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A Search for the Production of Direct Leptons in Nucleon-Nucleus and Nucleus-Nucleus Collisions

Progress Report for the period
April 1, 1988 - March 31, 1991

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Submitted by

The Intermediate Energy Nuclear Physics Group
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Introduction

The purpose of this report is to describe activities performed by the Intermediate Energy Nuclear Physics Group (IENPG) at the Louisiana State University (LSU) under the terms of grant DE-FG05-88ER40445. This report covers the period of two and a half years between April 1, 1988, and October 1, 1990.

Personnel

The IENPG currently comprises undergraduates Robert Blanchard, Mark Frey, Alfred Haimbach, and John Hellman; graduate students Lian Mao and Xiaocong Zhang; staff associate Dee Hart; senior postdoctoral research associate Zhi-fu Wang; and principal investigator P. N. Kirk. Of the four undergraduates, Mr. Frey is a senior, Mr. Blanchard is a sophomore, and Messrs. Haimbach and Hellman are entering freshmen. Mr. Zhang is a recent arrival at LSU, and Mr. Mao is now in his second year of graduate school. Neither has as yet taken the general examination. Zhi-fu Wang will soon complete the third year of his tenure in the IENPG, and he has indicated his intention to remain in this group for the next few years.

We regard the education of students as being an important part of our responsibilities to the DOE and to society as a whole. For this reason we take pride in the achievements of our undergraduates as well as our graduates students, and we are pleased to note that several of them have done well recently. Three of our former undergraduates received their degrees at the last convocation, and all three have entered outstanding graduate schools. Mr. Alijeet Bains, whose quiet and effective presence will be greatly missed in this laboratory, selected the University of Illinois from among his many options. Mr. Robert Ryland decided to enroll at the University of Maryland. Mr. Todd Murry enrolled in medical school at the Louisiana State University in New Orleans as a candidate for both the MD and the PhD degrees.

All of our current undergraduates, Messrs. Blanchard, Frey, Haimbach, and Hellman have been honored for their academic achievements. All four hold one of the so-called "Chancellor's Aide" fellowships, which is a distinction recently created by the Board of Supervisors in an attempt to entice Louisiana's most outstanding high school graduates into attending college in Louisiana rather than in one of the eastern universities as formerly seemed to be their custom.

Although we claim no credit for the abundant natural abilities of these students, we have played a major role in sustaining their general interest in physics and, more specifically, in developing their interest in nuclear physics. In fact during our final meeting before he left for Maryland, Mr. Ryland said "I learned as much physics during the year and a half that I worked in this lab as I learned in any four courses here.". Mr. Bains, expressing similar sentiments, even inquired as to whether or not there might be summer employment for him in this laboratory.

Publications

During the period between April 1, 1988, and the present twenty-seven papers that were supported in part by grant DE-FG05-88ER40445 appeared in print. These are:

1. Measurements of R and a Search for Heavy Quark Production in e^+e^- Annihilation at $\sqrt{s}$ = 48 and 50 GeV, E. Sagawa, et al., Phys. Rev. Lett. 60 (1988) 93

2. Search for Isolated Leptons in Low-Thrust e^+e^- Annihilation Events at $\sqrt{s}$ = 50 and 52 GeV, S. Igarashi et al., Phys. Rev. Lett. 60 (1988) 2359

3. First Observation of Dielectron Production in Proton Nucleus Collisions Below 10 GeV, G. Roche et al., Phys. Rev. Lett. 61 (1988) 1069

4. Experimental Mass Limit for a Fourth Generation Sequential Lepton from e^+e^- Annihilation at $\sqrt{s}$ = 56 GeV, G.N. Kim et al., Phys. Rev. Lett. 61 (1988) 911

5. Measurements of Cross Sections and Charge Asymmetry for $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ for $\sqrt{s}$ = 52, 55, and 56 GeV, A. Bacala et al., Phys. Lett. B 218 (1989) 112

6. Design of the Bevalac Heavy Ion Spectrometer System and Its Performance in Studying C^{12} Fragmentation, J. Engelage et al., Nucl. Instrum. Methods A 277 (1989) 431

7. Measurements of the e^+e^- Total Hadronic Cross Section and A Determination of M_Z and $\Lambda_{\overline{MS}}$, T. Mori et al., Phys. Lett. B 218 (1989) 499

8. Subthreshold Anti-Proton Production in Si^{28} + Si^{28} Collisions at 2.1 GeV per Nucleon, J. B. Carroll et al., Phys. Rev. Lett. 62 (1989) 1829

9. Threshold Behavior of Direct Electron Pair Production in P-Be Collisions, C. Naudet et al., Phys. Rev. Lett. 62 (1989) 2652

10. Search for the Substructure of Leptons in High Energy QED Processes at TRISTAN, S. K. Kim et al., Phys. Lett. B 223 (1989) 476

11. Dielectron Production in Ca + Ca Collisions at 1.0 and 2.0 GeV, G. Roche et al., Phys. Lett. B 226 (1989) 228

12. Experimental Evidence for the Non-Abelian Nature of QCD from a Study of Multijet Events Produced in e^+e^- Annihilations, I. H. Park et al., Phys. Rev. Lett. 62 (1989) 1713

13. Mass and Transverse Momentum Dependence of the Dielectron Yield in P-Be Collisions at 4.9 GeV, A. Letessier-Selvon et al., Phys. Rev. C 40 (1989) 1513

14. Search for Unstable Heavy Neutral Leptons in e^+e^- Annihilations at $\sqrt{s}$ from 50 to 60.8 GeV, N. M. Shaw et al., Phys. Rev. Lett. 63 (1989) 1342

15. Comparison of Quark and Gluon Jets Produced in High Energy e^+e^- Annihilations, Y. K. Kim et al., Phys. Rev. Lett. 63 (1989) 1772

16. Search for a Fourth-Generation Charge $-1/3$ Quark, S. Eno et al., Phys. Rev. Lett. 63 (1989) 1910

17. Subthreshold Anti-Proton, K^-, K^+, and Energetic Pion Production in Collisions between Relativistic Nuclei, A. Shor et al., Phys. Rev. Lett. 63 (1989) 2192

18. Measurement of $e^+e^- \rightarrow b\bar{b}$ Forward-Backward Charge Asymmetry between $\sqrt{s} = 52$ and 57 GeV, H. Sagawa et al., Phys. Rev. Lett. 63 (1989) 2341

19. Mid-rapidity π^-/π^+ Ratios in 1.05 GeV/nucleon $Ca^{40} - Ca^{40}$ Collisions, J. W. Harris et al., Phys. Rev. C 41 (1990) 147

20. Forward-Backward Charge Asymmetry in $e^+e^- \rightarrow$ Hadron Jets, D. Stuart et al., Phys. Rev. Lett. 64 (1990) 983

21. Multihadron-event Properties in e^+e^- Annihilation at $\sqrt{s} = 52 - 57$ GeV, Y. K. Li et al., Phys. Rev. D 41 (1990) 2675

22. A Search for SUSY Particles in e^+e^- Annihilation at $\sqrt{s} = 50 - 60.8$ GeV, Y. Sakai et al., Phys. Lett. B 234 (1990) 534

23. A Search for Lepto Quark and Colored Lepton Pair Production in e^+e^- Annihilations at Tristan, G. N. Kim et al., Phys. Lett. B 240 (1990) 243

24. Observation of Anomalous Production of Muon Pairs in e^+e^- Annihilation into Four Lepton Final States, Y. H. Ho et al., Phys. Lett. B 244 (1990) 573

25. The Di-Lepton Spectrometer, A. Yegneswaran et al., Nucl. Instrum. Methods A 290 (1990) 61

26. Mass Limits of Charged Higgs Boson at Large tanβ from e^+ e^- Annihilations at $\sqrt{s} = 50 - 60.8$ GeV, Y. Sakai et al., Phys. Rev. D 42 (1990) 949

27. Measurements of R for e^+ e^- annihilations at the KEK collider TRISTAN, T. Kumita et al., Phys. Rev. D 42 (1990) 1339

Ongoing Activities of the IENPG

The purpose of the remainder of this report is to acquaint the reader with a few of this group's more recent accomplishments. We shall address the questions which seem to us to be the most likely to occur, such as: In what specific ways has the IENPG contributed to the collaborations in which it participates? What are its areas of expertise? How do the individual members contribute? Have the students been effectively integrated into the program?

This report has been prepared under the assumption that the reader knows nothing about the IENPG other than what he or she reads in this report. Consequently some readers, such as the technical monitor himself, may find portions of the following pages repetitive. Specifically, some portions of sections (a), (b), and (e) were included in previous progress reports, although a large portion of all three of these sections is new. Sections (c) and (d) are entirely new.

(a) subthreshold production experiment

In February, 1989, the IENPG was invited to join a longstanding collaboration between Benenson of Michigan State and Schroeder of LBL. The collaboration has been studying the production of pions in collisions between heavy nuclei at energies, per incident nucleon, that lie below the threshold for the production of pions in nucleon-nucleon collisions. A former postdoctoral research associate in the IENPG, Dr. Jean-Francois Gilot, participated in the early activities of the collaboration while being supported by this contract, but the IENPG did not become involved collectively until February, 1989.

Although we were the final addition to the collaboration, we made significant contributions to the experiment. During the summer of 1989 two of our undergraduates, Messrs. Alijeet Bains and Todd Murry, flew to Berkeley and worked exclusively on this experiment. They cleaned the counting house, restored the beam line to some semblance of order, built two new hodoscopes,and repaired a third.

In addition during the summer and fall of 1989, Dr. Zhi-fu Wang and Mr. Lian Mao, a graduate student who came to us from Peking University, rebuilt the six multiwire proportional chambers that were used in the data logging runs. For reasons that are not understood by anyone, the wire chambers, which were left in place after the last data logging run several years ago, suffered some sort of catastrophe. Every sense plane in every chamber contained at least a few broken wires, and most planes contained nothing but broken wires. The chambers had been used for well over a decade and had required little maintenance during that period of time. That they should fail so suddenly and so completely is mysterious indeed, but that was the situation which the IENPG set about to remedy.

Three of the chambers are small, almost pocket-sized detectors, but three of them are large. Dr. Wang and Mr. Mao rewound the large chambers first and installed them during the summer. Dr. Wang rewound the three smaller ones during the months of September and October, and they were installed in the beamline during December, 1989, and January, 1990.

In summary, then, the IENPG built both the hodoscopes and the wire chambers that were used for data logging. We are especially proud to note that all these detectors were completed and mounted a month before the data logging began.

The spokesman for this experiment is Dr. Jack Miller, and we are enclosing below copies of mail messages he sent to us in regard to the contributions of the IENPG. The texts of Dr. Miller's messages have not been edited, but we have used bold faced type to emphasize portions of the texts to which we call the reader's attention.

From:	IN%"miller@LBL.BITNET"
	22-AUG-1989 13:34:36.76
To:	phkirk@LSUVAX.SNCC.LSU.EDU
CC:	
Subj:	
Received:	from JNET-DAEMON by LSUVAX.SNCC.LSU.EDU;
	Tue, 22 Aug 89 13:34 CDT
Received:	From LBL(MAILER) by LSUVAX with Jnet id 3221 for PHKIRK@LSUVAX;
	Tue, 22 Aug 89 13:34 CST
Date:	Tue, 22 Aug 89 11:29:56 PDT
From:	miller@LBL.BITNET
To:	phkirk@LSUVAX.SNCC.LSU.EDU
Message-Id:	(890822112956.23e01d89@Csa2.LBL.Gov)
	X-ST-Vmsmail-To: ST%"phkirk@lsuvax.bitnet"

Welcome back, Paul. Hope you had a great trip. You may have already spoken with Zhi-fu and Lian, but the status of the detector is as follows:

G2 and G3 have been reconstructed and installed, and G1 has been re-glued.

MWPC's P4, P5 and P6 have been bench tested and installed. The efficiencies were measured by Ken Suzuki with a borrowed PCOS system, and are

around 97-98%. Ken thinks that we can improve that a little by setting the discriminator thresholds sufficiently low.

All in all, a very productive summer, thanks in large part to the LSU crew. You have made a tremendous contribution to the experiment already, and I appreciate it very much. As advertised, Zhi-fu does the work of two ordinary mortals, and is a delightful guy, besides. Lian did an excellent job, as well. I look forward to having Zhi-fu come out during the fall, and I hope that you can spring Lian loose, at least for the winter run, which should coincide with his semester break.

Best regards,

Jack

From:	IN%"miller@LBL.BITNET"
	22-AUG-1989 13:51:46.96
To:	benenson%nscl%msuhep.hepnet@LBL.BITNET,
	cebra%nscl%msuhep.hepnet@LBL.BITNET,
	ogilvie%nscl%msuhep.hepnet@LBL.BITNET,
	stevenson%nscl%msuhep.hepnet@LBL.BITNET,
	westfall%nscl%msuhep.hepnet@LBL.BITNET,
	wilson%nscl%msuhep.hepnet@LBL.BITNET,
	phkirk@LSUVAX.SNCC.LSU.EDU
CC:	
Subj:	status report
Received:	from JNET-DAEMON by LSUVAX.SNCC.LSU.EDU;
	Tue, 22 Aug 89 13:51 CDT
Received:	From LBL(MAILER) by LSUVAX with Jnet id 3231
	for PHKIRK@LSUVAX;
	Tue,22 Aug 89 13:51 CST
Date:	Tue, 22 Aug 89 11:49:35 PDT
From:	miller@LBL.BITNET
Subject:	status report
Message-Id:	(890822114935.23e01d89@Csa2.LBL.Gov)
	X-ST-Vmsmail-To: @E957

1) MWPC's P4, P5, P6 have been installed, but not surveyed in place. Efficiencies, measured with a borrowed PCOS-3 system, are 97-98%. A new gas system has been installed, and N2 is flowing to all three chambers.

2) Scintillator hodoscopes G2 and G3 have been rebuilt and installed. G1 has been repaired.

3) The B30-3 cave and shack have been cleaned and painted.

Items 1) and 2) were accomplished thanks mainly through the efforts of Z. Wang, L. Mao, T. Murry, A. Bains (LSU) and T. Suzuki (RIKEN).

Please let me know asap when and whether you will be available during December and January.

J.M.

In Figure 1, which is on the following page, we show a photograph of the experimental area. The chambers that were denoted by the symbols P4, P5, and P6 in the text of Dr. Miller's messages are located behind the bending magnet. Chambers P1, P2, and P3 are located in front of the bending magnet. Like most other experimental areas, ours was a bit cluttered, and the reader may have difficulty in identifying our chambers. They are perhaps most easily located by visually following the white polyflow tubing that hung from the ceiling both in front of and behind the magnet.

We are especially pleased with the performances of our MWPC. During the entire run not one of the chambers failed or required maintenance. In fact, the author has been building MWPC for 20 years, and these are the finest wire chambers I have yet encountered. They were efficient, reliable, and extraordinarily quiet. Dr. Wang and I studied the characteristics of the chambers shortly after their installation, and in early January, 1990, we submitted a report on our findings to Drs. Miller and Schroeder. The text of that report follows Fig 1.

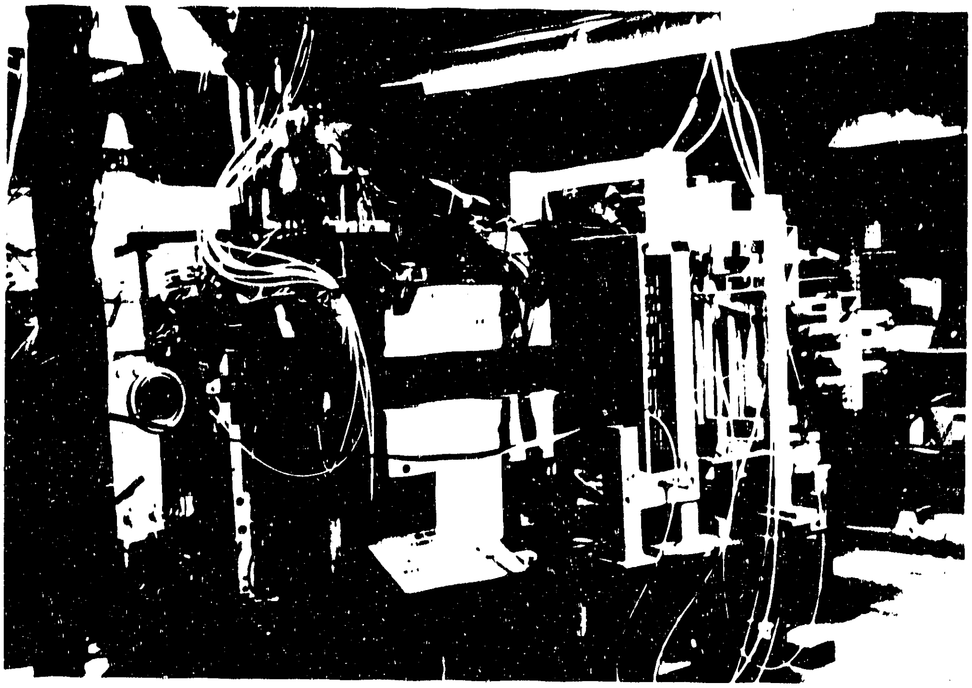


Figure 1

From:	DLS::KIRK	7-Jan-1990 23:23:02.82
To:	DLS::MILLER	
CC:	DLS::SCHROEDER	
Subj:	multiwire proportional chambers	

We have finishing checking the MWPC, and we would like to provide you with a copy of the results for future reference.

First let us define our coordinate system. We do not know whether or not you have established a standard coordinate system for the experiment. If a standard coordinate system does exist, then you might perhaps want to translate our results in order that they be consistent with existing conventions. Our z axis is defined by the line that joins the center of the target to the center of the entrance aperture of the magnet. Our y axis is antiparallel to the force exerted by gravity on anything, and our x axis is chosen so that the resulting coordinate system is right-handed. Consequently the x and z axes lie in the horizontal plane, and the y axis points upward.

The MWPC are numbered in order of increasing distance from the target. Chambers 1, 2, and 3 are located in front of the magnet, and chambers 4, 5, and 6 are located behind the magnet.

We have checked every wire in every chamber. We used an Fe^{55} source in order that the performance we observed might approximate the response of the chambers to minimumly ionizing particles. The test consisted of plugging the ribbon cable one-by-one into a single, 16 channel LeCroy amplifier. We then examined each channel individually using an ECL probe and a Tektronix oscilloscope, model 2467, that was borrowed from the DLS shack. This particular oscilloscope contains an image intensifier, and consequently single traces were easily visible.

The low voltages for the single amplifier card were set to +4.73 and -4.87 volts. The threshold voltage for the card was set to 2.4 volts. We made no attempt at all to establish a high voltage plateau for the chambers. Instead we just increased the high voltage until we observed conveniently bright traces when the chambers were illuminated with the source. For this reason the high voltages that are listed below should not be taken too seriously. Legitimate operating voltages for these chambers, like all the other detectors, should be established by proper high voltage plateaus.

The high voltages at which the tests were carried out are:

Chamber	Voltage
1	-3400
2	-3400
3	-2950
4	-4000
5	-4050
6	-4100

We are pleased to report that the chambers held high voltage beautifully. There was not a single breakdown during the entire duration of the tests, which was at least 20 hours.

Two questions were addressed in this test. First, we determined whether or not the wire under study delivered current to the amplifier when illuminated by the source. Second we determined how noisy the wire under study was when the source was removed.

Wires were classified as being noiseless, a bit noisy, noisy, very noisy, or VERY NOISY. By "noiseless" we do not really mean that the counting rate with the source removed was zero but rather that it was so low we could count individual pulses easily by observing the oscilloscope. In addition we connected the output of the amplifier to a visual scaler and measured the background counting rate for a fairly large sample of wires. **Wires classified as "noiseless" counted at a typical rate of 2 hz, and those classified as "a bit noisy" counted at a typical rate of 30 hz. For your amusement I am including here the results of measurements on the counting rates of wires classified as "noisy": 90 hz, 100 hz, 130 hz, 140 hz, 160 hz, 170 hz, 190 hz, 210 hz, 280 hz, 300 hz, 330 hz, 340 hz, 350 hz, and 360 hz. There weren't many wire classified as "very noisy", but typical rates for such wires were 550 hz, 570 hz, and 860 hz. There were too few wires classified as "VERY NOISY" to be concerned with, but counting rates for such wires varied between 20 khz and 100 khz.**

It is perhaps a measure of the relative success of this endeavor that we regard here as "noisy" background counting rates that would normally be regarded as excellent. We think you will agree that these are very quiet chambers indeed.

The letters "x" and "y" throughout the following table refer to the coordinate being measured. That is, the wires in an "x" plane are themselves vertical, but they measure a coordinate in the horizontal plane.

Here are our results:

Chamber 1
plane: forward x

number of wires:	64
dead wires:	0
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 1
plane: rear x

number of wires:	64
dead wires:	1 (#24)
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 1
plane: forward y

number of wires:	64
dead wires:	1 (#37)
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 1
plane: rear y

number of wires:	64
dead wires:	0
slightly noisy wires:	0
noisy wires:	0

very noisy wires: 0
VERY NOISY wires: 0

Chamber 2
plane: x

number of wires: 64
dead wires: 0
slightly noisy wires: 0
noisy wires: 0
very noisy wires: 0
VERY NOISY wires: 0

Chamber 2
plane: y

number of wires: 64
dead wires: 0
slightly noisy wires: 0
noisy wires: 2 (#38 and #47)
very noisy wires: 0
VERY NOISY wires: 0

Chamber 2
plane: u

number of wires: 96
dead wires: 0
slightly noisy wires: 0
noisy wires: 0
very noisy wires: 0
VERY NOISY wires: 0

Chamber 3
plane: x

number of wires: 64
dead wires: 0
slightly noisy wires: 0
noisy wires: 0
very noisy wires: 0
VERY NOISY wires: 0

Chamber 3
plane: y

number of wires: 64
dead wires: 2 (#20 and #21)
slightly noisy wires: 2 (#58 and #62)
noisy wires: 0
very noisy wires: 2 (#59 and #61)
VERY NOISY wires: 0

Chamber 4
plane: x

number of wires: 272
dead wires: 3 (#13, #14, and #31)

slightly noisy wires:	2 (#132 and #133)
noisy wires:	7 (#134, #135, #153, #166, #174, #186, #190)
very noisy wires:	2 (#67 and #170)
VERY NOISY wires:	0

Chamber 4
plane: forward y

number of wires:	208
dead wires:	0
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 4
plane: rear y

number of wires:	208
dead wires:	0
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 4
plane: u

number of wires:	319
dead wires:	3 (#162, #217, and #262)
slightly noisy wires:	0
noisy wires:	0
very noisy wires:	0
VERY NOISY wires:	0

Chamber 5
plane: x

number of wires:	288
dead wires:	1 (#145)
slightly noisy wires:	0
noisy wires:	11 (#27, #61, #97, #105, #142, #147, #164, #194, #203, #206, #254)
very noisy wires:	3 (#35, #49, and #50)
VERY NOISY wires:	2 (#62 and #88)

Chamber 6
plane: x

number of wires:	288
dead wires:	0
slightly noisy wires:	11 (#19, #23, #30, #31, #38, #49, #50, #67, #73, #90, #166)
noisy wires:	13 (#11, #37, #48, #94, #106, #159, #167, #171,

#195, #196, #201, #244)
#246)

very noisy wires: 0
VERY NOISY wires: 0

In summary these are certainly the best MWPC that we have yet built. In fact, their performance is almost too good to be true. Neither of us can see any reason to devote further effort to the chambers themselves, and with this report we are therefore terminating this project which has occupied us for the last six months.

The next obstacle will be the amplifiers, and if our experience with the DLS is a reliable guide, the amplifiers may present more serious problems than the chambers themselves.

We are delighted to report that the chambers worked as well during the experiment as they did during the bench tests. On the following pages we include a representative sample of distributions that were obtained under actual experimental conditions. Figures 2 and 3 show a vertical and horizontal profile, respectively, for the ensemble of particles that entered the spectrometer. Figure 4 is a scatter plot that shows a strong correlation between the x and x′ coordinates as measured in chamber 1. Figure 5 is a scatter plot that shows the correlation between the x coordinates as measured in chambers 1 and 2. The correlation is not as dramatic as that shown in Fig 4 because of the distance between the chambers and the angular divergence of the trajectories, but it is decidedly present.

(b) testing and selection of PCOS amplifiers

Two paragraphs above we alluded to experience with the PCOS III amplifiers that are used to process signals from the drift chambers in the DiLepton Spectrometer (DLS) at LBL. As the reader may perhaps have inferred, our experience with this system, initially at least, was not altogether satisfactory.

Although the PCOS III system is commonly used throughout this country and Europe, almost everyone who uses them has problems. First, it has been almost everyone's experience that if the low voltages are set to the recommended value, ±5.00 volts, then the amplifiers will oscillate no matter how fine the power supplies may be and no matter how well filtered the input lines may be. Second, after connecting a group of amplifiers to the wires in one of the chambers, we found it difficult and frequently impossible to find a single value for the threshold voltage at which every amplifier in the group functioned properly. For example, at some nominal value for threshold voltage a portion of the amplifiers would work properly and efficiently, but other amplifiers would be inefficient. In order to bring the inefficient amplifiers into efficient operation we would lower the threshold voltage only to discover that the previously efficient amplifiers began to oscillate.

It is possible to solve this problem by maintaining a high threshold voltage and by increasing the high voltage supplied to the chamber accordingly. For many months this was the solution adopted by our collaboration. Unfortunately this solution has undesirable consequences, such as an increase in the multiplicity of hits and a decrease in the lifetime

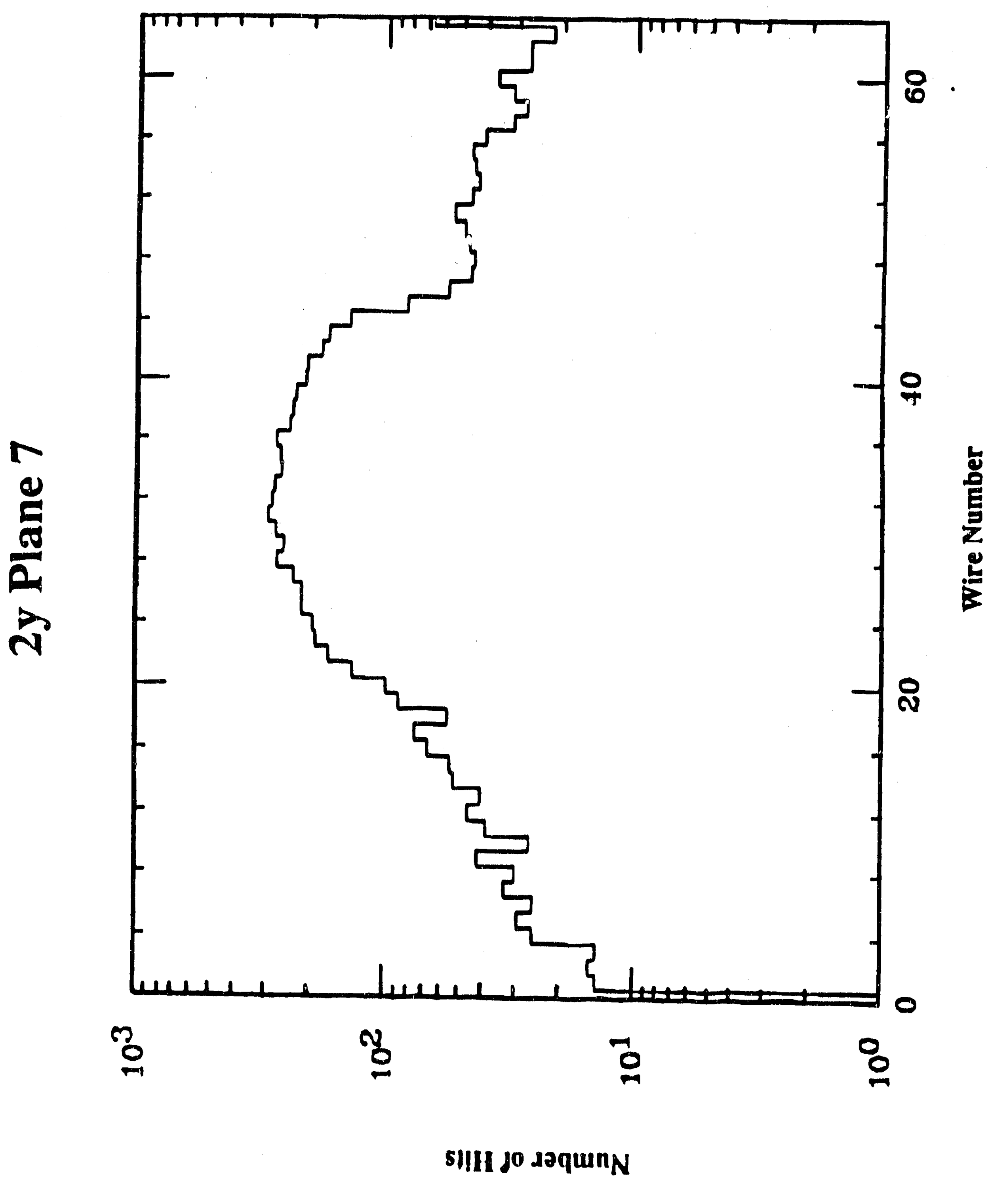


Figure 2

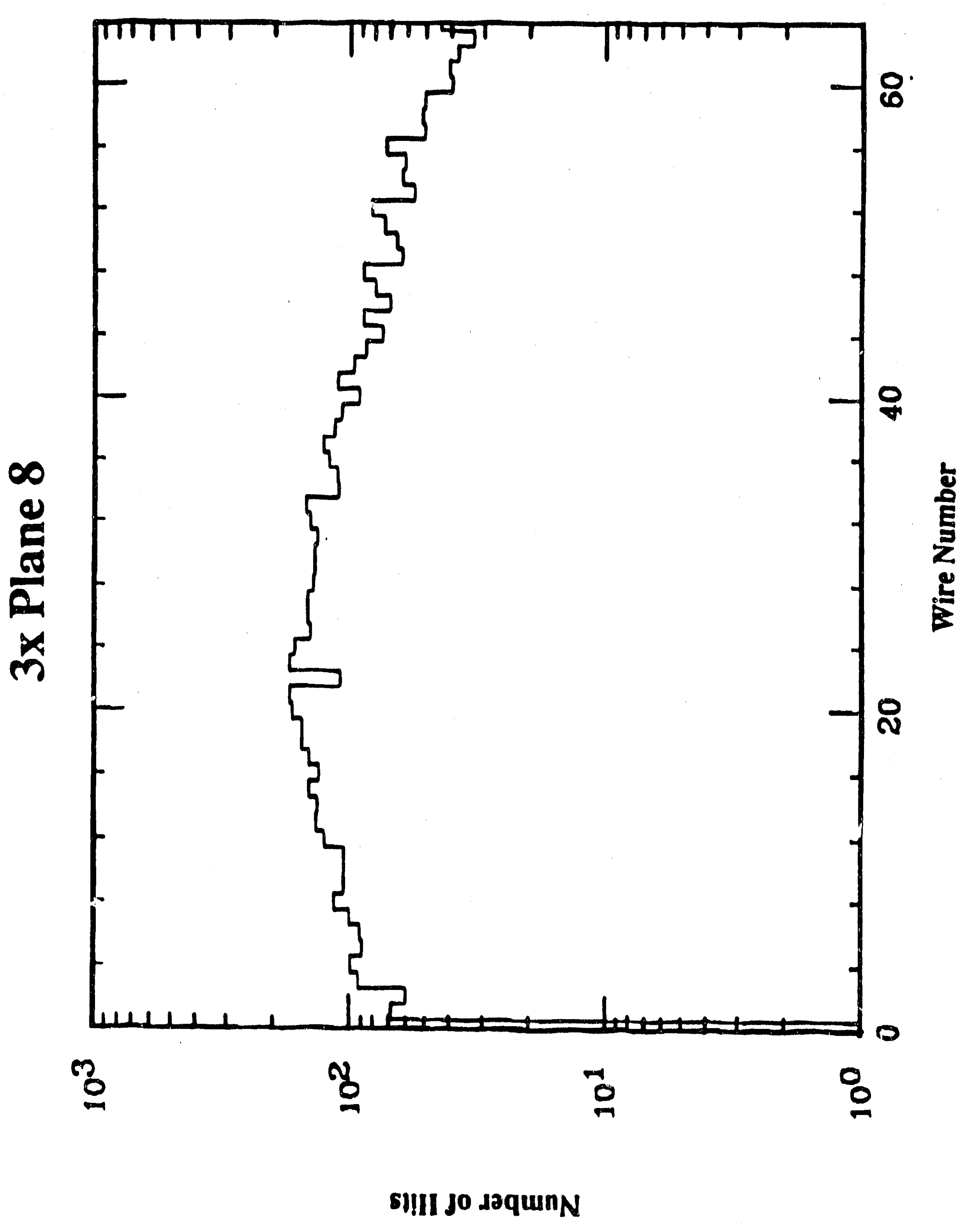


Figure 3

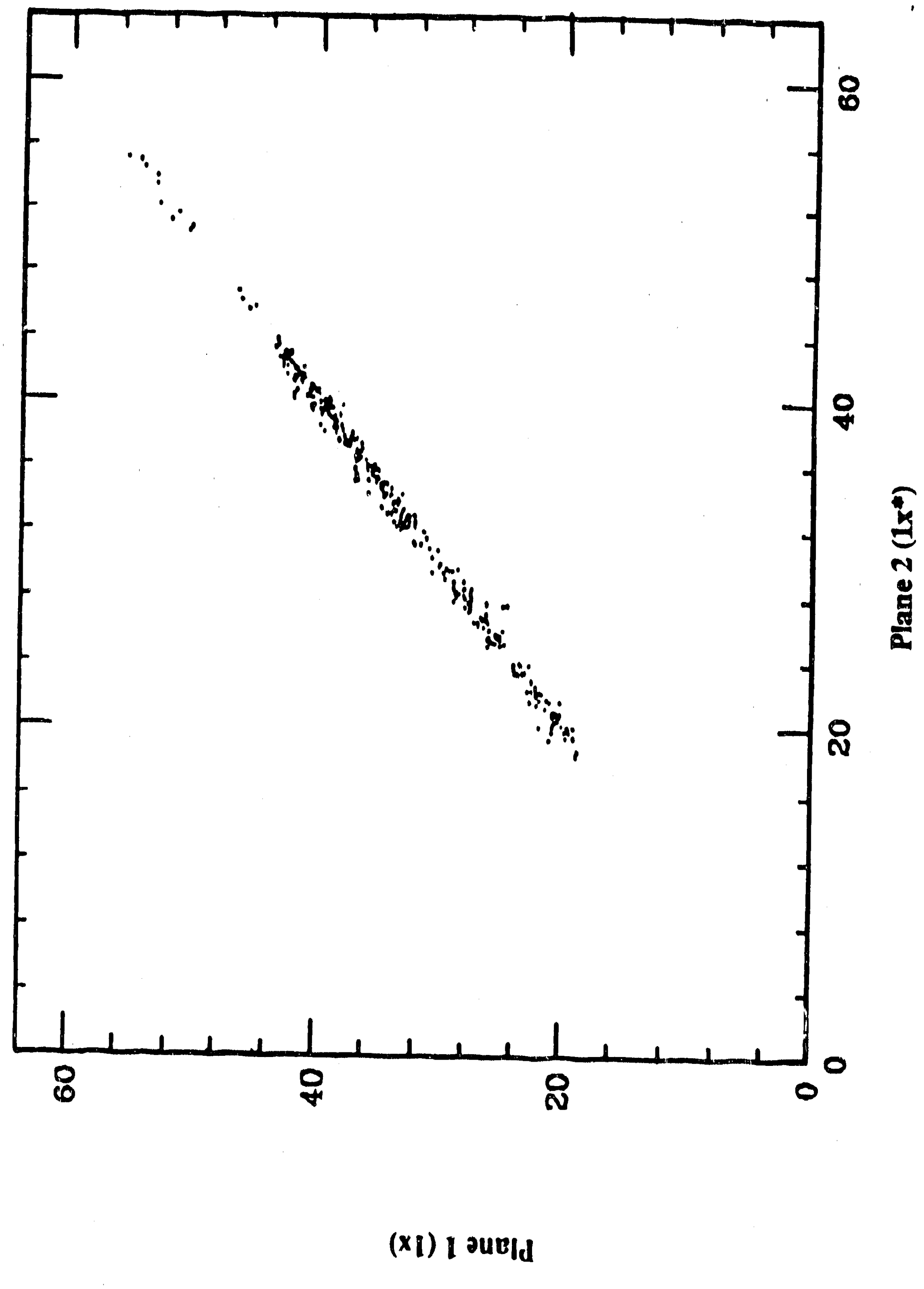


Figure 4

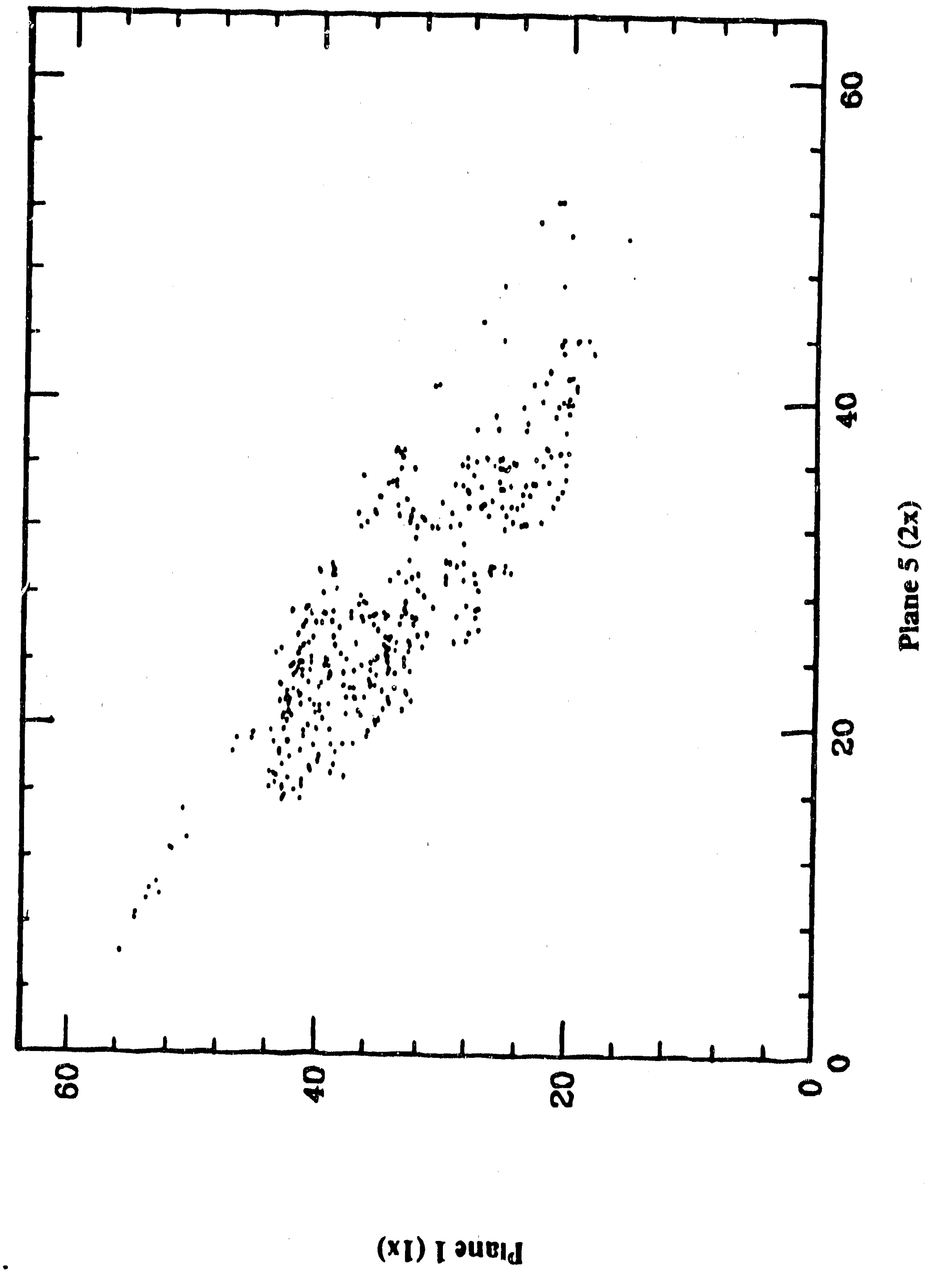


Figure 5

of the chamber itself.

The IENPG decided to devise a procedure for selecting amplifiers with similar characteristics. Our objective was to mount similar amplifiers on the same card and to use groups of similar cards on a chamber. This selection procedure was tedious but conceptually simple, and it was carried out at LSU by Mr. Mao.

The first step was to choose a value for the amplitude of the output pulse from a signal generator. This was done by arbitrarily selecting one amplifier as a standard for calibration. The low voltages applied to the standard amplifier were set to ± 5.00 volts, and the threshold voltage was set to 2.00 volts. The output of the signal generator, after appropriate attenuation and shaping, was connected to the input of the standard amplifier, and the amplitude of the pulse was slowly increased from zero. When the amplitude of the pulse reached some minimum value the standard amplifier began to fire, and at a slightly higher amplitude the standard amplifier fired with an efficiency of 100%. We shall denote the smallest amplitude at which the standard amplifier was fully efficient by the symbol A_s. According to the literature supplied by LeCroy, when the amplitude of the output pulse from the signal generator was fixed at A_s the current being supplied to the standard amplifier was 4.0 ± 0.8 microamps. The amplitude of the output pulse from the signal generator was fixed at A_s for the entire duration of the selection procedure.

After the amplitude of the output pulse from the signal generator was fixed, all amplifiers, including the standard one, were subjected to the same sequence of steps. First, the magnitude of the positive low voltage was decreased from 5.00 volts to 4.75 volts. The reduction in voltage was necessary in order to decrease the noise to a tolerable level. Because the magnitude of the positive low voltage also controls the gain of the amplifier, the decrease in voltage caused the amplifier being tested to stop responding to the input current. We then slowly lowered the threshold voltage until the amplifier being tested was once again fully functioning. This value of threshold voltage, which we shall label V_h, was recorded. Then the threshold voltage was lowered again until finally, at some value which we label V_l, the amplifier being tested began to oscillate. The range of threshold voltages, V_t, that satisfied the inequality $V_l \leq V_t \leq V_h$ was the range in which the amplifier being tested responded to currents of 4 microamps with full efficiency but without oscillation.

In what must be regarded as an act of either heroism or masochism Mr. Mao tested all 760 amplifiers in the group connected to the front drift chambers and recorded V_h and V_l for all of them. Many amplifiers had no acceptable range of operation at all, by which we mean that V_l was larger than V_h. These amplifiers were retired from use. Some amplifiers had ranges of acceptable operation that hardly overlapped at all with others. Nonetheless, as a consequence of Mr. Mao's efforts, we were able to select a single value of V_t at which all the remaining amplifiers functioned properly.

This effort was spectacularly successful. Indeed, it will be a long time until we enjoy a comparable success. In May, 1990, we were able to demonstrate our success quantitatively during two weeks of running that were devoted exclusively to the study of the MWPC and the testing of the liquid hydrogen target.

On the pages that follow we exhibit seven graphs. Each of these graphs corresponds to one of the seven planes of wires in the left front drift chamber. The ordinate on each graph is the probability for an accidental coincidence anywhere on the plane expressed in percent. The abscissa on each graph is the threshold voltage. We think the reader will agree that the results are striking, and perhaps we should discuss briefly the significance of these results.

On first glance one might be startled at an accidentals rate of say, 10%, but it is important to recall that some of the planes contain 50 wires. The probability for an accidental coincidence per wire is then seen to be 0.2%, which is excellent by any standard, especially since the width of the gate was 1 microsecond. One sees that at thresholds lower than approximately two volts oscillation and pickup from a local FM station become intolerable. The rise in accidentals rate is very nearly vertical, in fact. On the other hand for threshold voltages above approximately two volts there is no observable decrease in the probability for an accidentals coincidence, and this level then represents the irreducible minimum due to cosmic rays and background within the cave.

(c) the transverse energy, or E_t, detector

The IENPG also collaborated recently in an experiment that was designed to search for the production of antiprotons and antideuterons at the AGS. The spokesman for the experiment was Dr. Hank Crawford of the Space Sciences Laboratory at LBL. Also participating in the collaboration were physicists from Columbia University, BNL, Johns Hopkins University, Tokyo University, and UCLA. The data logging phase of the experiment began in early May, 1990, and the analysis is underway at this moment. Data were logged with both protons and relativistic Si nuclei as projectiles.

The IENPG was responsible for designing and building the so-called "transverse energy" detector, which we usually called "E_t" for convenience. In general the motivation for building a transverse energy detector is to measure the centrality of the collisions in which the experimenter happens to be interested, but the motivation for this particular transverse energy detector was a little different. This particular detector was built with an eye to a subsequent experiment rather than the present experiment, and in this sense the project was very much developmental in nature.

There were two aspects to the design of this detector that we thought interesting and challenging. First, because of the intense beams and thick targets that were used in this experiment, an interaction between projectile and target occurred every five to ten nanoseconds. In addition, the physical volume available for the detector was small.

My colleagues in the IENPG and I thought that no detector located in the forward hemisphere could possibly maintain linearity in the face of the enormous counting rates to

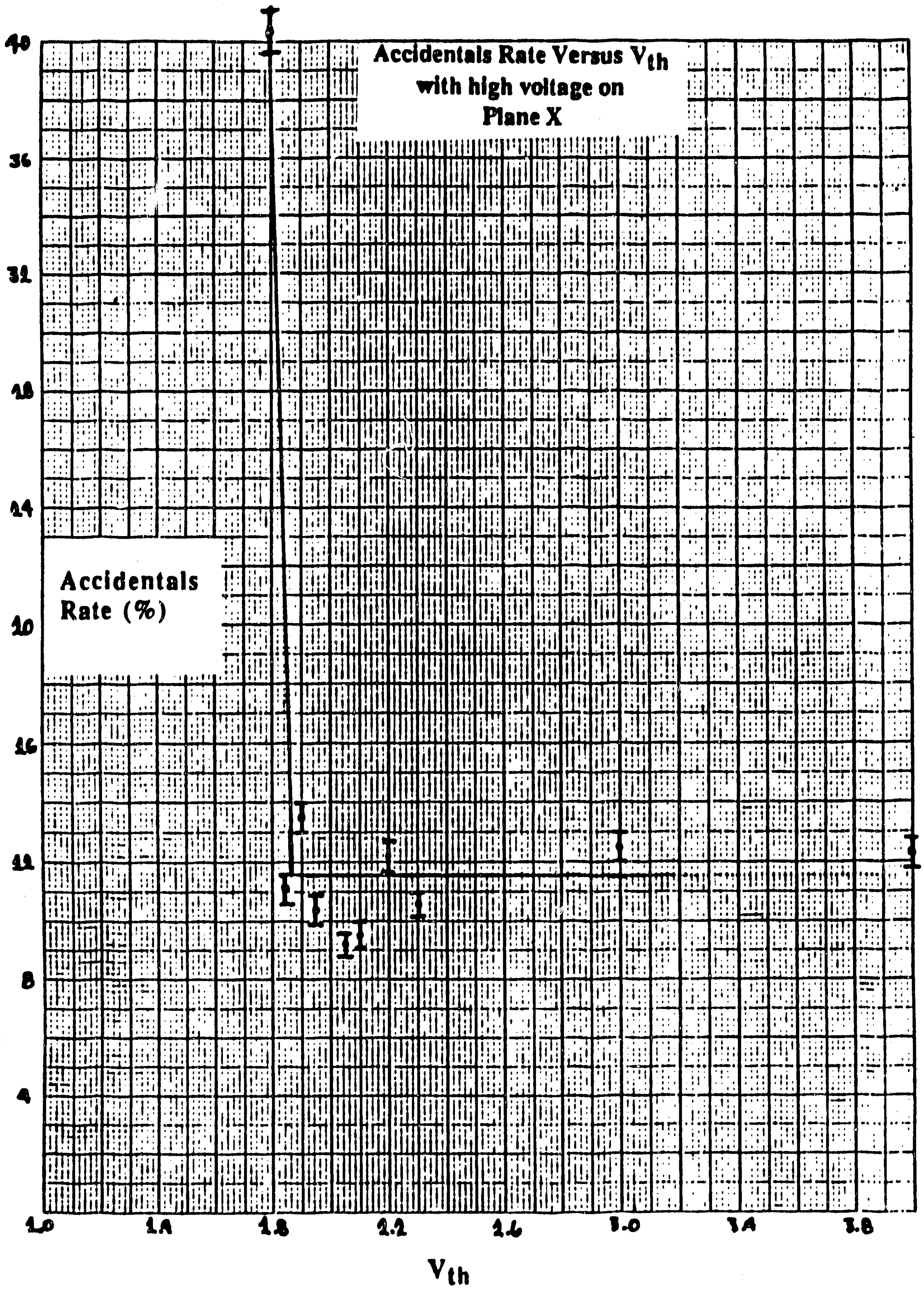

Accidentals Rate Versus V_th
with high voltage on
Plane X
Accidentals
Rate (%)
40
36
32
28
24
20
16
12
8
4
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
V_th

Figure 6

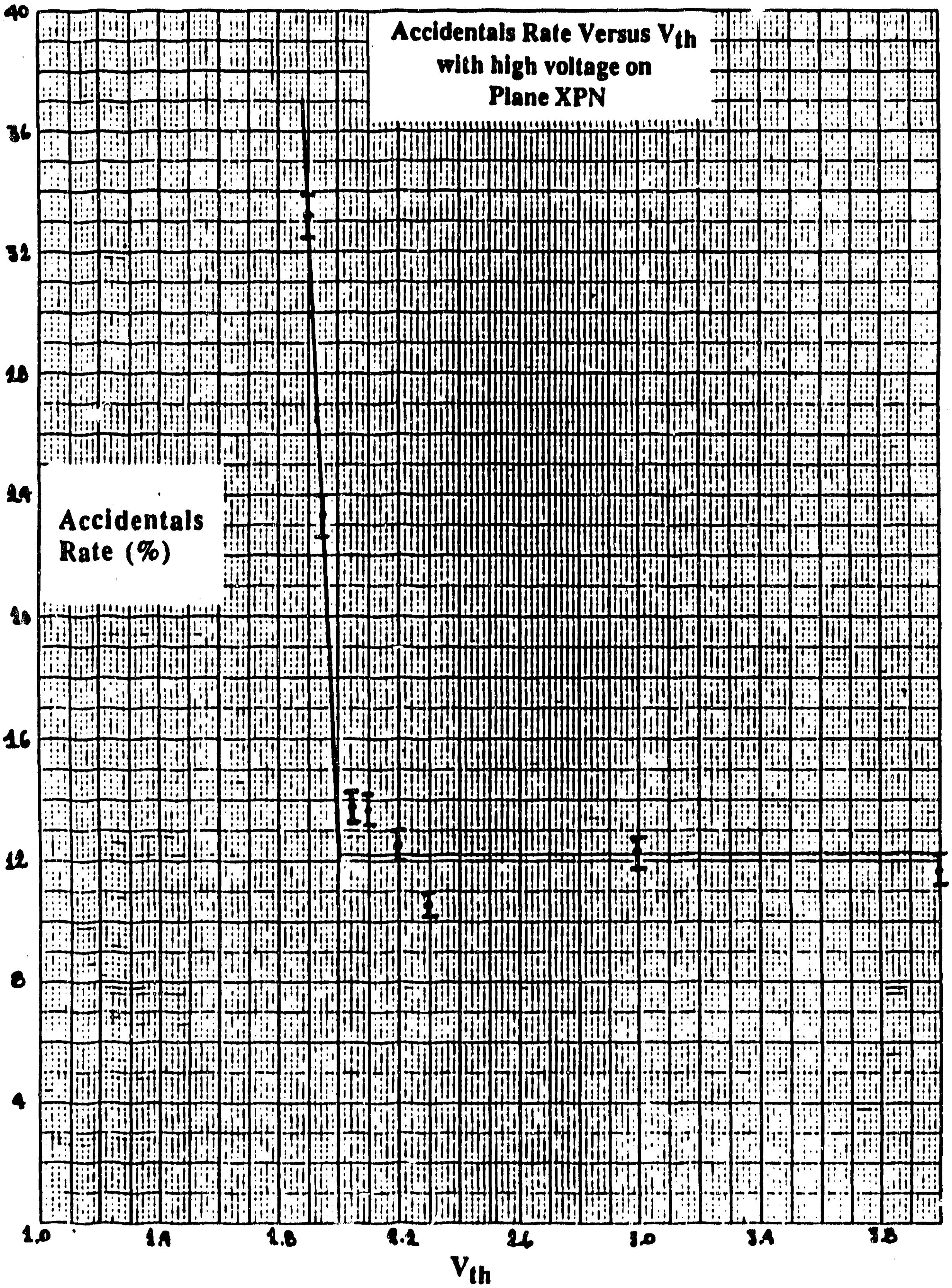

Accidentals Rate Versus V_{th}
with high voltage on
Plane XPN
Accidentals
Rate (%)
V_{th}

Figure 7

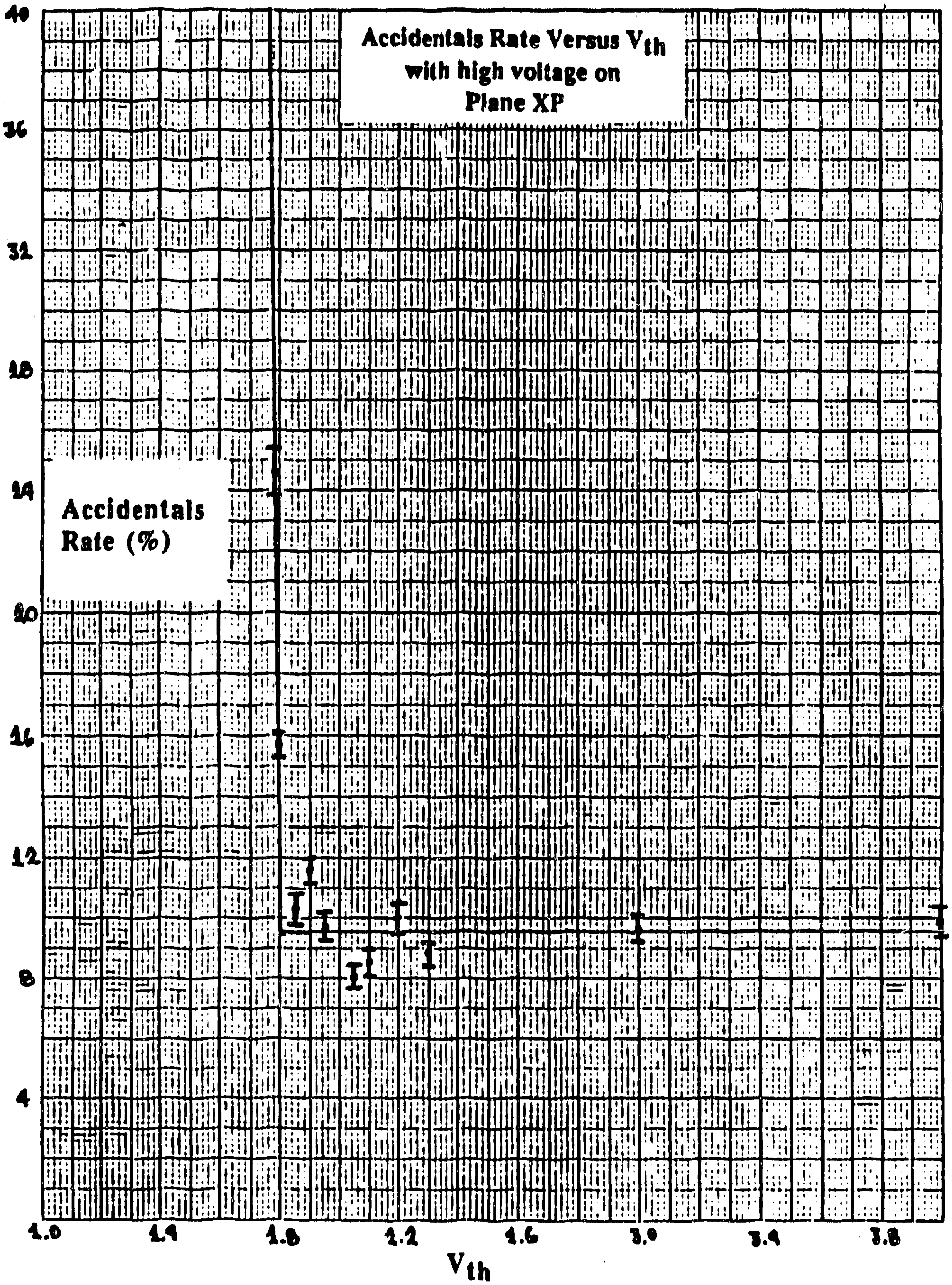
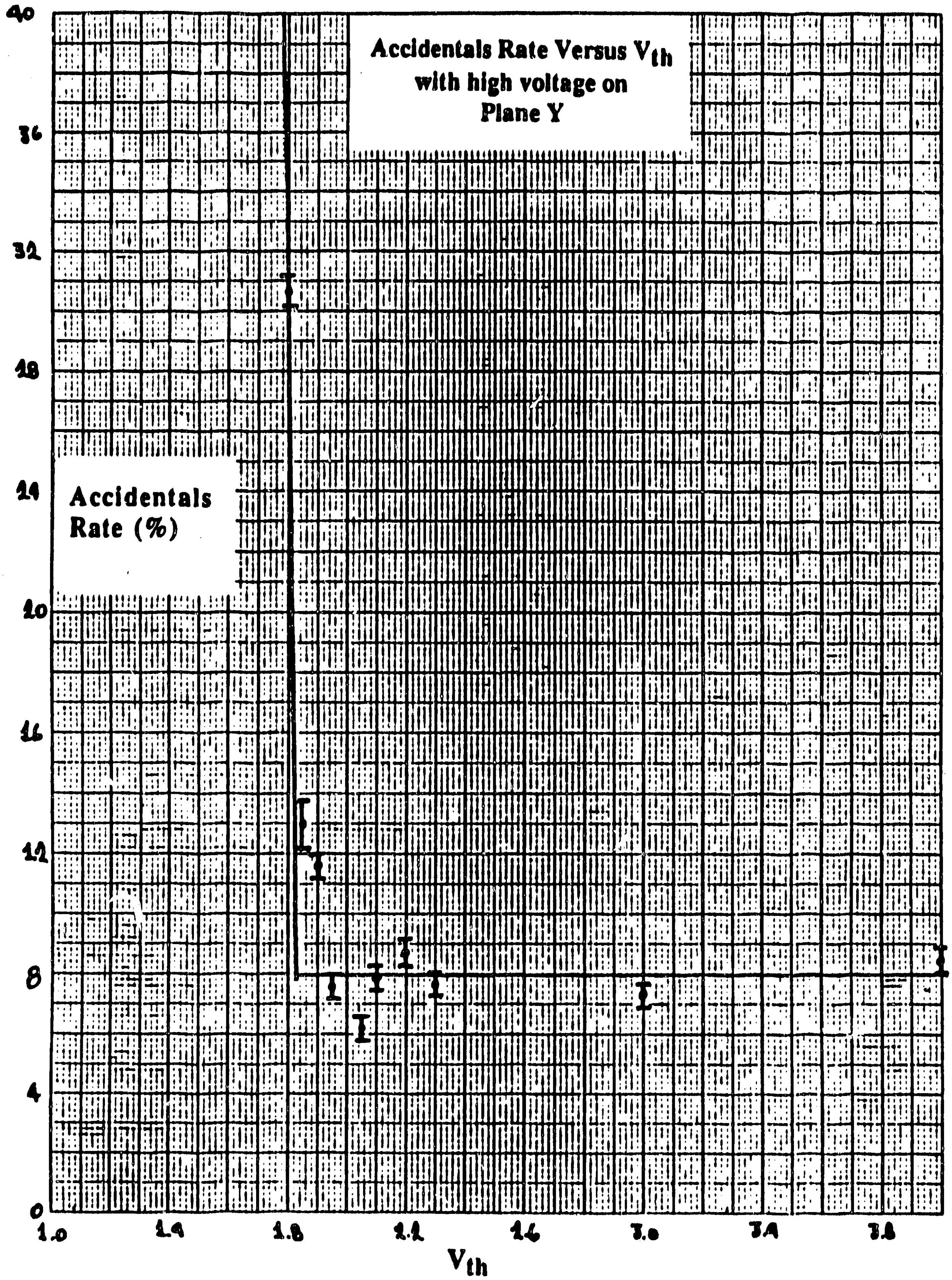
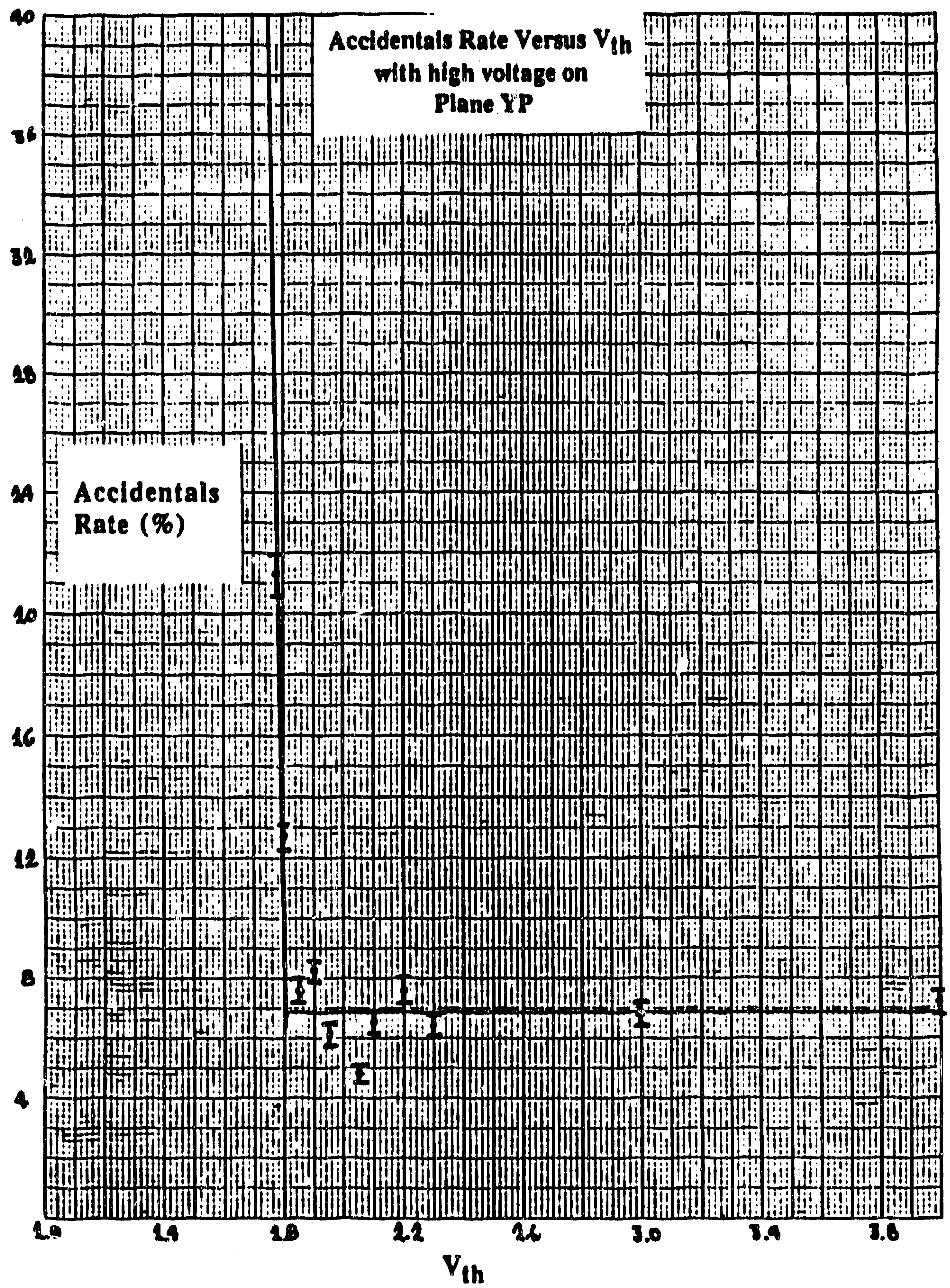

Accidentals Rate Versus V_{th}
with high voltage on
Plane XP
Accidentals
Rate (%)
40
36
32
28
24
20
16
12
8
4
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
V_{th}

Figure 8



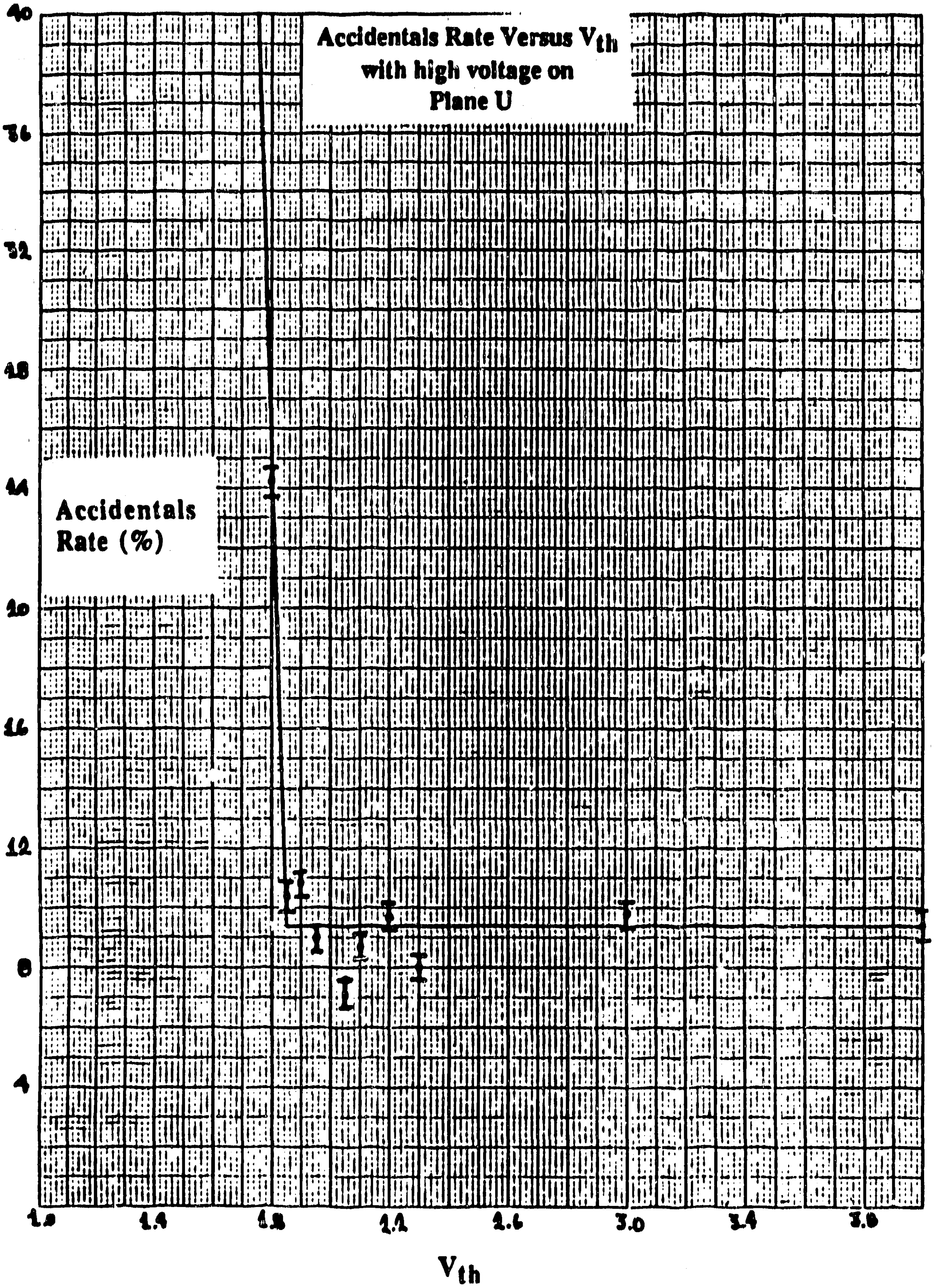
Accidentals Rate Versus V_{th} with high voltage on Plane Y
Accidentals Rate (%)
40
36
32
28
24
20
16
12
8
4
0
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
V_{th}

Figure 9



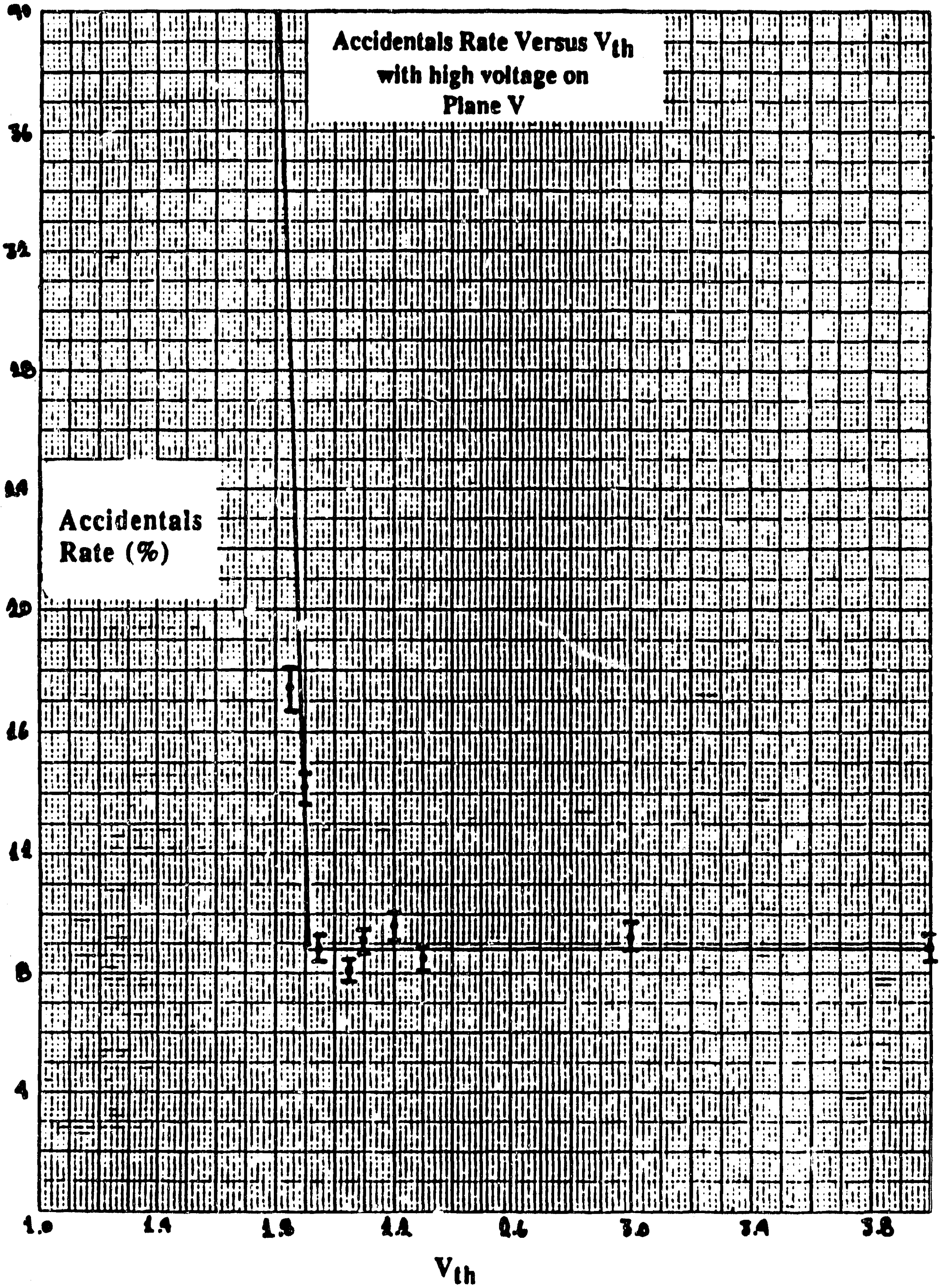
Accidentals Rate Versus V_{th}
with high voltage on
Plane YP
Accidentals
Rate (%)
40
36
32
28
24
20
16
12
8
4
1.0
1.4
1.8
2.2
2.6
3.0
3.4
3.8
V_{th}

Figure 10



Accidentals Rate Versus V_th
with high voltage on
Plane U
Accidentals
Rate (%)
12
8
4
1.4
3.0
V_th

Figure 11



Accidentals Rate Versus V_{th}
with high voltage on
Plane V
Accidentals
Rate (%)
V_{th}

Figure 12

which it would be subjected. Consequently we proposed to build a small electromagnetic calorimeter and to locate it in the rear hemisphere. The conceptual foundation for our proposal was simple. To first order the number of π^0s produced in a collision is a measure of its centrality, and each π^0 usually produces two gammas when it decays. It follows then that the number of gammas produced is also a measure of the centrality of the collision. In addition, the gammas may be found in the rear hemisphere although certainly they populate the forward hemisphere preferentially. In principle, we reasoned, it should be possible to measure the centrality of a collision by counting gammas in the rear hemisphere.

One of our colleagues, Dr. T. J. Hallman of Johns Hopkins University, established at least a semi-quantitative foundation for these qualitative ideas. Using the Fritiof code Dr. Hallman demonstrated that the number of gammas that are emitted into the rear hemisphere is indeed a function of the impact parameter of the collisions in which the parent pions were produced. In the fall of 1989 the collaboration as a whole endorsed our approach, and the construction of the E_t detector began.

On the following pages we present two photographs and a schematic drawing of the E_t detector. The essential ingredients of the detector were lead for converting the gammas into electromagnetic showers; lucite and water, both of which were used as radiators for the production of Cherenkov light; and photomultiplier tubes for the detection of the Cherenkov light. The lead converters were three radiation lengths in thickness.

There were a total of eighteen photomultiplier tubes in the detector, and each tube was equipped with specially designed base in order to prevent a decrease in the gain of the tube during the spill. The gain of each tube was studied as a function of applied voltage, and the tubes were operated at the same gain throughout the course of the experiment.

The data logged with the E_t detector have not as yet been completely analyzed, but final results will be available by New Year's day. The preliminary results are encouraging in two respects. First, the performance of the detector was monitored continually throughout the run, and we are pleased to report that it maintained linearity despite the enormous counting rates to which it was subjected. Second, the device responded to the presence of the target in a manner that was consistent with expectations. The detector was clearly a qualitative success, and we must now determine what quantitative information it can provide.

(d) development of a sensitive new preamplier

Several years ago, after extensive consultation with the DOE, the IENPG joined the AMY collaboration at KEK. Because the AMY collaboration is funded through the Division of High Energy Physics at DOE, several constraints were placed upon our participation, with the most notable of these being that no funds from this grant may be spent on supplies and equipment for AMY.

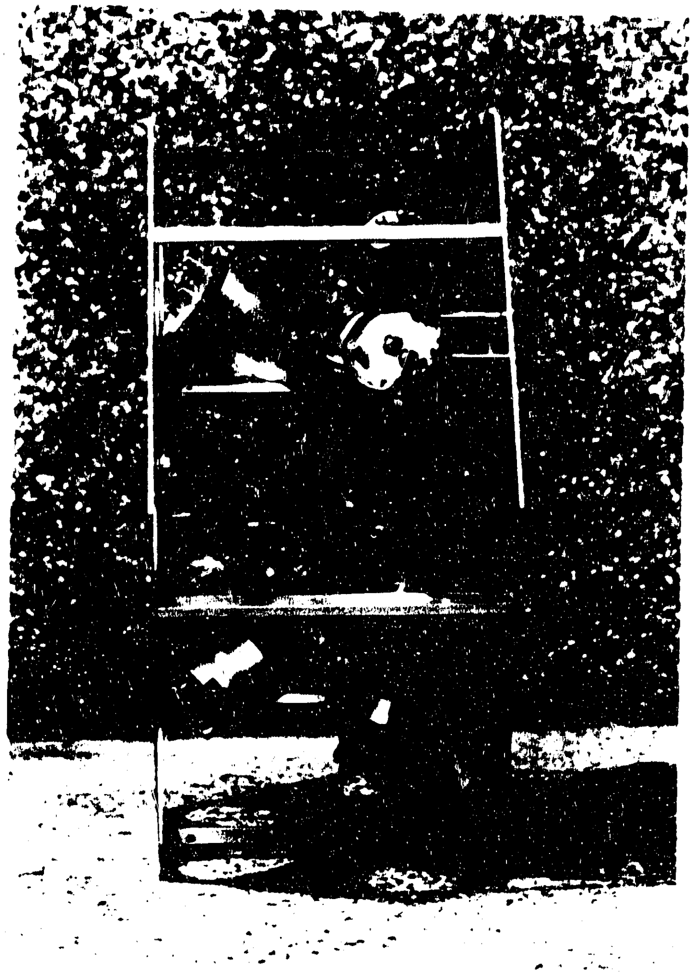


Figure 13

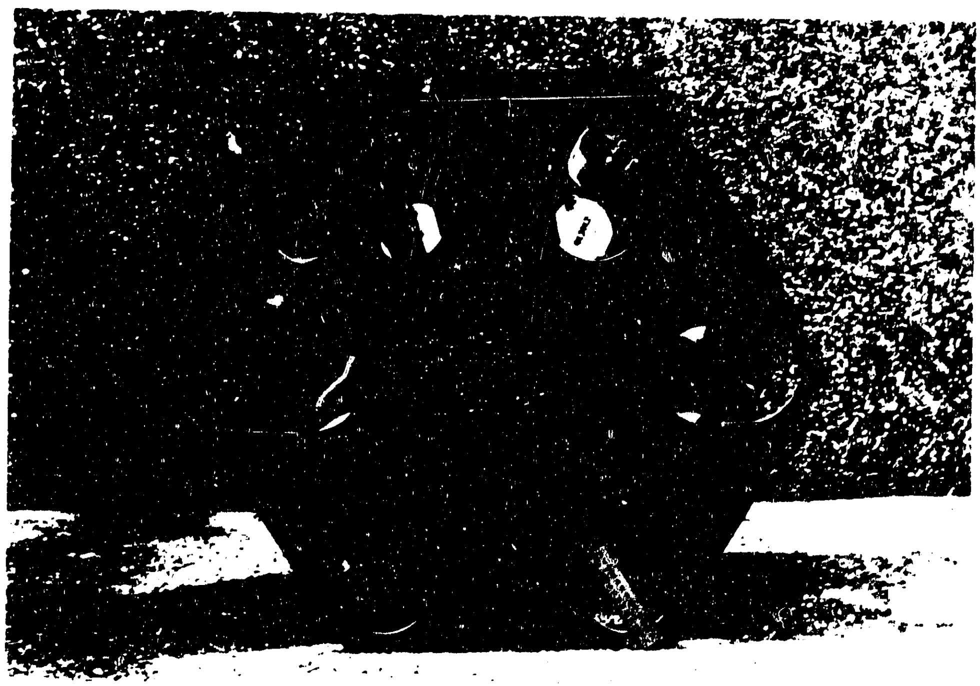


Figure 14

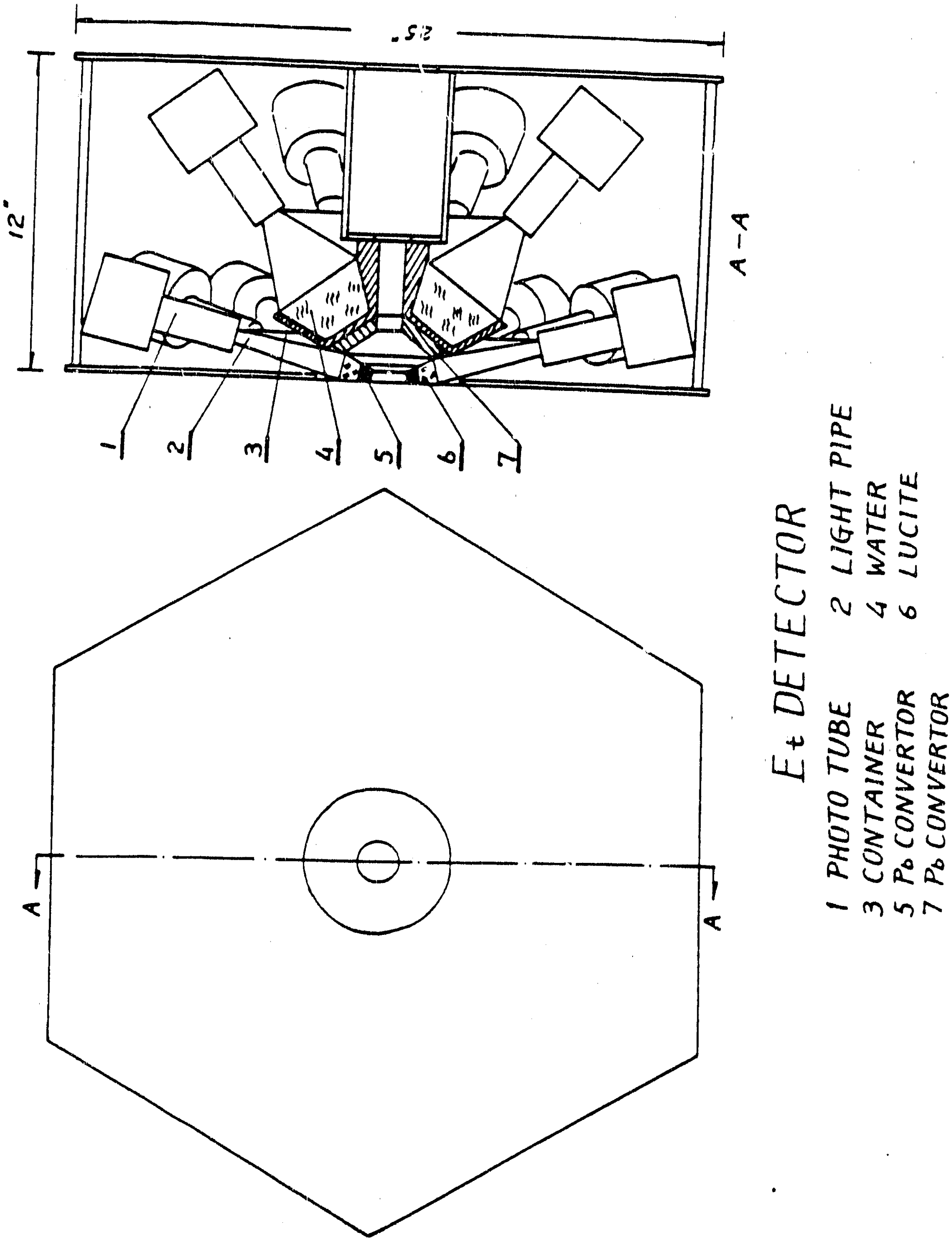

25"
12"
A-A
1
2
3
4
5
6
7
A
A
E_t DETECTOR
1 PHOTO TUBE
2 LIGHT PIPE
3 CONTAINER
4 WATER
5 Pb CONVERTOR
6 LUCITE
7 Pb CONVERTOR

Figure 15

Funding in high energy physics, even when expressed on a per capita basis, is far in excess of the funding in nuclear physics, and historically the higher level of funding has permitted high energy physicists to be more active than nuclear physicists in the development of new instruments and experimental techniques. Our participation in the AMY collaboration was approved by the DOE on grounds that it might facilitate the transfer of new techniques into the community of nuclear physicists.

In our opinion the hopes and expectations of DOE have been fulfilled. As just one specific example of the benefits that have resulted from our participation in AMY, we cite the development of a sensitive new preamplifier here in our laboratory at LSU. We emphasize that with the exception of small quantities of trivial items such as hook-up wire, solder, etc., the supplies and materials that were used in this project were supplied to us by our colleagues at the University of Rochester, not purchased with funds from this grant.

Our principal contact at the University of Rochester is Dr. Alan Sill, who is a senior postdoctoral research associate with the research group of Olsen and Bodek. Recently Dr. Sill developed a novel design for drift chambers and built two large arrays of them for installation in the existing AMY detector at KEK. The chambers, called the "front tracking chambers" (FTC) within the collaboration, were installed in September, 1990, during a regularly scheduled shutdown of the accelerator. Each of the sense wires will deliver its current to a preamplifier that will be mounted on the perimeter of the chamber, and the output of the preamplifer will then be bussed into the counting house for further amplification and processing.

Initially the responsibility for developing both the chambers and the associated electronics was borne by Dr. Sill and his colleagues at the University of Rochester. However, with the passage of time it became increasingly clear to everyone involved in this project that the responsibility for developing the preamplifiers should be transferred to LSU. We agreed to accept that responsibility with the clear understanding that the University of Rochester must continue to support the project financially. This arrangement has worked very well indeed to this date.

We accepted this responsibility for two reasons. First, of course we were interested in contributing to the success of the FTC themselves. Dr. Sill's design is novel, and if the FTC work as well as we hope they will, we believe that chambers of this design will be used in an ever increasing number of applications. Second, we have long thought it would be useful to develop a sensitive preamplifier for use with wire chambers of a more conventional design.

As the reader may perhaps be aware, the spacing between sense wires in most multiwire proportional chambers is at least two millimeters. Chambers with a spacing of one millimeter can be, and are, built, but in general wire with a diameter of 12 microns must be used to ensure the efficiency of operation. The IENPG never builds chambers with a spacing of one millimeter because we find it easier to build two planes, both of which have a spacing of two millimeters, and then to displace the two planes by one millimeter with respect to one another. This simple technique permits us to achieve an effective spacing of one millimeter while using wire of diameter 20 microns, which is far more convenient and easier to use than wire of 12 microns diameter.

Nonetheless there are applications in which the space available for instruments is limited and compactness of design is a primary consideration. In such applications, and they are numerous, chambers with a wire spacing of one millimeter would be useful. We believe that the most likely technique for building a sturdy, reliable chamber with a spacing of one millimeter between sense wires is to use sense wire of diameter 20 microns and then to develop a sensitive preamplifier to amplify the small currents that result. As a result of our participation in the AMY project we have successfully completed at least a first step in this direction.

In Fig 16 we show a schematic drawing of the preamplifier that was designed and tested in our lab by Dr. Zhi-fu Wang and graduate student Xiaocong Zhang. Also shown is the so-called "Cal-gate" circuitry which is used for periodic testing and calibration of the preamp. In Fig 17 we show a photograph of an actual prototype that contains eight channels. The discerning reader may wonder where are all the components, and we should perhaps mention that they are underneath the chip itself.

After a frustrating initial period of trial and error we devised a layout for the components in which the performance of the preamp is satisfactory. Specifically, the preamp does not oscillate even when it is operated at full voltage, and the amplification factors which have been realized in our bench tests are consistent with the manufacturer's specifications. Best of all, the performance of the preamp is satisfactory even when the input current is reduced to 0.3 microamps!

On the basis of discussions with other physicists, we estimate that the typical user of the PCOS III electronics sets the threshold voltage equal to four or perhaps five volts. This range of voltages corresponds to input currents between eight and ten microamps. As discussed in part (b) of this report, we can operate our amplifiers with the thresholds set as low as two volts, which corresponds to four microamps. The manufacture of the amplifiers claims to operate them during bench tests with the thresholds set as low as one volt, which corresponds to two microamps. We shall adopt this value of two microamps as being the limit to the useful sensitivity of the PCOS III amplifiers. Conservatively then, we have already achieved an improvement of almost one order of magnitude in sensitivity with respect to the best that can be achieved with the PCOS III system.

The principal motivation for this discussion is our belief that the project has resulted in a solid achievement that merits the readers' attention. In addition, however, we hope that the collaborative nature of this project will not be overlooked. This project was funded by high energy physicists and carried out by nuclear physicists. In our opinion it is a textbook example of how a collaboration between different groups with different objectives can be beneficial to all participants.

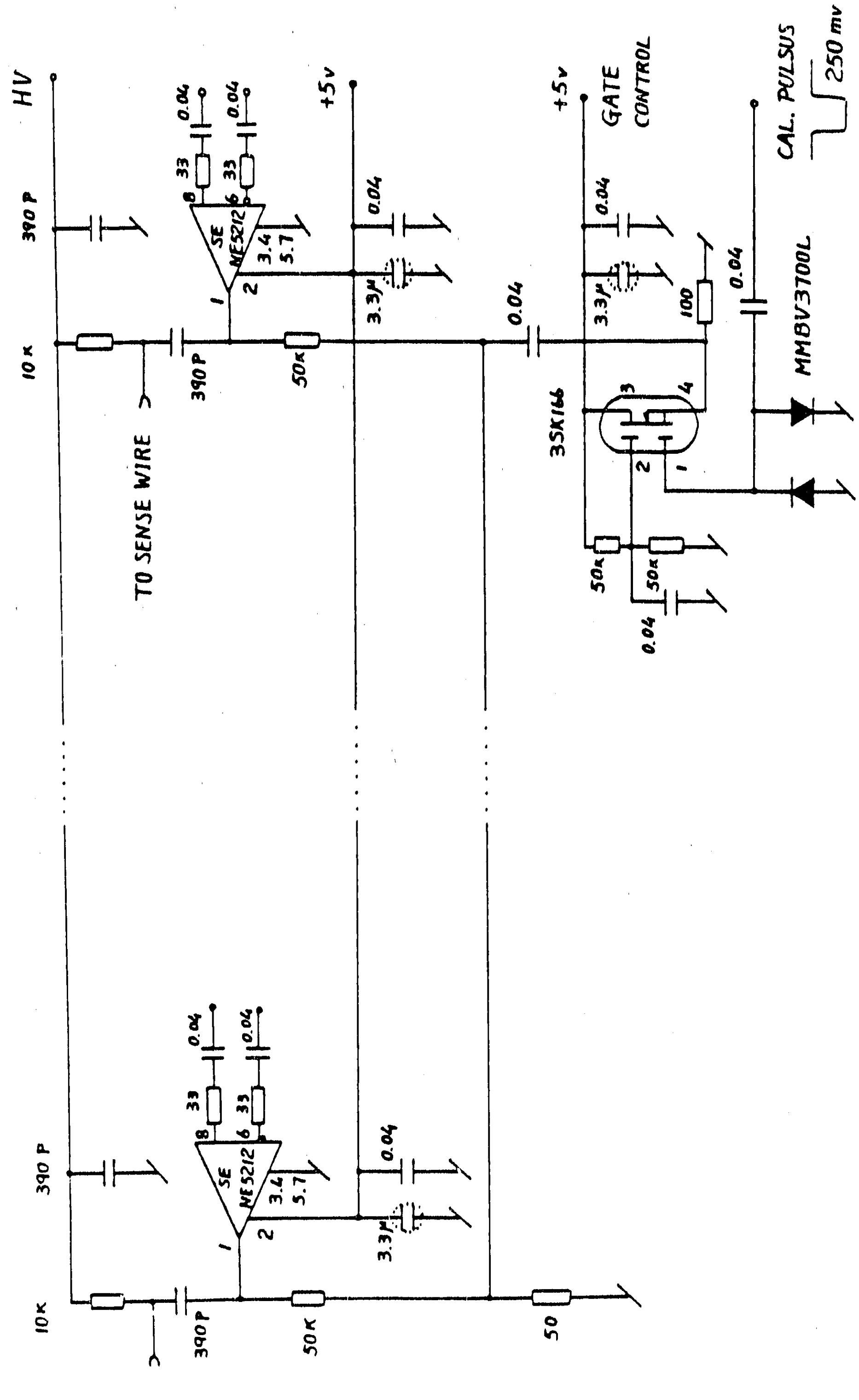


DIAGRAM OF PREAMP. FOR AMY DRIFT CHAMBER

Figure 16

Figure 17

(e) the single-lepton experiment

The floor space currently occupied by the DLS was at one time occupied by the Two Armed Spectrometer System, which is better known by its acronym TASS. A total of five experiments were carried out on TASS. Four of them have been analyzed and published, but the analysis of the fifth is not yet complete. This experiment was a search for the production of single direct leptons in collisions between protons and beryllium, and in many ways it may be regarded as the precursor to the experimental program currently underway on the DLS. In this discussion the term "direct lepton" will be used to denote those leptons that were created in the primary interaction itself rather than in one of the prolific yet uninteresting secondary processes such as the Dalitz decay of the π^0.

For several years the JENPG did not participate in the analysis of the data logged in this experiment, but because of a critical shortage of manpower within the collaboration, since the spring of 1989 we have been the only members of the collaboration who are actively analyzing these data. During this period of time we made considerable progress, and we believe that the end of the analysis is finally in sight. In order to provide the reader with some foundation for evaluating our progress we shall include here a brief discussion of the apparatus and the principles of data analysis.

Each arm of TASS contained a dipole magnet, three hodoscopes of scintillating plastic, one hodoscope of Cherenkov plastic, two gaseous Cherenkov counters, an array of lead-glass Cherenkov counters, a single counter of scintillating plastic located within the target chamber, and two additional single scintillation counters. Figure 18 is a plan view of TASS as it was configured for this experiment. In Fig 18 the letters "H", "S", and "C" are used to denote hodoscopes, single scintillators, and Cherenkov counters, respectively. The symbol "TD", denoting target detector, is used to denote the single counter within the target chamber. When drawn to scale TD is small, so it has been enlarged for convenience. Although there were differences between the two arms of TASS, they were minor and one may regard the two arms of TASS as being mirror images of one another.

Three Beryllium targets of thickness 0.00144 rl, 0.01331 rl, and 0.03634 rl were used during data acquisition. The kinetic energy of the incident protons was 4.9 GeV. Electrons and positrons were distinguished from pions by requiring pulses from both Cherenkov counters, and protons were distinguished from lighter particles by the absence of pulses in H4.

The measured quantities in this experiment were the differential momentum spectra for pions and leptons. The momentum of any detected particle was determined by the combination of counters in H1, H2, and H3 that were struck by the particle as it moved along its trajectory through the apparatus. Throughout the remainder of this discussion we shall use the letters I, J, and K to denote the struck elements of H1, H2, and H3, respectively; and we shall refer to specific combinations of I, J, and K as "coincidence bins". Hodoscopes H1, H2, and H3 contained 10, 16, and 16 elements, respectively, so that in principle there were 2,560 coincidence bins, although only a fraction of this number actually lay along physically realizeable trajectories. Our first undertaking was to determine the

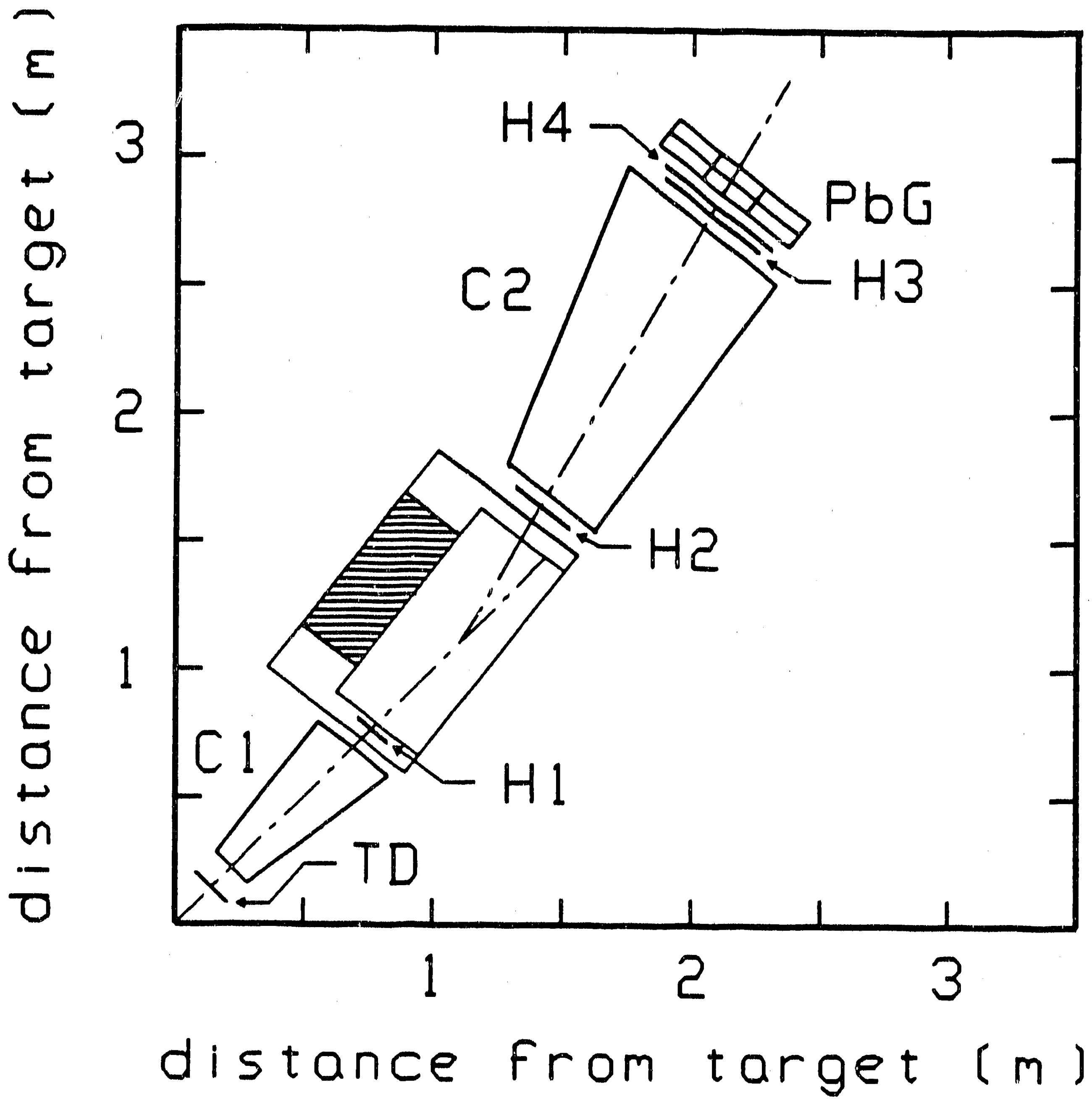

H4
PbG
C2
H3
2
H2
1
C1
H1
TD
3
distance from target (m)
distance from target (m)

Figure 18

correspondence between momentum and coincidence bins, and we are happy to report that this aspect of the analysis was completed in the summer of 1990. Using Monte-Carlo techniques, we have calculated the most probable momentum for each bin that lay along a physically realizeable trajectory, the uncertainty in the momentum of each bin, and the acceptance of each bin. On the following pages we exhibit histograms in which are plotted the number of bins versus each of these parameters.

The principal objective of the data analysis is to determine what portion of the detected leptons, if indeed any, are direct leptons, by which we mean that they were created within the volume of the primary p-Be interaction rather than in some secondary process. There are several secondary processes that result in the copious production of electrons, with notable examples of these being the Dalitz decay of the π^0 the Bethe-Heitler conversion of photons that are emitted in the decay $\pi^0 \rightarrow \gamma + \gamma$, Compton scattering, the leptonic decays of charged mesons, and the decay of the $\Delta^0\,(1232)$ resonance.

In order to demonstrate how one subtracts these backgrounds from the measured signal we shall include here a simple, first order calculation that incorporates many simplifications that would not be acceptable in a calculation of final results. Nonetheless, in our opinion it is an excellent illustration of the fundamental principles, and we present it in that spirit.

In the following discussion the symbol N_0 will be used to represent Avogadro's number; A, the atomic number of the target; X_0, the radiation length of the target expressed in cm; t, the thickness of the target in cm; ρ, the density of the target expressed in $g\,cm^{-3}$; N_p, the number of incident protons; Δ, the thickness of the TD detector expressed in radiation lengths; σ_0, the cross section for producing neutral pions; $\sigma_\pm$, the cross section for producing charged pions; B_d, the branching ratio for the Dalitz decay of the neutral pion; and $\eta\,(p,\,\theta,\,\phi)$, the geometrical efficiency for detecting a singly charged particle that is created with a momentum of magnitude p at a polar angle θ and an azimuthal angle ϕ in the laboratory system. The symbol K is defined as:

$$\mathrm{K} = \frac{\mathrm{N_p}\,\mathrm{N_0}\,\rho}{\mathrm{A}}.$$

First we shall derive an equation from which the numerical value for an important quantity called the "extrapolation point" may be calculated. To do so we shall adopt the convenient fiction that only neutral pions and charged pions are produced in the collision. In addition we shall assume that neutral pions produce electrons either by Dalitz decay or by external conversion of photons, but we shall temporarily neglect Compton scattering. For simplicity we shall refer to electrons that are produced by either of these two mechanisms as "pionic electrons".

The differential momentum distribution for electrons that originate in the Dalitz decay of neutral pions is readily found to be:

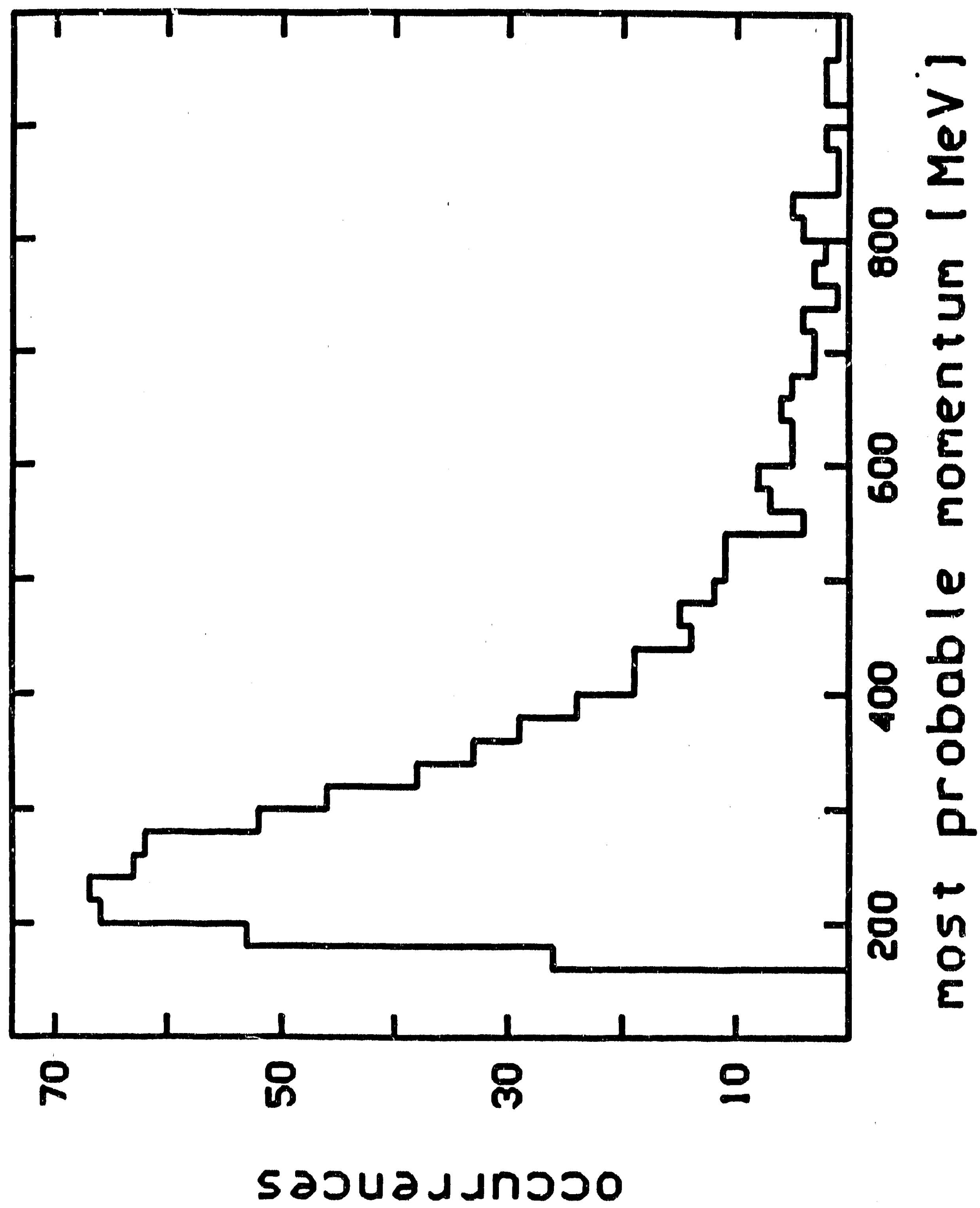

200
400
600
800
most probable momentum [MeV]
70
50
30
10
occurrences

Figure 19

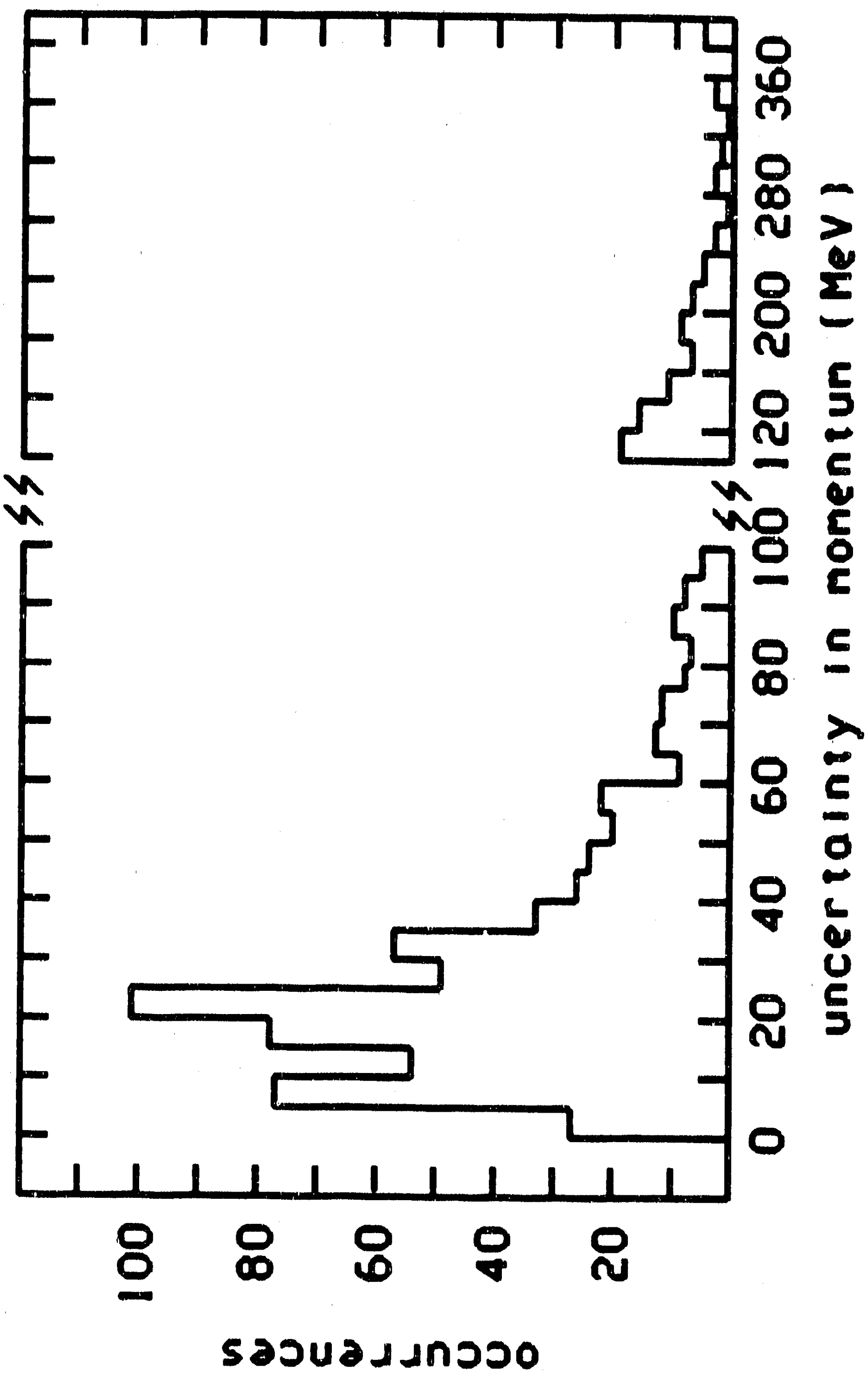
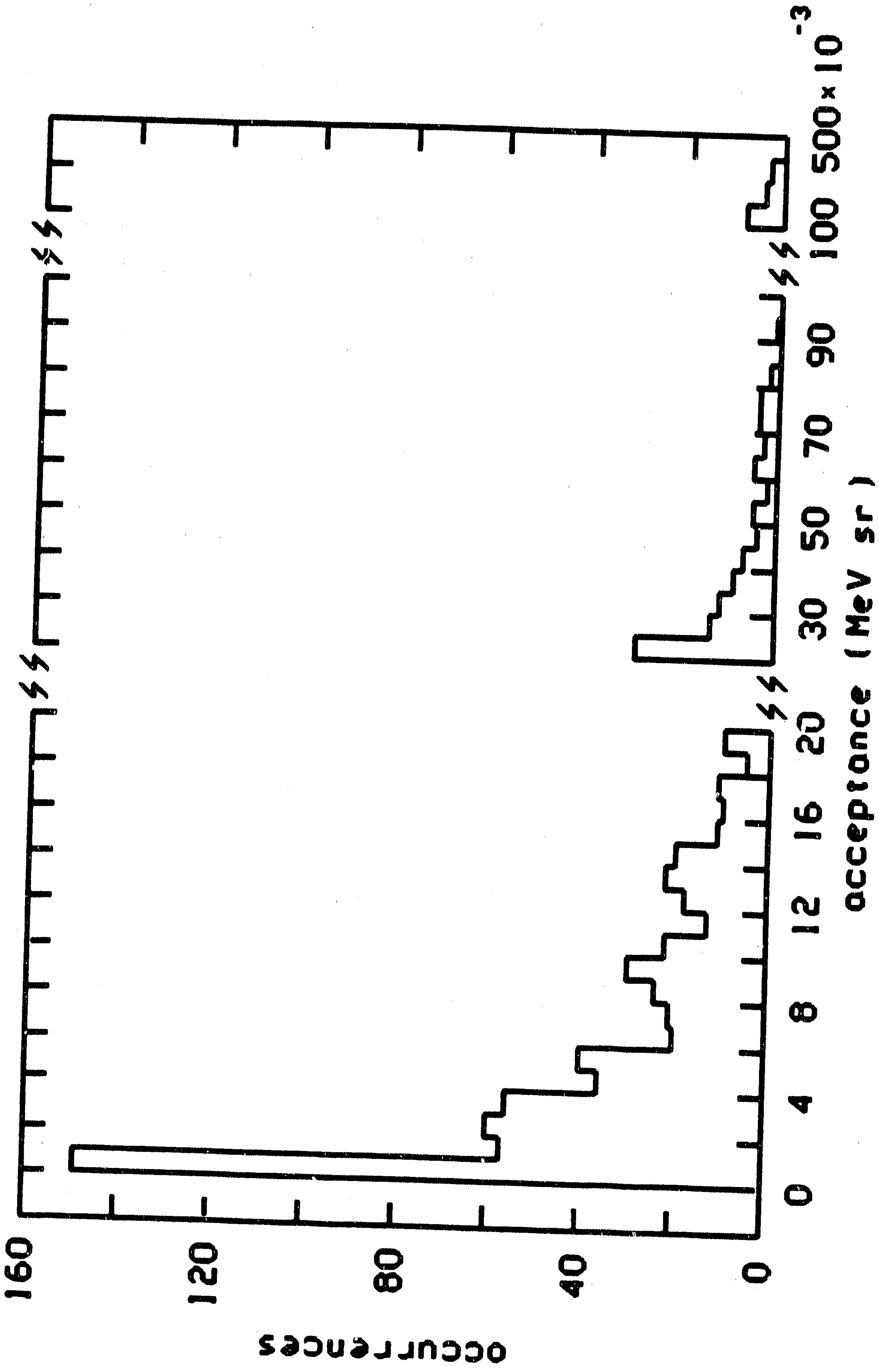

occurrences
100
80
60
40
20
0
20
40
60
80
100
120
200
280
360
uncertainty in momentum (MeV)

Figure 20



occurrences
0
40
80
120
160
acceptance (MeV sr)
0
4
8
12
16
20
30
50
70
90
100
500×10^-3

Figure 21

$$\frac{dN_e(p,t)}{dp} = \mathrm{K\,t}\,\sigma_0\,\mathrm{B_d} \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \mathrm{d}\theta\, \xi\,(\mathrm{p},\, \theta,\, \phi)\, \eta\,(\mathrm{p},\, \theta,\, \phi) \qquad (1)$$

where we call attention to the new function $\xi\,(p,\, \theta,\, \phi)$ that is introduced in the eq (1). This function is the triple differential probability distribution in the laboratory system for electrons produced by Dalitz decay.

The differential momentum distribution for electrons that originate in the external conversion of photons may be evaluated with slightly more effort and found to be:

$$\frac{dN_c(p,t)}{dp} = \frac{\mathrm{K}\,\sigma_0\,(1-\mathrm{B_d})\,7\,\mathrm{t}}{9} \int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \frac{\lambda\,(p,\, \theta,\, \phi)}{\cos\theta} \left[\frac{t}{X_0} + 2\,\Delta\,\cos\theta\right] \eta\,(p,\, \theta,\, \phi) \quad (2)$$

where $\cos\theta$ is the dot product between a unit vector that is normal to the target and a unit vector that points in the direction of motion of the gamma ray. The new function introduced in eq (2), $\lambda\,(p,\, \theta,\, \phi)$ is the triply differential probability distribution in the laboratory system for electrons produced by external conversion of photons.

The differential momentum distribution for charged pions may be written as:

$$\frac{dN_\pi(p,t)}{dp} = \mathrm{K\,t}\,\sigma_\pm \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \mathrm{d}\theta\, \mu\,(\mathrm{p},\, \theta,\, \phi)\, \eta\,(\mathrm{p},\, \theta,\, \phi)$$

where $\mu\,(p,\, \theta,\, \phi)$ is the triply differential probability distribution in the laboratory system for pions generated from a thermal distribution in the center of mass.

In this simple model the ratio of electrons to pions is a function of p and t. It is:

$$\frac{\epsilon}{\pi}\,(p,t) = \left(\frac{\sigma_0}{\sigma_\pm}\right)$$

$$\frac{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \left[B_d\, \xi\,(p,\, \theta,\, \phi) + (1-B_d)\left(\frac{7\,\lambda\,(p,\,\theta,\,\phi)}{9\,\cos\theta}\right)\left(\frac{t}{X_0} + 2\,\Delta\,\cos\theta\right)\right] \eta\,(p,\, \theta,\, \phi)}{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta\, \mu(p,\, \theta,\, \phi)\, \eta\,(p,\, \theta,\, \phi)} \qquad (3)$$

A principal objective of the analysis is the total elimination of pionic electrons from the data sample. The left hand side of eq (3) is the ratio of pionic electrons to pions, and so we shall therefore set the left hand side of eq (3) equal to 0. The equality sign can be maintained by setting the integrand in the numerator of the right hand side equal to zero also. Solving for t/X_0, one obtains:

$$\frac{t}{X_0} = -\cos\theta \left[\frac{9\,B_d\,\xi(p,\theta,\phi)}{7\,(1-B_d)\;\lambda(p,\theta,\phi)} - 2\,\Delta \right] \tag{4}$$

The special value of t/X_0 that one calculates by evaluating eq (4) is the famous extrapolation point that is so frequently mentioned in analyses like this. In words the extrapolation point is that value for the thickness of the target at which the ratio of pionic electrons to pions is zero. Because there is no physically realizeable thickness for which this ratio is zero, it is not surprising that the extrapolation point is negative. There are several other interesting features to this equation. First, the extrapolation point does not depend upon the ratio of the cross sections for production of neutral and charged pions. Second, in principle the extrapolation point depends upon both θ and ϕ, although in practice both of the functions ξ and λ are independent of ϕ and slowly varying functions of θ. Third, the extrapolation point will be independent of momentum only if the ratio of the functions $\xi\,(p,\,\theta,\,\phi)$ and $\lambda\,(p,\,\theta,\,\phi)$ is independent of momentum.

We know of only one practical technique for evaluating the functions and integrals that appear in eqs (3) and (4). That technique is the simulation of the relevant physical processes by means of a Monte-Carlo calculation into which the complete geometry of the apparatus has been incorporated. Fortunately Dalitz decay and the Bethe-Heitler conversion of photons are thoroughly understood, and the simulation of these processes by Monte-Carlo techniques is straightforward. In Fig 22 we show the results of such a simulation. The solid and dotted lines in Fig 22 represent, respectively, $\int_0^{2\pi} d\phi \int_0^{\pi} d\theta\; \lambda\,(p,\,\theta,\,\phi)\,\eta\,(p,\,\theta,\,\phi)$ and $\int_0^{2\pi} d\phi \int_0^{\pi} d\theta\; \xi\,(p,\,\theta,\,\phi)\,\eta\,(p,\,\theta,\,\phi)$ as a function of momentum. The solid line in Fig 22 is the absolute probability per MeV of momentum and per radiation length of converter for detecting a lepton that was created by the Bethe-Heitler conversion of either photon emitted in the decay $\pi^0 \rightarrow \gamma + \gamma$. The dotted line is the absolute probability per MeV of momentum for detecting a lepton that was created by the Dalitz decay of the π^0.

Monte-Carlo techniques are also convenient for summing over trajectories as is required by the functions of θ in eqs (3) and (4). In addition the factor of 7/9 in these equations approximates the probability per unit radiation length for the Bethe-Heitler conversion of a photon. This value is valid only in the high energy limit, and it should be replaced by yet another momentum dependent function in a more complete analysis. The dependence of the conversion probability upon momentum is also easily incorporated into a simulation by Monte-Carlo techniques.

On the other hand the production of pions is not understood on a fundamental level, and one cannot simulate pion production with the same degree of confidence and accuracy as one can simulate Dalitz decay. Fortunately, it is not necessary to do so because, as we noted above, the extrapolation point does not depend upon either of the cross sections σ_0 or $\sigma_{\pm}$. Consequently it is sufficient to *describe* pion production as opposed to *calculating* pion production, and it is possible to describe the production of pions by means of formulae that are both simple and fairly accurate.

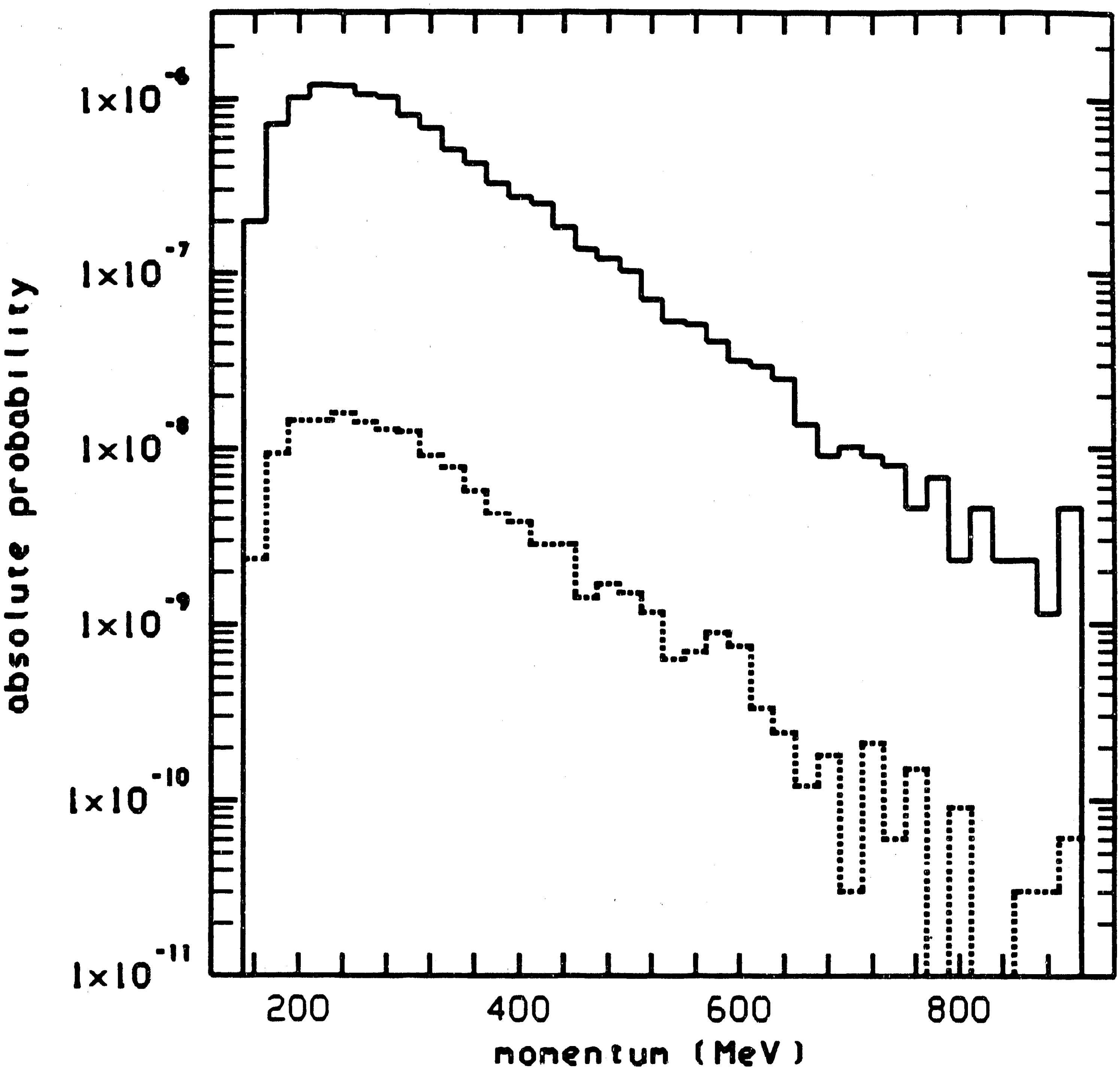

1×10⁻⁶
1×10⁻⁷
1×10⁻⁸
1×10⁻⁹
1×10⁻¹⁰
1×10⁻¹¹
absolute probability
200
400
600
800
momentum (MeV)

Figure 22

Two fundamental assumptions concerning pion production were incorporated into this analysis. These were: first, that the production of pions is isotropic in the center of mass system; and second, that the differential momentum distribution is:

$$\frac{dP}{dp} = \mathrm{K\,p\,E} \exp(-\mathrm{E}/\mathrm{T}) \tag{5}$$

where the symbols P, p, E, and T in eq (5) represent, respectively, the probability for production, the momentum of the pion, the total energy of the pion, and the temperature of the hadronic matter in which the pions were created. The quantities p, E, and T are to be expressed in MeV, and K is a normalization constant. The assumed value for T in this analysis was 100 MeV.

Our principal objective during the previous twelve to eighteen months has been the calculation of the extrapolation point and the evaluation of both the statistical and systematic uncertainties in the extrapolation point. The systematic uncertainties of greatest concern to us are those due to the assumed value for temperature and to the assumed angular distribution.

The dependence of the extrapolation point upon the temperature was easy to study because T is one of the parameters that is read into memory at the beginning of execution. In order to examine the dependence of the extrapolation point upon the angular distribution of the produced pions, we introduced a so-called "asymmetry parameter" into the angular distribution. Specifically we assumed that:

$$\frac{dP}{d\Omega} = \mathrm{K}\ (1 + \alpha\ \cos\theta) \tag{6}$$

where K is a normalization constant and α is the asymmetry parameter.

We have calculated the extrapolation point for three values of T, 80 MeV, 100 MeV, and 120 MeV; and for three values of the asymmetry parameter, -0.25, 0.0, and +0.25. We display our results in Figs 23 and 24. All points in Fig 23 were calculated under the assumption that the temperature is 100 MeV, and all points in Fig 24 were calculated under the assumption that the asymmetry parameter is zero. In Fig 25 we display the calculated dependence of the extrapolation point upon momentum. All points in Fig 25 were calculated under the assumptions that the temperature is 100 MeV and the asymmetry parameter is zero.

Let us bring this discussion to a conclusion by considering a slightly more complicated hypothesis. Let us assume that there are two additional sources of electrons, the decay of the η^0meson and an unknown source of direct electrons. The η^0 decays principally into pions, but it has a significant branching ratio both for Dalitz decay and for decay into two gammas. In reality there are additional decay modes of the η^0 that produce one or

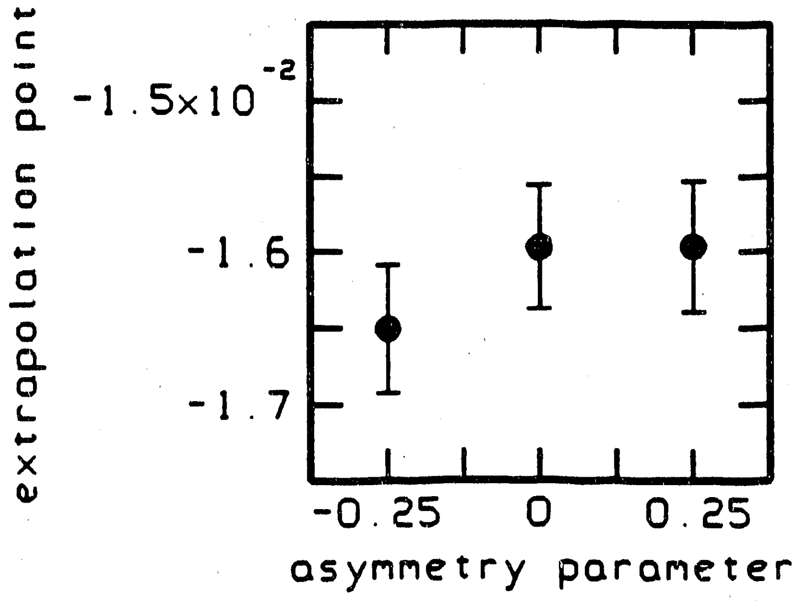


Figure 23

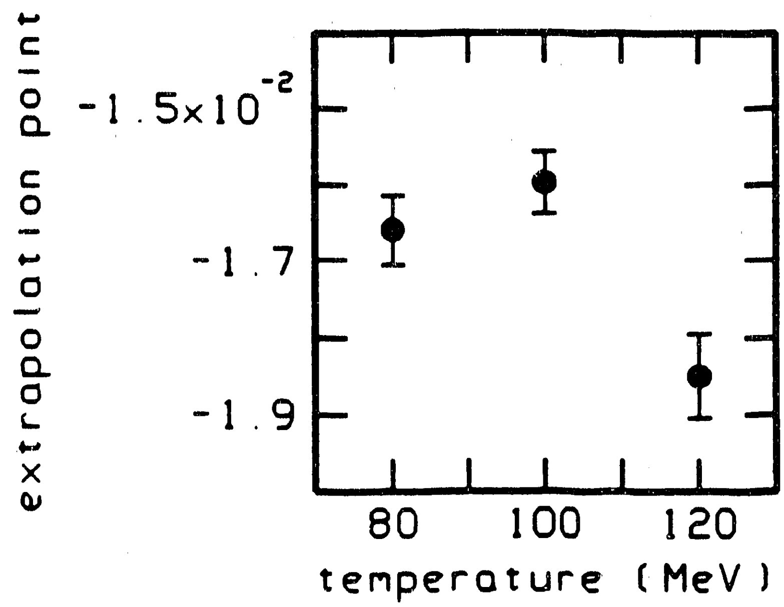


Figure 24

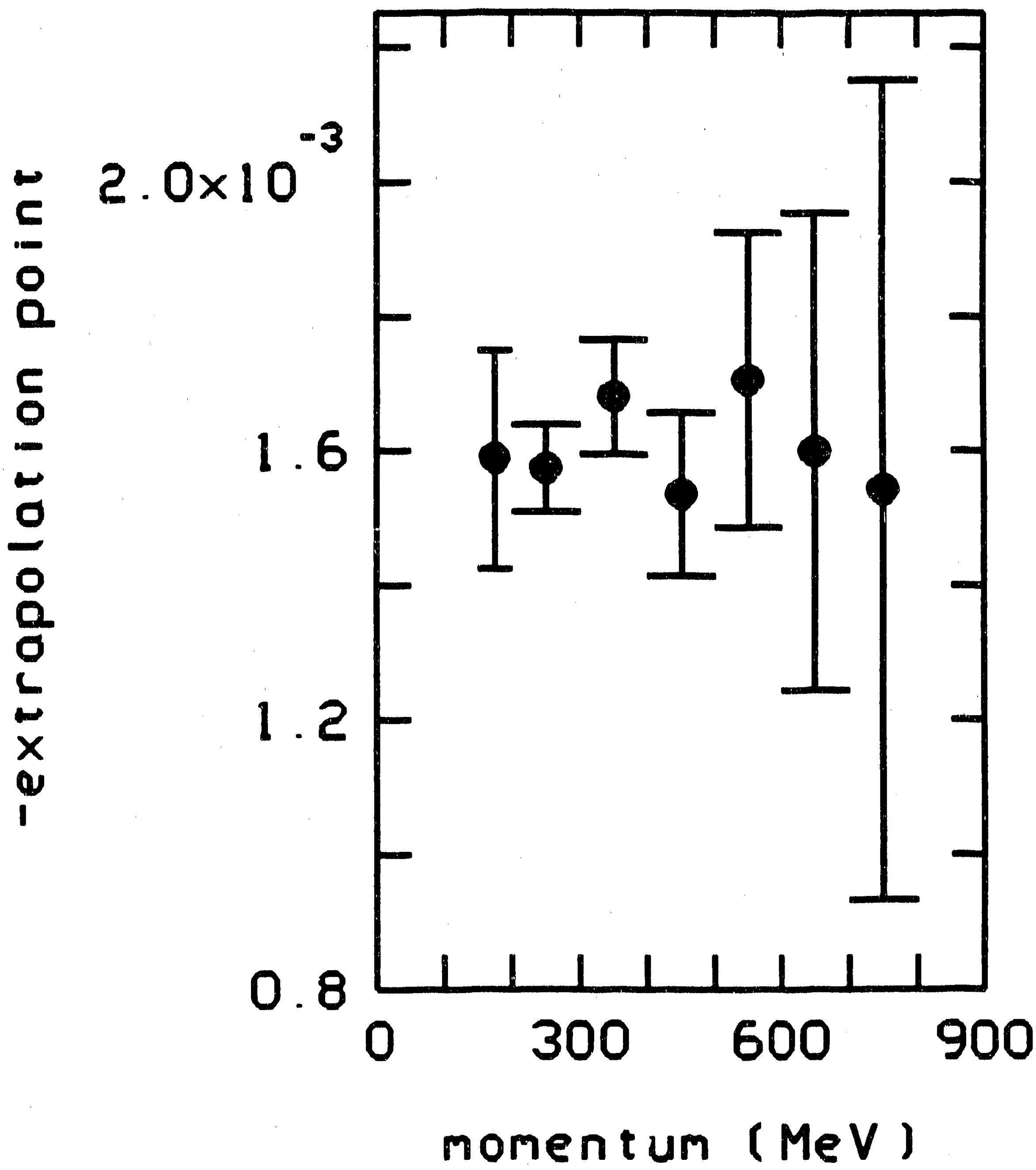

-extrapolation point
2.0x10^-3
1.6
1.2
0.8
0
300
600
900
momentum (MeV)

Figure 25

two gammas, but a consideration of these modes would complicate this discussion without adding insight, so we shall ignore them here.

The differential momentum distributions for the electrons that are produced in the Dalitz decay of the η^0 or by Bethe-Heitler conversion of the photons emitted in the decay $\eta^0 \rightarrow \gamma+\gamma$ may be evaluated in the same way as the corresponding contributions from the decay of the π^0. We shall use primes to distinguish quantities that pertain to the η^0 from quantities that pertain to the π^0. In addition the symbol $B'_{\gamma\gamma}$ will be used to denote the branching ratio of the η^0 into two gammas. For simplicity we shall ignore from now on the dependence upon θ and ϕ that were explicitly indicated in eqs (1) – (3). We find that:

$$\frac{dN'_e(p,t)}{dp} = \mathrm{K\,t}\,\sigma'_0\,\mathrm{B}'_\mathrm{d}\,\xi'(\mathrm{p})\,\eta(\mathrm{p})$$

and that

$$\frac{dN'_e(p,t)}{dp} = \mathrm{K}\,\sigma'_0\,\mathrm{B}'_{\gamma\gamma}\,\lambda'(\mathrm{p})\left(\frac{7\,\mathrm{t}}{9\,\cos\theta}\right)\left[\frac{\mathrm{t}}{\mathrm{X}_0} + 2\,\Delta\,\cos\theta\right]\eta(\mathrm{p})$$

We shall use the letter "X" to represent the contribution from the source of direct leptons to the ratio of electrons to pions. It is now a simple matter to write down an expression for the ratio of electrons to pions as a function of p and t. After a minor transposition the result may be written:

$$\frac{e}{\pi}(p,t) - \left(\frac{\sigma'_0}{\sigma_\pm}\right)\mu^{-1}(p)\left[B'_d\,\xi'(p) + \left(\frac{7\,B'_{\gamma\gamma}\,\lambda'(p)}{9\,\cos\theta}\right)\left(\frac{t}{X_0} + 2\,\Delta\,\cos\theta\right)\right]$$
$$= \left(\frac{\sigma_0}{\sigma_\pm}\right)\mu^{-1}(p)\left[B_d\,\xi(p) + (1-B_d)\left(\frac{7\,\lambda(p)}{9\,\cos\theta}\right)\left(\frac{t}{X_0} + 2\,\Delta\,\cos\theta\right)\right] + X \qquad (7)$$

The left hand side of eq (7) is the difference between the experimentally measured ratio of electrons to pions and the contributions to that ratio that originated from the decay of the η^0. Despite the proliferation of symbols and indices one can see that the entire left hand side is a linear function of t and that it could in principle be written as a + bt, where a and b are complicated functions of the parameters. The right hand side is the sum of the contributions from the decay of the π^0 and the unknown source of direct electrons. The essential point is that if one evaluates eq (7) at the extrapolation point the right hand side collapses to the single term X. Thus the ratio of direct electrons to pions is found by subtracting from the measured ratio of electrons to pions the contributions from the decay of the η^0 and then by evaluating the resulting straight line at the extrapolation point.

The extension of eq (7) to the real world in which there are many sources of electrons is obvious, and the technique for evaluating the ratio of direct electrons to pions does not change. We do note, however, that the ratio of the cross sections for the production of the

η^0 and charged pions is required, and uncertainty in this ratio will have a direct bearing on the uncertainty in the final values for the ratio of direct electrons to pions.

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