Proton Radiography: Cross Section Measurements and Detector Development: Final Report

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Research Areas: Low-Energy Nuclear Science

Primary Goals: Investigations of advanced diagnostic techniques relevant to proton radiography, including studies of potential background processes.

Secondary Goals: Development of advanced simulations and measurement techniques leading to improved radiation and particle detection methods in terms of energy and spatial resolution.

EXECUTIVE SUMMARY

Proton radiography has become an important tool for predicting the performance of stockpiled nuclear weapons. Current proton radiography experiments at LANSCE are confined to relatively small targets on the order of centimeters in size because of the low beam energy. LANL scientists have made radiographs with 12 and 24 GeV protons produced by the accelerator at Brookhaven National Laboratory. These energies are in the range required for hydrotest radiography. The design of a facility for hydrotest radiography requires knowledge of the cross sections for producing high-energy particles in the forward direction, which are incorporated into the Monte Carlo simulation used in designing the beam and detectors. There are few existing measurements of neutron production cross sections for proton-nuclei interactions in the 50 GeV range, and almost no data exist for forward neutron production, especially for heavy target nuclei.

Thus the data from the MIPP EMCAL and HCAL, for which our group was responsible, are critical to proton radiography. Since neutrons and photons cannot be focused by magnets, they cause a background "fog" on the images. This problem can be minimized by careful design of the focusing system and detectors.

The purpose of our research was to measure forward production of neutrons produced by high-energy proton beams striking a variety of targets. The forward-going particles carry most of the energy from a high-energy proton interaction, so these are the most important to proton radiography. This work was carried out in conjunction with the Fermilab E-907 (MIPP) collaboration.

Our group was responsible for designing and building the E907 forward neutron and photon calorimeters. With the support of our Stewardship Science Academic Alliances grants, we were able to design, build, and commission the calorimeters on budget and ahead of schedule. The MIPP experiment accumulated a large amount of data in the first run that ended in early 2006. Our group has almost completed the analysis the forward neutron production data. Large discrepancies between our neutron production data and Monte Carlo expectations have been found.

Introduction

Proton radiography has become an important tool for predicting the performance of stockpiled nuclear weapons [1]. The Los Alamos Neutron Science Center (LANSCE) is carrying out an extensive program of experiments at the Proton Radiography Facility [2, 3]. Current proton radiography experiments at LANSCE are confined to relatively small targets on the order of centimeters in size because of the low beam energy. LANL scientists have made radiographs with 12 and 24 GeV protons produced by the accelerator at Brookhaven National Laboratory. These energies are in the range required for hydrotest radiography of more realistic targets [4]. The design of a facility for hydrotest radiography requires knowledge of the cross sections for producing high energy particles in the forward direction, which are incorporated into the Monte Carlo simulation used in designing the beam and detector. There are few existing measurements of cross sections for proton-nuclei interactions in the 50 GeV range, and very little data exist for forward neutron production. Thus the data from the MIPP electromagnetic calorimeter (EMCAL) and hadron calorimeter (HCAL), for which our group was responsible, are critical to proton radiography. Since neutrons and photons cannot be focused by magnets, they cause a background "fog" on the images. This problem can be minimized by careful design of the focusing system and detectors.

The design of the focusing system and detectors is done using various Monte Carlo codes to simulate the interactions of protons in the object to be imaged and the subsequent interactions of the secondary particles in the material. There are, however, large differences between different hadronic shower simulation codes (FLUKA [5], MARS, MCNP [6], etc.). This imposes significant limitations on the simulations and design of the beam and detectors. The validation of these codes requires significantly more data, particularly in the forward direction for heavy target nuclei.

The physics goal of this project is to measure forward production of neutrons and photons produced by high-energy proton beams striking a variety of targets. This work is being carried out in conjunction with the Fermilab Experiment 907 (MIPP) collaboration [7]. Our group is responsible for the E907 forward neutron/photon calorimeters. These are the only detectors in the experiment that provide information on neutron and photon production. With the support of our previous Stewardship Science Academic Alliances grants, we were able to design, build, and commission the calorimeters on budget and ahead of schedule. We have taken a leading role in analyzing the forward production data and in developing an optimal detector for proton radiography.

The use of protons as a radiographic probe requires a knowledge of the proton interaction cross sections, the differential distribution of the outgoing proton in momentum and angle, and the distribution of other produced particles, especially in the forward direction. Much of the energy is carried by forward-going neutrons and gammas. There is very little data on forward neutron and π^0 production, so that these measurements are particularly crucial. In addition, measurements of proton interactions with a wide range of nuclei (from hydrogen to uranium) will provide data for simulations of the technique and for interpretation of the images. The goal of Experiment 907 at Fermilab is to do a comprehensive set of measurements of production cross sections for protons, pions, kaons, and neutrons for beam energies between 5 and 120 GeV for a wide variety of targets. The University of Michigan group is responsible for the forward detectors that detect neutrons and photons produced in the near-forward direction.

E-907 at Fermilab (MIPP)

E-907 (Main Injector Particle Production) at Fermilab is an experiment to measure particle production using primary and secondary beams from the Main Injector [7]. It is a collaboration of the University of Colorado, Fermi National Accelerator Laboratory, Harvard University, Illinois Institute of Technology, the University of Iowa, Indiana University, Lawrence Livermore Laboratory, the University of Michigan, Purdue University, the University of South Carolina, and the University of Virginia. MIPP will supply information critical to the Main Injector Neutrino Oscillation Search (MINOS) experiment and other basic physics experiments, as well as data needed to design and plan for proton radiography using higher energy beams.

E-907 officially started physics running at Fermilab in January 2005, and data taking continued through February 2006. Data were taken on a range of targets, from liquid hydrogen to uranium, at beam energies from 5 GeV/c to 120 GeV/c. The analysis of the data is challenging because data from many different detector systems must be understood and merged and over 31 million events were accumulated.

The MIPP Detectors

A plan view of the MIPP detectors is shown in Fig. 1 with the beam coming from the left. More detail is provided in Appendix I and at the MIPP web site, http://ppd.fnal.gov/experiments/e907. The experiment is set up in the Fermilab Meson Center beam line. Our group has many years of experience with neutron scattering experiments and hadron calorimeters. Thus it was natural for the University of Michigan group to take responsibility for the MIPP electromagnetic shower detector (EMCAL) and the neutron calorimeter (HCAL). The purpose of the EMCAL is to detect and measure the angles and energies of forward photons. The HCAL detects neutrons and other hadrons and measures their energies.

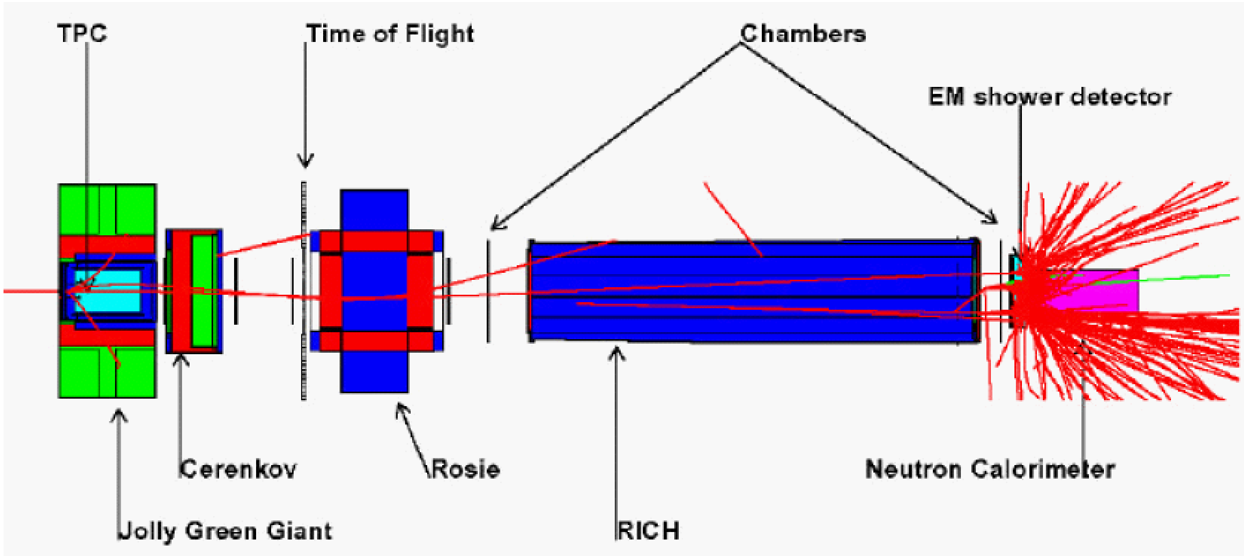

Figure 1. Schematic plan view of MIPP showing Monte Carlo generated showers in the EMCAL and HCAL

The calibrations of both the EMCAL and the HCAL are well understood. A paper describing the calibration was published in Nuclear Instruments and Methods [8]; this was the first publication in a refereed journal from MIPP.

A comparison of our overall hadron energy resolution to that of other calorimeters is shown in Table I. The energy resolution is comparable to or better than that of the others. Ours has the advantages of good spatial resolution in the EMCAL, low cost, and excellent separation between photons and hadrons (Figure 2).

Table I. Comparison of MIPP energy resolution for protons with other calorimeters.				
Experiment	**Cal Type**	**Resolution**	**Resolution @ 20 GeV**	**Resolution @ 120 GeV**
MIPP	Pb/Gas+Fe/Scint	$55.4\% / \sqrt{E} \oplus 2.6\%$	13.8%	5.9%
D0	U/LAr	$44\% / \sqrt{E} \oplus 4\%$	10.6%	5.7%
FOCUS	Fe/Scint	$85\% / \sqrt{E} + 0.86\%$	19.9%	8.6%
HyperCP[1]	Fe/Scint	n/a	n/a	9%
L3	BGO + U/Gas	$44\% / \sqrt{E} + 7\%$	17%	11%
RD-34	Fe/Scint	$41.3\% / \sqrt{E} + 4.3\%$	13.5%	8.1%
WA78	Fe/Scint	$55\% / \sqrt{E} \oplus 1.7\%$	12.4%	5.3%
ZEUS[2]	U/Scint	$43.6\% / \sqrt{E}$	9.7%	4%
ZEUS[3]	Pb/Scint	$70\% / \sqrt{E}$	n/a	6%

[1] The HyperCP resolution was measured with 70 GeV protons.

[2] The ZEUS resolution is for all events. The resolution for events fully contained in the calorimeter is 7.8% at 20 GeV and 3.2% at 120 GeV.

[3] ZEUS Forward Neutron Calorimeter. The resolution is for hadrons incident at the center of the tower modules. The resolution is $62\% / \sqrt{E}$ for hadrons incident at the center of the calorimeter.

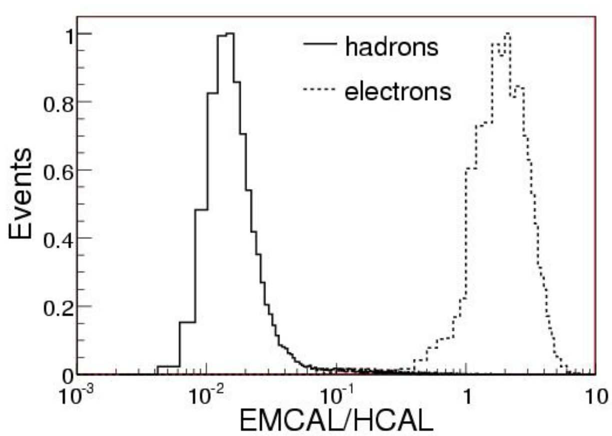

Figure 2. Ratio of energy in the EMCAL to the energy in the HCAL for 18.5 GeV electrons (dotted line) and 20 GeV hadrons (solid line). This shows that we have excellent separation between electrons/photons and neutrons.

Preliminary Results

In Table II we compare the Monte Carlo and data total cross sections for producing a neutron with momentum greater than threshold going into the fiducial volume of the HCAL. DPMJET was used for hydrogen targets, rather than FLUKA. The Monte Carlo simulation includes the geometry of the detector, the calorimeter energy resolution, and the same threshold neutron momentum as the data, so that it can be directly compared with the data. The predictions of the LAQGSM model are also included where available [9]. The measured cross sections are typically a factor of 2 higher than the FLUKA predictions and in even poorer agreement with LAQGSM. The table also reveals an internal inconsistency in FLUKA in that the neutron production cross section for carbon with atomic weight 12 is 78% larger than that for beryllium with atomic weight 9.

Target, Beam Momentum	σ_n (mb) Data	σ_n (mb) DPMJET/FLUKA	σ_n (mb) LAQGSM
H2, 58 GeV	8.2 ± 1.0	4.4	4.2
C, 58 GeV	56.8 ± 6.6	29.0	27.7
Bi, 58 GeV	255.9 ± 36.2	123.7	70.7
U, 58 GeV	234.0 ± 34.3	142.7	
H2, 84 GeV	12.3 ± 1.5	6.0	
Be, 120 GeV	68.1 ± 9.8	29.7	
C, 120 GeV	79.9 ± 10.1	53.0	39.5
Bi, 120 GeV	379.7 ± 64.7	273.5	100.1

TABLE II. Comparison of our measurements with FLUKA and LAQGSM Monte Carlos. Listed are cross sections for producing neutrons with energy greater than threshold and within an angular range of 22 mrad. The Monte Carlos include the detector geometry, calorimeter energy resolution, and threshold neutron momentum.

In Figure 3 we compare the neutron momentum distributions from hydrogen, carbon and bismuth targets with the FLUKA and LAQGSM predictions. Again, the Monte Carlo predictions include the geometry of the detector and energy resolution of the calorimeters. As we saw in Table II, the MC predictions are typically a factor of 2 or more lower than the data. The predicted momentum dependence is in serious disagreement with the data, especially at low neutron momentum.

The dependence of the measured neutron production cross sections on the atomic weight of the target is shown in Fig. 4. The cross sections have been corrected for neutrons that miss the aperture of the HCAL.

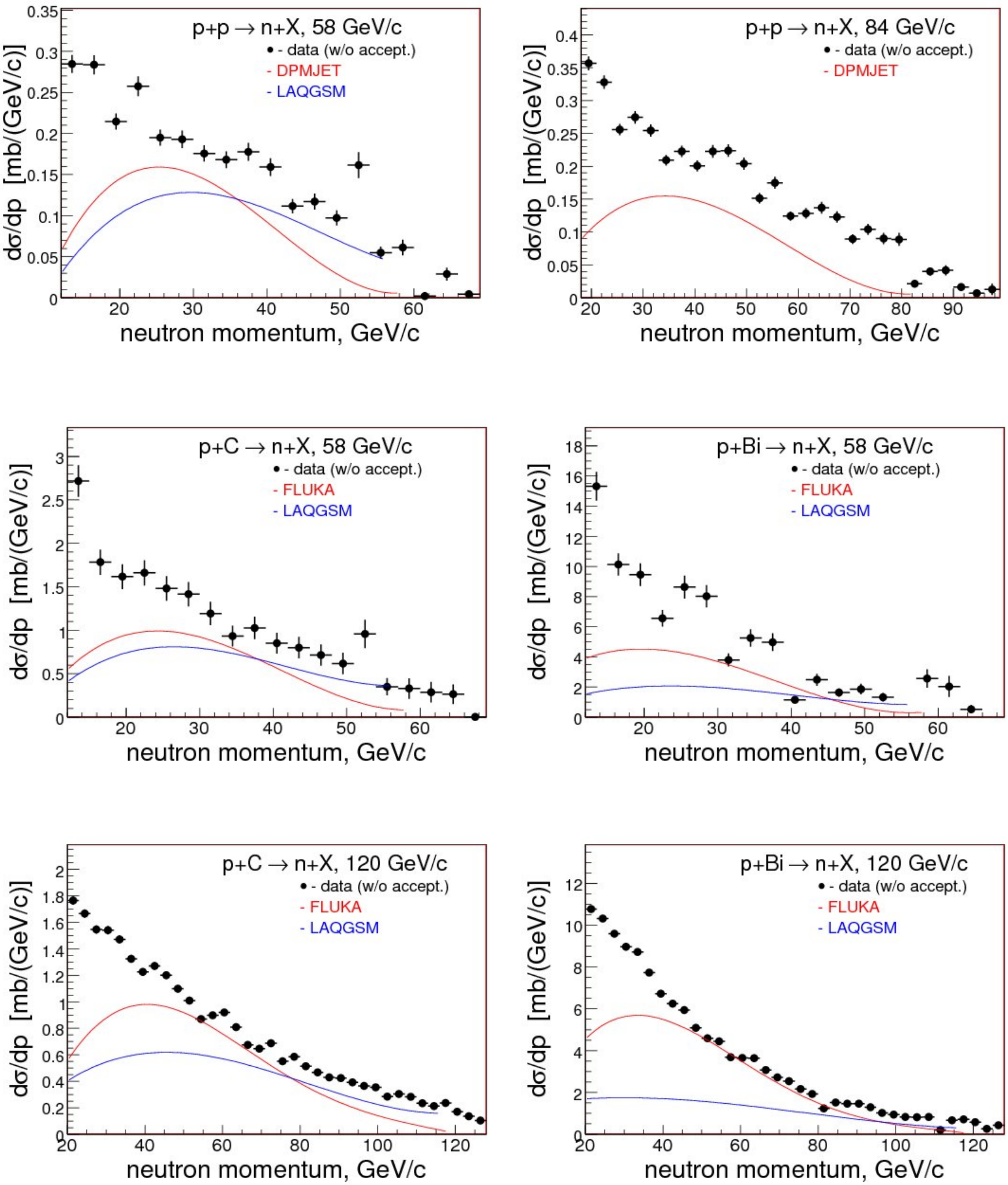

Figure 3. Measured cross sections from this experiment compared with predictions from Monte Carlo. Where available, predictions from both LAQGMS and DPMJET/FLUKA are shown.

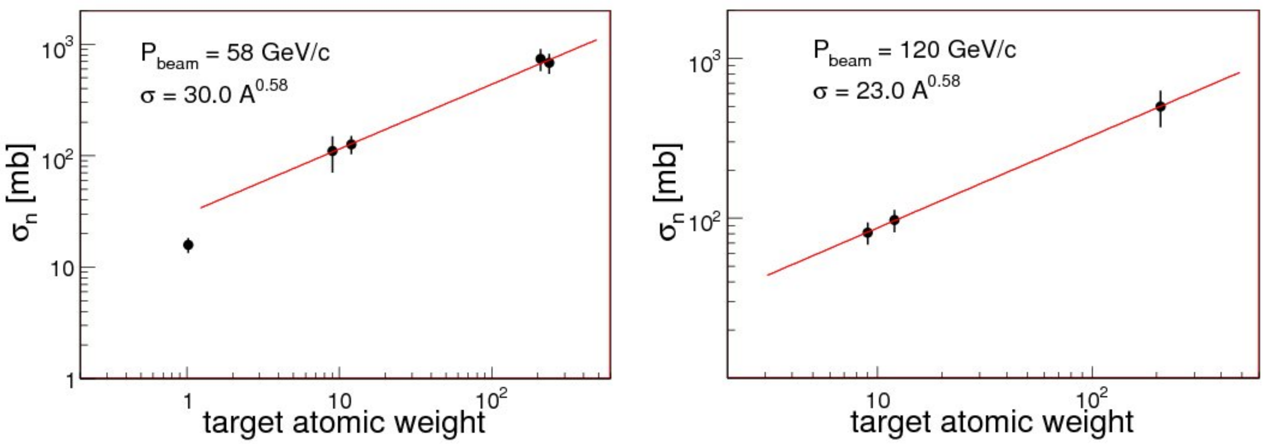

Figure 4. Neutron production cross sections as a function of target atomic weight A for 2 proton beam momenta.

Although our group was not responsible for the Time of Flight detector, we were asked to rescue that detector and make it useful for analyses. When we took over, the detector was not calibrated and its performance was not understood. We have completed the calibration of the detectors to take into account light propagation times as a function of position, pulse height slewing, attenuation, and temperature effects; fixed bugs in the reconstruction of the time-of-flight data; and made improvements in the time resolution. As a result of these efforts, the time-of-flight detector is now calibrated and has become a useful tool for separating pions, kaons and protons with a time resolution ~300 ps. Corrected time of flight data for a thick graphite target are shown in Fig. 5. Kaons are well separated from pions below about 1 GeV/c, and from protons below about 1.6 GeV/c. Particle identification at higher momentum relies on the Cerenkov counters.

Discussion

We have made the first comprehensive measurements of neutron production from a variety of targets for proton beams of 58 and 120 GeV/c. These neutron production data, though preliminary, are very relevant to proton radiography. They show that the background from high-energy neutrons would be a factor of 2 or 3 larger than predicted by state of the art Monte Carlos. They are also relevant to predictions of neutrino fluxes produced by proton beams ~100 GeV, since these rely on the Monte Carlo programs, like FLUKA, accurately reproducing the propagation of hadron showers in thick targets. Forward-going neutrons carry a significant fraction of the energy in the cascade and they propagate somewhat differently than charged hadrons due to the lack of Coulomb scattering.

We have also found an internal inconsistency in the A-dependence of the neutron production cross section in the popular FLUKA simulation.

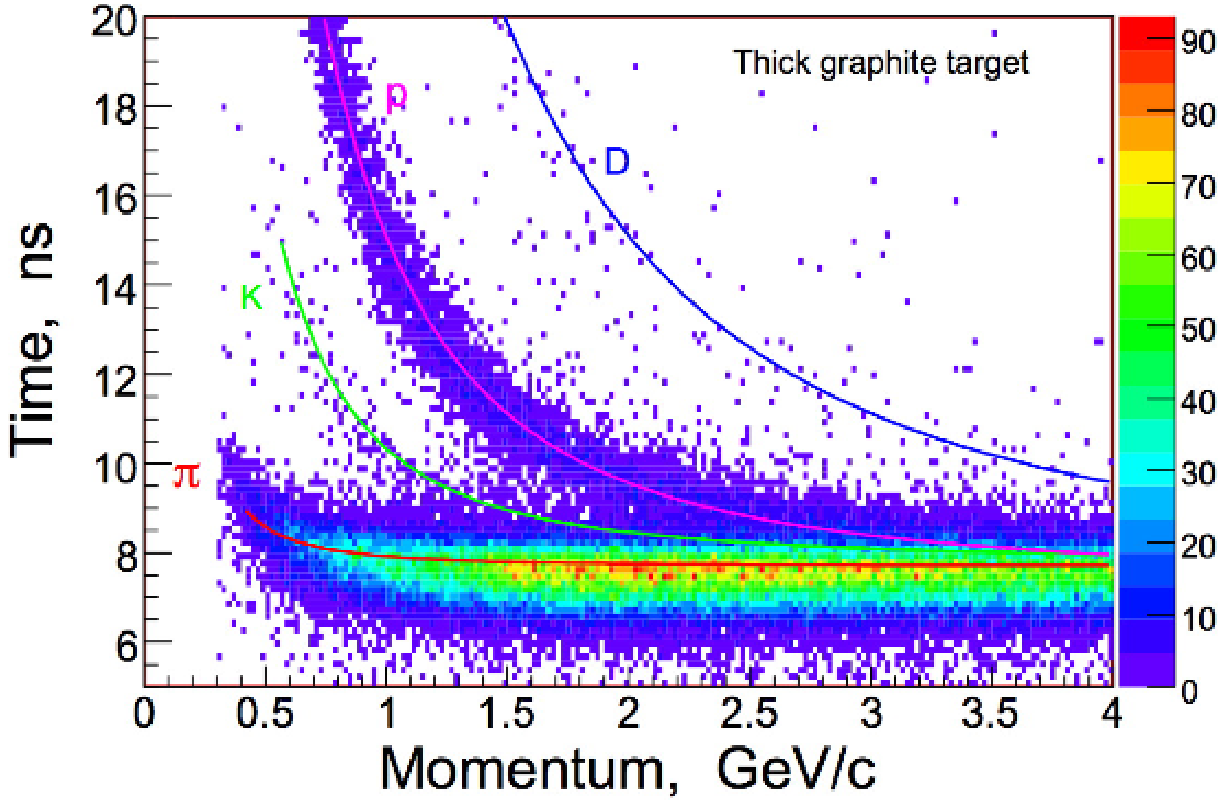

Figure 5. Time of flight data after corrections for position, pulse height slewing, attenuation, and temperature effects. The bands for pions, kaons, and protons are clearly delineated at lower momenta. A few deuterons are seen.

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Appendix I. The MIPP Detectors

A perspective layout of the MIPP detectors is shown below with the beam coming from the upper left. The experiment is set up in the Fermilab Meson Center beam line. The purpose of the EMCAL is to detect and measure the angles and energies of forward photons. The HCAL detects neutrons and other hadrons and measures their energies.

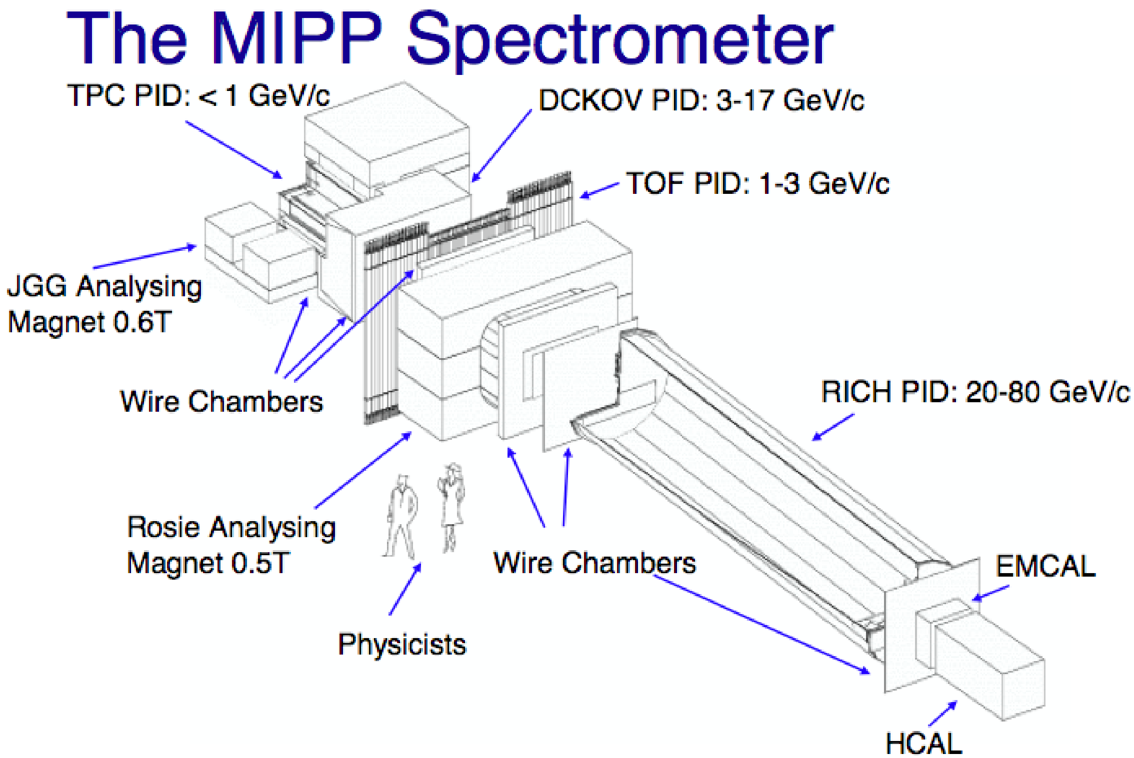

Figure I-1. Perspective view of the MIPP Detectors. Beam comes from upper left.

Appendix II. The Calorimeters

Figure II-1 shows a side view of the EMCAL and HCAL. Figure II-2 shows a more detailed side view of the HCAL. The EMCAL uses lead plates interspersed with wire proportional chambers. Photons shower in the lead plates and their energies and locations can be determined by the proportional chambers. Most of the photon energy is contained within the EMCAL. The HCAL consists of 1" thick steel plates interspersed with sheets of plastic scintillator. The light from the plastic scintillators is collected by optical fibers and brought to 8 photomultiplier tubes. The energy of the hadron can be estimated by the total pulse height from the phototubes.

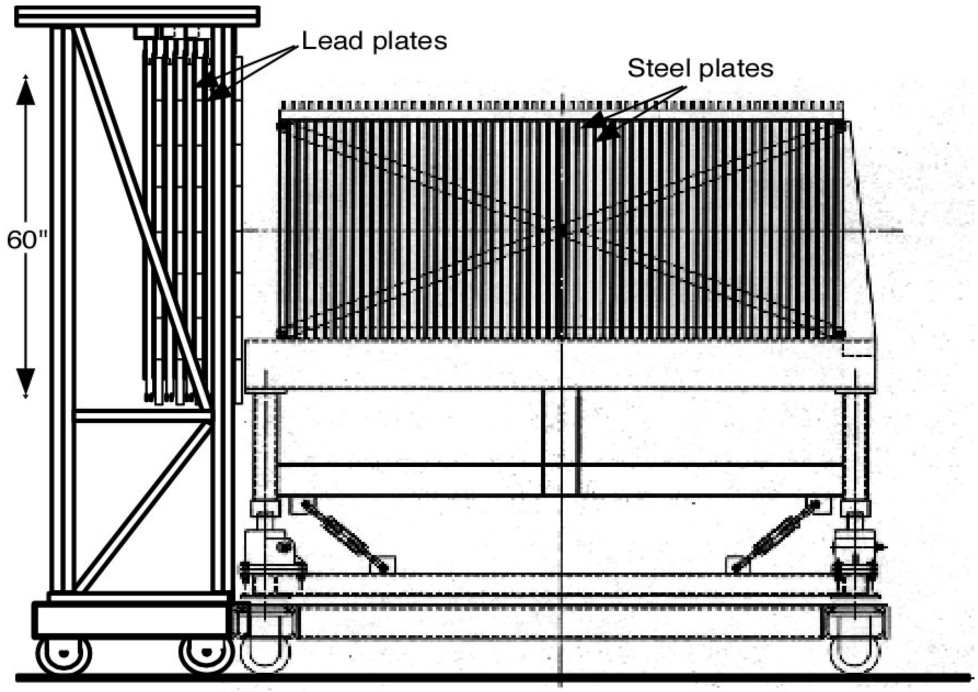

Figure II-1. Side view of the EMCAL and HCAL

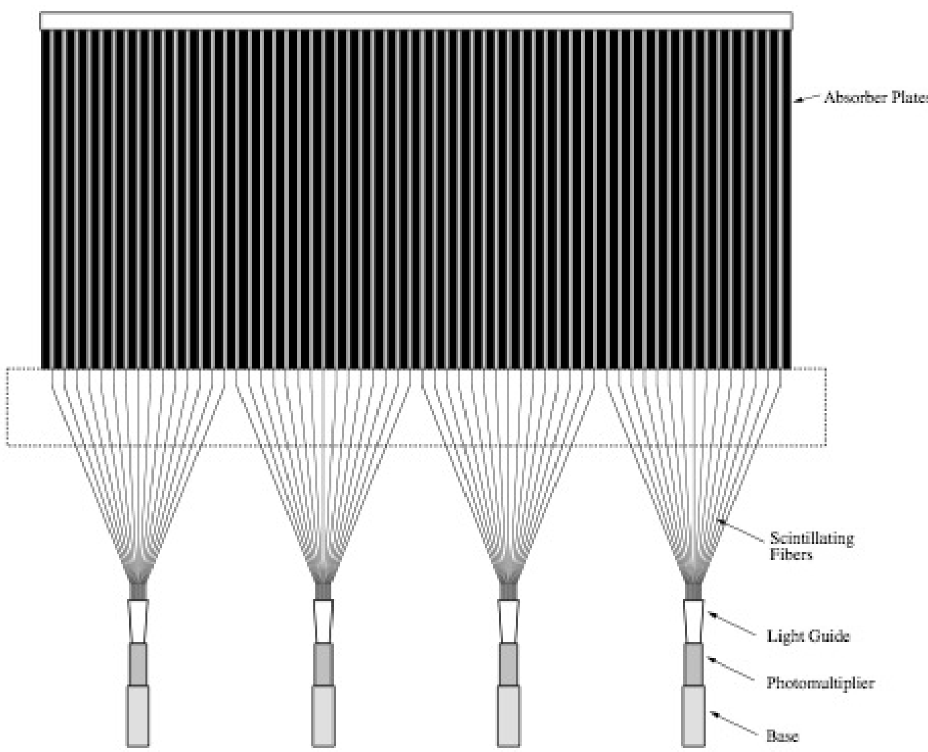

Figure II-2. Detailed side view of the HCAL. The absorber plates are 2.54 cm steel.