A COUNTER HODOSCOPE DIGITAL DATA AND ON-LINE COMPUTER SYSTEM USED IN HIGH-ENERGY SCATTERING EXPERIMENTS*)

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(presented by S.J. Lindenbaum)

1. INTRODUCTION

In this paper we shall describe a counter hodoscope system with automatic data handling and on-line computer analysis with immediate feedback of analysed results to the experimenters. This system was used recently at the Brookhaven 33 GeV Alternate Gradient Synchrotron (AGS) to investigate the differential cross-sections for elastic scattering of high energy protons, antiprotons, kaons and pions from protons. Due to the new techniques employed, up to two orders of magnitude increase in data accumulation rate accompanied by a higher systematic accuracy than previously attained in this type of experiment were possible and for the first time a wide survey of the field[1)] was practical in one experimental run. Two different methods were used to select elastic events. Experiment I used a high resolution magnetic spectrometer to separate elastically scattered particles in the range of scattering angle 10 mr to 50 mr, while Experiment II used the space correlations between scattered particle and recoil proton to separate elastically scattered particles. The latter technique was used for recoil momenta in the region 450 MeV/c to 1 GeV/c generally involving larger angles (up to ~150 mr) than Experiment I.

In each experiment, more than a hundred scintillation hodoscope counters were used in plane arrays with accompanying crossed (rotated 90°) arrays arranged to locate particles by their intersection so that the effective number of counters was several hundred. Trigger counters selected likely elastic events and then fast (30 ns) gates interrogated all hodoscope counters and the information on which counters were struck was transferred to a buffer memory. After 32 such events were stored, or after the AGS beam

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pulse ended, the whole memory was read to the Merlin computer for immediate on-line analysis and was also recorded on magnetic tape. The computer then analysed the events and returned oscilloscope displays to the AGS, thus permitting continuous monitoring of the experiment. At the end of each run, differential cross-sections were calculated by the computer.

2. EXPERIMENTAL ARRANGEMENT

Figure 1 shows a diagram of the experimental arrangement. The measured angular divergence of the 4.5° secondary beam used was ± 1.5 mr and the measured momentum spread was approximately 1.25%. A differential Cerenkov counter using CO_2 gas, placed in coincidence with the beam telescope, separated the various types of particle in the incident beam. The liquid hydrogen target was 48" long and 4" in diameter. Hodoscopes H1 and H2 measured the horizontal projection of the scattering angle. The scattered particles were then deflected by two 72" long magnets. The angle of deflection was measured with Hodoscope H3, a two dimensional hodoscope screen which thus also measured the vertical projection of the scattering angle. The trigger counters, L, in front of Hodoscope H2 made it possible to select the range of scattering angle included.

H1 was made up of 28 scintillation counters, each 1/4" wide × 4" high × 0.30" thick, while H2 was constructed from 80 counters, each 1/4" wide × 6" high × 0.30" thick. The photomultipliers used for the hodoscopes were RCA Type 6199, which had sufficient gain to produce more than 4 m.a. from the passage of a minimum ionising particle. The relatively low cost of this tube, together with its small size (1.5" diameter) and fast rise time, made it a suitable tube for our purposes. Since Hodoscopes H1 and H2 were made up of 28 and 80 counters, respectively, while the total number of inputs to the data handler was only 96, an input coding system was used to reduce the number of outputs of H1 and H2 while retaining the necessary information.

The five trigger counters, L, were all 5.5" high, which was enough to shadow the effective counter height in Hodoscope H2, and their widths were, respectively 3", 2", 5", 5" and 5" starting from the beam side. Hodoscope H3 was made up of four screens, each being a 12 × 12 hodoscope containing 24 plastic scintillators each 30" long, 2.5" wide and 0.5" thick, coupled via lucite light pipes to 6199 photomultiplier tubes. The outputs were added with cables in groups of four counters defining the same horizontal plane in order to reduce the number of signals while preserving the information, effectively forming a hodoscope of 48 × 12 counters. The above system defined the scattering angle to ± 1.3 mr relative to the mean incident beam line, and the momentum resolution was ± 1.25% (half width at half height.)

The momentum of the beam was accurately determined by centering the unscattered beam (with the hydrogen target empty) on three counters D1, D2, D3 alongside the Hodoscope H3. The momentum distribution of the incident beam at each momentum and the angular dependence of beam intensity were measured magnetically by deflecting the unscattered beam into Hodoscope H3.

2.1 Description of Arrangement of Experiment II

Figure 2 shows a drawing of the arrangement of Experiment II. The beam telescope and Cerenkov counter were identical to those described in Experiment I, but the liquid hydrogen target was 20" long and 4" in diameter. The two-dimensional Hodoscope HS detected the forward scattered particle and the Hodoscope HT (vertical counters) and the two-dimensional Hodoscope HR measured the direction of the recoil particle. The Hodoscope HO served to locate the incident particle in the directions transverse to the beam.

The Hodoscope HS was 24" wide × 12" high. The 12 vertical counters were 12" high, 2" wide and 0.5" thick, while the 12 horizontal counters were 24" long, 1" high and 0.5" thick. Since this experiment was designed to cover a fixed region of four momentum transfer, independent of incident energy, HS was mounted on a lift table which could be moved on V-grooved wheels along a rail parallel to the beam. After each move, the position of the hodoscope was measured with a surveying telescope. The Hodoscope HT was made up of 12 vertical counters, each 10" high, 2.5" wide × 0.25" thick. The Hodoscope HR comprised 96 counters, each 30" long, 2.5" wide × 0.5" thick. Pairs of counters were butted together end to end and the outputs were connected together, effectively forming 60" long counters which were used to construct a two dimensional 60" × 60" hodoscope. The Hodoscope HO was a two dimensional counter array, each array of which contained four counters 2.5" long, 0.5" wide and 0.25" thick.

The polar scattering angle resolution varied from ± 2 mr at 20 GeV/c incident momentum to ± 5 mr at 7 GeV/c incident momentum and the recoil polar angle resolution was ± 15 mr. The azimuthal angles were measured to ± 10 mr on the recoil side and, for the scattered particle, varied from ± 30 mr at the smallest scattering angle to ± 15 mr at the largest.

3. FAST ELECTRONICS

A block diagram of the most important parts of the electronic set-up is shown in Figure 3. The pulses from scintillation counters S1, S2 S3 and the differential Cerenkov counter C were placed in a fast ($\tau \sim 3$ ns) coincidence circuit with the anticoincidence $\bar{A}$ from the Cerenkov counter, which improves the rejection efficiency of the counter by inhibiting the system whenever particles of lighter mass than those selected pass through the telescope. A coincidence was then made between the beam particle defined by the above logic and several trigger counters. In Experiment I signals from trigger counters, L, were added, as were the Y plane counters of Hodoscope H3, using a twelve-fold adding circuit designed for this purpose. Thus, fast ($\tau \sim 10$ ns) three-fold coincidence was required between the beam particle, trigger counters L and Hodoscope H3. In Experiment II, the trigger signals were obtained by summing independently the outputs of Hodoscopes HT, the vertical counters of HR and the vertical counters of HS, then requiring a four-fold coincidence between these three signals and the beam particle. Upon such a signal all counters were interrogated as described in section 4.1.

Since the data handler (see section 4.3) was capable of storing only 32 events per AGS burst, in some parts of the experiment only a fraction of the available several hundred events could be accepted for analysis. An anticoincidence from the gate control circuit prevented the trigger coincidence circuit from firing more than 32 times a pulse (see section 4.2). By recording the event rate with and without this anticoincidence, the fraction of the offered events which was actually analysed was known.

The accidental rate in the beam telescope was never allowed to exceed 1.5% of the beam rate. Accidental coincidence between each hodoscope and the beam were measured to be < 0.5%.

4. DATA HANDLING SYSTEM

4.1 Gates

The data handling system is shown schematically in Figure 4. The fast (~ 30 ns full width) gates are opened by blocking oscillators triggered by a suitable pulse from a coincidence circuit (see section 3). When a signal greater than 2 m.a. arrives at the gate during the "gate open" time, a tunnel diode is "set". A later pulse from the gate control circuit resets the tunnel diodes, generating a signal to be fed to the input stage of the buffer memory, if a tunnel diode has been previously set.

4.2 Gate Control Circuit

An input signal to the gate control circuit from the trigger generator (i.e. coincidence circuit) indicates that an event has occurred and that the gates have been triggered. This signal switches an input flip-flop in the gate control circuit, causing an anticoincidence signal which switches off the coincidence circuit controlling the hodoscope gate generator, thus avoiding an additional triggering of the control circuit. If the data handler is not busy, the control circuit resets the gate tunnel diodes after .5 μsec, generating signals which are fed to the input flip-flops of the Digital Data Handler (i.e. the X-chassis, see section 4.3), and after a further .5 µsec sends a "store" command pulse to the data handler, causing the information in the input flip-flops to be transferred to the buffer memory, and also resetting the Gate Control Circuit. In order that a second event should not be sent to the data handler while it is busy storing an event, an inhibit circuit introduces a minimum 5 µsec delay between consecutive "reset and store" operations. On the other hand, an inhibit signal from the data handler itself prevents the resetting of the tunnel diodes and generation of store pulses during the "read out memory" cycle. As soon as the inhibit signal is removed, the "reset and store" cycle proceeds as normal.

4.3 Digital Data Handler

A diagram of the digital data handler is shown in Figure 5. The electronic design of this unit was by W. Higinbotham and D. Potter and the unit was originally built for us in the Instrumentation Division of BNL. The unit contains the necessary circuitry to store sequentially 32 words, each of 96 bits, in a fast (5 µsec) ferrite core memory ("write" mode) and subsequently to transfer this information to magnetic tape ("read" mode.) Information from the fast gates, transmitted on the command of gate control circuit, is received via gating transistors at the 96 inputs (henceforth called the "X-chassis") setting the relevant input flip-flops. When a "store" pulse is received by the data handler, the information in the X-chassis is transferred, using a coincidence current write, to one 96 bit word of the memory and the word number is increased by one. At the end of an accelerator burst, a clock circuit signal from the AGS starts the read mode. The read mode also starts automatically if the memory is filled with 32 events. The "Y" word is read out first, its bits information being transferred to the same flip-flops used as the input register. In order to prevent spurious pulses at the input from destroying the event, the input transistors are gated off during the read mode. The output format and speed are determined by the magnetic tape recording equipment, a tape character consisting of six information bits in parallel together with sprocket and parity check bits. The first six "X" bits are transferred to drivers which record them on magnetic tape, and also to drivers which transmit them on-line to the Merlin computer as described in the next section. This read-out and shift process is repeated 16 times until the whole word has been read out. Then the flip-flops are reset and the next "Y" word is transferred to the output register. This process is repeated until all information is transferred from the data handler, which is then ready to receive more events. The whole read-out process takes approximately one second.

All the electronics described in sections 4 and 5 were located in a data trailer on the AGS floor, an interior view of which is shown in Figure 6.

5. ON-LINE COMPUTER - DATA TRANSMISSION

In order to allow on-line data transmission to the Merlin computer*) the output of the Digital Data Handler was modified to include, in parallel with the magnetic tape drivers, an additional set of drivers which sent pulses to the Merlin computer (located about one mile away) via commercially leased telephone lines. Figure 7 is a photograph showing the Merlin computer.

6. ON-LINE COMPUTER PROGRAMME AND DATA PROCESSING

A flow chart of the computer program is shown in Figure 8.

The sequence commences in the lower left-hand corner with the computer operator typing in information received from the experimenters at the AGS. The computer calculates the necessary kinematic quantities, clears out the result storage locations and transfers to the display loop. As an event arrives over the telephone lines, it is assembled into two Merlin words by a 48 bit shift register. The two words are transferred to two rapid access 48 bit registers on the computer console. Then the computer is interrupted (trapped), i.e. the instruction in process is completed and then control is transferred to the instruction stored at location 0000 (the asterisk on the flow chart), where the routine for processing the event commences. The counters which were struck (corresponding to "1" in the data) are identified and counted. The run identification number is compared to a number stored in the computer and a warning light is lit if these numbers are not identical. Then the "multiplicity" of the event is determined, i.e. the number of counters in each screen of each hodoscope which sent a signal. If one and only one bit appears in each screen, the event is classified as "single" and further analysis ensues. Otherwise, a "fault" is counted and this analysis bypassed. The distribution of the single events among the various counters (the profile) is constructed to enable the experimenter to check for uniformity of counter response in the hodoscopes. Then the single event is reconstructed in space (the computer has previously been supplied the dimensions and locations of all the hodoscopes) and the "elasticity" determined.

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*) A 8,192 word of 48 bit length computer constructed several years ago by the Brookhaven Instrumentation Division, the computer is similar to the Los Alamos Maniac II, and has about 1/7 the speed of the IBM 7090.

In Experiment I the events were grouped in ten bins of roughly 5 mr angular width and the cross-sections were normalized by dividing the number of counter combinations which correspond to each bin. In Experiment II, the 12 bins were determined by the vertical counter struck in Hodoscope HS. This gave bins which overlapped in scattering angle somewhat but took advantage of the solid angle being well determined by the area of each HS counter.

Spectra (10 for Experiment I, 12 for Experiment II) of the number of events versus elasticity were made up and stored in memory. At this point, control returned to the display loop. During the read out of data, this served merely to use the few milliseconds remaining (of the thirty milliseconds between events) before the arrival of the next event and the next trap to the processing routine. After the data handler was empty, however, there were 0.5 to 2 seconds available for display of the results before the next AGS burst and the next trap during which the experimenter at the AGS could watch the events accumulate and the elastic peak grow on a pulse-by-pulse basis. For Experiment II, the spectra for both the coplanar and non-coplanar events were displayed, a peak at the kinematically expected location always being found in the former and not in the latter. Photographs of typical displays are shown in Figures 9 (a) and (b). When sufficient data was accumulated, the experimenter turned off the scalers and the data handler "store" pulses and pushed a button, setting a sense light to inform the computer that the run ended. Control then passed to the output routine which turned off the interrupt feature to prevent any accidental data traps and asked for scaler information by typing requests on the console typewriter. This information being typed in, the computer calculates a normalization factor for the cross-sections. Then it prints out the total number of pulses, events, faults, single events, processed events and blanks on the high speed printer. The double loop in the program indicates the search through the spectra for the peaks due to elastic events. The peaks are then integrated, a background measured from the regions on either side of the peaks is subtracted, and the cross-sections and momentum transfer values corresponding to each peak are calculated and printed. Finally, the profile, the parameters used, multiplicity distribution and all the spectra are printed. The whole output routine takes about two minutes. The internal run identification number is increased by one and the program returns to the start where the stored value of the particle and momentum are typed out and the computer pauses to allow changes to be made.

7. RESULTS

Differential elastic scattering cross-sections were calculated as a function of the square of the four-momentum transfer, t, the usual variable in high-energy scattering theory, and typical results are shown in Figures 10 (a) to (c).

The ordinate factor:

$$\left[\frac{\sigma\ \text{tot}\ (20)}{\sigma\ \text{tot}\ (p)}\right]^2$$ is inversely proportional to the value of $(\frac{d\sigma}{dt})t = o$

predicted by the optical theorem assuming an imaginary, spin independent scattering amplitude. This factor serves to remove from $\frac{d\sigma}{dt}$ any variation due to variations in the total cross-section. One of the most striking features of the data shown in the Figure 10 (a) is the dependence of differential cross-section on incident momentum for p - p scattering, i.e. shrinkage of the diffraction scattering with increasing energy. However, neither π^+ - p nor π^- - p scattering shows this behaviour (see Figures 10 (b) and (c)). For a more detailed discussion of the characteristics of elastic scattering, see reference 1.

8. DISCUSSION

The counter hodoscope digital data system with on-line computer technique described was run for several hundred hours at the Brookhaven AGS during our experiment and the system was capable of accumulating useable high accuracy data virtually without interruption. We estimate that the data taking duty cycle of this system was well over 95%.

Several months before the AGS experiment, the original version of the equipment was de-bugged in a series of parasitic beam runs at the Brookhaven Cosmotron. Some modifications were made in the data handler, gates and other parts of the system at that time to ensure a cleanly operating highly reliable system. However, once we were set up at the Brookhaven AGS, everything worked well and the first time that we tried on-line data transmission to the Merlin computer in the Fall of 1963, meaningful results were obtained.

We found that the immediate processing of data with an on-line computer greatly reduces the test time and trouble-shooting prior to and during the experimental run. Furthermore, in those few cases where a counter or other component malfunctioned or failed during a run, we were able to detect it almost immediately, repair the fault and go back into operation in less than an hour.

The availability of large effective numbers of scintillation counters, each of small area, allowed us to cover large solid angles while maintaining high resolution. These advantages allowed one for the first time to make a reasonable survey of high-energy elastic scattering by protons of all known long lived (greater than 10^{-8} sec) strongly interacting charged particles.

These data handling and on-line programmed computer analysis techniques are also ideal for experiments using sonic, wire and other digital spark or discharge chamber arrays. We are planning to apply them soon, not only to elastic scattering but to multi-particle inelastic events. Since our needs for computer speed and capacity, and the consequent cost, increase with the complexity of the experiment, we are considering on-line operation on a faster computer with a short period fractional duty cycle so that others can use the computer in between.

We believe that the above described system and techniques will allow us to exploit more fully the characteristics of high data taking rate and automatic fast logic inherent in the counter and digitized spark chamber techniques, which previously have been utilized to only a small degree.

ACKNOWLEDGMENTS

We wish to thank the members of the Instrumentation Division of Brookhaven National Laboratory for their generous and valuable cooperation in electronic problems and operation of the Merlin computer. We also wish to thank the members of the Brookhaven Accelerator Department for their valuable cooperation in providing desired beam characteristics, magnetic measurements, etc, throughout this project.

Reference

1. K.J. Foley, S.J. Lindenbaum, W.A. Love, S. Ozaki, J.J. Russell and L.C.L. Yuan, Phys. Rev. Letters 10 376, 543 (1963); 11 425, 503 (1963).

Figure captions

Fig. 1	Arrangement for Experiment I - elastic scattering identified by a counter hodoscope magnetic spectrometer.
Fig. 2	The arrangement of Experiment II which used the space correlation between scattered particle and recoil proton to identify elastically scattered particles.
Fig. 3	Fast electronics block diagram. For clarity, only the most important circuits are shown.
Fig. 4	Block diagram of the data handling system.
Fig. 5	A diagram of the Digital Data Handler.
Fig. 6	A photograph of the interior of the data trailer. The data handler is in the left foreground, the fast gates to the rear of it, and the computer driven oscilloscope at the right.
Fig. 7	A photograph of the Merlin computer.
Fig. 8	Flow chart of the on-line computer programme.
Fig. 9	a) Typical CRT display during Experiment I. b) Typical CRT display during Experiment II. The lower curve shows the spectrum of non-coplanar events.
Fig. 10	Differential elastic scattering cross-sections as a function of the square of the four momentum transfer - t. a) p - p scattering results of Experiment II. b) Some of the π^+ - p scattering results from both experiments. c) Some of the K^+ - p scattering results from both experiments.

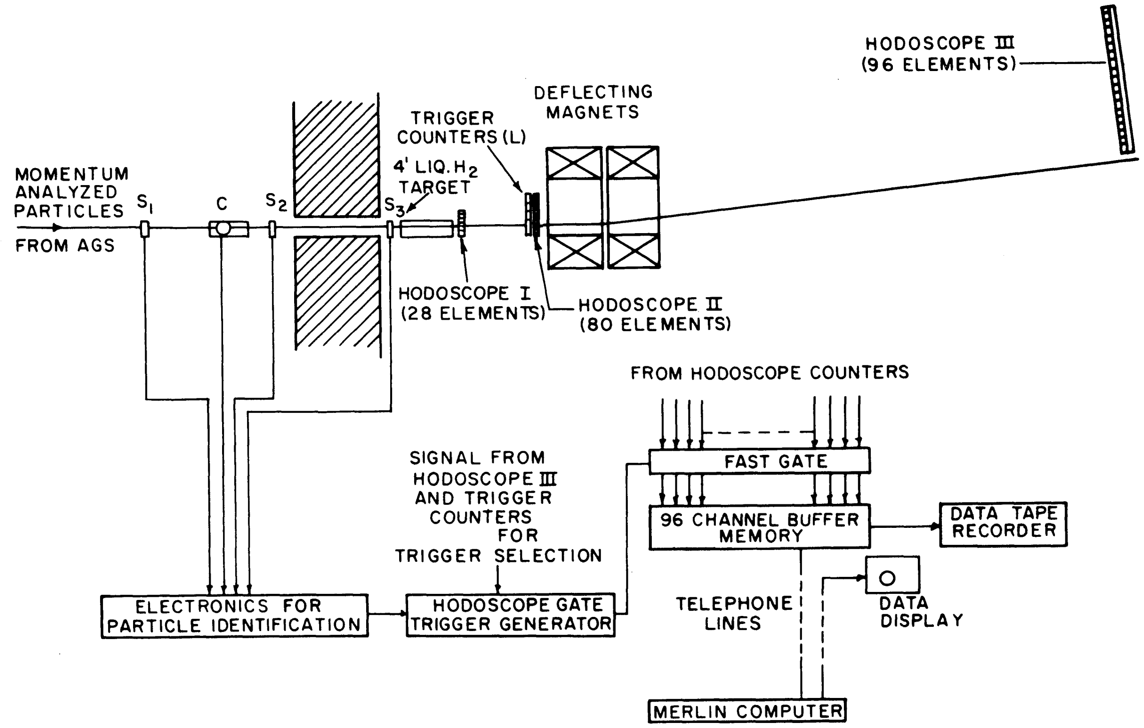

HODOSCOPE III
(96 ELEMENTS)
DEFLECTING MAGNETS
TRIGGER COUNTERS (L)
4' LIQ. H2 TARGET
MOMENTUM ANALYZED PARTICLES
FROM AGS
S1
C
S2
S3
HODOSCOPE I (28 ELEMENTS)
HODOSCOPE II (80 ELEMENTS)
FROM HODOSCOPE COUNTERS
FAST GATE
SIGNAL FROM HODOSCOPE III AND TRIGGER COUNTERS FOR TRIGGER SELECTION
96 CHANNEL BUFFER MEMORY
DATA TAPE RECORDER
DATA DISPLAY
TELEPHONE LINES
ELECTRONICS FOR PARTICLE IDENTIFICATION
HODOSCOPE GATE TRIGGER GENERATOR
MERLIN COMPUTER

Fig. 1

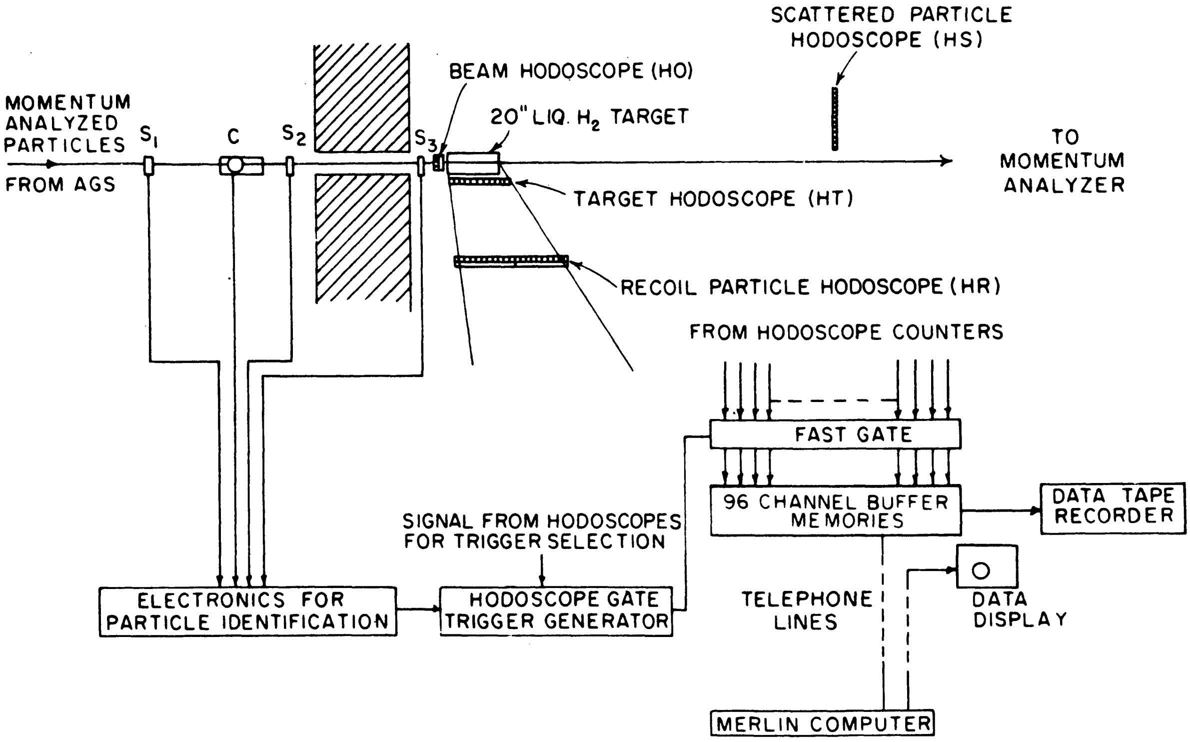

SCATTERED PARTICLE HODOSCOPE (HS)
BEAM HODOSCOPE (HO)
20" LIQ. H2 TARGET
MOMENTUM ANALYZED PARTICLES
FROM AGS
S1
C
S2
S3
TO MOMENTUM ANALYZER
TARGET HODOSCOPE (HT)
RECOIL PARTICLE HODOSCOPE (HR)
FROM HODOSCOPE COUNTERS
FAST GATE
96 CHANNEL BUFFER MEMORIES
DATA TAPE RECORDER
SIGNAL FROM HODOSCOPES FOR TRIGGER SELECTION
ELECTRONICS FOR PARTICLE IDENTIFICATION
HODOSCOPE GATE TRIGGER GENERATOR
TELEPHONE LINES
DATA DISPLAY
MERLIN COMPUTER

Fig. 2

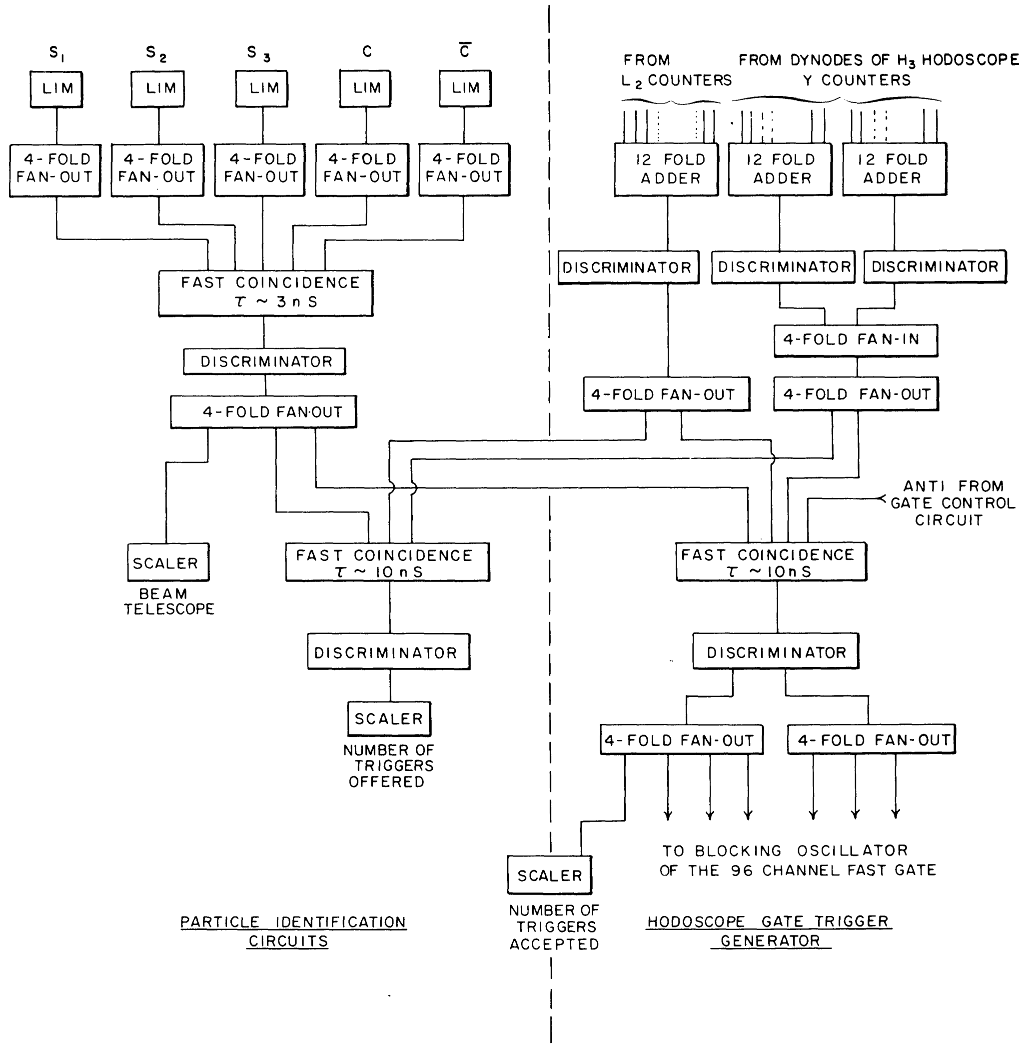

S1
S2
S3
C
C̄
LIM
4-FOLD FAN-OUT
FAST COINCIDENCE τ ~ 3 n S
DISCRIMINATOR
4-FOLD FAN-OUT
SCALER
BEAM TELESCOPE
FAST COINCIDENCE τ ~ 10 n S
DISCRIMINATOR
SCALER
NUMBER OF TRIGGERS OFFERED
FROM L2 COUNTERS
FROM DYNODES OF H3 HODOSCOPE Y COUNTERS
12 FOLD ADDER
DISCRIMINATOR
4-FOLD FAN-IN
4-FOLD FAN-OUT
ANTI FROM GATE CONTROL CIRCUIT
FAST COINCIDENCE τ ~ 10 n S
DISCRIMINATOR
4-FOLD FAN-OUT
TO BLOCKING OSCILLATOR OF THE 96 CHANNEL FAST GATE
SCALER
NUMBER OF TRIGGERS ACCEPTED
PARTICLE IDENTIFICATION CIRCUITS
HODOSCOPE GATE TRIGGER GENERATOR

Fig. 3

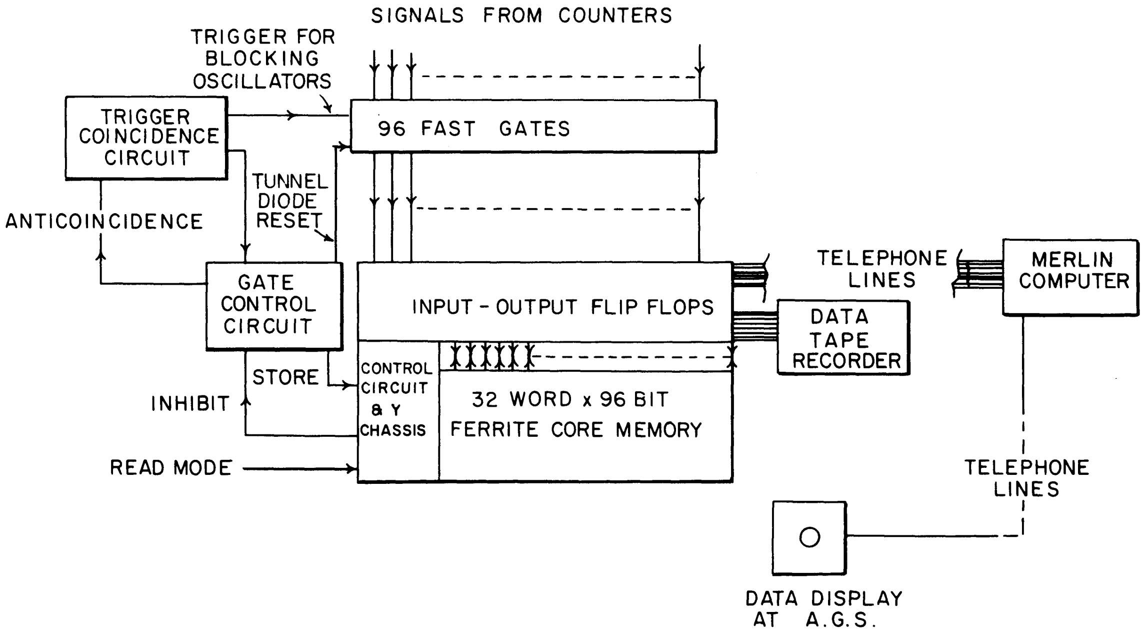

SIGNALS FROM COUNTERS
TRIGGER FOR BLOCKING OSCILLATORS
TRIGGER COINCIDENCE CIRCUIT
96 FAST GATES
TUNNEL DIODE RESET
ANTICOINCIDENCE
GATE CONTROL CIRCUIT
INPUT - OUTPUT FLIP FLOPS
TELEPHONE LINES
MERLIN COMPUTER
DATA TAPE RECORDER
STORE
INHIBIT
CONTROL CIRCUIT & Y CHASSIS
32 WORD x 96 BIT FERRITE CORE MEMORY
READ MODE
TELEPHONE LINES
DATA DISPLAY AT A.G.S.

Fig. 4

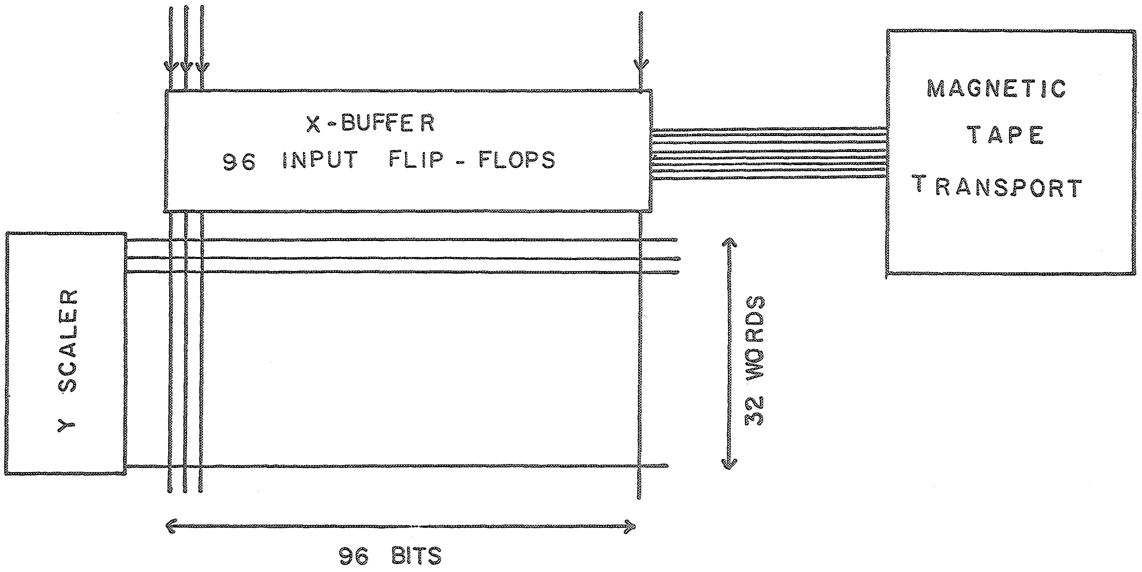

X-BUFFER
96 INPUT FLIP-FLOPS
MAGNETIC TAPE TRANSPORT
Y SCALER
32 WORDS
96 BITS

Fig. 5

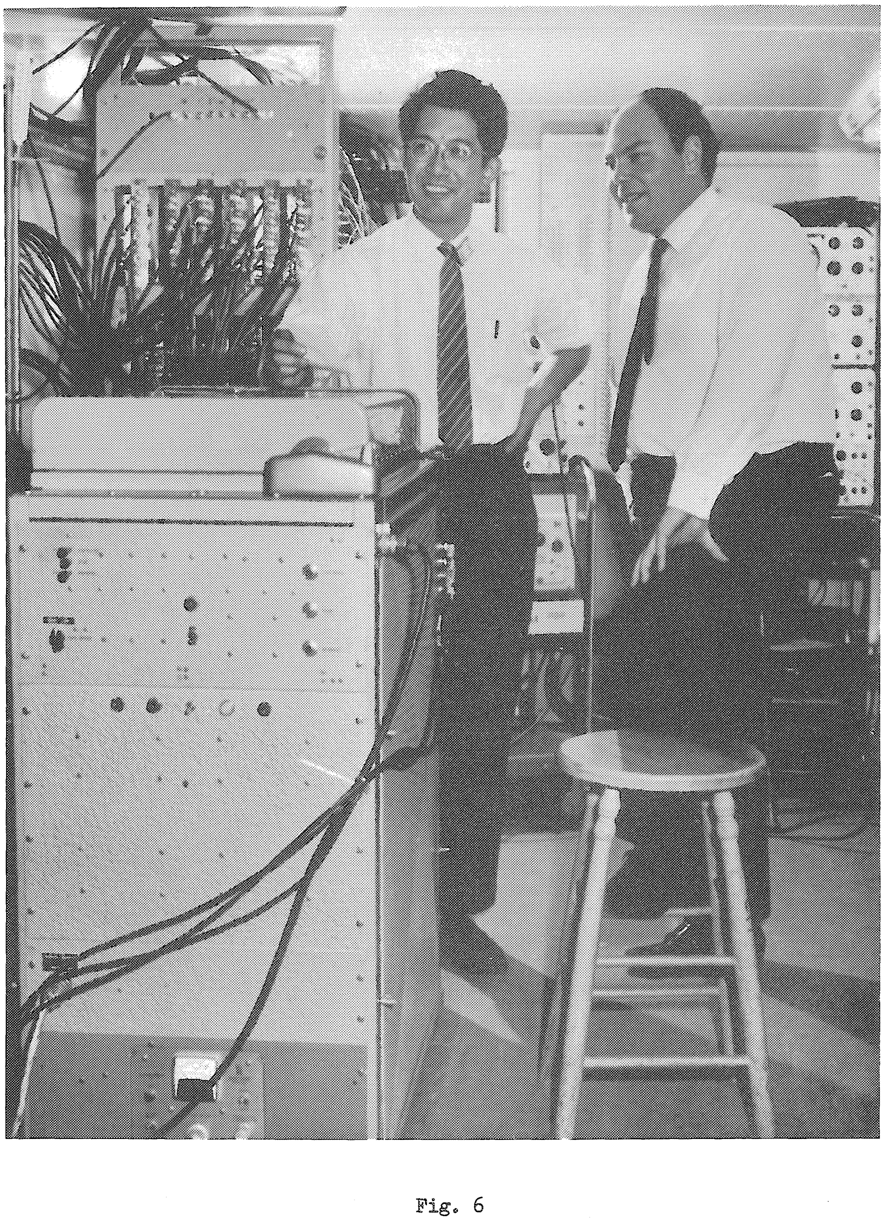


Fig. 6

Fig. 7

FLOW CHART FOR FIRST ON-LINE EXPERIMENTS

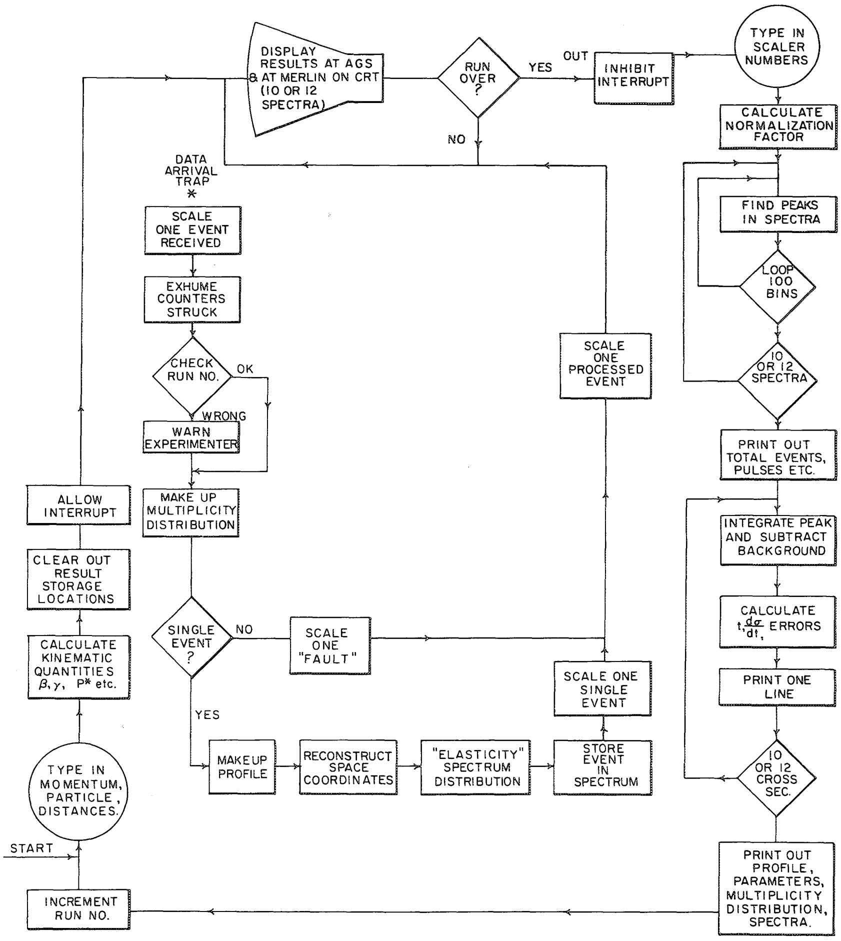


Fig. 8

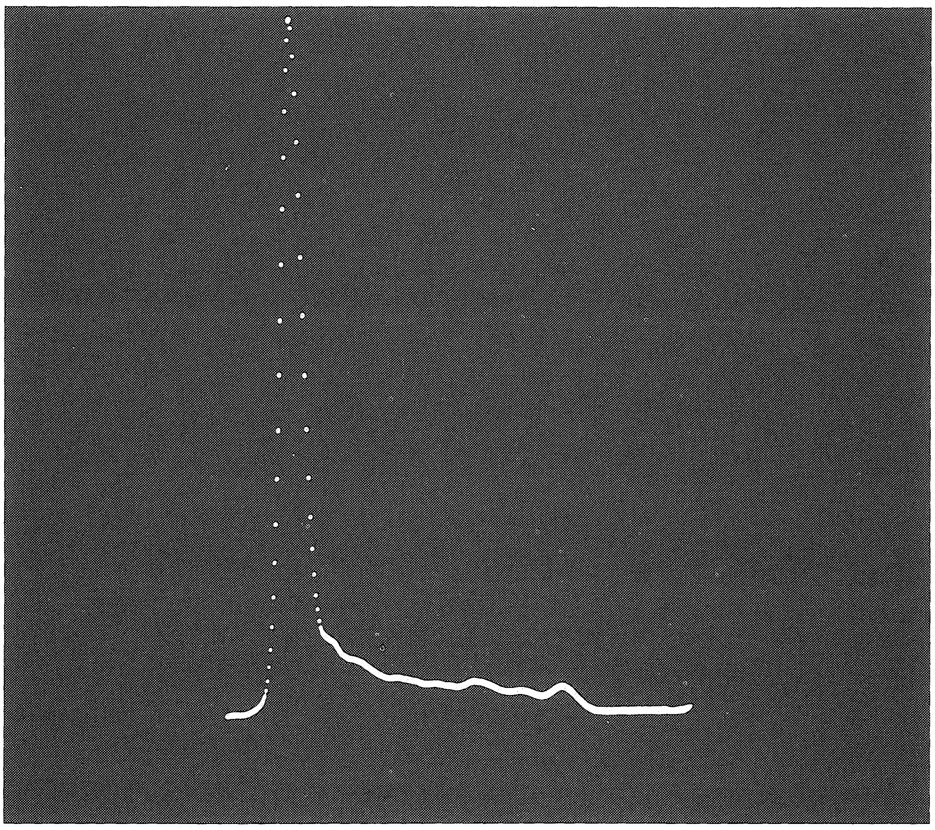
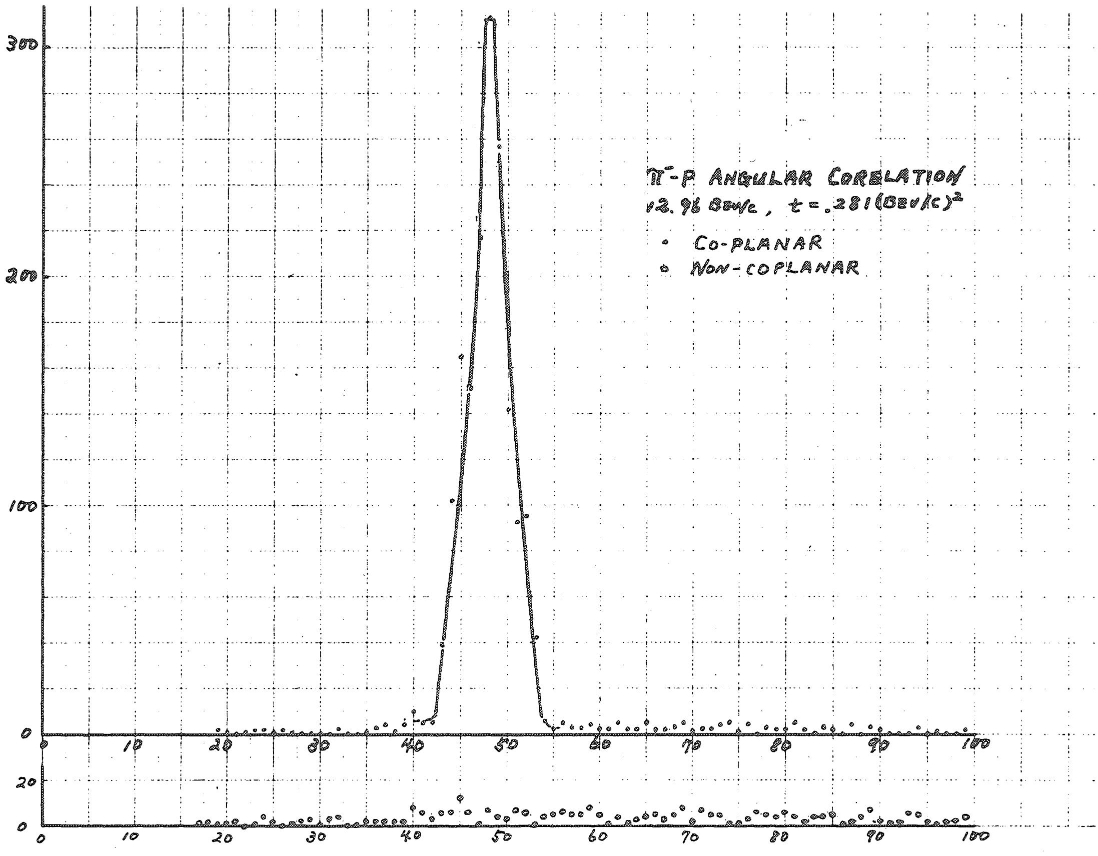


Fig. 9a



π⁻-P ANGULAR CORELATION
12.96 BeV/c , t = .281 (BeV/c)²
• CO-PLANAR
∘ NON-COPLANAR
300
200
100
0
20
0
0
10
20
30
40
50
60
70
80
90
100

Fig. 9b

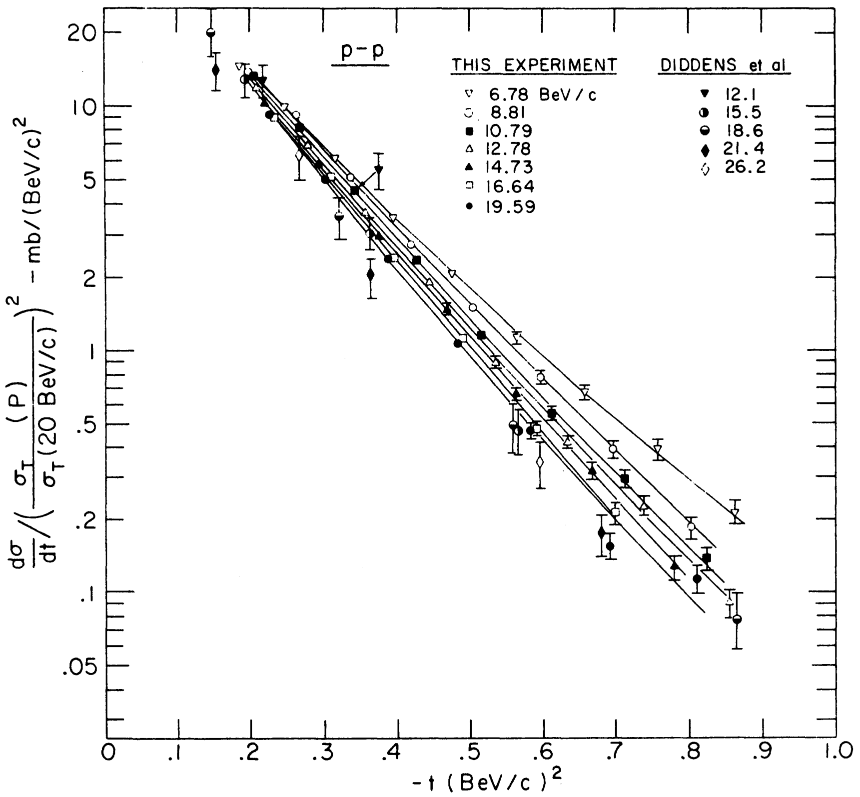


Fig. 10a

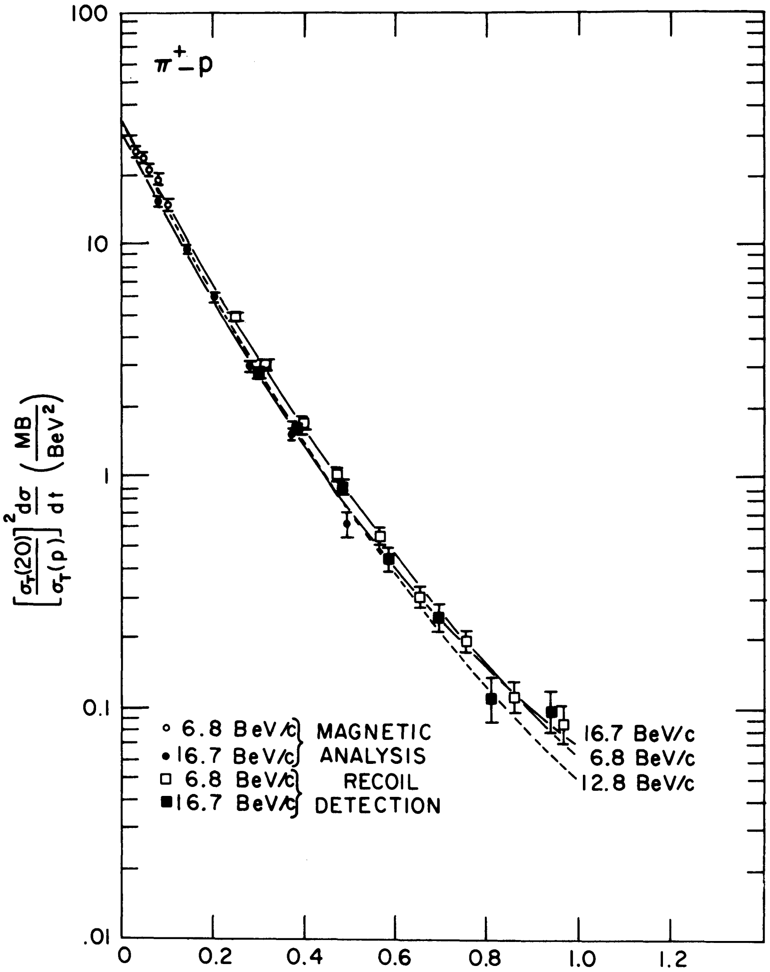


Fig. 10b

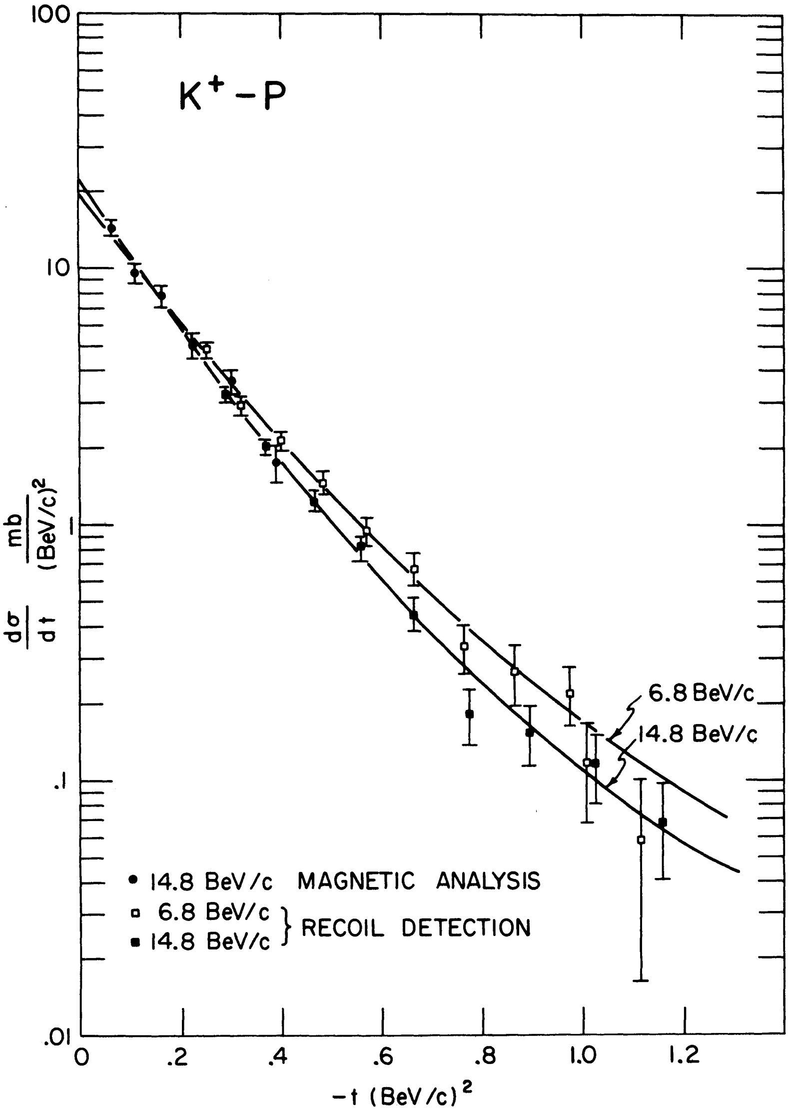

K⁺ – P
100
10
1
.1
.01
dσ/dt mb/(BeV/c)²
0
.2
.4
.6
.8
1.0
1.2
–t (BeV/c)²
6.8 BeV/c
14.8 BeV/c
● 14.8 BeV/c MAGNETIC ANALYSIS
□ 6.8 BeV/c
■ 14.8 BeV/c
RECOIL DETECTION

Fig. 10c