HADRON PRODUCTION IN 200 GeV μ -COPPER AND μ -CARBON
DEEP INELASTIC INTERACTIONS

The European Muon Collaboration

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Abstract

The measurements of the z and p_T^2 distribution of hadrons produced in the interactions of 200 GeV muons with copper and carbon nuclei are shown in different x_{Bj} and virtual photon energy intervals. Effects of the jet scattering are seen at the lowest virtual photon energies while for energies above 70 GeV there is no evidence of these effects. Comparison with a theoretical model indicates that at high jet energies the parton fragmentation distance is greater than the nuclear radius and that the parton absorption cross section is less than 10 mb.

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1. Introduction

Results on the ratio of the iron and the deuterium F_2 structure functions /1/ have shown that the structure function of the nucleon embedded in the nucleus is different from the one measured on a free nucleon. These results do not agree with the simple expectations from the Fermi motion and indicate the existence of other important nuclear effects probed by the virtual photon. As far as the hadron production is concerned, the fundamental fact observed in the experiments using any beam of sufficiently high energy interacting with the nuclear targets is the absence of intra-nuclear cascading of the high energy hadrons /2/ (see /3, 4/ for the review articles). This observation, which came as a surprise, is in fact expected from the uncertainty principle /5/ (see also /6/ for a review); the absence of cascading of high energy hadrons is explained by the large longitudinal distances needed for the formation of a high energy jet (/4/, /7/). For this reason the nucleus is a unique tool to study the properties of the state which propagates from the production region to the region where the final state hadrons are formed. This feature of an extended nuclear target is particularly attractive in case of a lepton beam, where the parton structure of a nucleon is clearly manifest. In this case, by studying the evolution of a pure parton jet one could learn about the confinement mechanism.

In the parton model / 8/, the process of hadron production in deep-inelastic lepton-hadron scattering has two independent stages:

In the first stage, the high- Q^2 ($Q^2 \geq 2 \text{ GeV}^2$) virtual photon interacts with the charged, point-like constituent of the hadron and the cross section for the absorption of the photon depends only on the square of the parton charge and on the probability that it has a given x_{Bj} .

In the second stage, the struck parton is subject to confining forces and it fragments into a jet of hadrons. With a virtual photon of four momentum $q = (\nu; 0, 0, \nu + \frac{Q^2}{2\nu})$, where ν is its energy and $-Q^2$ is its mass squared, the struck parton will have a momentum of the order of ν . If, in the parton rest system, the minimum space-time interval needed for the hadronisation is of the order of a hadron mass $m_0^{-1} \approx 1 \text{ fm}$ then, due to the Lorentz dilation, the hadronisation will extend over distances of the order of $(\nu/m_0^2) \text{ fm}$ in the laboratory system. The most popular theoretical belief is that hadrons of laboratory energy E ($E \leq \nu$) will be formed at distances $(E/m_0^2) \text{ fm}$.

Since the nuclear sizes are of the order of several fermi ($r(\text{Cu}) \approx 4.8$ fm, $r(\text{C}) \approx 2.7$ fm), the intranuclear cascading is expected to modify the low energy hadron spectrum, ($E \lesssim r \cdot m_0^2$), while high energy hadrons ($E \gg r \cdot m_0^2$) will be formed outside of the nuclear matter. Any modification of the spectra of such high energy hadrons should then be taken as due to other nuclear effects such as the manifestation of a hadronic structure of the virtual photon, modification of the parton distribution in the nucleus or due to the parton scattering in the nuclear matter. The essential features of the above picture formulated in terms of the naive parton model are not changed when one uses QCD-inspired parton models /9/, /10/.

The data presented in this paper were taken using the EMC spectrometer at the CERN SPS. The muon beam momentum was 200 GeV and the targets were C and Cu. With this set up we were able to study the hadron production in the deep-inelastic region ($Q^2 > 5 \text{ GeV}^2$) as a function of x_{Bj} ($x_{\text{Bj}} > 0.02$) and of the virtual photon energy ν ($50 < \nu < 180$ GeV) in the current fragmentation region ($z > 0.1$). We have also compared copper and carbon data to 120 GeV and 280 GeV hydrogen target data taken with the same equipment. In addition, to compare the relative yield of protons and antiprotons from different targets, we use our 280 GeV deuterium target data.

Preliminary results of the analysis of Cu and C data have been already presented /11/.

2. Definition of variables

Denoting the four-vector of the primary and secondary muon as p_μ , p_μ' , those of the target nucleon and a final state hadron as p_i and p_f , and the nucleon mass as M , we define the standard kinematic variables:

$$q = p_\mu - p_\mu', \quad -Q^2 = q^2 = (p_\mu - p_\mu')^2$$

$$\nu = (p_i \cdot q)/M = (E_\mu - E_\mu')$$

$$W^2 = 2M\nu + M^2 - Q^2$$

$$x_{\text{Bj}} = \frac{q^2}{2(p_i \cdot q)} = \frac{Q^2}{2M\nu}$$

$$y = \frac{\nu}{\nu_{\text{max}}}$$

For the hadron variables we use

$$z = (p_f \cdot p_i) / (q \cdot p_i) = E/\nu$$

$$x_F = p_L^* / (p_L^*)_{\max}$$

$$Y = 0.5 \cdot \ln \frac{E + p_L}{E - p_L}$$

where E and p are the hadron laboratory energy and momentum respectively and the asterisk refers them to the centre of mass system. The transverse and longitudinal hadron momenta, p_T and p_L respectively, are measured relative to the virtual photon or current direction.

In order to expose the nuclear effects we construct the ratios of the differential multiplicity distributions of hadrons produced on different nuclear targets:

$$R_{A_1/A_2}(z) = \frac{(\frac{1}{N_\mu} \frac{dn}{dz})_{A_1}}{(\frac{1}{N_\mu} \frac{dn}{dz})_{A_2}}$$

where n is the number of charged hadrons produced by N_μ interactions, and (A_1, A_2) denote H_2 , C or Cu targets.

In order to see the nuclear effects in the leading hadron we use also ratio of the integrated z - distributions:

$$\bar{R}_{A_1/A_2}(z_{\min}) = \frac{\int_{z_{\min}}^1 \frac{1}{N_\mu} \left(\frac{dn}{dz}\right)_{A_1} dz}{\int_{z_{\min}}^1 \frac{1}{N_\mu} \left(\frac{dn}{dz}\right)_{A_2} dz}$$

3. Previous results and their interpretations

The experiments on hadron production in deep-inelastic lepton-nucleus scattering are summarized in Table 1. Among these, the SLAC experiment /13/ had the highest statistics on several nuclear targets, including D_2 , which was used as a reference to measure the effects coming from heavier nuclei. The results of this experiment show a substantial depletion of the hadrons from the large nuclei in the x_F -distributions for $x_F > 0$. However the hadron energies were small and the observed effect may be dominated by the hadron intranuclear cascading. These results stimulated several theoretical models which will be discussed below.

On the other hand no such depletion of a current jet hadrons was seen in the experiments, from refs. /12/, /14/ - /16/, which covered regions of higher W^2 , but their conclusions are limited by the small number of events observed.

There are many models which predict hadron spectra from the current jet in the nuclear matter and they differ not only in the form of the spectra predicted but also in their underlying physics. Most of the models /18/ - /22/ emphasise the importance of a struck parton interaction in the nuclear matter but differ in the assumptions about its cross section. In addition, some of them /18, 19/ do not use the concept of the finite hadronisation distances and do not consider the intranuclear cascading of hadrons. In the most simple approach, assuming that a parton is totally absorbed in a single interaction, Dar and Takagi /18/ predict for $x_F > 0.2$ a constant depletion of hadrons which is independent of the parton energy. They indicate that in this region an Additive Quark Model absorption cross section of 13 mb fits the SLAC data. A similar model of Nilsson, Anderson and Gustafson /19/ assumes that parton can loose energy in subsequent scattering. Also in this case the SLAC data are well fitted but it requires a parton-nucleon cross section of about 20 mb. The model of Biaľas and Biaľas /20/ discusses the effects of both elastic and inelastic multiple parton-nucleon collisions and indicates the importance of nuclear effects not only in the longitudinal but also in the transverse momentum spectra of the leading hadron. In an extension of this model,

Biaľas /21/ allows also for the absorption of the leading hadron and a parton energy dependent hadronisation distance. It is shown that the SLAC data can be fitted equally well using different values of the parton-nucleon cross section provided the hadronisation distance is appropriately adjusted; a cross section of 15 mb implied hadronisation distances much larger than the size of the nucleus while 0 mb cross section could be compensated by a distance of 1 fm. In the model of Nikolaev /22/ the fast parton does not interact and the nuclear attenuation of hadrons comes from their cascading according to the hadron energy dependent hadronisation lengths. Therefore, as in the model of Biaľas it predicts that the current jet absorption will diminish at high energies.

There are also models which consider neither the struck parton nor hadron scattering. Consequently they predict no nuclear influence on the current jet independent of the energy. To this category belongs the model of Brodsky, Gunion and Kühn /23/ for Q^2 in the Bjorken scaling region and also that of Brodsky / 9/ which puts the emphasis on the role of the colour neutralization in hadron production. The same applies to the model of Mueller /10/ which uses perturbative QCD arguments and to the Dual Parton Model of Capella and Tran Thanh Van /24/.

At the other extreme there is the Modified Cascade Model extension of Hossain and Tow /25/ which predicts a substantial contribution of hadron cascading in high energy jets.

There exists also a preliminary attempt to use the Lund colour flux fragmentation model to describe lepton-nucleus scattering data. Using one additional parameter to describe the interaction of the colour flux with the nuclear matter, it is possible to fit the SLAC data and predict suppression of nuclear effects at higher energies /26/.

4. Experiment

The experiment was performed in the M2 beam line of the SPS at CERN at 200 GeV muon momentum. The muons scattered in copper or carbon targets and the produced hadrons were measured in the EMC forward spectrometer consisting of a 4 Tm large aperture dipole magnet and a system of drift and proportional chambers (Fig. 1). The muon identification was performed using chambers placed downstream of an iron absorber. The apparatus was

triggered by scattered muons which satisfied a set of coincidence conditions between five planes of scintillator hodoscopes. At the trigger level, a minimum muon scattering angle of 0.5° was imposed. A full technical description of the apparatus is given in ref. /27/.

The copper and carbon targets were in form of discs of 12 cm diameter. There were 6 copper discs (1.5 mm thick) or 8 carbon discs (2 of 1.3 cm and 6 of 2 cm thickness), which were equally spaced in the position normally occupied by the downstream half of the 6 m hydrogen target. In this way a similar geometrical acceptance was obtained for particles produced on all targets. Fig. 2 shows the vertex distribution for the events reconstructed in the off-line analysis from Cu and C data. The total thickness of Cu and C targets was chosen to be comparable, in terms of the radiation length, to the full length of the hydrogen target (6 m) in order to maintain the electromagnetic background processes at the same level. The imposition of similar geometric acceptances and trigger conditions limited systematic errors when comparing Cu and C data to 120 GeV and 280 GeV μ^+ hydrogen data taken with the same apparatus /28,29/. During data taking, Cu and C targets have been alternatively exposed to the beam.

The average beam intensity during the data taking was of the order of 10^7 μ /sec, resulting in an integrated luminosity of $5.3 \times 10^{35} \text{ cm}^{-2}$ and $11.5 \times 10^{35} \text{ cm}^{-2}$ for Cu and C respectively.

Table 2 shows the beams and targets used in the present analysis.

5. The data

The copper and carbon data were analysed and corrected for the acceptance and the efficiency of the apparatus using the same method as for the analysis of the hydrogen data (/28/ - /30/).

Table 3 shows the cuts applied to the Cu and C events. These cuts were made in order to ensure good acceptance for muons and hadrons, to reduce background from pion decays and to avoid regions where the resolution is poor or radiative corrections are large. The number of events taken within the cuts are shown in Table 4 together with the average values of W^2 , ν , Q^2 and x_{Bj} .

The events are analysed in three regions of x_{Bj} and also in three regions of the virtual photon energy ν . In addition, the corresponding results from 120 GeV and 280 GeV H_2 target data are also presented. The cuts applied to hydrogen data are shown in Table 3 and the number of events, together with the average values of the kinematic variables, in Table 4. The lower energy H_2 data were used in order to cover the small ν region of the 200 GeV C and Cu data. After the cuts all data sets have a similar kinematic range. Table 5 and 6 show the average values of the kinematic variables in all data sets for x_{Bj} and ν bins respectively. The remaining kinematic differences between the (C, Cu) and H_2 data sets can contribute to small effects in the hadron spectra due to factorisation and scale breaking /29/. These possible effects are included in the systematic errors.

5.1 Acceptance corrections

The Monte Carlo acceptance corrections were made in the same way as for the hydrogen data /29, 30/.

The strongest acceptance variation is seen for the z - distribution at the smallest x_{Bj} interval, as illustrated in Fig. 3. The drop of the acceptance at large z is due to 40 cm radial cut around the beam region at the end of the hadron part of the spectrometer (in the W4 and W5 chambers - see Fig. 1). Uncertainty in the apparatus efficiency close to the beam region is the major contribution to the systematic errors of the leading particles at small x_{Bj} or large ν .

For the H_2 events the acceptance at the highest z is twice as large as for C or Cu events. This is mainly due to the better efficiency of the chambers during hydrogen data taking.

5.2 Radiative corrections

In addition to the radiative corrections applied to H_2 data, the C and Cu data were corrected for coherent radiative processes. For the bin of $0.02 < x_{Bj} < 0.10$ the average correction factor is 1.05 for copper and 1.03 for carbon data. For higher x_{Bj} the correction factor is consistent with 1.0.

The Monte Carlo simulation has shown that the hadron contamination by asymmetric e^+e^- pairs from hard photon conversion /31/ in the nuclear target make a sizable contribution to the particle spectra for $z > 0.8$ and so this region has been excluded from the plots. For $0.6 < z < 0.8$ the contamination is about 5 % and drops below 1 % for the remaining z range.

5.3 Interaction of hadrons with the other nuclei of a target

The effect of hadron interactions due to the finite length of the Cu and C target was studied using a Monte Carlo program. All outgoing hadrons were assumed to be pions. Their interaction cross section with the other nuclei was assumed to be energy independent with the magnitude as measured in ref. /32/. The secondary, leading particle spectra were taken from the measurements of ref. /33/. The interaction had to satisfy approximately energy and charge conservation. The calculations showed that, after the cuts imposed by the apparatus acceptance, 12 % of hadrons produced on C interacted in the target and 10 % of the measured hadrons were secondaries. The overall correction factor for the multiplicity loss was found to be 1.03. For the Cu target the corresponding numbers were 4.4 %, 3.7 % and 1.007. The studies made previously for the H_2 target gave the correction factor of 1.05 /30/. After the corrections the results correspond to zero target length (e.g. single target nucleus).

5.4 Systematic errors

We have studied the following sources of the systematic errors in Cu/C and (C, Cu)/ H_2 ratios: a) beam and scattered muon momenta, b) hadron selection, c) apparatus efficiency, d) scaling violation and factorisation breaking, e) radiative photon conversion, f) conversion of γ from π^0 , g) Fermi motion smearing, h) non-isoscalarity of the H_2 target.

- a) with the typical z -distribution of $\sim \exp(-6z)$, a 1 % systematic error in beam or scattered muon momentum gives rise to the relative error in (dn/dz) of $(1\%) \times 6z (E_\mu - \nu)/\nu$. In the most unfavourable case of the lowest ν -bin at 200 GeV this gives 12 % error at $z = 0.8$. This error does not contribute to Cu/C ratios because both targets were in the same beam,

- b) association of tracks to the interaction vertex gives rise to $\pm 1 \%$ error in Cu/C ratio and $\pm 8 \%$ error in (C, Cu)/H₂ ratios,
- c) for C and Cu data the uncertainty in the apparatus efficiency close to the beam region gives rise to the error which increases with z and is important at large ν or small x_{Bj} . In the most unfavourable case of the Cu/C ratio at the smallest x_{Bj} it is negligible up to $z = 0.3$ and rises to 23 % at $z = 0.6 - 0.8$. For $x_{Bj} > 0.1$ it is lower than 7 %. This error has been determined separately for Cu/C and the (C, Cu)/H₂ ratios,
- d) scaling violation and factorisation breaking effects contribute only to (C, Cu)/H₂ ratios for large x_{Bj} and small ν on the level of + 4 %.
- e) radiative photon conversion contributes at $z = 0.6 - 0.8$ to + 1 % for Cu/C ratios, - 5 % for (C, Cu)/H₂ ratios and is negligible for smaller z ,
- f) conversion of γ from π^0 contributes only at small z ; for $z = 0.1 - 0.2$ it is + 2 % for Cu/C and 2 - 3 % for (C, Cu)/H₂ ratios,
- g) Fermi motion produces smearing of z given by $\Delta\nu = \vec{q} \cdot \vec{p}_f/M$ where $\vec{q}$ and $\vec{p}_f$ are photon and nucleon momenta respectively. Using a Monte Carlo simulation the effect was found negligible for $z < 0.8$,
- h) using parton distributions for the proton, Field-Feynman fragmentation functions and isospin invariance, the expected difference in the z - distributions of all charged hadrons between H₂ and D₂ target was found to be smaller than 1 %.

The Cu/C ratios are sensitive only to the errors c) and f). All systematic errors are assumed to contribute independently. The resulting total systematic errors will be discussed in the analysis presented below.

6. Results

The nuclear effects in the hadronic jets will be searched for in the z - and p_T^2 - distribution of all charged hadrons, in the z - distributions of the ratio of the positive to the negative charge hadrons and in the fraction of the jets with the leading baryon.

The overall nuclear effect in the hadronic multiplicity for the events from all the kinematic range defined in Table 3 can be estimated from the z - and p_T^2 - distributions shown in Fig.4 and 5 respectively. For $z > 0.1$ the average charged hadron multiplicity is 1.58 ± 0.02 for C and 1.69 ± 0.02 for Cu target, an average increase of $7\% \pm 2\%$ (stat.) $\pm 3\%$ (syst.).

In order to better expose effects of this magnitude in the charged multiplicity we show the ratio of the z - distributions from Cu relative to C and the absolute values of $\langle p_T^2 \rangle$ for the individual targets. These results are shown as a function of x_{Bj} (in section 6.1) and ν (in section 6.2), where also $(C, Cu)/H_2$ ratios are presented. Although the kinematic variables in x_{Bj} and ν bins are correlated, we expect the x_{Bj} - dependence to show the effects which are probed by the virtual photon, while the ν - dependence shows the jet (initial parton and/or hadron) interactions which will be interpreted with the model of ref. /21/. Since our data covers a high Q^2 region ($\langle Q^2 \rangle = 22 \text{ GeV}^2$), the x_{Bj} - dependence of the charged multiplicity could be influenced by the nuclear effect in the parton distribution observed by the EMC /1/ and interpreted as due to the nuclear sea enhancement /34/. With this interpretation, effects should show up mainly in the ratio of the positive to the negative multiplicity of the leading hadrons. The idea behind this is that the charge of the leading hadron and that of the struck parton are expected to be strongly correlated. Therefore this ratio depends on the magnitude of the sea relative to the

valence region. The results on the charge ratios from H_2 , C and Cu targets will be presented in section 6.3. In the last section we will present the results on the fraction of jets with a leading proton or antiproton, from H_2 , D_2 , C and Cu targets.

6.1 x_{Bj} - dependence

The x_{Bj} bins were chosen to cover the region dominated by sea ($0.02 < x_{Bj} < 0.1$), valence partons ($x_{Bj} > 0.2$) and the region in between. Table 5 shows the average values of the kinematic variables in the three regions. It is seen that x_{Bj} and $\langle Q^2 \rangle$ are nearly proportional so that it is not possible to decide which is the relevant variable.

The average multiplicity ratios for Cu relative to C in $z < 0.1$ region are shown in Table 7. An excess in the average multiplicity in Cu relative to C is mainly seen at small x_{Bj} (in the sea region) or small Q^2 while for large x_{Bj} (or Q^2) this excess is not present. With our event statistics and relatively large systematic errors in the smallest x_{Bj} region it is not possible to study this effect further or check its relevance to the nuclear effect seen in the F_2 structure function [1/].

Figure 6 shows the ratio of the z - distributions of hadrons from Cu and C targets. Assuming that the z - dependence can be parametrised by a straight line, the best fit to the points gives the solid lines shown in the figure. The dashed-dotted lines limit the area containing lines which have a $\chi^2 - \chi_{min}^2 < 1$, where systematic errors have also been included. The slopes of the best lines for the z - dependence are $0.37 \pm 0.30 \pm 0.23$ in the sea region, $-0.19 \pm 0.22 \pm 0.03$ in the intermediate region and $-0.32 \pm 0.25 \pm 0.03$ in the valence region, where the errors are statistical and systematic respectively. The overall trend seen in the x_{Bj} dependence is to produce a small depletion of the leading hadrons at large x_{Bj} compared to $0.02 < x_{Bj} < 0.1$. This trend contributes to the previously discussed decrease of the integrated ($z > 0.1$)

multiplicity ratio as a function of x_{Bj} .

Fig. 7a shows $\langle p_T^2 \rangle$ for $p_T^2 < 4 \text{ GeV}^2$ and $z > 0.1$ as a function of x_{Bj} for Cu, C and also H_2 target. For x_{Bj} in the valence region there is an indication of broadening of jets from C and Cu targets relative to H_2 .

The combined trend seen in z and $p_{\perp}^2$ distributions at large x_{Bj} in Cu relative to C and H_2 is therefore to produce jets which have softer longitudinal and harder transverse momentum spectra. This might be due to either a change in the strange and charm contribution to the F_2 structure function, or to new effects seen in the fragmentation functions, or, more likely, to the jet (the struck parton or the leading hadron) interactions in the nuclear matter. This ambiguity can be clarified by studying the ν -dependence of the hadron spectra.

6.2 ν - dependence

The purpose of looking for the ν -dependence in the hadroproduction is to see jet scattering effects which are expected to decrease with the parton and/or hadron momenta. Therefore two narrow bins were chosen at the beginning of the available range of $\nu > 50 \text{ GeV}$. The average multiplicity ratios for Cu relative to C and the ratio of their z -distributions is shown in Fig. 8. As in Fig. 6 the solid lines are the results of the straight line fits and the dashed-dotted curves show the one standard deviation contour, including systematic errors. The slopes of the z -dependence for $50 < \nu < 70 \text{ GeV}$, $70 < \nu < 90 \text{ GeV}$ and $\nu > 90 \text{ GeV}$ are $-0.77 \pm 0.27 \pm 0.03$, $0.30 \pm 0.32 \pm 0.10$, $0.01 \pm 0.21 \pm 0.14$ respectively, where the first error is statistical and the second systematic. The results in the smallest ν -region are consistent with a depletion of large z hadrons which is stronger than the one observed for the largest x_{Bj} . There is no indication of such an effect for $\nu > 90 \text{ GeV}$ nor in the intermediate ν -range. A similar trend, seen in the ν -dependence of the rapidity distribution of hadrons from the antineutrino interactions in Ne, has been recently reported /17/.

Fig. 7b shows $\langle p_T^2 \rangle$ as a function of ν for Cu, C and H_2 target. Again, at small ν there is evidence for broadening of the jets from Cu and C targets.

Comparison of Fig. 8a and 6c shows that the indication of the nuclear effects in the leading hadron distributions seen at large x_{Bj} and the more clear effect occurring at small ν may be trivially correlated. Tables 5 and 6 show that it is indeed most probably the case; the strongest effect is seen when the ν -range is largest (Table 6) and not when x_{Bj} -range is largest (Table 5). In addition, $\langle Q^2 \rangle$ is nearly the same for all ν -bins so that the observed effect also does not depend on Q^2 for $Q^2 > 5 \text{ GeV}^2$ but only on ν (or W^2).

In Fig. 9 we show the individual ratios of the z -distributions from Cu and C relative to H_2 target. The dashed-dotted lines indicate the size of the systematic errors on the data points. The effects observed in Cu/C ratio are also seen here. Within given systematic and statistical errors it is not possible to conclude whether in the small ν -region there is also a nuclear effect in the C target.

The shaded areas in Fig. 9a show the low energy SLAC data /13/ (see also Table 1) on Cu/ D_2 and C/ D_2 ratios. The nuclear effect seen in the SLAC kinematic range is more pronounced and the shape of the z -dependence of the effect is different. This might be mainly due to the difference in ν , but also could reflect the different Q^2 -range of the two experiments. As explained in section 5.4.h it is not due to the differences in the fragmentation functions off hydrogen and deuterium. Assuming that the magnitude of the effect depends only on ν and that it is mainly due to the nuclear interactions of jets, one can compare the data from both experiments with the model of ref. /21/. With the broad range of $3 < \nu < 180 \text{ GeV}$ one can aim to answer several basic questions: 1) what is the magnitude of the cross section which determine the absorption of the leading hadron? 2) is the value consistent with the picture in which the leading hadrons interact at distances proportional to ν ? 3) if this is the case then, at large ν , what is the magnitude of the residual absorption which might be attributed to the interaction of a jet at an early stage in its formation and could therefore be visualized as due to a struck parton interaction?

In Table 8 we show the average multiplicity ratios and their statistical and systematic errors for the leading ($z > 0.5$) hadron from Cu and C relative to H_2 . These values, together with the value from the SLAC data

are plotted in Fig. 10 as a function of ν , where the error bars on data points indicate only statistical uncertainties. Table 9 shows the prediction for the leading hadron multiplicity ratios from the model of ref. /21/ and compares them to our results averaged over $\nu > 70$ GeV and to the SLAC results from $3 < \nu < 17$ GeV. The predictions are given for different extreme assumptions on the hadronisation distance (τ) and the value of the initial quark cross section (σ_q) with the leading hadron having the cross section of a pion ($\sigma_h = 20$ mb). From the comparison with the data one can get two relatively clear conclusions: while the SLAC data disfavour $\sigma_q = 0$ and large fragmentation distances ($\tau \gg r_A$, where r_A is the nuclear radius), the EMC data disfavour the other extreme case of zero fragmentation distances ($\tau = 0$) and of the large quark cross sections ($\sigma_q = 20$ mb). Therefore fragmentation distances at least of the order of r_A and also $\sigma_q \leq 10$ mb are required to understand both the SLAC and the EMC data. In view of the large errors on the EMC data points, more specific conclusions are difficult to draw. However accepting the trend shown in Fig. 10 the results favour the solution with ν -dependent fragmentation distances and $\sigma_q \approx 0$. With the proportionality factor between τ and ν fixed at 0.1 fm to fit the SLAC data one predicts the ν -dependence of the absorption in Cu and C targets shown by solid and broken curves respectively. Therefore the nuclear effects seen at small ν can be interpreted as due to intranuclear interactions of hadrons and their absence at large ν as due to the ν (or E)-dependent increase in the jet fragmentation length.

6.3 n^+/n^- ratio

In the kinematic range of our data ($\langle x_{Bj} \rangle = 0.11$, $\langle Q^2 \rangle = 21 \text{ GeV}^2$) the nuclear structure function F_2 as measured in the iron has been observed to be 12 % (± 9 %) higher than that measured in deuterium. This implies that the parton distributions in nuclei are different from those in quasi-free nucleons in deuterium. In particular, it is consistent with an increase in the sea of the nucleus /34/. Various theoretical models have been proposed to explain this effect (see /35/ for reviews) but there is no consensus on its origin.

It should be noted that besides the structure functions the leading hadron in the jet carries information about the flavour and the charge of the struck parton /36/. For the virtual photon interactions with the sea alone there

should be an equal number of positively and negatively charged hadrons for all z (see the expression (6.1)). If the interactions were only with the valence partons of the proton then, due to the difference in the charge of the u and d partons, one might expect at $z \approx 1$ to have $n^+/n^- = 8$. In the present kinematic range both the sea and the valence partons contribute and for the H_2 target the z -distribution of the charge ratio is as shown in Fig. 11. For the isoscalar target (like D_2 or C) the ratio should be somewhat smaller than for H_2 due to the presence of neutrons; for valence partons alone it should be smaller by 50 % at $z \approx 1$ with the difference tending to zero for smaller z . When the sea contribution is included this difference further diminishes. Such a trend is seen for the carbon results also shown in Fig. 11. The differences between the n^+/n^- ratio for Cu relative to C which are due to the excess of neutrons over the protons are expected to be negligible compared to the difference between C and H_2 . Fig. 11 shows also the z -distribution of the charge ratio for the Cu target. Integration over the region $0.4 < z < 0.8$ gives $n^+/n^- = 1.92 \pm 0.15$ and 1.62 ± 0.13 for C and Cu target respectively, a $16 \% \pm 9 \%$ decrease. Such a trend is consistent with the sea in copper being bigger than the one in carbon but it is not statistically conclusive.

The leading hadron interactions observed at small ν (section 6.2) should have negligible effect on the charge ratio; the region $50 < \nu < 70$ contains only 14 % of all the events and also the σ_{π^-p} and σ_{π^+p} inelastic cross sections differ by less than 5 % at 20 GeV.

6.4 Leading proton and antiproton production

A significant proton and antiproton fraction among all the charged forward produced hadrons from H_2 has been observed by the EMC /37/. In this section we show corresponding results obtained with the nuclear targets. It should be noted that the nuclear attenuation of the leading hadron, discussed in section 6.2, should be more pronounced if it is a proton or antiproton since their absorption cross sections are 50 % higher than for an average hadron, most likely being a pion. Therefore the nuclear absorption effects do not cancel in the ratio of $(p + \bar{p})$ to all hadrons. However taking the events from all the ν -region ($\langle \nu \rangle = 125$ GeV in Table 10) can wash out the effect completely. It should also be noted that the leading protons and antiprotons might be more sensitive to the

nuclear structure function effects then the average leading pions due to their differences in the quark content.

Using the threshold Cerenkov counter C_2 (Fig. 1) filled with Ne gas protons and antiprotons in the momentum range 50 - 80 GeV can be identified. A detailed description of the method is given elsewhere /37/. Identical procedure has been applied to our Cu, C and H_2 data, as well as to D_2 data at 280 GeV, and the events were selected using the cuts given in Table 3.

Table 10 shows the experimental results for the various targets. Presented are the number of observed proton and antiproton tracks giving no signal in the Cerenkov counter in the momentum range of 50 - 80 GeV, together with the total number of hadrons in the same momentum range. Also the average values of W^2 , ν , Q^2 , x_{Bj} and z for the selected events are given. The differences in the average kinematical variables are small, thus a direct comparison of the data from all targets is justified.

The observed number of protons and antiprotons have to be corrected for inefficiencies of the Cerenkov detector, e.g. misidentified pions and kaons and for noise in the detector. The efficiency for π detection has been taken directly from the measured μ -efficiency (98.5 ± 0.03 %). The average K-detection efficiency (80.5 ± 2.0 %) has been calculated using the π -efficiency to derive the response in the K-threshold region and taking a K-momentum spectrum as obtained from the Lund model /38/. Taking the noise to be 14 % /39/ and the pion content as derived from the pion identification momentum range (20 - 40 GeV), the corrected proton-antiproton fraction in the momentum range (50 - 80) GeV is obtained from the observed number of particles given in Table 10, assuming that the $\pi/K/p$ ratio does not differ in the two momentum ranges.

After these corrections the final results on the proton-antiproton fraction relative to all charged hadrons in the momentum range 50 - 80 GeV are shown in Fig. 12. It should be noted that 50 % of hadrons which enter this ratio have $z > 0.5$ (Table 10) and that the distributions were integrated over ν . The results for the isoscalar targets (D_2 , C, Cu) do not show any nuclear effect.

7. Conclusions

The overall nuclear effect seen in copper relative to carbon on the hadronic charged multiplicity gives rise to $7\% \pm 2\%$ (stat.) $\pm 3\%$ (syst.) excess of hadrons from Cu. Stronger nuclear effects show up in the leading particle region ($z > 0.5$) when the data is evaluated in different kinematic regions of the virtual photon.

The dominant effect is the strong ν -dependence of the leading particle distributions; for the smallest $\nu = 50 - 70$ GeV we observe the absorption of the fastest hadrons from copper relative to carbon, while such an effect is not seen for $\nu > 90$ GeV. The scattering effect observed in the z -distribution is consistent with the broadening of jets at small ν seen in the p_T^2 -distribution of hadrons.

Interpretation of these results in terms of the model of ref. /21/ leads to the conclusion that the parton fragmentation distances are comparable or larger than the size of the nucleus and also that the absorption cross section of the struck parton is smaller than 10 mb. When the model interpretation is extended also to the lower energy SLAC data /13/ then the overall trend seen in the ν -dependence of the leading hadron absorption is consistent with ν (or E) - dependent fragmentation distances. In view of the errors on our data points the precise determination of the parton cross section is not possible.

A weak x_{Bj} (or Q^2) - dependence seen in our data on the z -distribution of the hadronic charge multiplicity can be understood as due to the correlations between x_{Bj} and ν within our kinematics range, the dominant effect being the ν -dependence. The excess in the integrated multiplicity at $z > 0.1$ hadrons in Cu relative to C is seen mainly for the x_{Bj} in the sea region (or small Q^2).

The z -distribution of the ratio of positive over negative charge hadrons from copper and carbon show a trend which is consistent with the sea in copper being bigger than the one in carbon but this trend is not statistically conclusive. Other nuclear structure function effects which might manifest themselves in the fraction of jets with protons-antiprotons can not be seen within our statistical accuracy.

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Table 1

Experiments on hadron production in lepton-nucleus interactions

Experiment	Beam	Energy GeV	Targets	W^2 GeV ²	Q^2 GeV ²	Charged hadron variables
FNAL /12/	$\nu, \bar{\nu}$		H ₂ +Ne (64 %) ⁺	< 120		$Y > -1.0$ (74e ⁻ , 47e ⁺ events)
SLAC /13/	e	20.5	H ₂ , D ₂ , Be, C, Cu, Sn	7.0-31.0	0.35-5.0	$x_F > 0.0$ $p_T < 1$ GeV ($\sim 10^4$ events)
FNAL /14/	μ	150	Emulsion ($\langle A \rangle \approx 64$)	6.3-256.0	0.6-21.0	$n^{(*)} > -1.5$ $n_s^{(*)}, N_h^{(*)}$ (88 events)
FNAL /15/	$\bar{\nu}$	10-200	H ₂ +Ne (21 %) ⁺	4.0-100.0 ($\langle W^2 \rangle \approx 15$)	< 10.0	$x_F > -0.7$ (600 events)
CERN /16/ (BEBC)	ν	200 (NBB)	H ₂ +Ne (73 %) ⁺	25.0-64.0	4.0-16.0	$Z_R^{**})$ (3100 events)

*) η is the pseudorapidity ($\eta = -\ln \tan (\theta_{lab}/2)$)
 n_s is the number of shower particles ($\beta \geq 0.7$)
 N_h is the number of heavily ionising particles ($\beta < 0.7$).

***) Z_R is the fraction of the total charged particles energy.

+) molar percent of Ne.

Table 2

Beams and targets

Beam	p_μ GeV	Target	Total thickness		
			g/cm^2	$\%L_{\text{rad}}$	$(\%L_{\text{int}})_\pi$
μ^+	200	Cu	8.1	62	5
μ^+	200	C	30.9	72	26
μ^+	280	H ₂	21.0	33	25
μ^+	120	H ₂	14.0	22	17

Table 3

Data selection cuts

Target	p_μ GeV	θ_{min} rad	Q^2_{min} GeV ²	ν_{min} GeV	$(x_{\text{Bj}})_{\text{min}}$	y_{max}	W^2_{min} GeV ²	W^2_{max} GeV ²	$(p_{\text{had}})_{\text{min}}$ GeV
Cu, C	200	0.02	5	50	0.02	0.85	25	290	6
H ₂	280	0.014	5	70	0.02	0.85	25	290	6
H ₂	120	0.014	5	50	0.02	0.85	25	---	6

Table 4

The number of events within the cuts and the average values of W^2 , ν , Q^2 and x_{Bj} for data

Target	p_μ GeV	Events	$\langle W^2 \rangle$ GeV ²	$\langle \nu \rangle$ GeV	$\langle Q^2 \rangle$ GeV ²	$\langle x_{\text{Bj}} \rangle$
Cu	200	10417	188	112	21	0.11
C	200	13920	186	110	21	0.11
H ₂	280	9770	174	108	29	0.15
H ₂	120	8957	121	71	12	0.10

Table 5

The average values of W^2 , ν and Q^2 in x_{Bj} -bins

$x_{Bj} :$		0.02 - 0.1			0.1 - 0.2			> 0.2		
$\langle x_{Bj} \rangle :$		0.06			0.14			0.29		
Target	p_μ GeV	$\langle W^2 \rangle$ GeV ²	$\langle \nu \rangle$ GeV	$\langle Q^2 \rangle$ GeV ²	$\langle W^2 \rangle$ GeV ²	$\langle \nu \rangle$ GeV	$\langle Q^2 \rangle$ GeV ²	$\langle W^2 \rangle$ GeV ²	$\langle \nu \rangle$ GeV	$\langle Q^2 \rangle$ GeV ²
Cu	200	225	127	13	154	96	25	116	86	46
C	200	223	125	13	152	94	25	112	84	45
H ₂	280	223	127	15	160	100	27	121	91	52

Table 6

The average values of W^2 , x_{Bj} and Q^2 in ν -bins

ν (GeV):		50 - 70			70 - 90			> 90		
$\langle \nu \rangle$ (GeV):		60			80			128		
Target	p_μ GeV	$\langle W^2 \rangle$ GeV ²	$\langle x_{Bj} \rangle$	$\langle Q^2 \rangle$ GeV ²	$\langle W^2 \rangle$ GeV ²	$\langle x_{Bj} \rangle$	$\langle Q^2 \rangle$ GeV ²	$\langle W^2 \rangle$ GeV ²	$\langle x_{Bj} \rangle$	$\langle Q^2 \rangle$ GeV ²
Cu	200	91	0.20	23	127	0.16	23	221	0.09	20
C	200	91	0.20	22	127	0.16	23	220	0.09	20
H ₂	120	99	0.11	13						
H ₂	280				123	0.18	27	214	0.12	30

Table 7

Average multiplicity ratios for $z > 0.1$ in x_{Bj} - bins *)

x_{Bj} :	0.02 - 0.10	0.1 - 0.2	> 0.2
$\bar{R}_{Cu/C}(0.1)$	$1.15 \pm 0.03 \pm 0.05$	$1.06 \pm 0.03 \pm 0.03$	$0.99 \pm 0.04 \pm 0.03$

*) The errors are statistical and systematic respectively

Table 8

Average multiplicity ratios for $z > 0.1$ and $z > 0.5$ in ν - bins *)

$\nu(\text{GeV}):$	50 - 70	70 - 90	> 90	
Target $z_{\min}$	$\bar{R} (z_{\min})$			
Cu/C	0.1	$1.08 \pm 0.05 \pm 0.03$	$1.05 \pm 0.04 \pm 0.03$	$1.09 \pm 0.02 \pm 0.04$
	0.5	$0.78 \pm 0.13 \pm 0.05$	$1.27 \pm 0.20 \pm 0.10$	$1.04 \pm 0.12 \pm 0.14$
C/H ₂	0.1	$1.02 \pm 0.04 \pm 0.13$	$0.99 \pm 0.04 \pm 0.12$	$1.07 \pm 0.02 \pm 0.11$
	0.5	$1.07 \pm 0.13 \pm 0.17$	$0.77 \pm 0.12 \pm 0.11$	$1.16 \pm 0.12 \pm 0.20$
Cu/H ₂	0.1	$1.11 \pm 0.04 \pm 0.14$	$1.04 \pm 0.04 \pm 0.13$	$1.16 \pm 0.02 \pm 0.12$
	0.5	$0.84 \pm 0.12 \pm 0.14$	$0.97 \pm 0.14 \pm 0.13$	$1.20 \pm 0.12 \pm 0.20$

*) The errors are statistical and systematic respectively

Table 9

Predictions of the model of ref. /21/, using $\sigma_h = 20$ mb and the extreme cases of τ and σ_q compared to our experimental results on $\bar{R}$ (0.5) and the results from SLAC /13/

Model				This experiment ($\nu > 70$ GeV)		SLAC /13/ ($3 < \nu < 17$ GeV)	
τ fm	σ_q mb	$\bar{R}$ (0.5)		$\bar{R}$ (0.5) *)		$\bar{R}$ (0.5)	
		C/H ₂	Cu/H ₂	C/H ₂	Cu/H ₂	C/D ₂	Cu/D ₂
0	any value	0.76	0.52	$0.98 \pm 0.07^{+0.18}_{-0.16}$	$1.08 \pm 0.08^{+0.19}_{-0.16}$	0.82 ± 0.05	0.60 ± 0.08
any value	20	0.76	0.52				
$\gg r_{Cu}$	10	0.86	0.70				
$\gg r_{Cu}$	0	1	1				

*) The errors are statistical and systematic respectively

Table 10

The number of hadrons and the average values of the kinematical variables in the momentum range for $p/\bar{p}$ identification (50-80 GeV).

Target	Number of ($p+\bar{p}$)	Number of all hadrons	$\langle W^2 \rangle$ GeV ²	$\langle \nu \rangle$ GeV	$\langle Q^2 \rangle$ GeV ²	$\langle x_{Bj} \rangle$	$\langle z \rangle$
H ₂	145	973	204	122	26	.12	.54
D ₂	212	1732	209	127	29	.13	.51
C	33	286	199	119	25	.11	.53
Cu	35	330	201	120	25	.12	.52

Figure Captions

- Fig. 1 Plan view of the EMC spectrometer (NA2). BH are beam hodoscopes, V1-3 are veto hodoscopes, P0-3 are multiwire proportional chambers, W1-7 are drift chambers, H1, 3-4 are scintillator hodoscopes, H₂ is the calorimeter and C2 is the Cerenkov counter.
- Fig. 2 Reconstructed vertex distribution along the beam line for the events from carbon and copper target. The origin of the vertex position axis is at the centre of the spectrometer magnet.
- Fig. 3 Acceptance of the charged hadrons from copper as a function of z in different regions of x_{Bj} .
- Fig. 4 $N_{\mu}^{-1} dn/dz$, the charged hadron multiplicity distribution for all events from carbon and copper targets, as a function of z .
- Fig. 5 $N_{\mu}^{-1} dn/dp_T^2$, the charged hadron multiplicity distribution for all events from carbon and copper targets, as a function of hadron transverse momentum squared relative to the virtual gamma direction.
- Fig. 6 The ratio of the charged hadron multiplicity distribution from the copper target to the distribution from the carbon target, as a function of z , in different regions of x_{Bj} : a) $x_{Bj} = 0.02 - 0.10$; b) $x_{Bj} = 0.1 - 0.2$; c) $x_{Bj} > 0.2$. The solid lines are linear fits. The dashed-dotted lines are their one standard deviation contours including systematic errors.
- Fig. 7 The average of the hadron transverse momentum squared relative to the virtual gamma direction for the events from H₂, C and Cu targets in the region $p_T^2 < 4 \text{ GeV}^2$ as a function of a) x_{Bj} and b) the virtual gamma energy (ν).
- Fig. 8 The ratio of the charged hadron multiplicity distribution from the copper target to the distribution from the carbon target, as a function of z , in different regions of the virtual gamma energy (ν): a) $\nu = 50 - 70 \text{ GeV}$; b) $\nu = 70 - 90 \text{ GeV}$; c) $\nu > 90 \text{ GeV}$. The solid lines are linear fits. The dashed-dotted lines are their one standard deviation contours including systematic errors.

Fig. 9 The ratio of the charged hadron multiplicity distributions from copper and carbon targets to the distribution from the hydrogen target, as a function of z , in different intervals of the virtual gamma energy (ν): a) $\nu = 50 - 70$ GeV, b) $\nu = 70 - 90$ GeV, c) $\nu > 90$ GeV. The dashed-dotted lines indicate the size of the systematic errors on the data points. The hatched areas show the z -distributions of the SLAC data (/13/ and Table 1).

Fig. 10 Comparison of the ratio of the leading hadron ($z > 0.5$) multiplicity from Cu and C target to the multiplicity from the hydrogen target, as a function of the virtual gamma energy, to the prediction of ref. /21/. See text for detailed explanations. Only statistical errors are shown.

Fig. 11 The ratio of the number of the positive charge to the negative charge hadrons as a function of z for the events from H_2 , C and Cu targets.

Fig. 12 The percentage of forward protons and antiprotons among all charged hadrons of $50 < E_h < 80$ GeV as a function of the target mass number.

EMC FORWARD SPECTROMETER

FIG. 1

Fig. 2

Fig. 3

Fig.4

Fig. 5

Fig.6

Fig.7

Fig. 8

Fig.9

Fig. 10

Fig. 11

FIG. 12

Fig. 17