MASTER

HIGH ENERGY PHYSICS STUDIES OF PARTICLE
INTERACTIONS IN HEAVY ELEMENTS

Annual Progress Report

for the period

May 15, 1977 - May 14, 1978

Contract AT(45-1)-2225

Task Agreement No. 27

with

United States

Department of Energy

Prepared by

J. J. Lord, Principal Investigator

R. J. Wilkes, Research Associate

University of Washington
Seattle, Washington

March 22, 1978

PREPARED FOR THE DEPARTMENT OF ENERGY

EY-76-S-06-

UNDER CONTRACT NO. AT(45-1)-2225, Task Agreement No. 27

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

I.	Hadron-Nucleus Multiparticle Production	1
II.	Deep-Inelastic Muon Interactions	5
	References	8
	Table 1	9
	Figures	10
Appendix I:	Abstract of paper read at APS Meeting, 2/77	18
Appendix II:	Report on E382 event 21-2237	19
Appendix III:	Description of counter system for E382	24
Appendix IV:	Description of E382 event tagging	30
Appendix V:	Draft of paper giving results from E382	48
Appendix VI:	Abstract submitted to 1978 APS Spring Meeting.	81

1. HADRON-NUCLEUS MULTIPARTICLE PRODUCTION

PHYSICS MOTIVATION AND BACKGROUND

Theoretical interest in the interactions of high energy ($\gtrsim 50$ GeV) hadrons with nuclei has remained high for several years [1]. Data on elementary hadron-hadron collisions [2] has proven insufficient to answer a fundamental question: is the observed multiparticle final state produced directly, or is it the product of an intermediate excited state of hadronic matter produced in the initial collision? In elementary hadron-hadron (e.g., p-p) collisions, only the asymptotic final state is observed. In contrast, when an interaction occurs in a heavy nucleus, it is possible that downstream nucleons will interfere with any intermediate state produced, while if direct particle production occurs, intranuclear cascading must occur.

The current theoretical and experimental situation has been comprehensively reviewed by Otterlund [3], and we will limit ourselves to the following general comments:

- 1) Since hadron-nucleus multiplicities are greater than hadron-hadron multiplicities at equal energy, but less than those predicted by naive cascade models, some form of limited intranuclear cascading must occur.
- 2) The "extra" particles produced in nuclear collisions predominantly populate the lower part of the rapidity spectrum.
- 3) The number of heavy tracks N_h is in some way correlated with the number of intranuclear collisions of the projectile and/or its progeny.

Models of the Gottfried [4] type are the most promising candidates for explaining these phenomena, but considerable refinement is required before a true theory can be established.

EXPERIMENTAL TECHNIQUE

Our group has developed techniques for preparing nuclear emulsion plates containing microgranules of several heavy metals (^{52}Cr , ^{108}Ag , ^{184}W). We embed a layer of metal powder granules (typical diameter $\sim 20\mu$) in the middle of a 600μ thick emulsion plate (fig. 1). The granules provide a pure target material, yet are too small to cause significant extranuclear secondary interactions, or to affect the observation of secondary particles; moreover, scanning effort can be confined to a single plane in the emulsion plate. Details of the method have been published [5].

In addition, we have prepared plates containing embedded tungsten and chromium wires. Wire embedded plates provide a considerable increase in scanning speed over powder plates since the scanning procedure is essentially one-dimensional. Wires of 20 micron diameter are now readily available. The wires are wound over a frame employing threaded rods as winding guides. Glass plates pre-coated with a 300μ layer of emulsion are slipped into the frame and shimmed into contact with the wire planes. A second 300μ emulsion layer is then poured over the wires. The process is illustrated in fig. 2. The wire-wound plates are not as useful as the powder plates at the present time, however. Emulsion undergoes severe and non-uniform swelling and shrinkage during processing, and the wires apparently produce residual stresses resulting in severe local distortion in the vicinity of the wires. We are continuing to develop this technique.

The plates are poured, dried and wrapped in Seattle and then hand-carried to Chicago for exposure. During the flights to and from Chicago, care is taken to keep the plates oriented horizontally, so that the cosmic ray background tracks will be perpendicular to the accelerator beam tracks. Exposures are performed at Fermilab with the assistance of Dr. Lou Voyvodic and his staff.

Following exposure at Fermilab, the plates are brought back to Seattle, where they are developed in our darkroom and scanned. Our experimental technique permits the determination of:

- 1) n_s , the number of fast ($\beta > 0.7$) particles produced;
- 2) N_h , the number of heavily-ionizing particles;
- 3) the pseudorapidity distribution ($-\ln \tan [\theta_{lab}/2]$) for fast particles.

In addition, we would observe the decay of short-lived particles ($c \tau < 1000 \mu$) indicating the presence of charmed particles or heavy leptons.

RECENT PROGRESS

Over the past several years, we have performed a series of experiments designed to map out the main features of the multiparticle production process as a function of energy, projectile type, and target mass. Table I lists previous experiments in the series, their current status and results, as well as proposed experiments.

During the past year, our major thrust has been to complete the analysis of E387 (200 GeV pions on tungsten and chromium). As indicated in Table 1, this project is the thesis topic of Ms Phyllis M. Y. Lee, who has already presented preliminary results at the Chicago APS meeting (see Appendix I). Results on the multiplicity distributions are shown in figs. 3 -4, and fig. 5 gives the pseudorapidity distributions. As indicated in fig. 6, the correlation between n_s and N_h is not significantly target-dependent, and fig. 7 demonstrates that KNO scaling can be applied to nuclear interactions [5]. Finally, fig. 8 shows the relationship between R , the ratio of $\langle n_s \rangle$ in nuclear interactions to $\langle n_s \rangle$ in pion-proton interactions at equal energy, and $\bar{v}$, the mean number of intranuclear collisions (thus, a parameter describing nuclear size). The data quite clearly favor the functional relationship $R = \frac{1}{2} + \frac{1}{2} \bar{v}$.

Although Gottfried has proposed the form $R = \frac{2}{3} + \frac{1}{3} \bar{v}$, it has been suggested that the basic Gottfried-type picture of the intranuclear cascade process does not require these specific parameters. [3,4]

The results presented are preliminary, and we are now preparing a final report for publication.

II. DEEP INELASTIC MUON INTERACTIONS

INTRODUCTION

Since 1975, our group has participated in a hybrid counter/emulsion experiment studying deep inelastic muon scattering (Fermilab experiment E382), in collaboration with physicists from Cornell, Fermilab, Michigan State, and Krakow, Poland. The experiment was designed to search for charmed particle production, and to study multiparticle production processes in deep inelastic interactions. In December, 1975 24 emulsion stacks (totalling 5 liters of emulsion) were successfully exposed to the FNAL 150 GeV muon beam. A key feature of the experiment was the development of a method for precisely locating the emulsion stacks relative to the electronic detector system (drift chambers, magnetic spectrometer) which tagged the interacting muons [6]. The counter system and event trigger and selection criteria are discussed in Appendix III and details of the locating technique are given in Appendix IV, both of which are internal memos describing the hardware and procedures used.

PAST PROGRESS

Following exposure, all of the emulsions (approximately 2500 plates) were developed in our darkroom, and the processed plates were equally divided between the Seattle and Krakow emulsion groups for scanning. By mid-summer 1976, the procedures for locating event vertexes in emulsion from drift chamber data had been worked out and were operating smoothly. After various geometric, Q^2 , and data quality cuts were applied to the raw electronic data, we obtained a list of ~ 260 events, all of which have been searched for at least once. Of these, 96 tagged events have been located and analyzed. For each event found, we perform two separate analysis procedures:

- 1) charm search:

- a) each charged track is followed for 3 mm (or until it leaves the emulsion plate,) and any kinks or secondary vertices (potential decay points) are recorded
 - b) a search for V^0 's is conducted within a cone-shaped volume of emulsion of half-angle 30° and length 1 mm.
- 2) multiparticle production analysis: the analysis methods used in our work in hadronic interactions are applied; for each event, the multiplicities n_s , N_h (see sec. I) are determined, and the production angles of the minimum-ionizing particles are measured.

The Krakow group has followed identical procedures on half the data sample. When each group completed the analysis of its allotment, the emulsion plates were exchanged for cross-checking.

As noted above, we have located 96 events of the 260 defined by the electronics data. At present there is some feeling that the electronics may have produced spurious events; we find it difficult to believe that our event-locating efficiency is much less than 80% based on past experience. The 96 events found have been measured and the multiplicities have been recorded. We have prepared a paper on the multiparticle production aspects of the data and a meeting was held in December 1977 with our Polish collaborators in order to finalize the draft version. Publication will occur shortly. The draft is attached as Appendix V.

The charm-search work has been partially completed. Charged-track following can be done relatively quickly (one scanner-day per event) and has been finished for all found events. The search for neutral vees is much more time-consuming (one to two scanner-weeks per event) and has been completed for only a few events. Thus far, in all events but one, all the kinks and V^0 's observed can be attributed to

conventional processes (elastic scattering of low-energy secondaries, gamma conversions). Event 21-2237 appears to exhibit a kink, a vee and a direct electron! The event has been subjected to exhaustive analysis, including ionization and multiple-scattering measurements on all charged tracks; a complete report is attached as Appendix II. At present we are not prepared to present a definitive explanation of this event. An abstract has been submitted to the Washington APS Meeting (Appendix VI), at which time we expect to describe the results of the charm-search aspects of E382.

REFERENCES

1. L. Bertocchi, "Multiparticle Production on Nuclei - Theory", High Energy Physics and Nuclear Structure:1975, p. 238, AIP, New York, 1975
2. G. Giacomelli, "Inelastic Reactions at Very High Energies", Fermilab Report NAL-Pub-73/73-EXP (1974)
3. I. Otterlund, "Inclusive Production in Emulsion with Accelerator Beams," invited talk at Topical Meeting on Multiparticle Production at Very High Energy, Trieste, June, 1976 (University of Lund preprint LUIP-CR-76-07)
4. K. Gottfried, Phys. Rev. Lett. 32, 957 (1974)
5. J. Florian, et al, Phys. Rev. D13, 558 (1976)
6. R. J. Wilkes, et al, Bull.APS 21,631 (1976)

TABLE I: STATUS AND RESULTS OF PREVIOUS EXPERIMENTS IN THIS SERIES

<u>Experiment/Spokesman</u>	<u>beam</u>	<u>status</u>	<u>publications & theses</u>
E-171 / Lord	200 GeV p	completed	Florian, et al, Vanderbilt Conf. (1973) p. 126 J.R. Florian, PhD thesis, U. of Wash. (1974)
E-237 / Lord	300 GeV p	completed	Florian, et al, Phys. Rev. D <u>13</u> , 558 (1976)
E-387 / Wilkes	200 GeV π^-	preliminary results available	M.Y.Lee, et al, Bull. APS <u>21</u> #1 M.Y.Lee, PhD thesis, U. of Wash. (March, 1978)
E-471 / Lord	400 GeV p	analysis in progress	- - -
E-524 / Wilkes	500 GeV p	approved, to be scheduled	
E-525 / Wilkes	360 GeV π^-	Analysis in progress	- - -

NUCLEAR EMULSION PLATES
WITH EMBEDDED METAL GRANULES

FIGURE 1

PREPARATION OF EMBEDDED-WIRE EMULSION
PLATES (two prepared at a time)

Another 300 micron thick emulsion layer is coated on top of the wires. After drying the wires are cut at the edges and the plates removed from the frame.

Plates are exposed a slight angle with the beam direction so that particles produced in one wire will not strike an adjacent wire.

FIGURE 2

Fig. 3

Fig. 4

W: 54 events, 819 tracks.

CR: normalized to 54 events for comparison.

Average pseudo-rapidity: $W=2.886 \pm 0.052$

$CR=3.193 \pm 0.062$

Fig. 5

Line 1: linear square fit for π -Em data $\langle n_s \rangle = 8.24 + 0.51(N_h)$

Line 2: Same for π -W data. $\langle n_s \rangle = 10.01 + 0.41(N_h)$

Fig. 6

$$Z = n / \langle n \rangle$$

$$X(n) = \langle n \rangle \cdot \sigma(n)^{\text{inel}} / \sigma^{\text{inel}}$$

Curve: least square fit of Slattery type function for π -W data.

$$X(z) = (.842z + 26.13z^3 - 6.323z^5 + .445z^7) \exp(-3.276z)$$

Fig.. 7

(ν, R): CR = (1.99, 1.51 ± 0.08), W = (2.73, 1.89 ± 0.13)

Fig. 8

for the Annual Meeting of the
American Physical Society
Chicago, IL

February 7-10, 1977

Physics and Astronomy

Classification scheme

Number: 13.80Hm

Bulletin Subject Heading

in which Paper should be

placed: Strong Interactions
at High Energy

Interactions of 200 GeV Pions with
Chromium and Tungsten.* M.Y.LEE, J.R.FLORIAN,
J.J. LORD, J.W. MARTIN, R.J. WILKES, Univ. of
Washington, R.E.GIBBS, Eastern Wash. St. Univ.,
L.D. KIRKPATRICK, Montana St. Univ. -- Nuclear
emulsion plates containing embedded micro-
granules of ^{52}Cr and ^{184}W were exposed to
200 GeV/c π^- at Fermilab and processed in
Seattle. The plates were area-scanned for
inelastic interactions, and for each event
found, the number of "shower" tracks ($\beta > 0.7$) n_s ,
the number of "heavy" tracks ($\beta < 0.7$) N_h , and
the production angles θ_{lab} of the shower tracks
were determined. Preliminary values for $\langle n_s \rangle$,
 $\langle N_h \rangle$, and $\langle r \rangle \equiv \langle \ln \tan(\theta_{\text{lab}}/2) \rangle$ will be pre-
sented. The nuclear multiplicity ratio
 $R_A \equiv \langle n_s \rangle_{\pi A} / \langle n_s \rangle_{\pi p}$ appears to fit the expression
 $R_A = \frac{1}{2} + \frac{1}{2} \bar{v}$ where $\bar{v}$ is the mean number of intra-
nuclear collisions.

*Research supported by USERDA.

†Submitted by J. J. Lord.

Submitted by

J. J. Lord
Dept. of Physics, FM-15
Seattle, WA 98195.

MEMO TO: E382 collaborators
 FROM: Seattle emulsion group
 SUBJECT: Summary of data on event 21-2237
 23 February, 1977

Data from electronics

$$p' = 109.63 \text{ GeV}/c$$

$$|Q^2| = 2.2897 \text{ (from Litt memo)}$$

$$= 2pp'(1-\cos\theta) = 2.93 \text{ GeV}^2 \text{ (using } \theta \text{ measured in emulsion)}$$

$$v = E - E' = 40.37 \text{ GeV}$$

$$W_{\text{had}} = (M_p^2 + 2M_p v - |Q^2|)^{1/2} = 5.98 \text{ GeV}$$

Note: χ^2 per degree of freedom for muon spectrometer fit was 8.9; thus p' and Q^2 values may be unreliable.

Event Location and tagging

predicted location: plate 21-42, $x_{\text{plate}} = 178$ microns

$$y_{\text{grid}} = 59.64$$

Found at:

plate 21-42, $x_{\text{plate}} = 37$ microns

$$y_{\text{grid}} = 59.22$$

$$z_{\text{grid}} = 41.53$$

Offsets: $\Delta x = -.021$ mm (note: offsets are calculated

$\Delta y = .889$ mm relative to front-face entry point)

Average offsets for stack 21: $\overline{\Delta x} = .403 \pm .106$

$$\overline{\Delta y} = .329 \pm .171$$

Predicted muon slopes: $\theta_x = -0.4$ mrad

$$\theta_y = 12.9 \text{ mrad}$$

Slopes for track closest to predicted direction (track 5)

$$\theta_x = -3.1 \text{ mrad}$$

$$\theta_y = 14.1 \text{ mrad}$$

Emulsion data

1. Coordinates of each grain within a few hundred microns of the vertex were measured. Attached drawings were made from these measurements.
2. Multiple scattering measurements were made on each track, along with grain counts for dE/dx .

3. Tracks were parameterized by fitting straight lines to grain measurements. Each point was weighted according to its probable multiple scattering deviation, as determined by step (2).

Results of the procedures described are given in the attached table.

Least-counts on the Koristka microscope are:

x = 0.07 microns

y = 1.0 micron (beam direction)

z = 2.3 microns (vertical)

TRACK	I.D.	grains/100μ	β	pβ, MeV	m, MeV	SPACE ANGLES		SLOPES		INTERCEPTS	
						θ°	φ°	Tanθx	Tanθy	x(Z=0)	y(Z=0)
PRIMARY	μ	18.94±.45	-	-	-						
1	p	20.1±.6	.783 ^{+.020} _{-.018}	980±200	980 ⁺²¹⁶ ₋₂₁₈	24.38	11.5	.444	.0909	.0164±.054	-.941±.052
2	-	20.6±.9	.771 ^{+.026} _{-.022}	491±123	526 ⁺¹⁴² ₋₁₄₄	12.73	313	.155	-.1644	-.0519±.0431	.588±.043
3	-	24.0±5.5	.702 ⁺ _{-.080}	[TOO LITTLE TRACK LENGTH]		2.55	307	.0268	-.0356	.1460±.0804	-1.92±.080
31	e	16.4±1.5	.993 ^{+.007} _{-.033}	32±11	3.8 ⁺⁶ _{-3.3}	6.50	215	-.0934	-.0653	13.49±1.768	3.01±1.768
4	e	18.4±1.0	.9999 ⁺ _{-.2}	38.9±9.7	0.46 ^{+32.7} _{-?}	1.96	75°	.0089	.0331	-.2373±.4772	-.383±.477
5	(SCATTERED MUON)		-	-	-	0.83	257	-.0031	-.0141	.0167±.0326	.575±.0326
6	-	15.3±1.4	.960 ^{+.036} _{-.071}	508±170	154 ⁺¹⁴⁹ ₋₁₁₇	4.93	251	-.0274	-.0818	.2388±.0514	-.0029±.0514
7	-	18.5±0.9	.99996	2.75 ⁺ _{-.76}	25 ⁺ _{-?}	5.53	194	-.0983	-.0238	.4455±.0322	-.0443±.0322
71	e	17.9±4.2	.845 ⁺ _{-.107}	0.59±.26	.44 ^{+.35} _{-?}	68.39	103	-.5696	2.460	12.61±17.72	74.91±17.72
8	p, π	136.0±5.0	.257 ^{+.007} _{-.006}	81±16	1180±240						
10	p	202.3±10.6	.204±.007	50.0 ± 15.	1190±370						

EVENT 21-2237, Y VS X (EXPANDED Y SCALE)

Fermilab Dec. 12, 77

Electronic Trigger and Event Location

The layout of the electronic detector is shown in Fig. 1. Since the purpose of the electronics in this experiment was only to identify and locate events in the emulsion which had a high probability of containing unusual features, the basic trigger was kept very simple. An event was recorded for further analysis when it gave a coincidence of the beam defining counters, C1, C2, C3 and C4, with two of the scattered muon detectors, SA and SB. It could be vetoed by the presence of a halo particle in the HV counter, or an undeflected muon in the beam veto counters BV_I and BV_{II}. Rejection of events outside the emulsion was done only in the off line analysis to avoid any instrumental bias which might deplete the sample of good, high Q^2 , events.

The location of the incoming muon was found by means of 8 proportional wire chamber planes and 6 drift chamber planes. The proportional wire planes had 2 mm spacing and were arranged as two sets of triplets near the target and an x-y doublet for upstream of the target. Details of their construction and operation are given elsewhere. Reference appropriate E26 paper. The drift chambers each consisted of four wires with 1/2 in. wire-to-wire spacing, that is 1/4 in. drift space on each side of a wire. The chambers were continuously flushed with an Argon-Ethane gas mixture, chosen for its rapid saturation of drift velocity and consequent insensitivity to small variations in the electric field. The uniformity of the field across the drift space was aided by the addition of 10 field shaping wires. The arrangement of these wires is shown in Figure (X).

Fig. (X)

The pulses from each wire were amplified and discriminated by electronics of FNAL design mounted on the chamber inside the aluminum chamber housing to avoid noise problems. During the run these chambers were found to have quite noise-free and reliable signals.

C. Kramlich

The discriminated signals from the sense wires were used as STOP pulses in a set of EG & G 8 channel time-to-digital-converters which were given a common START by the event trigger. At least count in these digitizers corresponded to a displacement of about 5 μ m, so that their contribution to the resolution was negligible. The number of counts recorded for that TDC channel was thus directly proportional to the distance, d , of the particle from that sense wire, under the assumption of a constant drift velocity (discussed below).

$$d = v_d (t - t_0)$$

where v_d is the drift velocity.

The parameters, then, which had to be determined for each wire (channel) were the base time, t_0 , and the drift velocity. Furthermore, the alignment of the chambers with each other had to be determined to within $\sim 50\mu$ m (= .002 in.) by using fitted beam tracks as that was beyond the accuracy of our survey. In order to get the base times for each wire, we measured the signal delay in each amplifier and discriminator and in the cable to the TDC. The time of flight between chambers was also taken into account. The counting rate was measured for each channel by generating START and STOP pulses from a pulser and varying the STOP delay by a known number of nanoseconds. When all these effects were taken into account, we should have been left with only one overall base time for all channels, which would be determined by the delay in the trigger circuitry. We quickly found in the analysis that this was not the case. We were led to the conclusion that there were significant (several nanoseconds) differences between channels in the TDC's in the times it took for STOP signals to register. These times had to be fitted from the data also.

Each of the 6 chambers received its high voltage from a separate supply, for which we used FNAL design miniature supplies. There were small differences in the field in each chamber due to both the difference in supplies and the differences in loading resistors. Thus, there could be small differences between the chambers in drift velocity. However, the 4 wires within a chamber would have to be the same. We found this to be, in fact, the case with a typical value of $1/v_d = 188$ ns/cm.

These 6 chambers were arranged with chambers 7, 9, and 11 reading out a y coordinate of the particle and 8, 10, and 12 reading x. The outside two, e.g., 7 and 11, we set with their sense wires at, very nearly, a common lateral displacement, (x), and the center chamber was displaced 1/4 in. with respect to them. For the normal case of all chambers giving a clean signal we had 6 coordinate readings in each projection for a beam track, 3 from the PWC's and 3 from the drift chambers. The very long lever arm of the far upstream PWC's meant that our best information on the track angle came from them, in spite of the much better resolution of the drift chambers. Our drift chambers were of a pioneering design and so had no internal hardware capability of telling on which side of the sense wire the particle passed. This "left-right ambiguity" was resolved by the PWC trajectory except in those cases where the hit was so close to a wire that both solutions were acceptable. In those events a minimum χ^2 line was fitted through all available points. The member of the ambiguous pair farthest from this line was thrown out, and a new line fitted through the surviving hits.

Several techniques were used to obtain the alignment constants and the 30 parameters needed for the drift chambers. The two PWC triplets were taken as the basis of the coordinate system and all other alignments found with respect to them. One of the more useful techniques was to make a "K plot" for each wire of the drift chambers, where the displacement of the wire from a PWC particle trajectory is plotted against the time registered for that particle. This yielded a good number for the alignment and the drift velocity for that chamber. However, because of the poor resolution of the PWC's there was a large scatter of points on the plots and the determination of t_0 for each wire was not adequate by this method. To refine these numbers we used an iterative process, where the particles position at the center drift chamber was calculated from a line between the hits in the two outside chambers, x_c and subtracted from the hit position in that wire, x_m . An incorrect t_0 will cause a bi-modal distribution in a histogram of $(x_m - x_c)$. The base times were varied to minimize the width of this distribution. Such an approach is possible of course, only because of the staggering of the chamber wires. Even so the problem is not mathematically completely determined and the technique is useful only for refinement of base times that are known approximately.

A study of the characteristics of the bimodal distributions indicated that the individual drift chambers should have been capable of resolutions of about 80-100 μm . However, largely because of the unanticipated difficulties with the parameters of the chambers, we only achieved an over all resolution for the system of about 170 microns. In the process of studying the resolution of the chambers we investigated possible non-linear effects in the drift time. In particular, we took the hypothesis of a constant mean free path and developed a simple, first order, formula for non-constant drift velocity. We found that such effects were completely unobservable in our data.

The method used to link the chamber coordinate system to the emulsion coordinate system is discussed in detail below.

EVENT IDENTIFICATION

99% of the triggers in this experiment resulted from interactions in the 2 m iron muon shield. The problem for the electronic analysis was to identify that 1% which occurred in the emulsion, to tell the emulsion scanners where to find them, and give the scanners enough identifying characteristics that when they located an event, they could tell it from one of the plentiful background of very low Q^2 events and hadronic events.

The first step was to reconstruct the tracks in the four sets of spark chamber planes immediately downstream of the muon shield. Each set of planes consisted of x, y, u and v planes (u and v at 45° to x and y) and was thus capable of distinguishing 3 dimensional tracks. The track finding procedure was to search for the best track in these sets of chambers (a maximum of 16 sparks), remove all sparks on that track from the sample, and reinitiate the search. The fitting continued until the minimum criterion of 7 sparks per track could no longer be satisfied.

Because of the long memory time of the spark chambers, they could hold tracks from old events or old halo tracks; we therefore could not ask that the spectrometer hold only muon track. Each track found had to be tested to see whether it was a muon from the emulsion target. Our definition of an event muon was that it project back to within 4.0 cm of the beam track at the target center and have a deflection greater than 6.5 mr. This made a generous

allowance for multiple scattering in the iron and passed a few events from shield.

The second step was to reconstruct all possible tracks in the downstream proportional chamber-drift chamber system. The 6 downstream drift chambers were 24-wire planes with 2 cm wire spacing. Their signals were read by LeCroy 2770 multi-time digitizer, for which each wire signal was a START and the event trigger was a STOP. This avoided the problems of having to delay a large number of signals for a long time, but made these susceptible to noise problems from after-pulses. These were solved by mounting single shot discriminators on the chambers. The operating parameters for these chambers were found by similar methods to those for the upstream chambers.

However, two fundamental limitations of drift chambers became significant for these because of the high multiplicities of particles. If two particles traversed the same cell, only the one closer to the wire would be recorded. Also occasionally a particle would produce a δ -ray which headed toward the sense wire and gave a false reading. The track fitting had to contend therefore with both missing points and false points.

A track in the downstream system was defined as having at least 3 of the 5 possible points, in any one view. It was not usually possible to correlate tracks between views. Two point tracks were allowed only where the angle was so large as to preclude finding more than 2 points. All tracks had to project to within 1 mm of the incident track at the center of the target. Even so, it was not possible to completely eliminate false tracks and so points were not eliminated from the sample for further track fitting as they were for the spark chambers. In particular, the left-right ambiguity of the sense wires usually caused wide angle tracks with only 2 hits and, therefore, 4 hit images to produce more than one line which satisfied the selection criteria. When a complete set of possible tracks was obtained, shared hits, if any, were deleted from the track with the worse χ^2 and the affected track refitted. Our initial hope in this process was to produce reliable z coordinates for the vertices. However, it soon became evident that the probability was so high for the production of secondary vertices that our z calculation could not be counted on and a different procedure was devised.

We could then generate a preliminary scan list of likely events. An event was selected for inclusion in the list of it

1. Had a good beam track

AND

2. Had an acceptable scattered muon in the spectrometer.

OR

Had 2 or more tracks reconstructed in at least one view of the downstream PC-Dc system.

This cut out initial sample of about 10^5 triggers to about 1200. Each of these selected events was then looked at with a program which would display a reconstruction of the event on a 4010 graphics terminal. One selected the x or y view and it drew the emulsion, each chamber with the hits in that chamber, the reconstructed muon, if any, and all tracks found in the PC-DC system. It could also enlarge any section of the event, which allowed one to take a close look at reconstructed lines at the emulsion position and decide on a z position. Every event in the sample was scrutinized by a physicist who passed on its potential interest.

This process quickly revealed the large number of events which were caused by 1) the passage of a halo particle which escaped the veto, 2) an event in the iron which gave a track that happened to point to the emulsion on 3) a $Q^2 \times 0$ event in the emulsion which had one, essentially undeflected muon track and one very wide angle track. This cut the sample of events to be searched for to about 150. A list of these remaining events with their coordinates and hard copies of their computer reconstructions were forwarded to the scanners. Several of the event pictures are shown as figures (-).

TO: E382

FROM: Seattle Emulsion Group

RE: Description of event tagging technique,
draft of possible Nucl. Instr. or Rev. Sci. Instr. paper

Theoretical studies have predicted that charmed hadrons might have a lifetime just below the detection limit for bubble chambers, but within range of nuclear emulsion techniques.¹ The observation of possible anomalies in deep inelastic muon scattering² provided the motivation for construction of the apparatus described here. The experiment (designated E382 by Fermilab) was similar in design to the previously completed experiment (Cornell-Fermilab-Michigan State, E26) which had produced the anomalous muon scattering results.³ A system of counters, spark chambers and magnets is used to detect and momentum-analyze scattered muons, and the emulsion target provides an intimate view of the interaction vertex (fig. 1). The resolution of emulsion is sufficient to detect separations of 0.5 μm in individual events.

The main difficulty in the emulsion technique is the problem of locating events in a reasonable amount of scanning time. The problem is especially acute when the process of interest has a long mean free path, as in deep-inelastic muon scattering. The idea of using counter techniques to select and locate events in emulsion is not new, and several experiments using hybrid emulsion/spark chamber systems have been described in the literature.⁴ However the relatively coarse spatial resolution of conventional chambers ($\sim \pm 0.5$ mm) coupled with the difficulty of accurately locating an emulsion

stack with respect to the spark chamber coordinate system, has prevented the full power of the hybrid approach from being reached. Drift chambers⁵ provide nearly an order of magnitude increase in resolution ($\pm 50 \mu\text{m}$), and the system described here represents, to our knowledge, the first application of drift-chamber technology in a hybrid emulsion experiment. This paper will discuss only the emulsion aspects of the experiment; the electronic system will be described elsewhere.⁶

Preparation and Exposure of Emulsion Stacks

Ilford K5 emulsion was purchased in pre-cut pellicles measuring (nominally) $7.5 \times 5.0 \times 0.06 \text{ cm}$. Stacks were assembled from 85 - 100 pellicles to produce a block of solid emulsion $7.5 \times 5.0 \times \sim 7.0 \text{ cm}$. Twenty-six stacks were prepared, for a total of about 6.5 litres of emulsion. Two of the stacks were made from an older batch of Ilford G5 pellicles. Background exposure before the experimental run totalled approximately 6 mo. at sea level and about 12 hr at jet altitude.

The emulsion clamp (fig. 2) consisted of two aluminum bars fastened with four $3/8"$ D stainless steel threaded rods. Lucite spacers kept the emulsion from contacting aluminum, with which it would react chemically. The aluminum bars were machined to close tolerances, and the lower bars were selected to be identical to within $\pm 0.001"$ ($25 \mu\text{m}$) in all dimensions.

The stacks were assembled and tightly clamped in a dark-room, after which they could be safely handled in ambient

light, since only the outer edges of each pellicle are exposed. The stacks were then taken to the Fermilab machine shop, where the front and left side face of the emulsion were milled flat and parallel to the corresponding faces of the lower aluminum clamp bar. The machinist measured and recorded the locations of four points on each machined face with respect to the aluminum reference surfaces, as well as the thickness of the stack at each corner. Finally, a scribe mark was made across the front face of the emulsion at an angle of 50° above horizontal (see fig. 3).

During exposure, the stacks were mounted on an aluminum stand bearing three locating pins (fig. 4) to contact the lower clamp bar of each stack. Tests showed that the stacks could be removed and replaced with an error of less than 0.002" (50 μm). The pellicles were oriented with their 5 cm dimension in the beam direction, and each stack was used until a track density of $3-5 \times 10^5$ muons/cm² was accumulated. Immediately following exposure, the stack measurements made after emulsion machining were repeated, to detect possible changes caused by emulsion responding to environmental factors. Differences were negligible in most cases. The stacks were then unclamped and sent to Seattle for processing. Due to the high (≈ 200 lb/in²) clamping pressure used, the pellicles tended to stick together in a solid block, even after the clamping members were removed.

Processing.

Pellicles are normally mounted on a supporting glass plate and contact-printed with a reference grid before development. The grid-printing apparatus used is shown in fig. 5. A small lamp provides an effective point source approximately 1 m. from the printing surface, whose intensity and duration are controlled by an autotransformer and timer switch respectively. A lucite top plate equipped with guide bars and a grid negative complete the setup. The grid negative, a portion of which is shown in fig. 6, was kindly supplied by Prof. H. Heckman of LBL. The machined surfaces of an emulsion stack were pressed against the guide bars, the bottom pellicle was gridded, peeled off the stack and mounted, and the process repeated. Each pellicle was numbered with a sharp pencil, which left pressure marks that would come out in development. Thus each pellicle's grid was applied before any mechanical distortions could be introduced by the rather rough peeling and mounting procedure.

Pellicles were mounted on specially-treated glass obtained from Ilford, using a mounting solution containing 5 ml glycerine, 15 g gelatin, and 0.5 ml photographic wetting agent per liter of water. (The solution is mixed with boiling water, filtered and cooled to room temperature before using). The pellicle and glass are immersed in the mounting solution, and when the pellicle is felt to grip the glass the plate is removed, covered with a thin sheet of Teflon, and rolled with a heavy rubber photographer's roller. The glass plates were also

numbered, using a diamond-point pencil. A crew of four could mount pellicles at the rate of ~ 90 sec/plate for short periods.

After some testing, it was felt that the best development was obtained by using a variant of the Bristol formula given by Prof. Barkas⁷; typical grain densities for minimum-ionizing tracks were $\sim 20/100$ μm . Following development by the two-temperature method, the plates were fixed for 80-100 hr at 5°C , washed an equal length of time, and soaked in a solution of 5% glycerine in ethanol before drying.

Event Selection, Location and scanning

The 150 GeV muon beam was parallel to better than ± 2 mrad, and contained less than 1% hadron contamination. The beam diameter was larger than the target size; upstream counters defined an effective beam area. Trigger criteria selected events with a single incoming muon scattered in the emulsion into the active area of the magnetic spectrometer with no accompanying beam or halo particles. Post-processing determined the momentum change of the muon, and the experiment yielded ~ 250 deep inelastic ($Q^2 \geq 1 \text{ GeV}^2/c^2$) events out of

triggers. The stacks were equally divided between the two emulsion groups (Krakow and Seattle) for scanning.

The upstream drift chambers provided an accurate ($\sim 80 \mu\text{m}$) estimate of the location at which the beam track initiating an interaction entered the front face of the emulsion stack. Since the vertexing information provided by the downstream chambers gave a less accurate estimate of the event location,

it was decided to use the beam track coordinates to define the transverse location of the event, and the downstream data to indicate the approximate location in the beam direction. Due to the shallow production angles characteristic of high energy interactions, the vertexing problem was inherently ill-conditioned, and in many cases it was necessary to scan the entire length (5 cm) of the plate; however with sufficient transverse accuracy, the scanning volume was still managably small. (see fig. 7)

Drift chamber data provided the x and y coordinates ($\hat{z}$ = beam direction, $\hat{x}$ = vertical, $\hat{y}$ = horizontal) of the beam particle entry point with respect to the chamber-survey coordinate origin, which had a fixed relationship to the lower front corner of all stack clamps. Individual stack measurements (made in the machine shop and repeated after exposure) allowed us to determine the y-coordinate of the machined edge of each pellicle. As noted above, each pellicle was contact-printed with a grid of numbered 1 mm x 1 mm squares. Distortions in the grid negative were measured and parameterized, so that one could compute the true distances of each grid line from the grid edge. The grid edge did not necessarily coincide with the pellicle edge, due to placement error during grid printing, but these offsets could be determined by measuring the actual distance from the edge to the first grid line.

Thus positions relative to grid lines could be converted into absolute distances from machined pellicle edges (and thence into the drift chamber coordinate frame) and vice-versa. The distance between the scribe mark notch at the emulsion-glass interface (which was clearly visible on the front edges of the processed plates) and the machined edge was measured on each pellicle; this gave the x-coordinate (height) of the bottom surface of the pellicle. The use of the scribe-mark notch to determine the actual vertical position of each pellicle was crucial, since pellicle thickness varied by as much as 20%. All measurements described were made on the lower surface of the emulsion, whose dimensions are unaffected by processing shrinkage. Measurements were made with a measuring stage manufactured by LBL, with a least-count of $1 \mu\text{m}$.⁸

The scanning procedure was as follows:

- 1) Given an event's x and y coordinates from drift chamber data and assuming a constant (average) pellicle thickness, an initial estimate was made of the plate number and y-square (grid coordinate) location of the muon's entry point at the front face of the stack.

- 2) the scanner determines the notch location (hence actual x coordinate) of the specified plate, and if necessary moves up or down a plate or two.

- 3) having determined the correct plate, the scanner measures the grid offset of the plate, and corrects the y-square estimate.

entered the front edge of the plate, and begins scanning across the pellicle. Although the pellicles were not in general perfectly parallel to the beam direction, this caused no difficulty, since the scanner simply followed the trend of nearby beam tracks in moving across the plates; all locating is done in a single plane (the front face), and beam tracks provide a convenient reference to compensate for tilts and distortion. Although the locating procedure seems complex, a system of scanning forms and visual aids made the calculation and locating procedure routine.

Scanning was performed using standard Leitz binocular microscopes equipped with 10X air objectives and 15X wide-field oculars. Higher powered oil lenses were used to examine objects of interest encountered during scanning. The 16x15 arrangement was sufficient magnification to provide high efficiency for events with 2 or more black (heavily-ionizing) tracks while keeping worst-case scanning time well below 2 hr/event. Events not found by this procedure will be searched for later at higher magnification.

Initially, a swath 2 mm wide was scanned across each of 3 to 5 plates. As events were found, their deviations from the predicted location were measured by tracing the beam track back to the front edge of the pellicle and inverting the locating procedure. Stack-by-stack variations in the average offset were found, probably due to the mechanical jolting inherent in the stack changing process, so a running average offset was tabulated for each stack, and included as

a final correction factor in the locating procedure. Thus each event found in a given stack helped improve the locating accuracy for subsequent events, and the search volume could eventually be reduced to a width of ± 500 microns (one field of view at 10x15 magnification). Fig. 8 shows the distribution of deviations ($X_{\text{found}} - X_{\text{predicted}}$) for 36 events found in Seattle after removal of stack offsets.

Event identification

When an interaction is found, it is necessary to positively identify it as the sought-for event. The scattering angle of the muon is known, and so the production angles of secondary tracks in an event candidate were measured and compared to the muon direction. Rough agreement was sufficient (~ 20 mrad) to warrant further work on the candidate. Final identification was made by comparing the pattern of secondary tracks observed in emulsion to a computer-generated drawing of the tracks observed in the downstream drift chambers.

References

1. Gaillard, Lee & Rosner, Rev. Mod. Phys. 47 277 (1975)
2. Watanabe, et al, Phys Rev. Lett. 35 898 (1975)
3. Y. Watanabe, dissertation (unpublished) MSU 1975
4. Duff, et al Nucl Instr.&Meth. 29 351 (1964)
Dauber, et al Nucl. Instr. & Meth. 84 199 (1970)
Goza, et al Rev. Sci. Instr. 41 219 (1970)
5. Atac, et al Nucl. Instr. & Meth. 120 147 (1974)
6. Hand, et al to be published
7. Barkas, W. "Nuclear Research Emulsions, v.I",
Academic Press 1963
8. Hodges, J. "Equipment for Nuclear Emulsion Analysis",
UCRL-99089, U.C.-LBL, 1960

**FNAL EXPERIMENT E382
150 GeV TAGGED MUON-EMULSION**

1m

FIGURE IV - 1

Fig. IV-2

MACHINING E382 EMULSION STACKS

FIGURE IV - 3

Fig. IV-4

EMULSION STAND

Fig. IV-5

	070	071	072	073	
	+	+	+	+	
	079	079	079	079	
	+	+	+	+	
59	070	071	072	073	07
	+	+	+	+	
50	050	050	050	050	05
	+	+	+	+	
59	070	071	072	073	07
	+	+	+	+	
51	031	031	031	031	03
	+	+	+	+	
5	070	071	072	073	07
	+	+	+	+	
	032	032	032	032	
	+	+	+	+	
	071	072			

(a)

(b)

FIGURE IV - 6

SCANNING OF EMULSION STACKS FOR
EXPERIMENT E 382

FIGURE IV - 7

Figure IV - 9 : Histogram of deviations between drift chamber predictions and actual locations of tagged events.

Deep inelastic lepton scattering provides an important tool for studying the hadronic interaction. The lepton-photon vertex is well-known via QED, and the virtual photon, parameterized by its mass Q^2 and energy ν , interacts with a nucleon to produce a hadronic final state of invariant mass $W^2 = m^2 + Q^2 + 2m\nu$. A basic result from the electron scattering experiments is the observation of scaling: the nucleon structure functions $W_1(s, q^2, \nu)$ and $\nu W_2(s, q^2, \nu)$ are in fact functions of a single variable, $x = Q^2 / 2m\nu$, indicating that scattering occurs off point-like constituents of the nucleon. [1] The availability of high energy muon beams at Fermilab has permitted the extension of such studies to higher ν (hence W^2) values than are accessible at electron machines. One of the first results from Fermilab was the observation of apparent scaling violations at high Q^2 . [2] The discovery of the Ψ/Ψ' particles [3] and the observation of non-strangeness-changing neutral currents in neutrino interactions [4] suggested the existence of a new quantum number, charm, and therefore the existence of new, charm-bearing hadrons. Since the sort of scaling violations observed would be characteristic of the opening of new particle production channels, deep-inelastic muon scattering seemed a likely source for charmed particles. Due to the short lifetimes predicted for such particles [5], the expected decay

lengths would be 10^{-6} to 10^{-4} m, a range accessible only to nuclear emulsions. In this paper we will describe multiparticle production results from a hybrid experiment performed using the Fermilab 150 GeV μ^+ beam, in which a system of counters, spark chambers and magnets was used to detect and momentum analyze muons scattered in nuclear emulsion targets. A total of 5.6 l of emulsion was exposed, divided into 26 emulsion stacks, each composed of 80 - 100 Ilford K5 pellicles of dimension 7.5 x 5 x .06 cm (5 cm in the beam direction), yielding a sample of 96 deep inelastic events. The emulsions provided a high resolution view of the interaction vertexes, and results of a search for new particle production in these events will be reported separately. [6]

The experimental arrangement, similar to that of ref. 2, is shown in fig. 1. The trigger used was C·S·BV·HV ($C = \Pi C_i$, $S = SA \cdot SB \cdot SC$, etc.); i.e., a single in-geometry incoming track, and a scattered muon detected in the magnetic spectrometer unaccompanied by undeflected penetrating particles. The muon beam had $\Delta p/p \sim \%$, with hadron contamination less than one part in 10^{-6} . The muon identifier, intended to facilitate the identification of possible dimuon events, was not used in the data sample discussed here. The muon spectrometer had momentum resolution $\Delta p/p \sim 15\%$.

Triggers were selected as candidates for emulsion scanning according to the following criteria: 1) beam track within 3 ($=2 \times \sqrt{2}$) mrad of the surveyed beam direction, 2) scattered muon momentum greater than 10 GeV, 3) no tracks within 3 mm of

the projected beam track location in the downstream drift chambers, but at least one other track visible. Event vertexes were found by area scanning along the beam track trajectory defined by the upstream proportional and drift chambers. For each event search, a minimum emulsion volume of 90 mm^3 (1mm x 50 mm on each of 3 adjacent plates) was scanned, with the search volume increased if no candidates were found on the first pass. Scanning was performed under 225x magnification. When an event candidate was found, tagging was verified by comparing the angle of the scattered muon measured by the muon spectrometer with the track angles seen in the emulsion plate. From a list of 262 scanning candidates, 96 interaction vertexes were found. Details of the apparatus and event locating technique will be given elsewhere. [7]

For each event tagged, the number of minimum-ionizing tracks n_s ($\beta \geq 0.7$, "shower" tracks in the conventional emulsion nomenclature) and the number of heavily-ionizing tracks N_h ($\beta < 0.7$) was recorded, and the angles of the shower tracks were measured relative to the incoming beam track. Fig. 2 shows the number of events found in each (n_s, N_h) category. Since n_s includes the scattered muon, we shall use $n = n_s - 1$ to denote the number of relativistic charged hadrons produced.

Fig. 3 shows the integral distribution of N_h . Due to the area-scanning technique used to locate events, biases against events with low N_h are expected. One of the fundamental results from emulsion studies of hadronic interactions is the invariance of the N_h distribution over a wide energy

range. [8] In Fig 3 comparison is made with the N_h distribution obtained from a pooled sample of 5896 proton-emulsion interactions at 67 and 200 GeV. The apparent deviation of the muon-induced N_h distribution below $N_h = 3$ is therefore assumed to reflect scanning bias, and all other data presented here is based on the sample of 88 events with $N_h \geq 3$. Assuming that the N_h distributions for muon-induced and hadron-induced interactions are identical, we estimate the event loss due to scanning bias to be 35%.

Fig. 4 shows the distributions of Q^2 and W for the final sample of events. The mean value of W for our data is $\langle W \rangle = 10.2$. Thus the energy available for hadron production is approximately equivalent to that in 60 GeV pion-emulsion interactions ($\sqrt{s} = 10.7$) and 67 GeV proton-emulsion interactions ($\sqrt{s} = 11.3$) [9]. In table 1, the multiplicity parameters $\langle N_h \rangle$, $\langle n \rangle$, $D = \langle n^2 \rangle - \langle n \rangle^2$, and $f_2 = \langle n(n-1) \rangle - \langle n \rangle^2$ are shown for this experiment, and for the equivalent-energy hadron interactions. (For the hadron data, $n = n_s$)

Fig. 5 gives the distribution of n presented in terms of $z = n / \langle n \rangle$. Slattery [10] has shown that p-p multiplicity distributions over a wide energy range are well represented by a single function of z ; such "KNO scaling" behavior [11] has been shown to apply also to hadron-nucleus multiplicities by several authors [12]. For comparison, fig. 5 also shows pion-emulsion and proton emulsion data at several energies. The curve represents a fit to the form

$$\Psi(z') = A(z' + B) \exp(Cz' + Dz'^2)$$

where $z' = \frac{(n - \alpha)}{(\langle n \rangle - \alpha)}$ suggested by Buras et al [13].

Fig. 6 shows D vs $\langle n \rangle$ for muon interactions (divided into two energy bins, $W \leq 10$ GeV and $W > 10$ GeV; the overall average is also shown; see table 2), along with results from hadroproduction over a broad energy range [9, 14, 15]. Also shown is a curve given by Wroblewski [16], $D = 0.576(\langle n \rangle - 1)$, which fits the p-p data from 4-205 GeV. The linear correlation between D and $\langle n \rangle$, another manifestation of KNO scaling, appears to be projectile-independent.

N_h is a measure of the nuclear excitation produced by the interaction. Many authors have suggested that N_h is correlated with the degree of intranuclear cascading present, parameterized in most currently popular models by $\mathcal{V}$, the number of intranuclear collisions suffered by the projectile or its successor particle(s). [16] Since $\langle \mathcal{V} \rangle$ is proportional to the atomic mass A ,

$$\langle \mathcal{V} \rangle = A \frac{\sigma_{pp}}{\sigma_{pA}} \quad [17]$$

it is commonly assumed that events with large N_h occur in heavy nuclei (Ag, Br) and small- N_h events are in light nuclei (C, N, O, H).

In fig. 7 we show the N_h dependence of $\langle n \rangle$ for muon, pion, and proton induced interactions. All three sets of data show a linear correlation, but the N_h dependence of muon interactions is clearly weaker than in hadroproduction. The correlation is energy dependent, as shown in fig. 8, where $\langle n \rangle$ is given as a function of N_h for two energy bins; the

low-W data is not significantly N_h -dependent.

In emulsion experiments, where only track angles are measured, the pseudorapidity variable

$$\eta = -\ln \tan (\theta_{\text{lab}}/2)$$

is a useful approximation to the true rapidity

$$y = \ln \left(\frac{E + p_1}{E - p_1} \right)$$

for tracks with $m^2/p_t^2 \ll 1$. [18] For muon events,

θ_{lab} is measured relative to the virtual photon direction, determined from the muon scattering angle and momentum.

Fig. 9 shows the $\langle n \rangle$ versus N_h correlation for muon, pion and proton data in four η bins; here $\langle n \rangle$ represents the average number of particles produced per event in the specified η range. For $\eta < 2.1$ (backward hemisphere in the CM) $\langle n \rangle$ is proportional to N_h for both muon- and hadron-produced events; however, the muon data becomes N_h -independent above $\eta \sim 2.1$, while the hadroproduction data remains N_h dependent up to $\eta \sim 3.2$. Table 3 gives the parameters of the fitted curves.

Fig. 10 shows the inclusive η distribution, $(1/N)dn/d\eta$, for all events with $N_h \geq 3$, compared with equivalent-energy pion and proton data. The muon and hadron-induced distributions coincide in the extreme forward and backward directions; the additional tracks (reflecting the higher $\langle n \rangle$ for hadroproduction) appear in the central and near-forward regions. Note that the difference between the pion and proton distributions is also significant only in the central region.

The muon data shown in fig. 10 covers a broad range of W , and a completely satisfactory estimate of the distortions introduced by such averaging cannot be made, because there is insufficient data on hadron-emulsion interactions in the appropriate energy range to construct an equivalent averaged sample. Nor do adequately reliable models exist to compute corrections. Nevertheless, our data shows that these distortions are relatively unimportant; in fig. 11 we compare a sample of 43 muon events with $9 < W < 14$ GeV, $\langle W \rangle = 11.2$ GeV, with the p-emulsion data at 67 GeV ($\sqrt{s} = 11.3$). Within errors, the situation seen in fig. 10 also holds for this equivalent-energy comparison. Thus the differences between muon-emulsion and hadron-emulsion rapidity distributions and multiplicity parameters shown in fig. 10 and Table 1 are not introduced by the fact that the muon data covers a broad energy range. On the other hand, it is important to note that the measurements of multiplicities and angular distributions in electro- and muoproduction on hydrogen [19,20] showed no significant differences when compared at equivalent CM energy of the produced hadronic system.

In order to appreciate the fact that we are dealing with virtual photons in a nuclear medium, we have divided our events into two energy bins, $W > 10$ and $W \leq 10$ GeV, and plotted their pseudorapidity distributions in fig. 12; the multiplicity parameters for these energy bins are given in table 2. In fig. 12 one observes that the right hand side of the distribution shifts with an increase of energy, while the

left hand side remains stationary. The same effect is seen in hadron data. [21]

In order to study nuclear effects in muoproduction without equivalent-energy ep or pp data, we can proceed by assuming that it is valid to extrapolate lower-energy lepton-hadron interaction data; as shown by Albini et al [22], the average charged hadron multiplicity in both hadron- and lepton-proton interactions is well represented by

$$\langle n_{ch} \rangle = 2.5 + 2.8 \ln E_a + 0.53 \ln^2 E_a$$

where $E_a = \sqrt{s} - (m_a + m_b)$ is the CM energy available, for particle production and m_a, m_b are the masses of the initial-state particles.

One commonly-used parameter which describes nuclear effects in hadron-nucleus interactions is R , the normalized mean multiplicity:

$$R_{\mu(h)} = \frac{\text{average multiplicity of produced hadrons in } \mu(\text{hadron}) - \text{emulsion interactions}}{\text{average multiplicity of produced hadrons in } \mu(\text{hadron})\text{-proton interactions}}$$

Thus R represents the ratio of mean charged multiplicities (minus the initial-state particles) for equivalent-energy nuclear and elementary interactions. Since data on proton targets is not available at all energies, we shall use n_{ch} calculated using the formula given above. Then for muon and hadron interactions respectively,

$$R_{\mu} = \left\langle \frac{n}{n_{ch}-1} \right\rangle = \frac{1}{N} \sum_{i=1}^N \frac{n_i(E_{ai})}{(\langle n_{ch}(E_{ad}) \rangle - 1)}; \quad E_{ai} = V'_i -$$

$$R_h = \frac{\langle n_s - 1 \rangle}{\langle n_{ch} \rangle - 2}$$

($\langle n_{ch} \rangle - 1$ is used in R_μ because in μ -p experiments the scattered muons are identified and removed from the reported multiplicities. Note that unlike the comparable hadroproduction data, which is monoenergetic, R_μ represents an average over energy as well as multiplicity.)

Fig. 13 shows R_μ , R_p and R_π , as functions of energy. Values of R for the various data samples discussed are given in tables 1 and 2, indicating that the average multiplicity of particles produced by virtual photons in emulsion is

a) significantly greater than on hydrogen; b) significantly less than the multiplicities produced by hadrons at equivalent energy. We can obtain the lower limit for R_μ (all N_h) by assuming that for the $N_h \leq 2$ events excluded from our final data sample, there is no nuclear effect: $R_\mu = 1.0$, $N_h \leq 2$.

Then

$$R_\mu, \text{ all } N_h \geq 1.4$$

To study further nuclear effects in muoproduction without using the extrapolated values of n , we subdivided our sample into 2 groups: $N_h = 3-8$ and $N_h^{ch} > 8$. The forward subsample could be considered a crude approximation to muon-proton interactions. Figure 14a and 14b show pseudorapidity inclusive distributions for these two subsamples.

The dependence of nuclear effects on η can be displayed by introducing the following functions:

ratio:
$$\rho(\eta) = \frac{\frac{1}{N} \frac{dn}{d\eta} \Big|_{N_h > 8}}{\frac{1}{N} \frac{dn}{d\eta} \Big|_{N_h = 3-8}}$$

difference
$$\Delta(\eta) = \frac{1}{N} \frac{dn}{d\eta} \Big|_{N_h > 8} - \frac{1}{N} \frac{dn}{d\eta} \Big|_{N_h = 3-8}$$

These functions are shown in Figures 15 and 16, where comparison is also made with hadron induced reactions. Both $\rho(\eta)$ and $\Delta(\eta)$ reveal similar behavior for different projectiles. The increase of multiplicity due to nuclear effects is localized in the range of small values of η (below about 2.5). Nuclear effects in muo-production are smaller than in hadron interactions but nevertheless significant and clearly seen.

TABLE 1

	No of events	$\sqrt{s}, \bar{W}$ GeV	$\bar{N}_h$	$\bar{n}$	$\bar{D}$	f_2	$\bar{R}$	$\overline{Q^2}$ GeV ²	$\bar{w}$
$\mu - \text{Em}$ TOTAL SAMPLE	96	10.3	9.4 ± 0.7	7.68 ± 0.43	4.19 ± 0.32	8.9 ± 2.6	1.72 ± 0.10	4.6	52.3
$\mu - \text{Em}$ $N_h > 2$	88	10.2	10.2 ± 0.7	7.80 ± 0.45	4.24 ± 0.34	9.2 ± 2.7	1.77 ± 0.11	4.4	53.1
60 GeV $\pi^- - \text{Em}$ $N_h > 2$	544	10.7	10.3 ± 0.3	9.63 ± 0.22	5.19 ± 0.22	17.3 ± 2.2	2.15 ± 0.07	-	-
67 GeV p - Em $N_h > 2$	458	11.3	11.2 ± 0.3	11.39 ± 0.28	6.06 ± 0.26	25.4 ± 3.0	2.67 ± 0.09	-	-
$\mu - \text{Em}$ $N_h > 2$ $9 \leq W \leq 14$	43	11.2	9.8 ± 0.1	7.86 ± 0.66	4.32 ± 0.57	9.8 ± 4.6	1.56 ± 0.13	4.6	56.1

TABLE 2

	No of events	$\sqrt{s}, \bar{W}$ GeV	$\bar{N}_h$	$\bar{n}$	$\bar{D}$	f_2	$\bar{R}$	$\overline{Q^2}$ GeV ²	$\bar{w}$	$\bar{r}$ fm
$\mu - \text{Em}$ $N_h > 2$ $2 < W < 10$	41	7.0	10.2 ± 0.9	6.93 ± 0.59	3.78 ± 0.33	6.3 ± 2.3	2.00 ± 0.18	5.9	17.1	3.5
$\mu - \text{Em}$ $N_h > 2$ $10 < W < 16.5$	47	13.0	10.2 ± 1.0	8.55 ± 0.65	4.47 ± 0.49	10.4 ± 4.1	1.57 ± 0.12	3.1	89.2	18

TABLE 3

Results of fits to $\langle n \rangle = a + b N_h$

Data	a	b	χ^2/DF
$\mu - E_m$ $N_h > 2$, all W	$6.097 \pm .728$	$0.160 \pm .066$	.64
$\pi^- - E_m$ 60 GeV, $N_h > 2$	$6.511 \pm .245$	$0.313 \pm .025$	.48
p - E_m 67 GeV, $N_h > 2$	$6.654 \pm .241$	$0.391 \pm .024$	.89
$\mu - E_m$: W ≤ 10	6.439 ± 1.236	$0.050 \pm .101$	.145
W > 10	6.034 ± 1.022	$0.246 \pm .104$	.05
$\eta < 1.2$:			
$\mu - E_m$	$.547 \pm .258$	$.124 \pm .034$	.08
$\pi - E_m$	$.582 \pm .115$	$.116 \pm .013$	.65
p - E_m	$.547 \pm .115$	$.168 \pm .013$	1.81
$1.2 \leq \eta < 2.1$:			
$\mu - E_m$	$1.206 \pm .333$	$.082 \pm .032$	.27
$\pi - E_m$	$1.253 \pm .138$	$.118 \pm .017$	.34
p - E_m	$1.335 \pm .125$	$.147 \pm .013$	.92
$2.1 \leq \eta < 3.2$:			
$\mu - E_m$	$2.446 \pm .396$	$-.045 \pm .029$	.42
$\pi - E_m$	$2.078 \pm .126$	$.085 \pm .013$	.03
p - E_m	$2.330 \pm .125$	$.085 \pm .013$	1.60
$3.2 \leq \eta$:			
$\mu - E_m$	$1.948 \pm .437$	$-.006 \pm .040$	.53
$\pi - E_m$	$2.607 \pm .097$	$-.008 \pm .007$	.03
p - E_m	$2.360 \pm .098$	$-.007 \pm .008$	4.36

References

1. J. Friedman and H. Kendall, Ann. Rev. Nucl. Sci. 22 203 (1972)
2. D. Fox, et al, PRL 33 1504 (1974)
3. J. Aubert, et al, PRL 33 1404 (1974)
J. Augustin, et al, PRL 33 1406 (1974)
4. "Neutrinos - 1974", AIP Conf. Proc. #22, C. Baltay, ed. (1974)
5. M. Gaillard et al, Rev. Mod. Phys. 47 277 (1975)
6. E. Friedländer et al, to be published
7. Z. Hord, et al, to be published
8. Krakow preprint (reference to be supplied)
9. J. Babecki, et al, Acta Physica Polonica 5B 315 (1974)
J. Gierula, et al, Acta Physica Hungarica, 29 suppl. 3, 157 (1970)
10. P. Slattery, PRL 29 1624 (1972)
11. Z. Koba, et al, Nucl. Phys. B40 317 (1972)
12. J. Flouan, et al. Phys. Rev. D13, 558 (1976)
J. Hébert, et al, Phys. Rev. D15, 1867 (1977)
13. A. Bursas, et al, Phys. Lett. 47B 251 (1973)
14. J. Babecki, et al, INP (Krakow) preprint 929/PH (1976)
15. B. Anderson, private communication
16. For an excellent review of current models, see
W. Butya, in "High Energy Physics and Nuclear Structure - 1975", AIP Conf. Proc. #26, (1975), p. 211
17. A. Eliaş & W. Czyż, Phys. Lett. B51, 179 (1974)
- 18.

19. B. Gibbard, et al PR D11 2367 (1975)
20. C. Di Papa et al PR D13 2934 (1976)
21. J. Babecki, et al, Phys Lett B47 268 (1973)
22. E. Alzini, et al, Nuovo Cimento 32A 101 (1976)

Figure Captions

- Fig. 1: Experimental arrangement
- Fig. 2: Scatterplot of n_s vs N_h , 96 events.
- Fig. 3: Integral N_h distribution, $P(>N_h)$. Proton data from a pooled sample of 5896 proton interactions at 67 ± 200 GeV (refs. 9, 14). Muon data is normalized to give $P_h(>4) = P_p(>4)$.
- Fig. 4: Scatter plot of Q^2 vs W for 88 events with $N_h \geq 3$.
- Fig. 5: $f(z) = \langle n \rangle \sigma_n / \sigma_{inel}$, $z = n / \langle n \rangle$. Data from 67 GeV p, 60 GeV π (ref. 9); 200 GeV p, 200 GeV π (ref. 14), 400 GeV p (ref. 15).
- Fig. 6: D vs $\langle n \rangle$ for $W \leq 10$ GeV, $W > 10$ GeV, and all data; also ^{nuclear} emulsion data from refs. 9, 14, 15.
- Fig. 7: $\langle n \rangle$ vs N_h ; comparisons with 60 GeV π and 67 GeV p (ref. 9)
- Fig. 8: $\langle n \rangle$ vs N_h for $W >$ and $W \leq 10$ GeV
- Fig. 9: $\langle n \rangle$ vs N_h for four η bins; comparison with 67 GeV p and 60 GeV π^- [9, 14]
- Fig. 10: η distribution, with comparison to 60 GeV π and 67 GeV p data.
- Fig. 11: η distributions for 43 events with $9 < W < 14.6$ $\langle W \rangle = 11.2$; comparison with 67 GeV p ($\langle W \rangle = 11.3$)
- Fig. 12: η distribution for two W bins, $W \leq 10$ GeV and $W > 10$ GeV

Fig. 13: $R = \frac{\langle n \rangle}{(\langle n_{ch} \rangle - 2)}$ vs $\sqrt{s}$; comparison
with p, π data.

Fig. 14: a) η distribution for events with $N_h \leq 8$
b) same, $N_h > 8$

Fig. 15: $\rho(N_h > 8 / N_h \leq 8)$ - see text.

Fig. 16: $\Delta((N_h > 8) - (N_h \leq 8))$ - see text.

FNAL EXPERIMENT E382
150 GeV TAGGED MUON-EMULSION

Fig 1

Fig. 2

Fig. 3

Fig. 4

Fig 5

Fig. 6

Fig. 7

Fig. 8

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14a

Fig. 14 b

U. OF WASHINGTON COSMIC RAY LAB PLOTS 12/08/77

Fig. 15

Fig. 16

APPENDIX VI:

Abstract Submitted

for the Washington Meeting of
the American Physical Society
24-27 April 1978

Physics and Astronomy

Classification

Number 13.60

Bulletin Subject Heading
in which Paper should be
placed:

Photon and Lepton Inter-
actions with Hadrons

Deep-Inelastic Interactions of Tagged 150 GeV
Muons in Nuclear Emulsion Targets.* J. FLORIAN, K.
GOTTFRIED, L. HAND, D. PETERSEN, H. SCOTT, Cornell Univ.,
M. ATAC, A. READ, L. VOYVODIC, Fermilab, W. CZYZ, A.
DWURAZNY, R. HOLYNSKI, S. KRZYWDSINSKI, W. WOLTER, Inst.
of Nuc. Phys.-Krakow, Poland, E. FRIEDLANDER, Lawrence
Berkeley Laboratory, R. BALL, J. KILEY, A. KOTLEWSKI, L.
LITT, Michigan State Univ., J. LORD, R. WILKES, U. of
Wash.-- Multiplicities and angular distributions of
hadrons produced in deep inelastic muon interactions with
 $Q^2 > 1 \text{ GeV}^2$ are analyzed. The sample of interactions
was obtained in a hybrid counter and nuclear emulsion
experiment performed at Fermilab. The similarity between
muon interactions and those induced by hadrons indicates
clearly the existence of an hadronic component in high
 Q^2 space-like photons.

* Work Supported by NSF and DOE.

Submitted by

R. J. Wilkes

R. J. Wilkes
Dept. of Physics, FM-15
University of Washington
Seattle, WA 98195