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NUCLEAR EFFECTS IN MUON SCATTERING*

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ABSTRACT

The results of measurements of structure functions in iron and deuterium by the European Muon Collaboration are presented. In addition some newer data on the measurements of hadrons produced in the interaction of muons with nuclei are discussed. The prospects for future measurements at CERN and Fermilab are outlined.

INTRODUCTION

The subject of deep inelastic scattering of muons has been discussed often[1] and a brief definition of terminology will suffice for this report.

Muon scattering occurs primarily through the exchange of a single virtual photon and the cross section within this approximation is given by

$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y-Mxy)\frac{F_2^A}{x} + y^2 F_1^A\right]$$

Q^2 and ν are respectively the mass squared and energy of the virtual photon, $y=\nu/E_{BEAM}$ is related to the center of mass scattering angle of the muon. $x\equiv Q^2/2M\nu$ is defined using the nucleon mass irrespective of the nature of the actual target. The hadronic physics is contained in the two unknown structure functions $F_{1,2}^A(x,Q^2)$. The relationship between F_2 and F_1 contains information on the spin of any scattering center.[2]

Within the quark parton model, the structure functions are considered to be the sum of the momentum distributions of the different quark species within the target, weighted by the charge squared which is the probability of coupling to the photon.

The quark parton model describes the general[2] features of the data rather well. The data scale, i.e., $F_2(x,Q^2) \rightarrow F_2(x)$ which is the basic[2] evidence for point-like constituents. The observed deviations[2] are consistent with QCD corrections. The data are consistent with the scattering centers being mainly spin 1/2 and the relation $F_2^{\mu Fe} \sim 5/18\, F_2^{\nu Fe}$, from the charges of the quarks, holds to better than $\sim$ 10%. In short, this model is an excellent description at moderate to high Q^2 of the data on nucleon structure functions. One should however note that a lot of data, especially neutrino scattering, were obtained with higher A targets, iron, marble, neon, etc. For nuclei there were two anticipated complications to this picture which were expected to manifest themselves in well-defined kinematic regions; the one, shadowing, at low Q^2, the second, Fermi motion, at very high x.

Shadowing is expected in many models[3] and is basically the manifestation by the photon of hadron-like properties leading to it interacting with the surface of the target rather than the volume. Experimentally the situation is unclear. Shadowing has been observed for $Q^2 \neq 0$ with difficulty at low energies[5] and with low statistics at high energies[6], but no systematic mapping in terms of Q^2 and x is available.

Fermi motion smearing of the measured structure functions was generally expected at high x. Many details of the models used for calculation are unclear, but there is general agreement that rather small effects for x < 0.6 with a rapid divergence at high x (see Fig. 1) were to be expected.

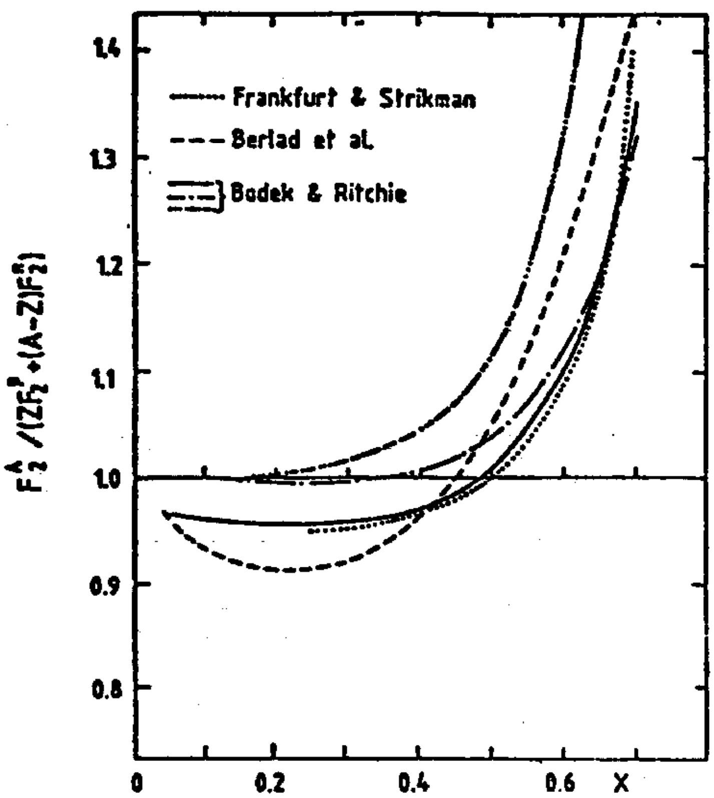

Fig. 1 The ratio of F_2^A for a nucleus and the sum of the F_2 for the component nucleons within a variety of Fermi Motion models. See Ref. 7.

The EMC performed structure function measurements with a range of incident beam energies and with hydrogen, deuterium, and iron targets. The data[7,2] as a function of x and Q^2, are shown in Fig. 2 for the deuterium and iron targets. At low x the iron data are systematically higher than the deuterium, at $x \sim 0.25$ they agree rather well, while at high x the iron data are low. Within the accuracy of the data, no Q^2 dependence is seen. Averaging over the common Q^2 range the ratio between the two data sets as a function of x is shown in Fig. 3. A quick glance shows immediately that the expectations expressed in Fig. 1 are not fulfilled. The shaded band in Fig. 3 indicates the systematic variation of the slope as a function of x permitted by the data. In addition there is a ±7% normalization uncertainty.

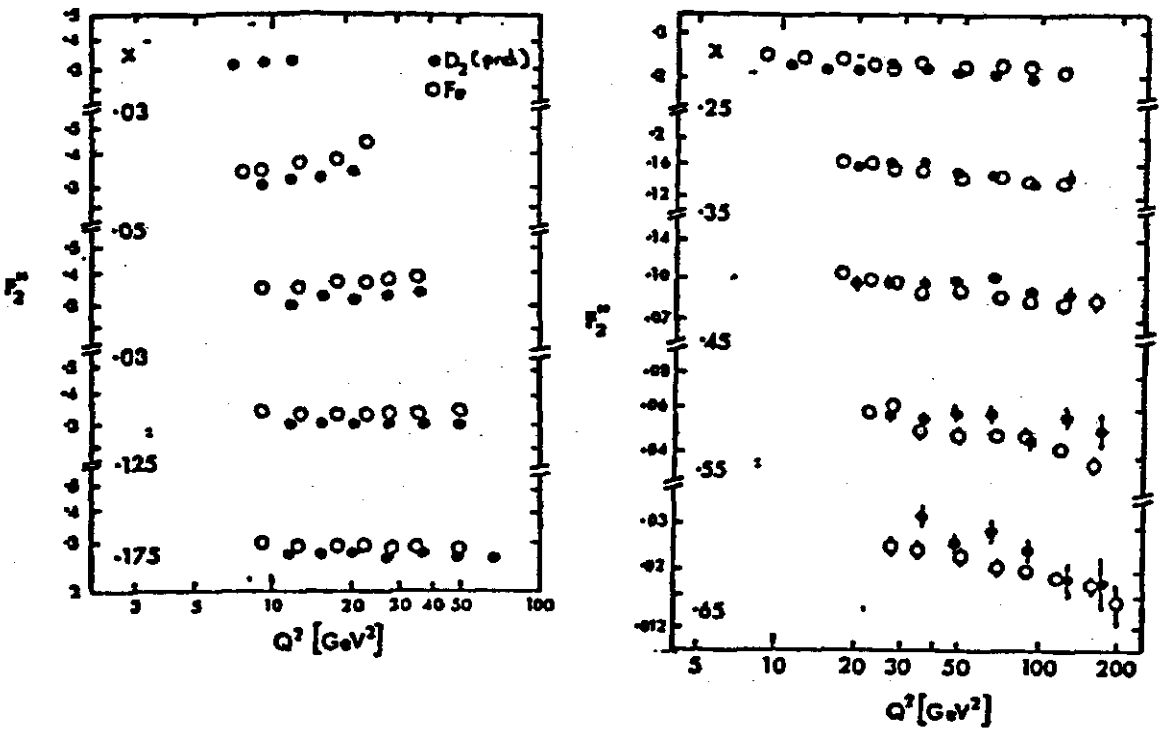

Fig. 2 F_2^A as measured in Iron and in Deuterium as a function of x and Q^2. See Ref. 2.

The theoretical interpetation of this data is wide ranging and is reviewed by West[8] at this conference. One can say however that the data represents evidence that a picture of the nucleus as an ensemble of separate free nucleon entities is not adequate.

Hadron production within the QPM requires the addition of further functions analogous to F_1 and F_2 which describe the fragmentation of the struck quark into the observed hadrons. Measurements on nuclei are therefore potential sources of information both on the initial target quark and antiquark distributions, and on the way the fragmentation process is perturbed by the interposition of nuclear matter.

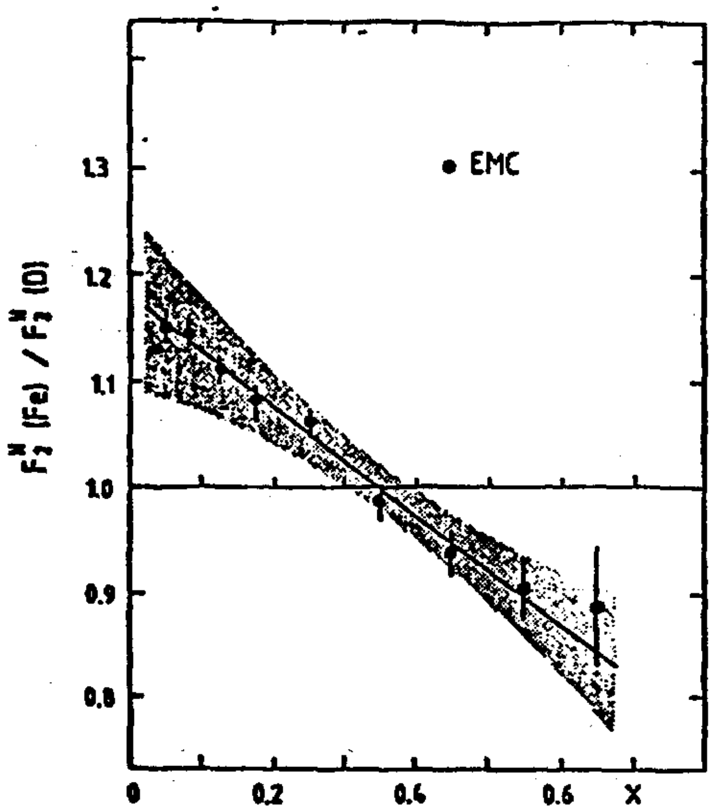

Fig. 3 The ratio of F_2^N as measured in iron with that measured in deuterium as a function of x, averaged over Q^2. See Ref. 7.

While there are several theoretical approaches to the fragmentation of the quarks, a concrete model which embodies, in a phenomenological way, some basic ideas is that of Białas.[9] In this model there are three stages: a) the struck quark propogates through the nuclear matter and interacts with a cross section σ_q^{eff}. (Many theorists expect this cross section to be small.) b) after some distance, the quark fragments into hadrons. (This distance could be zero, but another common prejudice would be that it is some finite fragmentation distance, a hadronic size Lorenz expanded in the lab frame when the quark has high momentum.); c) the produced hadrons, if formed inside the nucleus, interact with a typical 20 mb cross section. In general any interaction will lead to a degradation of the momentum ($z = E_{hadron}/\nu$) spectrum, a depletion at high z and possibly an accretion at low z. If $\sigma_q^{eff} = 0$ and the fragmentation distance is greater than the nuclear size, the spectra should be independent of the target. If the fragmentation distance is zero, the effects of $\sigma_{hadron} \sim 20$ mb will be observed. Conversely there exist other models[10] which predict an enhancement at high z.

Data[11] measured by EMC on copper and carbon are compared in Figs. 4 and 5. Neither the z distribution nor the p_T^2 (measured with respect to the virtual photon direction) show any marked differences. To proceed further it is necessary to compare with hydrogen data (for the sum of charged hadrons the data for hydrogen and deuterium are the same). The data have been integrated for $z > 0.5$, to look specifically for a depletion, and the ratio of copper to hydrogen and carbon to hydrogen constructed. The results are plotted as a function of ν in Fig. 6 along with some earlier, low ν, data from SLAC.[12] While the SLAC data show a clear depletion there is little depletion in the EMC data and none for $\nu > 90$ GeV. Within the Białas Model, this is evidence for a finite (> nuclear radius) fragmentation distance and an effective quark interaction cross section consistent with zero. Also indicated on Fig. 6 are the specific model lines which fitted the SLAC data and were therefore in some sense a prediction for the higher energy data.

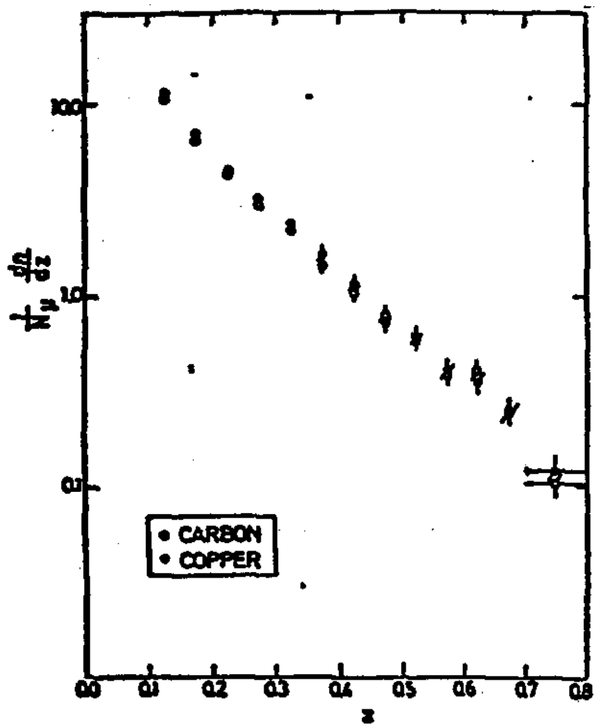

Fig. 4
z spectra per interaction measured using carbon and copper targets. Ref. 10.

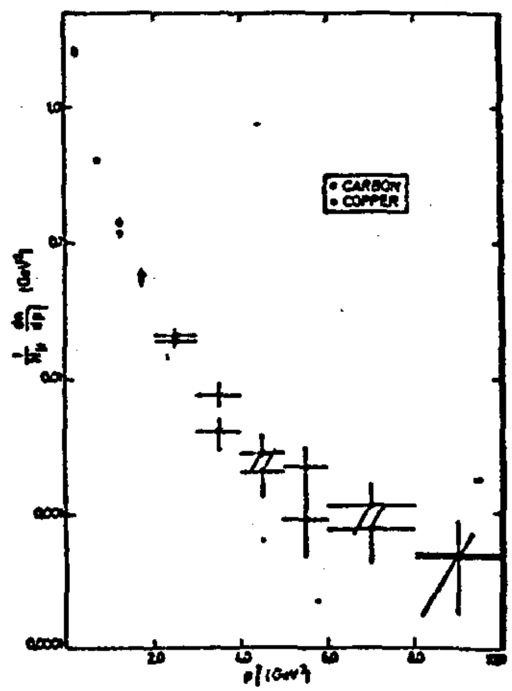

Fig. 5
p_T^2 spectra per interaction measured using carbon and copper targets. Ref. 10.

Given this evidence that the interposition of nuclear matter does little to perturb the fragmentation process, hadron production data can now be examined for clues to the origin of the structure function differences. One sensitive measure of the quark content is the ratio at high z of h^+/h^-. In hydrogen at $x \sim 0.1$, it approaches 2 as $z \to 1$ (in deuterium it is a little lower but still ~ 1.8) dominated by the 4/9 charge squared of the u quarks in the proton (and neutron). A reduction would be evidence for an increase of the charge symmetric sea quark content of the nucleon (nucleus).

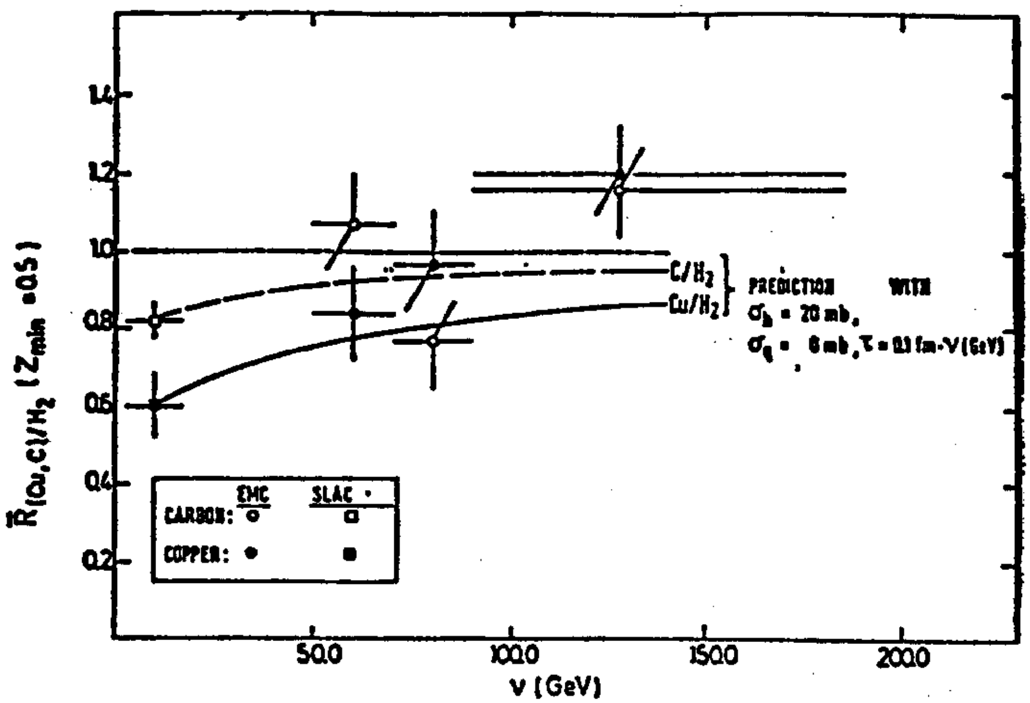

Fig. 6 Ratio of total yields of hadrons per interaction for z > 0.5 from carbon and copper targets with that for hydrogen. Data are from Refs. 10 and 11 and the curves from the model of Ref. 9.

This ratio as measured[12] is shown in Fig. 7. The data from the different targets are at the same value of x and Q^2. There is a hint that the copper is lower than the carbon at high z. Taken literally the change in the highest z point would represent a substantial increase in the sea since the ratio only gets to unity when the sea completely dominates; however, the errors on the data do not permit a concrete conclusion.

Finally there are measurements[13,14] of J/ψ production on both hydrogen and deuterium and on iron. The determination of the event kinematics is aided in the case of the iron data[13] by the hadronic energy measurement in the calorimetric target which was not available for the liquid target. The data have been analyzed in a uniform manner ignoring the target calorimeter information and the ratio of the cross section per nucleon for the process ($\mu N \to J/\psi x$) between iron and H_2/D_2 is found to be 1.45 ± 0.12 (stat) ± 0.20 (syst). This result is preliminary as yet; however, when $\sigma(\gamma N \to J/\psi x)|_{Q^2=0}$ is deduced from the data, good agreement is obtained with previous muon and photoproduction measurements. The relevance of the measurement to the structure function comes from the fact that J/ψ production is dependent on the direct $c\bar{c}$ or indirect $\gamma + G \to c\bar{c}$ charm contents of the nucleon.

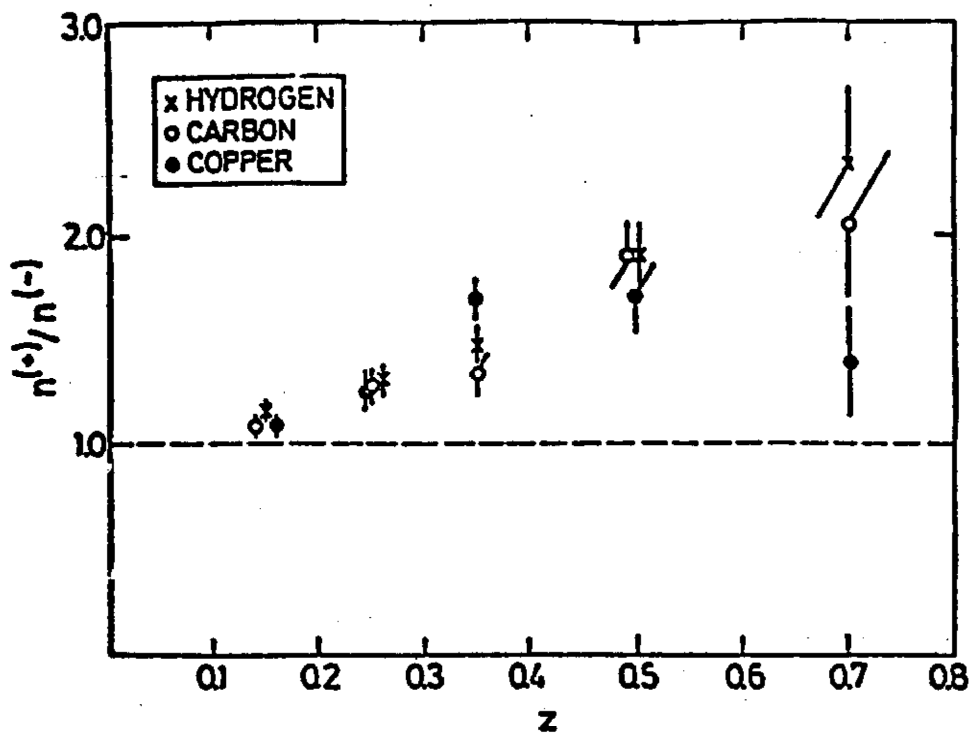

Fig. 7 Ratio h^+/h^- for forward produced hadrons as a function of z for hydrogen carbon and copper targets.

At CERN there are two measurements for which the data were taken in 1983. The BCDMS collaboration took data for $x \gtrsim 0.10$ and high Q^2 with deuterium, nitrogen and iron targets with at least two of the targets in place at a given time so as to reduce systematic effects. Results from this measurement are expected in the next few months. The EMC experiment has taken data at low x and low Q^2 ($\theta_\mu \gtrsim 2$ mr) to investigate the shadowing region and has about 100,000 events on each of four targets with widely different A values.

During 1984/85 EMC intends to perform systematic measurements of both the structure functions and the forward hadron production from nuclei. In addition there are attempts to form a new collaboration to carry these studies forward into 1986 and beyond.

At Fermilab the Tevatron muon beam ($E_\mu \lesssim 800$ GeV) will be commissioned in early 1985 and the E-665[15] experiment has, as a large part of its program, the study of hadron production from nuclear targets. A layout of the apparatus is shown in Fig. 8. The apparatus will be largely commissioned in parallel with the beam in spring 1985 in preparation for a full data run starting before summer 1986.

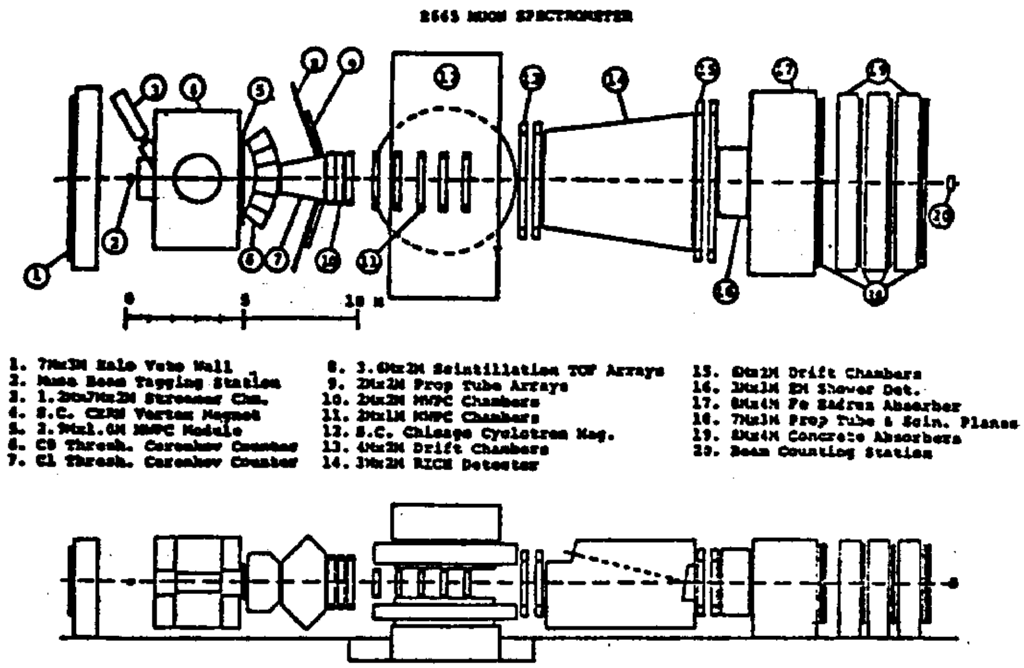

Fig. 8 Sketch of the apparatus being assembled for the E-665 Tevatron Muon Scattering Experiment at Fermilab. Ref. 13.

CONCLUSION

In conclusion we summarize the points made:

1. The structure functions per nucleon measured in deuterium and in iron are different.

2. Study of hadron production for nuclei reveals:

   i) The fragmentation distance at high energies is long with respect to nuclear size and the effective quark interaction cross section is small.

   ii) Study of more detailed aspects of the hadron production e.g., charge ratios and J/ψ production produce further suggestive indications for the change of the quark structure of nucleons in nuclei.

   iii) These studies are as yet rudimentary and deserve considerable improvement.

3. There is an approved series of experiments at both CERN and Fermilab which promises an improvement of the data in this field. It is probably true, however, that the extent of the interest in both nuclear and particle physics fields generated by the structure function results should generate an even more lively experimental program.

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