance decays, was found to have the form $(1-z)^{2.1 \pm 0.2}$.

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Figure Captions

Fig. 1 $\Sigma(z) = \frac{1}{N_{\mu}} \left(\frac{dN^+}{dz} + \frac{dN^-}{dz} \right)$ integrated over x and Q^2 for $30 \leq W^2 \leq 330 \text{ GeV}^2$.

Fig. 2 $\Sigma(z, W^2)$ integrated over x and Q^2 in two W^2 regions:
 $100 \leq W^2 \leq 210 \text{ GeV}^2$ and $210 \leq W^2 \leq 330 \text{ GeV}^2$.

Fig. 3 $\Delta(z, x) = \frac{1}{N_{\mu}} \left(\frac{dN^+}{dz} - \frac{dN^-}{dz} \right)$ for the x regions:
 $0.04 \leq x \leq 0.15$ (open symbols) and $0.15 \leq x \leq 1.0$ (full symbols)
a) Hydrogen, b) deuterium. The solid lines are the result of the fit to eqn. (7) with common B for the two x regions, for $z \geq 0.25$.

Fig. 4 $\Delta(z)$ for deuterium in the range of $0.15 \leq x \leq 1.0$ for identified pions (6) and all charged hadrons. The solid lines are the result of the fit to Eqn. (7) with common B for the two kinds of measurements, for $z \geq 0.25$.

Fig. 5 $Q(x) = \int_{0.25}^{1.0} \Delta(z, x) dx$ for hydrogen, deuterium and neutron targets.

FIG. 1

FIG. 2

FIG. 3a

FIG. 3b

FIG. 4

FIG. 5