1972

An Experiment to Study 10 Tev Hadron Interactions.

David Russell Humphreys

Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation

https://digitalcommons.lsu.edu/gradschool_disstheses/2219

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
INFORMATION TO USERS

This dissertation was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.

2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.

3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again - beginning below the first row and continuing on until complete.

4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.

University Microfilms
300 North Zeeb Road
Ann Arbor, Michigan 48106
A Xerox Education Company
HUMPHREYS, David Russell, 1942-

AN EXPERIMENT TO STUDY 10 TeV HADRON INTERACTIONS.

The Louisiana State University and Agricultural and Mechanical College, Ph.D., 1972

Physics, elementary particles

University Microfilms, A XEROX Company, Ann Arbor, Michigan
AN EXPERIMENT TO STUDY 10 TeV HADRON INTERACTIONS

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in

The Department of Physics and Astronomy

by

David Russell Humphreys
B.S., Duke University, 1963
May, 1972
PLEASE NOTE:

Some pages may have
indistinct print.
Filmed as received.

University Microfilms, A Xerox Education Company
FOREWORD

This dissertation describes the apparatus of a high energy cosmic ray experiment. The apparatus is now being used at the Louisiana State University Cosmic Ray Laboratory. It is located on Chalk Mountain near Climax, Colorado, at an altitude of twelve thousand feet. The dissertation has two parts, each of which has been published. The first part is a description of the whole experiment, to which many others besides myself contributed. The second part is a description of the pulse height recording system, which was a part of my own work.

The project started in 1964 as an idea in the minds of Professors K. Pinkau and R. W. Huggett. It moved to Colorado in 1968, and is producing data today after an expenditure of over one million dollars. Many people have contributed, but the project might never have succeeded without Mr. Leonard D. Chisholm. He was the indispensable engineer, project manager, and general "spark plug" of the experiment. I count it a privilege to have known him, as well as the others.

I also appreciate the financial aid of the Dr. Charles E. Coates Memorial Fund donated by George H. Coates.
TABLE OF CONTENTS

FOREWORD........................................ ii
LIST OF FIGURES................................ iv
ABSTRACT........................................ v
1. GENERAL DESCRIPTION OF EXPERIMENT........... 1
2. PULSE HEIGHT RECORDING SYSTEM............... 13
   2.1 Introduction............................... 13
   2.2 Method of Operation........................ 14
   2.3 Circuitry Details........................... 19
   2.4 Performance and Accuracy................... 26
   2.5 Possible Improvements....................... 30
REFERENCES...................................... 31
VITA............................................. 32
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Schematic diagram of entire apparatus</td>
<td>2</td>
</tr>
<tr>
<td>2. Plan view of spectrometer</td>
<td>5</td>
</tr>
<tr>
<td>3. Side view of spectrometer</td>
<td>8</td>
</tr>
<tr>
<td>4. Vertical cascade in spectrometer</td>
<td>10</td>
</tr>
<tr>
<td>5. Inclined shower in spectrometer</td>
<td>11</td>
</tr>
<tr>
<td>6. Block diagram of pulse height recording system</td>
<td>16</td>
</tr>
<tr>
<td>7. Relationships in height-to-time conversion</td>
<td>18</td>
</tr>
<tr>
<td>8. Oscilloscope display of output</td>
<td>20</td>
</tr>
<tr>
<td>9. Block diagram of height-to-time converters</td>
<td>21</td>
</tr>
<tr>
<td>10. Circuit diagram of height-to-time converters</td>
<td>22</td>
</tr>
<tr>
<td>11. Voltage versus current characteristic of level detector</td>
<td>25</td>
</tr>
<tr>
<td>12. Calibration curve of converter</td>
<td>27</td>
</tr>
</tbody>
</table>
ABSTRACT

Part 1 of the dissertation describes an experiment which is underway to study the properties of gamma rays emitted from individual interactions of known ultra high energy (∼10 TeV). This experiment is being carried out at an altitude of 3.7 km (660 g/cm²) in the Louisiana State University Cosmic Ray Laboratory located near Climax, Colorado. An emulsion chamber of unique design is used to determine the energies and spatial relationships of gamma rays emitted in the decay of π⁰ mesons originating from individual interactions of ultra high energy hadrons in a carbon target located above the emulsion chamber. The total energy of an event is determined using an ionization spectrometer having a low-Z (glass) absorber which is about 11 interaction mean free paths deep. Ionization within the spectrometer is sampled every 2 radiation lengths by layers of plastic scintillator which are viewed by photomultipliers. Space and energy resolution within the spectrometer are achieved by using image intensifier cameras that give right-angle stereoscopic photographs of high energy cascades passing through the layers of scintillator. Time resolution with the emulsion chamber is achieved by pulsing the image intensifier cameras as well as neon flash tube hodoscopes when the ionization energy loss within the
spectrometer exceeds a threshold value. Soon after the events of interest have occurred, emulsions containing the events are removed for processing and analysis.

Part 2 describes in detail the pulse height recording system used in the experiment. This system can photographically record with one dual-beam oscilloscope the amplitudes of 10 simultaneous photomultiplier pulses over a four-decade dynamic range with an accuracy of ±1.5% over the entire range. The signal processing time is 2.2 usec. The basic circuit is a logarithmic pulse-height-to-time converter with two triggering levels, requiring twelve transistors per input channel. The dynamic range of the device could be easily extended to six decades, and the two-level technique can be applied to digitized recording systems and pulse height analyzers. The circuit has been found to meet the above specifications over a temperature range from -19 to +38°C.
1. GENERAL DESCRIPTION OF THE EXPERIMENT

An experiment is being carried out to obtain information about the gamma rays emitted from individual interactions in carbon of hadrons of known ultra high energy. The apparatus for this experiment is being operated at an altitude of 3.7 km (660 g/cm²) in the Louisiana State University Cosmic Ray Laboratory located near Climax, Colorado.

A schematic diagram of this apparatus is shown in Fig. 1. An incident ultra high energy hadron strikes first the 15 cm thick carbon target. If the hadron suffers an interaction in the target, most of the secondaries will escape and pass downward into the emulsion chamber. A space has been provided between the target and the emulsion chamber to allow the secondaries to undergo some lateral spreading. The emulsion chamber consists of alternate layers of lead and emulsion, a total of about 11 radiation lengths. Hence, in the emulsion chamber all of the gamma rays from the primary interaction will produce electromagnetic cascades. Ideally, none of the secondary hadrons would interact in the emulsion chamber, and they would leave the emulsion chamber along with the remnants of the electromagnetic cascades. (In practice, there will be some interactions in the emulsion chamber of these secondary hadrons. Their effects will have to be separated from...
Fig. 1. Schematic diagram of the entire apparatus. The diagram shows the relative positions of the neon flash tube hodoscope arrays, the carbon target, the emulsion chamber, and the ionization spectrometer.
those of the pure electromagnetic component.) Finally, all particles plunge into an ionization spectrometer which is used to measure the primary energy.

Above and below the carbon target as well as above and below the emulsion chamber are crossed double layers of neon flash tubes (1.75 cm in diameter). When a suitable signal has been obtained from the ionization spectrometer the flash tubes are pulsed and photographed. The neon flash tube photographs and/or the image intensifier photographs (see below) give the direction of the primary as well as the lateral position of the event in the emulsion chamber. Thus, the emulsions which contain events can be removed for processing and analysis. Fresh emulsions can be inserted into the chamber to replace those removed. The emulsions removed will be processed and scanned for the cascades. Since the cascade must exceed some minimum energy in order to be found, it is felt that the primary energies that will be involved in this experiment will be around 10 TeV.

The emulsion chamber is made of strips of lead which are inclined at an angle of 19° to the vertical. These lead strips form slots into which glass-backed Ilford K-5 emulsions 27 cm x 10 cm x 0.3 cm are placed. There are approximately 2000 compartments for these emulsion plates. The emulsions in these compartments are readily accessible for removal and replacement. Furthermore, they will be
oriented at such an angle that for near-vertical events, most of the electromagnetic cascades will be near the optimum length per emulsion plate for most efficient scanning. Because of the vertical spacing of the emulsion chamber and the target, 2000 GeV cascades will be separated by about 200 microns in the emulsion chamber. These can be readily resolved. On the other hand, the cascade separations will be sufficiently small so that the great bulk of the gamma rays (including those with energies as low as 25 GeV) will be contained within an area of about 1 cm².

The ionization spectrometer is shown schematically in more detail in Fig. 2. The total depth of the spectrometer is about 11 interaction lengths. The ionization within the spectrometer is sampled by 20 sheets of Pilot Y plastic scintillator. Each sheet of scintillator has dimensions of 91.5 cm x 183 cm x 2.54 cm. The scintillators are viewed two at a time through air by pairs of photomultipliers (with added outputs) using the geometry shown in Fig. 2. This geometry gives a uniformity of ±4% over the entire 1.7 m² area of the scintillator sheets. Pulse heights from the 10 photomultiplier channels are measured over a dynamic range of four decades using a logarithmic pulse height-to-time converter developed specifically for this project. This system allows the ten pulse heights to be displayed on the face of a single dual-beam oscilloscope. Absolute calibrations of the system are made using muons.
Fig. 2. Plan view of ionization spectrometer, photomultipliers (PMT), mirror arrays, and image intensifier cameras. (This was the configuration used in the Baton Rouge testing. In the mountain installation the 183 cm intensifier system is on the opposite side to the left of the 91.5 cm intensifier.)
Relative calibrations are made using a pulsed nanosecond light source. See Section 2 for the details.

The ionization spectrometer is unique in that it employs a low-Z absorber, glass. This absorber was chosen for several reasons: a) Due to the low atomic number of the absorber, the fraction of the primary energy going into energy of nuclear disintegrations will be relatively small. b) The mean atomic number of the absorber is fairly close to that of the scintillator so that spurious effects within the scintillator resulting from low-energy charged evaporation particles from nuclear disintegrations will be minimized. c) The critical energy of the absorber is fairly close to that of the scintillator so that (transition) effects\(^5\) on the cascades when they pass from the absorber into the scintillator should be minimized.

The low density absorber has the disadvantage that it reduces the geometrical factor of the spectrometer. The geometrical factor for this apparatus is 0.1 m\(^2\) sr.

The high energy hadrons incident on the apparatus will for the most part be secondary particles from an interaction that has occurred in the atmosphere above. Incident particles with energies around 10 TeV will have on the average separations of 5-10 cm upon reaching the apparatus. Now this is much less than the lateral dimensions of the apparatus. Hence, there will usually be multiple incidence upon the apparatus of the ultra high energy
particles with which the experiment is mainly concerned. It is thus necessary to have space resolution and the capability for measuring the individual energies of these simultaneous ultra high energy nuclear-electromagnetic cascades within the spectrometer. This is achieved by stereoscopically photographing much of the development of the cascades as they pass through the layers of plastic scintillator within the spectrometer. For this, two pulsed image intensifier cameras and mirror systems are used. These are shown schematically in Fig. 2 and Fig. 3.

The scintillator sheets are viewed from two sides by the image intensifier cameras. On each of two adjacent sides of the spectrometer is a complex array of strip mirrors which equalize the light paths from each of the scintillators and compress the field of view to exclude most of the glass absorber. Light from the cascades is imaged onto the input photocathodes of EMI 9694B image intensifiers. These are four stage, cascade-type intensifiers with magnetic focusing. The tubes are operated with steady high voltage across the first three stages, but with no voltage across the last stage. Thus, in the steady condition photoelectrons are prevented from reaching the output screen of the tube. The last stage is pulsed when the electronic logic circuitry has determined that an event of interest has occurred. The intensified image then reaches the output screen. Thus, the intensifiers store the images
Fig. 3. Side view of spectrometer, showing photomultipliers, mirror arrays, and intensifier.
of the cascades while the electronics is making the decision to pulse. Of course, the intensifiers also amplify the light signal. When operated at a full gain of about $10^6$, the threshold for photographing a cascade in a sheet of scintillator corresponds to the cascade having a few hundred closely spaced particles in that scintillator sheet.

The system has been in operation at the mountain-altitude laboratory since January 1969. Two of the early photographs of ultra high energy showers obtained with the system are shown in Figs. 4 and 5. In Fig. 4 is a nearly vertical cascade which in the lower half of the spectrometer attained sufficient development to be recorded. (The vertical column of bright images to the right of the photograph is the result of fiducial lights.) Fig. 5 shows an inclined shower incident from the right on the lower half of the spectrometer.

Thus, the initial operation of the system indicates that with the ionization spectrometer employing plastic scintillator, one can take advantage of the possibilities of the luminescent chamber. From the right-angle stereoscopy, it appears possible to determine the directionality of simultaneously-occurring, ultra high energy cascades and thereby locate these events in the emulsion chamber. Furthermore from measurements of the optical densities of the images on these photographs, it should be possible to determine the ratios of the energies of these cascades (if
Fig. 4. Image intensifier photograph of a nearly vertical cascade which in the lower half of the spectrometer attained sufficient development to be recorded. The vertical column of bright images at the right of the photograph is the result of fiducial lights.
Fig. 5. Image intensifier photograph of an inclined shower incident from the right on the lower half of the spectrometer.
not the energies themselves). This information along with that from the photomultipliers (which measure the total ionization within the spectrometer) will give energies of the individual nuclear-electromagnetic cascades in the spectrometer.

The basic measurements in this experiment will involve the energies and angles of the gamma rays from each ultra high energy hadron interaction in carbon as well as the energy of the primary hadron. From these measurements, one can obtain for the gamma rays of each event transverse momenta, center-of-mass system energies, center-of-mass system angles, and the multiplicity. It should be possible to measure the energies of individual gamma rays to an accuracy of about 20% up to indefinitely high energies. Primary energies should be measurable to an accuracy of around 10-20%.

The experiment concentrates on determining rather completely and well the properties of one component of the secondaries from ultra high energy interactions, namely, the gamma rays. These gamma rays arise mainly from the decay of neutral pions. These neutral pions reflect the properties of all of the produced pions. Since pions constitute about 80% of the particles produced in the interactions, this limited experiment has the capability of determining many of the gross features of multi-particle production at ultra high energies.
2. PULSE HEIGHT RECORDING SYSTEM

2.1 Introduction

For this experiment, it was necessary to have a data-gathering system which would record the heights of many simultaneous photomultiplier tube pulses whose amplitudes could differ by as much as a factor of $10^4$. It was desired that the recording process be finished within 2 μsec after the initiation of the pulses in order to avoid interference from a subsequent high-voltage transient generated elsewhere by the experimental apparatus. The event rate is low, about one per day, so the data can be recorded in an analogue form on oscilloscope photographs rather than in a digital form. Yet, an accuracy of at least a few percent over the entire range of amplitudes was desired.

There are at least two other wide-range recording systems, both for cosmic ray experiments, but they have signal processing times of the order of 100 μsec. One system requires many oscilloscopes, while the other requires at least 27 transistors per input channel and has only 10% accuracy.

The technique chosen here is a modification of the logarithmic pulse-height-to-time converters used in some analyzers. In those analyzers, the input pulse is admitted through a linear gate and charges a capacitor. The gate is
then closed and the capacitor discharges slowly into a level-detector circuit. The decay time constant is usually of the order of milliseconds. In the meantime, a clock oscillator has begun to send pulses to a digital counter which is started the instant the capacitor is charged. At the instant the capacitor voltage decays below some preset trigger voltage, the level detector cuts off the clock oscillator. The counter then registers a time which is proportional to the logarithm of the initial voltage to which the capacitor was charged. Some shortcomings of that system are (1) wide-range linear gates are difficult to build, (2) large pulses require a long time to be processed, and (3) the accuracy begins to suffer when the pulse height gets over 100 times higher than the triggering level. These factors limit the range of pulse heights which can be recorded in a short time with reasonable accuracy.

The system described here overcomes the dynamic range limitation by using several triggering levels which differ by several orders of magnitude. The system uses no linear gates or storage capacitors. Instead, the photomultiplier pulses (from emitter followers) are applied directly and simultaneously to high- and low-level triggers.

2.2 Method of Operation

The system makes use of the purely exponential shape of photomultiplier pulses. By varying the anode resistance and capacitance at each photomultiplier, the decay time
constant of the pulses is preadjusted to 432 nsec. (The rise time should be less than 20 nsec.) When an event occurs, two things happen. A coincidence circuit triggers an oscilloscope sweep, and pulses appear simultaneously on the anodes of each photomultiplier and start to decay. In our experiment, we have 20 photomultipliers and emitter follower circuits from which 10 pulses are derived by means of passive mixer circuits. The resulting 10 exponentially-decaying voltages go to 10 two-level pulse-height-to-time converters. (See the system diagram in Fig. 6.)

Each converter consists of two level-detectors (tunnel diode Schmitt triggers) whose sole duty is to emit a short time marker pulse (10 nsec wide) whenever the input voltage falls below a preset level. The upper threshold is 200 mV, and the lower threshold is 2 mV. The input pulse is applied simultaneously to both detectors with one of the three following results: (1) If the initial amplitude is less than 3 mV, neither detector emits a time marker pulse. (2) If the initial amplitude is greater than 3 mV but less than 300 mV, the low-level detector emits a spike at the instant the input voltage decays below 2 mV. The high-level detector is not triggered. (3) If the pulse height exceeds 300 mV, both detectors emit spikes. First, the high-level detector is triggered when the input voltage decays through 200 mV. Next, the low-level trigger emits a spike when the voltage has decayed through 2 mV. The high-
INPUT FROM PHOTOMULTIPLIER EMITTER FOLLOWERS

NEGATIVE PULSE, 430 NSEC DECAY CONSTANT 3MV TO 35V

 INPUT FROM EVENT TRIGGER

1. 200 MV, 10 NSEC SPIKE, EITHER POS OR NEG, OCCURRING A MAX OF 2.2 µSEC AFTER INITIATION OF EVENT

Fig. 6. Block diagram of pulse height recording system.
and low-level spikes are always separated by a fixed interval, in this case, 2.0 μsec.

Figure 7 illustrates the relevant relationships.

The length of time between the beginning of the event and the occurrence of the spikes is directly proportional to the natural logarithm of the initial pulse height:

\[(t_h - t_0) = \text{time from start of event to high-level spike} = 432 \log_e(E/200) \text{ nsec,}\]

\[(t_l - t_0) = \text{time from start of event to low-level spike} = 432 \log_e(E/2) \text{ nsec, where } E \text{ is the initial amplitude of the pulse in mV. Therefore, the occurrence time of a spike is a measure of the initial pulse height, which can be computed as follows:}\]

\[E = 200 \exp[(t_h - t_0)/432] \text{ mV,} \quad E = 2 \exp[(t_l - t_0)/432] \text{ mV,}\]

where the time intervals are in nanoseconds.

The high-level spike is positive and the low-level spike is negative. Both of these spikes go to the output of each converter. A dual-beam oscilloscope displays the spikes from all 10 converters, 5 on each beam. The heights of the spikes on the oscilloscope screen are coded so that one can distinguish the spike from one input channel from that of another. A spike from channel 1 is 1/4 cm high, positive or negative; from channel 2, 1/2 cm high, positive or negative; and so forth.

If the oscilloscope trace were exactly 2.0 μsec in length, only one spike from each channel would appear on
Fig. 7. Relevant relationships in pulse-height-to-time conversion. Upper graph shows typical input to a converter, superimposed on the two triggering levels of the converter. $I$ is initial amplitude of pulse. Lower graph shows output of the converter. $t_0$ is the starting time of event; $t_h$ and $t_l$ are the times that the pulse decays through the upper and lower levels, respectively.
the trace. (If the high-level spike were on the trace, the low-level spike following 2.0 μsec behind the first would be off the trace.) So only five spikes would appear on a trace. However, the trace duration to be used in this experiment is 2.2 μsec in order that there be suitable overlapping between upper and lower levels. Thus, in a few cases there may be more than five spikes per trace. Since the spikes are narrow compared to the trace width, they rarely coincide; when they do, the information is still recoverable.

Figure 8 shows a typical oscilloscope display. The polarity of each spike indicates the level triggered, the height of each spike tells which input channel it represents, and the occurrence time of each spike (relative to a dot marking \( t_0 \)) is a measure of the pulse height in the corresponding input channel. The recording process is completed by photographing the display.

The triggering levels, decay time, and trace width selected give a minimum recordable pulse height of 3 mV and a maximum of 32 V. That is, the dynamic range is more than 4 decades, or 80 dB.

2.3 Circuitry Details

Each two-level converter is hardly more than three X10 amplifiers in series and two tunnel diode Schmitt triggers. (See Figs. 9 and 10.)
Fig. 8. Typical oscilloscope display of system output. Reference dot marks start of event. Height of each spike identifies channel of origin; polarity indicates whether high- or low-level; occurrence time indicates amplitude of corresponding input pulse.
Fig. 9. Block diagram of one of the two-level height-to-time converters.
Fig. 10. Circuit diagram of the two-level height-to-time converter. The 120, 15, 6.8, and 1.5 μF capacitors are tantalum electrolytics. $C_3$, $C_4$, $C_5$ are Erie 0.001 μF feed-through capacitors. The 0.01 μF, 0.001 μF, and 390 pF capacitors are ceramic. All resistors are 1/4 W unless otherwise indicated. The 1% resistors are IRC CEM T-0 metal film resistors. $Q_1$, $Q_3$, $Q_4$, ..., $Q_8$ are 2N3905's; $Q_2$ is a 2N3250; $Q_9$, $Q_{10}$, $Q_{11}$, $Q_{12}$ are 2N708's; $D_1$, $D_2$, $D_3$, $D_4$ are 1N4739A Zener diodes; $D_5$ and $D_6$ are 1N3712 tunnel diodes; $D_7$ and $D_8$ are 1N914 diodes; $T_1$ is an inverter transformer, 10 bifilar turns on a Ferroxcube 1041T060/3E2A core. (Core is not critical.)
The amplifiers are essentially grounded-base amplifiers with heavy feedback and heavy biasing. The input and output of each stage is negative-going. Each stage is (unnecessarily) linear up to an input voltage of 400 mV, where the amplifiers saturate.* The impedance of the converter input is constant (about 50 Ω) up to an input amplitude of 5 V, at which point it drops sharply. This results in an apparent clipping of all pulses at the 5 V level. The clipping does not matter in operation, since the PMT emitter followers effectively isolate the PMT anodes from the converter inputs.† But the effect makes calibration more

*Saturation of the amplifier does not matter, since the amplifiers only chop off the top of the pulse at 4 V, whereas the triggers operate at 2 V. That is, the voltage at the low-level trigger decays through 2.0 V only a few nanoseconds after the instant that the input has decayed through 2 mV, regardless of saturation at 4 V, and this instant is all that the circuit is concerned with. For this reason, the amplifiers do not have to be linear over four decades. In fact, they do not have to be linear at all.

†Our emitter follower is a three-stage transistor circuit whose input resistance is about 400 kΩ. There is a variable 15 kΩ swamping resistor and a 20 pF swamping capacitor in parallel with the input to the emitter follower. The purpose of the swamping resistor and capacitor is to reduce the effect of any changes in the input impedance of the emitter follower, because it is essential that the decay time constant of the PMT pulses remain constant. The total input capacity (including anode, stray, emitter follower input, and swamping capacitance) is about 40 pF. An 11 kΩ setting of the swamping resistor gives the required 430 nsec decay constant. Tests show that the decay constant seems to be stable to much less than 1% over a 55 °C temperature range. The maximum peak anode current for which the PMT response is linear to 1% sets an upper limit on the total capacitance at the PMT anode. We suspect that this maximum current is about 100 mA for an RCA 8055. A maximum pulse amplitude of 35 V and a rise time of 20 nsec implies that the maximum tolerable anode capacitance is about 60 pF.
difficult for pulses greater than 5 V.

The rather large 120 µF capacitors between stages ensure that the exponential pulse will not be quasidifferentiated, so that the circuit response will be purely logarithmic. This makes the amplifiers prone to oscillate at a low frequency unless care is taken in constructing the circuitry and in providing supply voltage filtering. Ground-plane construction, subminax cable, shielded sections, and filtering with Zeners and tantalum capacitors were used to achieve this.

The tunnel diodes in their quiescent state are forward biased well into the diode region, at point A in Fig. 11. A negative pulse exceeding 3.0 V sweeps the diode to point B, where it conducts heavily. During the pulse decay the operating point moves toward point C. When the input voltage decays through 2.0 V, the diode snaps off from point C to point D, causing a 300 mV step in the voltage across the diode. (The threshold voltages can be adjusted with the biasing potentiometers, \( R_3 \) and \( R_4 \).) The rise time of the voltage across the diode is limited by the capacitance to ground at that point, so the circuit construction should minimize stray capacitance across the tunnel diodes.

The differentiators \( R_1C_1 \) and \( R_2C_2 \) extract a positive spike from the positive-going edge of the tunnel diode pulse. The spike from the high-level trigger goes directly
Fig. 11. Voltage vs current characteristic of tunnel diode level detector, showing sequence of operation. Point A is quiescent state.
to the output; the low-level spike is first inverted and then sent to the output. The amplitude of both spikes is about 200 mV.

Passive mixer circuits then combine the spikes into two groups of five and attenuate them according to their channel of origin. The spikes drive two fast linear amplifiers,* which in turn drive the inputs of a Fairchild 777 dual beam 100 MHz oscilloscope.

2.4 Performance and Accuracy

We have tested several units with actual photomultiplier pulses ranging from 3 mV to 35 V. We used an artificial nanosecond light source to simulate scintillations. Pulse heights and output times were photographed on a dual-beam 30 MHz oscilloscope. We also used simulated pulses from an external pulser, ranging from 3 mV to 5 V, and heights and times were recorded on a more accurate 85 MHz oscilloscope. The two methods agreed within their limits of accuracy.

Figure 12 shows the actual calibration curve of a typical unit at 20°C. The decay time of the photomultiplier pulse determines the slope of each line; the Schmitt trigger thresholds determine the intercepts. The time constant in

*Since the article was published, we have changed the system. It now uses a separate avalanche pulse generator for each of the 20 possible spikes. This was one of Mr. Chisholm's contributions.
Fig. 12. Actual calibration curve of a typical converter module at 20°C. Curves at +38 and -19°C do not differ enough to show on graph.
The two factors which limit the circuit accuracy in practice are (1) phototube noise pulses which occur during the 2 μsec processing time or a few microseconds before the event, and (2) the precision with which one can measure the occurrence time of a spike from a photograph.

The error due to phototube noise is small whenever the signal pulses can be made much larger than the height for which noise pulses have less than, say, 1% probability of occurring in a 2 μsec interval. This is the case in our system except in calibration, which uses single muons.*

*To demonstrate that PMT noise is negligible in our case, we set up a prototype of our scintillator-PMT system, simulating scintillations with an artificial nanosecond light source mounted within the scintillator. The smallest cascade we expect to record contains about 100 minimum-ionizing particles, so we set the light source at 100 times the intensity of a single minimum-ionizing muon. We then measured the signal pulse height and the noise pulse frequency under various conditions. Below is one set of data.

Scintillator: 2.54 cm thick plastic (Pilot-Y).
PMT: RCA 8055 12.7 cm diam.
Arrangement: PMT 91 cm from thin edge of scintillator, light source 91 cm within scintillator.
PMT voltage: 1100 V.
PMT temperature: 20°C.
Average signal pulse height: 275 mV.
Frequency of noise pulses greater than 2.75 mV: 1022 pulses/sec.

We will probably reduce the signal pulse height to 3 mV with attenuators placed after the PMT emitter followers,
The relative error in the pulse height $E$ due to the error $\Delta(t_h - t_0)$ in measurement of the time interval $(t_h - t_0)$ is approximately $[\Delta(t_h - t_0)]/(432 \text{ nsec})$.

The same relation applies to the lower level. The percentage error is independent of pulse height, and it depends only on the size of the time error as compared to the decay constant of the pulse. A measure of the reading error $\Delta(t_h - t_0)$ is the halfwidth at half-maximum of the output pulses, i.e., 5 nsec. The corresponding percentage error is ±1.2%.

Temperature variation and internal circuit noise contribute less error than the reading error. The low-level pulse has some time jitter due to amplifier noise. This jitter is about ±2 nsec (±0.5%). The high-level pulse has no measurable jitter. The circuit has been tested from -19 to +38°C. The average temperature variation of a typical unit was +0.08% per deg C for the low level and -0.018% per deg C for the high level. The largest temperature error was 0.16% per deg C. Since we control the circuit temperature to ±2.8°C, our error due to temperature variations is less than ±0.5%. The rms value of all these errors (thermal, noise jitter, and measurement errors) is 1.4%.

but that would not change the signal-to-noise ratio. The data imply that $P = \text{probability of a noise pulse (greater than 1\% of the minimum signal) occurring in any 2 \mu sec interval} \approx 0.2\%$. 
The circuit can handle input amplitudes from 3 mV to 35 V, with the output representing the input to an accuracy of about ±1.5% over the whole range of input amplitudes.

2.5 Possible Improvements

A new design incorporating the same principles should use a simpler amplifier, one which is not as linear as the one described here. Also, each tunnel diode should drive an avalanche transistor directly. This would eliminate the necessity for the linear amplifiers which drive the oscilloscope, and it would provide narrower spikes.

Each level could cover three decades instead of two, or additional levels with different coding could be used to increase the dynamic range to six or seven decades. Multi-channel analyzers could use a linear decay with several (nonzero) triggering levels to extend their range and accuracy. When inexpensive 100 MHz scalers become available the output could be easily digitized.

Because it selects amplitude ranges in a natural way, the multilevel technique is applicable to a variety of experiments.

I want to thank Wolfgang Schmidt\textsuperscript{†} for clearly outlining the shortcomings of conventional analyzers to me and for suggesting that tunnel diodes be tried as Schmitt triggers.

\textsuperscript{†}Now at the Max Planck Institute for Extraterrestrial Physics, Munich, Germany.
REFERENCES


VITA

David Russell Humphreys was born February 2, 1942, in Wyandotte, Michigan. He graduated from Orangeburg High School in Orangeburg, South Carolina, and entered Duke University in 1959. After receiving the B.S. degree in June 1963, he married Bonita Carol Roye of Baltimore, Maryland, and entered the Graduate School of Louisiana State University. His life was changed drastically when he received Christ in July 1969 in the mountains near Frisco, Colorado.

The Humphreys have three children: Julia, Jeffrey, and Debbie.
Candidate: David Russell Humphreys

Major Field: Physics

Title of Thesis: An Experiment to Study 10 TeV Hadron Interactions

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Robert F. Coddell

[Signatures]

Edward Zajac

James A. Peters

[Signatures]

Date of Examination:

4 February 1972