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Final Report on Contract NAS8-31895 entitled

INVESTIGATIONS IN COSMIC AND GAMMA RAY ASTRONOMY AND NUCLEAR INSTRUMENTS

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for the period March 19, 1976 through October 31, 1981

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ABSTRACT

This report summarizes the results of work done under Contract NAS8-31895 in two areas: gamma-ray instrument design studies and cosmic ray measurements and design studies.

Gamma Ray Studies: Introduction

The Nuclear Radiation Monitor (NRM) will fly on the Spacelab 2 vehicle as part of a set of instrumentation designed to measure the ambient physical environment on Spacelab in orbit. The NRM will operate before, during, and after the 9-day mission to measure the natural and induced gamma-ray activity. Such measurements are considered to be of great value to astronomers with instruments on board the Spacelab.

The instrument is constituted of a 5" x 5" (NaI (Tl)) crystal viewed with a single phototube and surrounded by a plastic anticoincidence shield. It will be mounted on a pedestal and placed, with its electronics, on the Spacelab pallet.

Under this contract the detector head was designed and a development model fabricated and tested. Extensive software studies for on-board and GSE microprocessors for use with the NRM were also made.

Gamma Ray Studies: Technical Report:

Cosmic rays and protons trapped by the Earth's magnetic field interact with nuclei in the materials of any orbiting vehicle causing excitation and mutation. One of the most significant indications of this process is the flux of γ-rays emitted by the excited target or product nucleus as it decays to a more stable state. The flux of such induced gamma-rays is not expected to be constant and will be highest during and just after passage through the south Atlantic anomaly, where the Van Allen belts approach the Earth more closely than elsewhere.

The detector, though not of the highest resolution capability, is capable of resolving and identifying the strongest gamma ray lines. Usable energy range will be 100 keV to 20 MeV with a resolution figure of 8% at 622 keV. The instrument has nearly omnidirectional response. A plastic scintillator shield surrounding the central crystal permits removal of counts caused by charged particles.

The mechanical design of the NRM has been completed and has passed its preliminary and final design reviews. The assembly also passed an analytical examination by the MSFC structures group to determine its ability to withstand the increased accelerations specified for Spacelab 2. A development and test model has been fabricated and delivered and was successfully flown piggyback on the May 1982 long duration balloon flight of the Burst and Transient Source Experiment. Assembly drawings and part-lists were delivered to NASA, MSFC and are now part of the NRM documentation.

Studies were made of software systems for on-board and GSE microprocessors required to accumulate and format data as well as perform checkout and diagnostic procedures. The results of these studies were implemented and are currently on disc file in the Astrophysics Branch of Space Sciences Laboratory, MSFC.

Cosmic Ray Studies

The emphasis of the UAH-MSFC cosmic ray research program has moved from high-resolution measurements of the charge spectrum in the energy region around 1 GeV per nucleon toabundance measurements in energy regions several orders of magnitude higher, where the spectral indices of the elements are still only poorly defined. The studies are proceeding along two lines. Firstly, the addition of a Freon-12 gas Cerenkov detector to the experiment stack for the Fall 1978 flight allowed direct and continuous energy measurement from 0.5 GeV/n to $\sim$ 100

GeV/n. The measurement also allowed calibration of the relativistic rise of ionization loss in the xenon-filled ion chambers. Results on the ion chamber response have been published and are included in the addendum to this report. Work is continuing on the more abundant elements to test calculations which predict that the response in xenon should allow energy measurement to at least 500 GeV/n.

The second avenue of the high energy investigation is an emulsion experiment of the Japanese-American collaboration. With exposures achieved to date, the series of flights has extended flux measurements to 100 TeV total energy. A draft (March 1982) of a paper on the proton and helium spectrum above 1 TeV, which is to be submitted to Physical Review Letters, is also included in the addendum to this report.

A test of a new high energy method (acoustics) was attempted in 1980. A position sensitive scintillator was designed and built to trigger the readout of the acoustic detectors when an event of sufficient energy passes through the experiment. A new set of GSE was also designed for this experiment and the software prepared and implemented. The acoustic experiment was inconclusive since the acoustic detectors did not perform according to specification.

The Fall 1978 Flight of the MSFC-UAH High Energy Cosmic Ray Experiment

The scientific objectives of the Fall 1978 flight were two:

1. To improve the statistical significance of the flux measurement over the energy range 0.5 - 2 GeV/n made during the 1976 flight for elements B to Ni. To achieve measurements of differential fluxes of the rarer elements at least 40 hours was required for our geometrical

aperture. Only 17 hours were achieved during the 1976 flight and much of this was at air thicknesses greater than 5 g cm^{-2}.

2. Flux measurements in the range 20-50 GeV/n have been made with most statical significance by the Chicago group. While theirs is a powerful and effective method it relies upon consistency checks between detectors for rejection of showers and nuclear interactions. The MSFC-UAH experiment with a large freon-12 gas Cerenkov counter added is capable of energy measurement in the 20-50 GeV/n region as well as having the distinct advantage of following the particle track through the experiment with the 8-layer MWPC. This has shown itself to be extremely efficient at both selecting clean particle events and rejecting interactions and showers.

The following work was done to bring the instrument to the required condition: the new configuration of detectors is shown in the figure.

1) Both MWPC modules were opened and all wires and grids checked. Everything appeared in perfect order in spite of 3 attempted launches and 2 actual launches and recoveries in 1976.

2) Both Cerenkov detectors were rebuilt with 8 PM tubes instead of 4. Laboratory tests showed that for fast muons about 10-11 photoelectrons were produced per muon for the new Teflon counter compared with about 6 for the previous version.

3) The Lucite (Pilot 425) Cerenkov detector (C_p) was placed above the gas counter modules (it was below them for the 1976 flight). This takes more advantage of the proportional counters' ability to perceive nuclear interactions within C_p. Also, slowing in C_T is not then so important.

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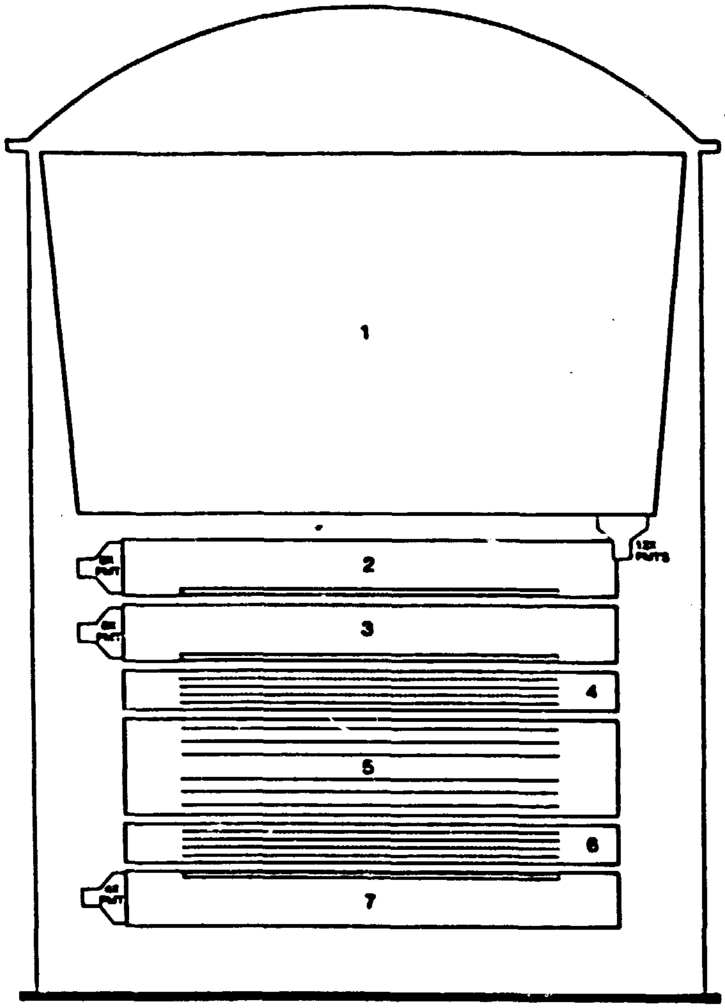
MSFC COSMIC RAY BALLOON FLIGHT EXPERIMENT



OBJECTIVES

1 MEASURE RELATIVE ABUNDANCES OF COSMIC RAYS $28 \geq Z \geq 4$, $60\ GeV/n \geq T \geq 0.5\ GeV/n$
2 MEASURE ABSOLUTE FLUX OF COSMIC RAYS FOR $28 \geq Z \geq 4$ AND $T \geq 0.5\ GeV/n$
3 DEVELOP INSTRUMENTATION FOR SPACELAB AND THE COSMIC RAY OBSERVATORY

DETECTORS

1 CERENKOV COUNTER, FREON GAS, KINETIC ENERGY $T > 20\ GeV/n$
2 CERENKOV COUNTER, TEFLON $2 > T > 0.5\ GeV/n$
3 CERENKOV COUNTER, LUCITE
- $0.5 > T > 0.33\ GeV/n$
- NUCLEAR CHARGE Z, $T > 0.5\ GeV/n$

4 MULTIWIRE PROPORTIONAL COUNTER
- TRAJECTORY,
- REJECT BAD EVENTS

5 DUAL ION CHAMBER (XENON GAS)
- NUCLEAR CHARGE Z
- $20\ GeV/n > T > 2\ GeV/n$

6 SAME AS 4
7 PLASTIC SCINTILLATOR, NE102
NUCLEAR CHARGE Z

4) The plastic scintillator (NE 102) at the bottom of the stack was a new detector. A diffuse reflecting white box was used with the plastic viewed by 4 three-inch PM tubes instead of the old light-pipe-coupled version. Much better light collection uniformity was obtained.

5) The design and manufacture of the Freon-12 gas cerenkov detector was constrained strongly by the low weight and cost budget allowed and the very short lead time available. The entire detector, in the form of a section of a right cone 30 inches high and 56 inches across at the base, with 12 five-inch PM tubes was designed and built in the laboratory within 3 months of the launch date.

The detector weighed about 100 lbs. including 50 lbs. for the tubes, bases and shields. It was painted outside with black paint and inside with G.E. Glyptal, followed by a white primer and four coats of Eastman Kodak white reflectance coating. This latter proved to be inadequate and was later covered with white Millipore paper.

Calculations show Cerenkov light emitted by sea-level muons to be insufficient for calibrating this detector.* However, two sea-level muon checks were devised, one utilising the output of muons in the glass face of a PM tube and lucite window, and the other produced in a 1 inch thick slab of lucite placed in the box. This latter material produced ∿ 750 photons when traversed by a fast muon. Since most muons detected will not have such high energy a figure of 600 photons was used for estimating collection efficiency. For a conversion efficiency of 15% and a measured distribution width corresponding to ∿ 12 photoelectrons a collection efficiency of ∿ 13% was calculated.

For a carbon particle of energy > 50 GeV/n normally incident upon the counter we estimate a yield of 70 photoelectrons. This indicates an error of about 5 GeV/n at 30 GeV/n. The PM tubes are grouped in sets of 6 and connected to separate amplifiers. Coincident pulses from these which are not consistent to a high degree indicate the passage of a knock-on electron through the window of a PM tube. Such an event can severly distort the pulse height associated with the primary event since the windows produce typically 10 times the light output for a $z = 1$ particle in the gas. Collection efficiency for these photons is several times greater also. The track visualisation allowed by the MWPC information provides a powerful means of detecting showers masquerading as primary particle events. Thus when the gas Cetenkov tube sets show

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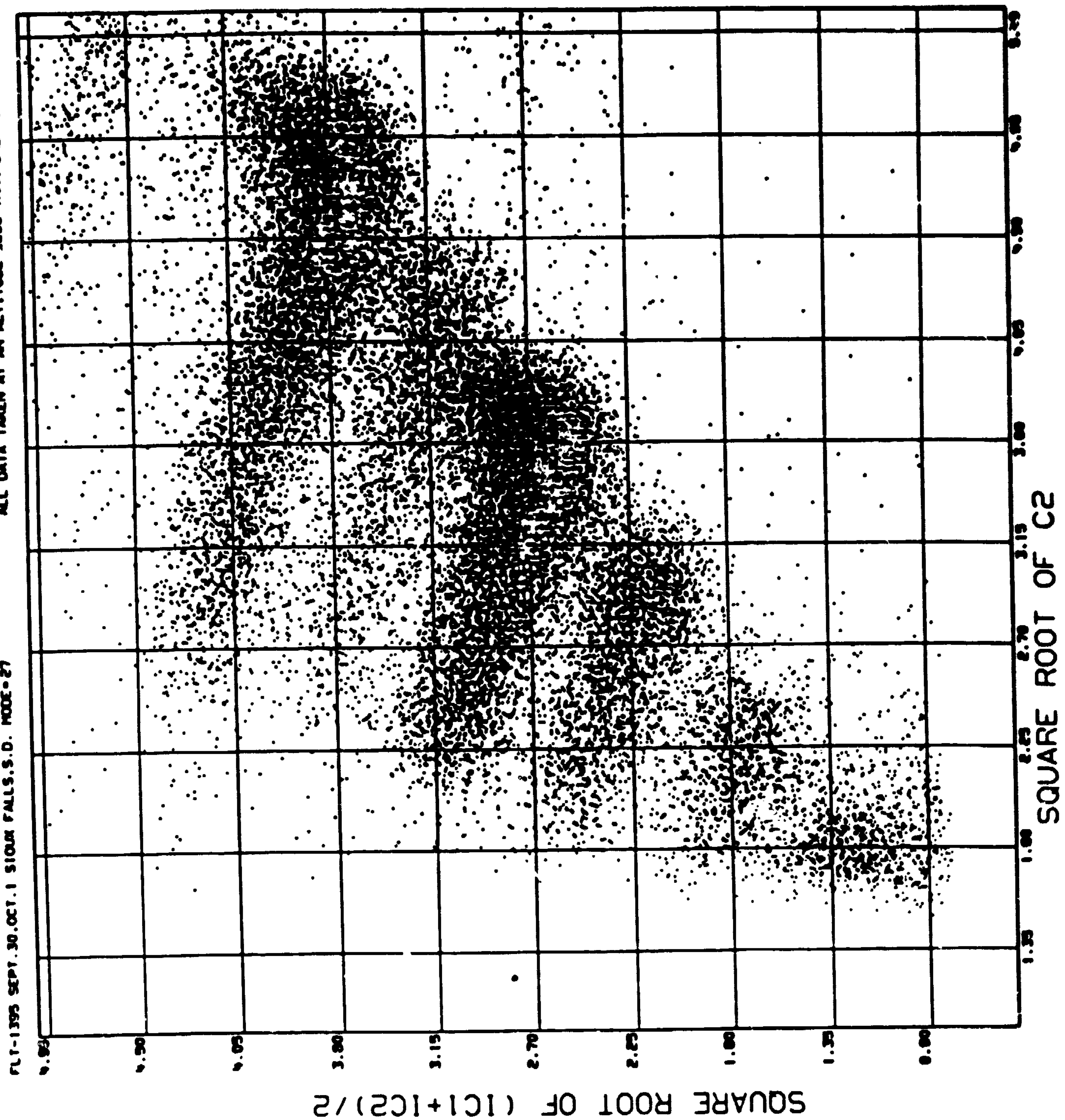
* A muon at Cerenkov saturation in the gas produced only 3 photoelectrons in all 12 tubes co[illegible]ned in this detector.

inconsistency, but the track shows well in the MWPC and the other detectors are consistent, a correction to the gas Cerenkov ADC pulse height may be made. Studies of the elemental fluxes derived during the 1976 and 1978 flights are still continuing. Typical crossplots showing charge resolution obtained by the instrument are shown in the following figures.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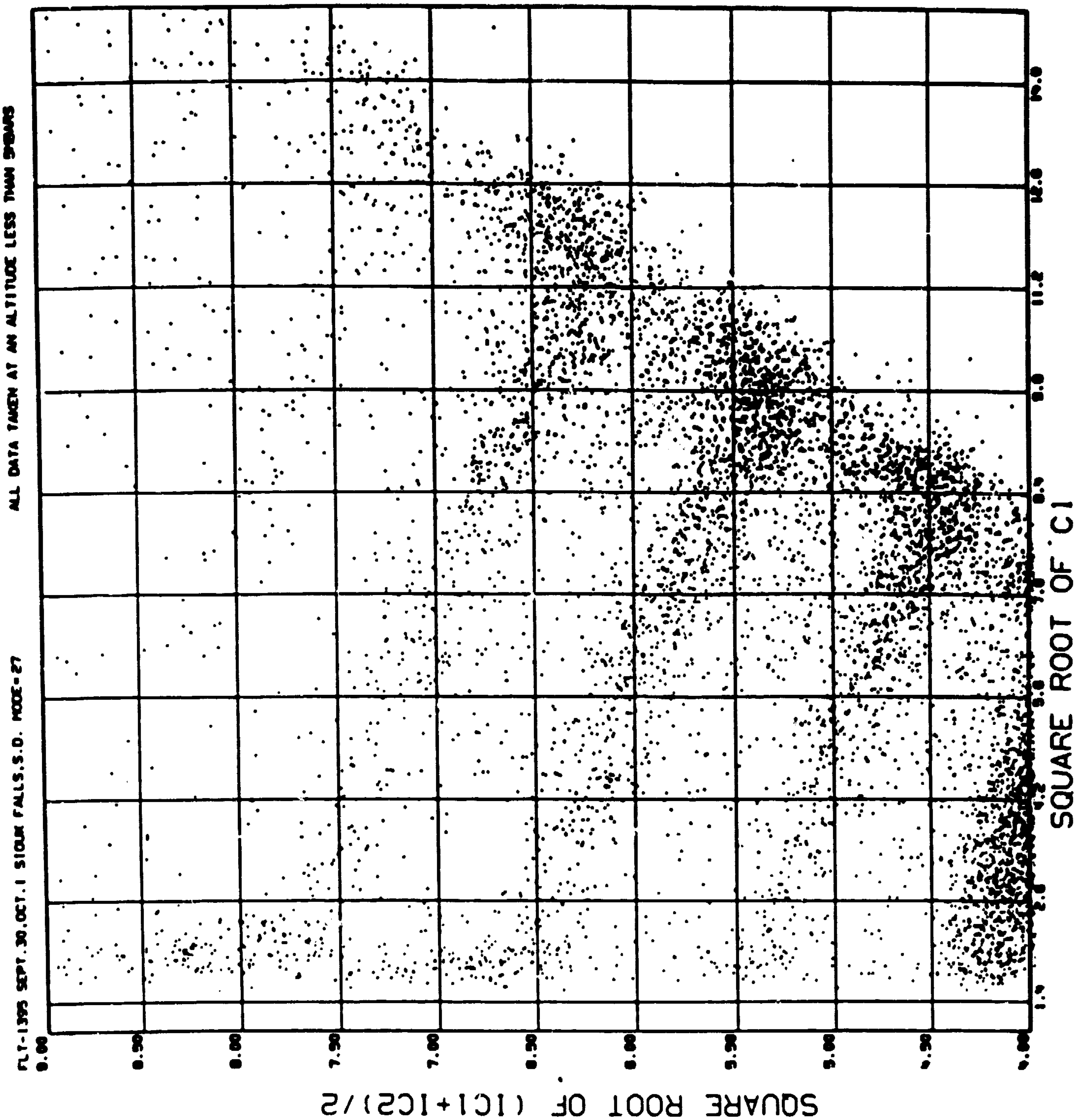
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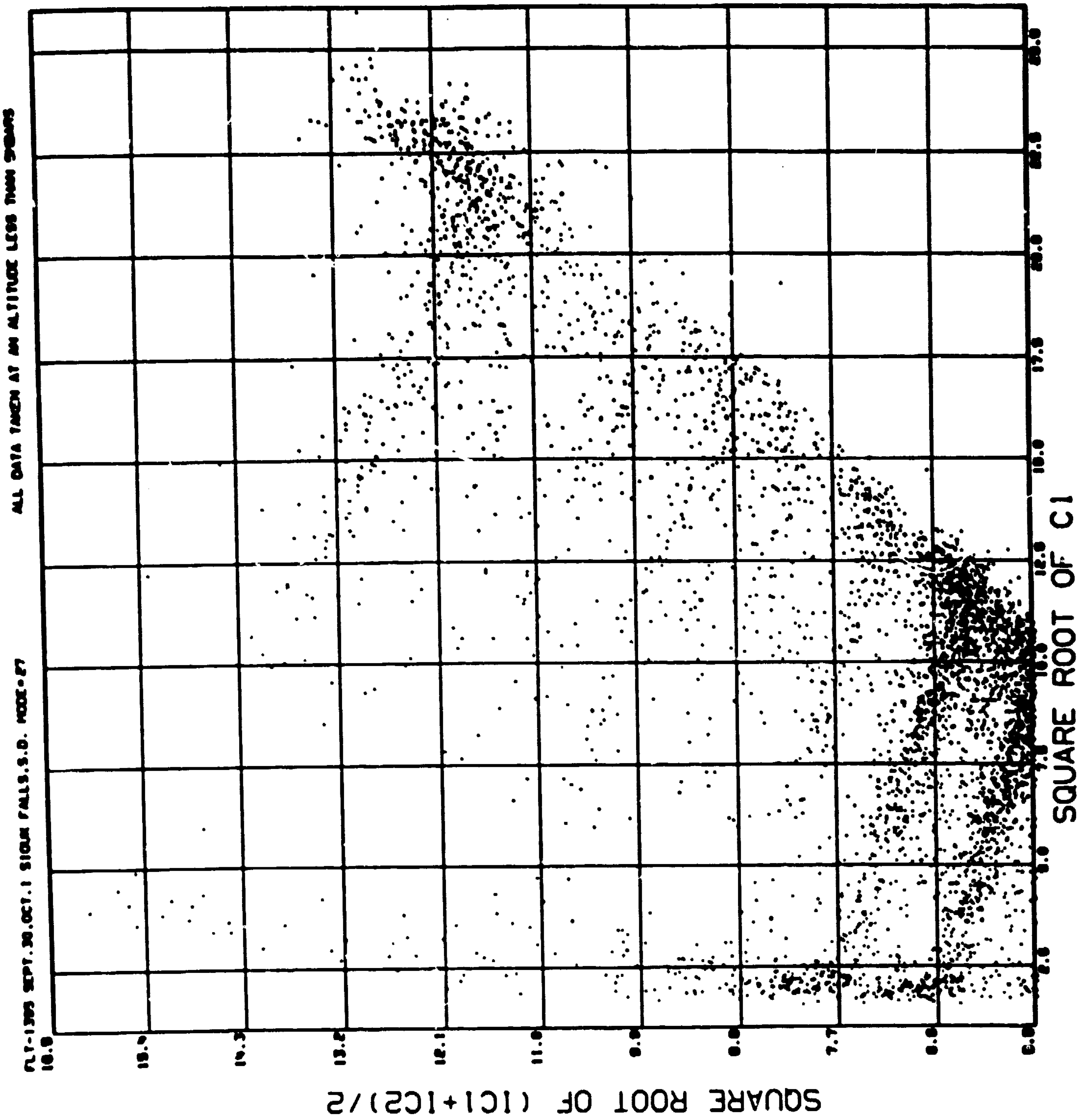
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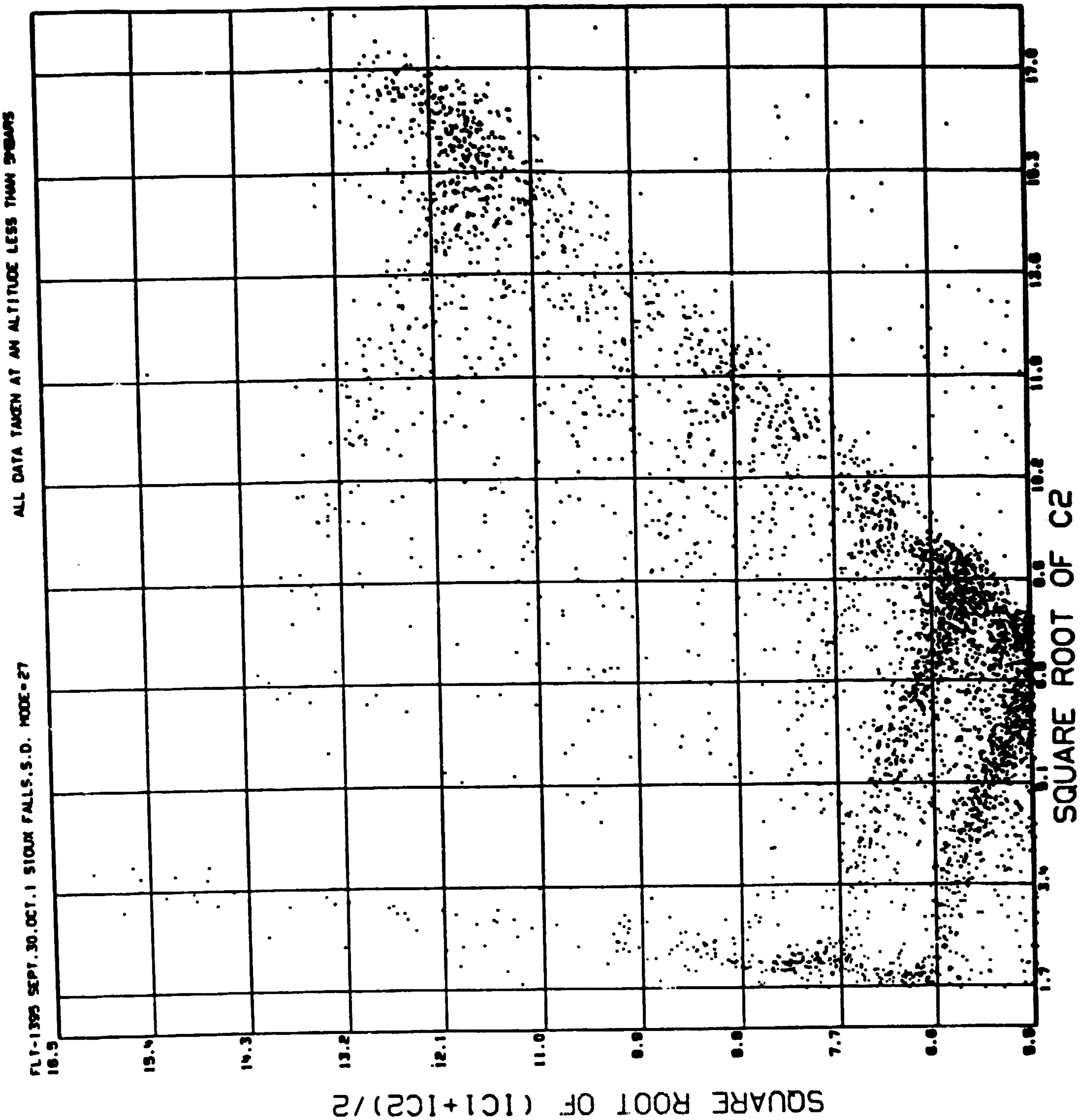

ADDENDUM: PUBLICATIONS

The first two papers were published in the Proceedings of the 15th International Cosmic Ray Conference, (Plovdiv, Bulgaria, 1977) and are not reproduced here. They describe the preliminary results of a Fall 1976 flight of a cosmic ray experiment from Sioux Falls, South Dakota. This experiment was a collaborative effort between the Marshall Space Flight Center and the University of Alabama in Huntsville, and was designed to measure differential fluxes above 500 MeV per nucleon of cosmic rays from $3 \leq z \leq 28$. Work continues on the flux data with a UAH graduate student.

The two papers concern technical aspects of interaction of cosmic rays with an instrument, and show the manner in which the primaries and the secondary electrons manifest themselves in two kinds of MWPC hodoscopes.

1) EFFECTS OF SECONDARY ELECTRONS FROM HEAVY PRIMARY COSMIC RAYS IN A MWPC HODOSCOPE, by J. H. Derrickson, T. A. Parnell, and J. C. Gregory.

2) THE RESPONSE OF AN RC LINE MWPC TO PRIMARY COSMIC RAYS, by J. C. Gregory, W. J. Selig, R. W. Austin, J. H. Derrickson, and T. A. Parnell.

3) A MEASUREMENT OF THE RELATIVISTIC RISE IN XENON-FILLED IONISATION CHAMBERS FOR COSMIC RAY IRON, by J. C. Gregory and T. A. Parnell, published in the Proceedings of the 16th Annual Cosmic Ray Conference, Kyoto, Japan, Vol. XII, 355 (1979).

4) RELATIVISTIC RISE MEASUREMENTS FOR HEAVY COSMIC RAYS IN XENON, by J. C. Gregory, T. A. Parnell and J. Watts, published in the Proceedings of the 17th Annual Cosmic Ray Conference, Paris,

France, Vol. 9, 299 (1981).

5) PRIMARY COSMIC RAY PROTON AND HELIUM SPECTRA ABOVE 10^{12} eV, by the JACEE Collaboration, draft, March 1982, for submission to Physical Review Letters.

A MEASUREMENT OF THE RELATIVISTIC RISE IN XENON-FILLED IONISATION CHAMBERS FOR COSMIC RAY IRON

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ABSTRACT

The relativistic rise of ionization in a pair of xenon-filled pulse ion chambers was measured for primary iron nuclei during a recent balloon flight. Energy calibration over the range 21.5 - 60 GeV/n was made with a Freon-12 gas Cerenkov detector. This allowed a comparison with recent calculations of the relativistic rise in xenon counters and an estimate of the ion chamber resolution above 21.5 GeV/n to be made.

1. Introduction

The relativistic rise in ionisation energy loss has been previously studied and used for identification of singly charged particles at high γ in accelerators. Poor quantitative agreement between theory and experiment on the rate and extent of the rise has discouraged its more extensive use. Recently a method has been reported (Cobb et al., 1976) for calculating the relativistic rise which gives a good match to the experimental results for singly charged particles in argon-filled counters. Tueller et al, 1979, have used these calculations and a balloon-borne argon ion chamber to estimate Ni/Fe and Zn/Fe cosmic ray abundance ratios in the energy range 7 - 12 GeV/n.

As a technique for measuring the energy spectum of cosmic ray primaries, the use of the ionization energy loss in gas filled detectors has several advantages. The detectors are easily constructed and low in mass and thus invite extension to large geometry factors. Low mass allows multiple sampling to improve energy resolution. The method also offers a continuous measurement of energy from just above minimum ionising to several hundred GeV/n, where possible changes in elemental spectral indices would carry significant information on cosmic ray containment and propagation.

We report here the response of two xenon-filled ionisation chambers to the cosmic ray Fe group above 21.5 GeV/n. Xenon is expected to show performance in energy resolution and dynamic range superior to other gases appropriate for use in ion chambers. The data was obtained during a flight of the MSFC-UAH cosmic ray experiment in September 1978. For the set of particles discussed here kinetic energy measurement from 21.5 to 60 GeV/n was made with a Freon-12 gas Cerenkov counter and in the same range particle charge was independently determined with two solid

Cerenkov counters. These measurements allowed the ionisation chamber response to be calibrated, compared with the calculations, and an estimate of the resolution in that energy range to be made.

2. Relativistic Rise and Fluctuations in Ionization Energy Loss

The relativistic rise and density effect in ionization energy loss for charged particles in gas filled counters has been studied for many years, both for application to particle identification, and to resolve discrepancies between measurement and theoretical calculations of energy loss (Crispin and Fowler, 1970). Recent work by an Oxford group, Allison et al., (1976), Cobb et al., (1976) has resolved those discrepancies for $z=1$ particles in argon-filled counters. They also performed calculations for several other gases, of which xenon was predicted to have the steepest rise extended to a higher energy ($\gamma \sim 1000$) than any other gas. Xenon has also a high intrinsic $dE/d\chi$ making it particularly suitable for use in ion chambers. Their energy loss curves, calculated for 1.5 cm thick counters are shown in Figure 1, curves A, B and C. Curve A is the most probable energy loss in xenon; curve B (truncated loss) is the calculated result of discarding the upper 40% of 330 measurements and taking the mean and C is the most probable energy loss in argon.

We have estimated the fluctuations in energy deposit in our chambers using the results of Epstein et al., (1971). They show that these fluctuations in an ion chamber covered by a slab of mass several g cm^{-2} thick are described by:

$$\sigma^2 = \xi \, \eta \, \ln\left(\frac{E_m}{\eta}\right) \tag{1}$$

where

$$\xi = 0.3 \, \frac{m_e c^2}{\beta^2} \cdot \frac{Z}{A} \cdot z^2 \chi \text{ MeV}$$

z and β refer to the primary particle, Z and A refer to the absorber, χ is the absorber thickness in gm/cm^2, E_m is the maximum kinematic energy of secondary electrons and η is the energy of the electron whose range is χ. This result gives good agreement with data below minimum ionizing for our ion chambers.

Since $dE/d\chi$ in the relativistic rise region can be represented by $K \ln E$, fluctuations in energy loss are given by

$$\delta\left(\frac{dE}{d\chi}\right) = K \frac{\delta E}{E} \tag{2}$$

In making estimates of energy resolution we equate $\delta\,(dE/d\chi)$ with σ and determine K from the curves of Figure 1.

From (1) and (2) above:

$$\frac{\delta E}{E} = \frac{\sigma}{K}$$

and since σ varies as z and K as z^2, we have

$$\frac{\delta E}{E} \propto \frac{1}{z}$$

that is, energy resolution improves with z. It is noted that σ also varies as $(\ell n\beta\gamma)^{\frac{1}{2}}$, producing only a slight degradation of energy resolution with primary energy until the onset of the Fermi plateau.

3. Instrument Description

The cosmic ray instrument is shown diagrammatically in Figure 2. It comprises a 76 cm deep, 1 atmosphere pressure, Freon-12 gas Cerenkov counter with twelve five-inch photo-multiplier tubes; Teflon and Lucite solid Cerenkov radiators each in $BaSO_4$-coated boxes and viewed by eight five-inch tubes; two 93% xenon/7% CH_4-filled ionization chambers, each 8.4 cm thick; an 8-plane MWPC hodoscope and a plastic scintillator. The gas Cerenkov tubes are connected in banks of 6 each and pulse-height analyzed separately. This enables events contaminated by light from δ-rays in the tube windows to be more readily identified.

The instrument is designed to measure the elemental spectrum and abundances for $3 < Z < 28$ over the kinetic energy range $0.5 < T < 60$ GeV/n. In the energy range discussed here, the 2 solid Cerenkov detectors are in saturation and together with the plastic scintillator provided unambiguous z determination. The experiment flew from Pierre, S. Dakota in September 1978 achieving some 37 hours at a float altitude of $< 5 gcm^{-2}$, with a livetime of 75%. The geometry factor including the gas Cerenkov detector was 0.104 m^2 sr.

In the data set examined here only Fe primaries of kinetic energy > 21.5 GeV/n were selected. Even though mapping corrections for the solid Cerenkov detectors have not yet been applied, charge assignment is unambiguous in > 90% of the cases. This should improve when these corrections are made and consistency with the plastic scintillator is required.

4. Results

In this preliminary analysis a set of events was selected which was intended to include all Fe nuclei that produced an output exceeding the Cerenkov threshold in the Freon counter by a small but significant amount. The data are shown in Figure 3 as a cross plot of the mean relativistic rise in the 2 ion chambers versus gas Cerenkov output. The requirement that $C_G > 40$ on this scale excludes a great number of particles at or below Cerenkov threshold which appear because of residual scintillation or Cerenkov radiation from δ-rays and the primary in the $BaSO_4$ paint. This component appears to be about 8% of saturated output. In calculating the energy scale of C_G we have assumed this component to be constant over the energy range, though it probably increases somewhat with energy (Lesniak, 1976). The requirements for acceptance in the ion chambers was an energy deposit exceeding 0.75 of minimum ionizing Fe at normal incidence. Thus a number of other particles of $Z > 20$ were selected but were not included in the data shown. Fe events were readily selected from a cross plot of the Teflon and Lucite Cerenkov outputs. Confidence in charge assignment is >90%; this should improve when mapping corrections and a scintillator consistency requirement are applied. A clean track in the MWPC hodoscope was required, eliminating all obvious showers and interactions.

52 Fe events were selected by these criteria. After correcting for instrument mass (9.0 gms/cm^2), livetime, geometrical factor, and overlying atmosphere, this integral number of events was compared with the absolute fluxes above 2.4 GeV/n of Orth et al., (1978). Such a comparison would be consistent with an iron spectrum index near 1.50. However, analysis of lower energy data sufficient to confirm our current estimate of instrument efficiency has not yet been performed.

The solid curve in Figure 3 corresponds to the expected Freon Cerenkov counter response and the calculation of Cobb et al. for the "truncated mean" of the ionization loss in a large set of thin xenon filled counters (curve B in Figure 1). It is noted that the observed rise extends to at least 1.58 times I_{min}. Even though the experimental situation does not precisely correspond to the calculated one, the fit appears satisfactory for the available statistics. The comparison will be more definitive when oxygen nuclei are included.

Energy deposit fluctuations in the ion chambers were estimated using 39 events between 21.5 and 50 GeV/n, and using the solid line in Figure 3 as the mean. This yields an observed average fluctuation of 3.5% standard deviation of ionization energy deposit over this energy range, for the two ion chamber signals summed. Plots of each ion chamber signal separately against C_G indicated that the chambers were effectively decoupled from each other as had been previously established below minimum ionizing energies. The above fluctuations, when applied to a primary energy near 30 GeV/n, and using the observed relativistic rise (curve B, Figure 1) would predict an energy resolution of the relativistic rise method of approximately 52% FWHM.

In order to compare this with a calculated value we have used the method described in section 2 above. For our ion chamber this yields a fluctuation in energy deposit at 30 GeV/n given by:

$$\sigma = 2.11 \text{ MeV} \quad \text{or}$$

$$\sigma = 2.94\% \text{ for curve B of Figure 1.}$$

Including our current estimates of trajectory errors and electronic noise this becomes

$$\sigma_{total} = 3.2\%$$

which yields a predicted energy resolution of 48% FWHM at 30 GeV/n. Considering the statistics available the agreement is not bad.

5. Conclusions

The relativistic rise of energy deposit for iron primary nuclei in xenon-filled parallel plate ion chambers was compared with calculations for z = 1 particles. The rise extends at least to 1.58 times minimum ionizing. The uncertainty in energy measurement in our counters using the relativistic rise technique was estimated to be 52% FWHM for iron nuclei around 30 GeV/n, which compares with a predicted value of 48%. The relativistic rise method has excellent potential for energy measurements on the heavier cosmic rays over the continuous range from minimum ionizing to a few hundred GeV/nucleon. The calibration of the relativistic rise with a gas Cerenkov counter allows primary energy spectra to be derived over a wide range. The accurate extrapolation of these spectra to energies near the Fermi plateau may require calculations similar to those of the Oxford group but for heavy nuclei in detector configurations used for the measurement.

6. Acknowledgements

We wish to thank Robert Austin and William Selig for their expert engineering work on this experiment and James Derrickson for his continuing contributions. Appreciation is extended to NCAR for a near perfect launch and recovery. Part of this work at the University of Alabama in Huntsville was funded under Contract NAS8-31895.

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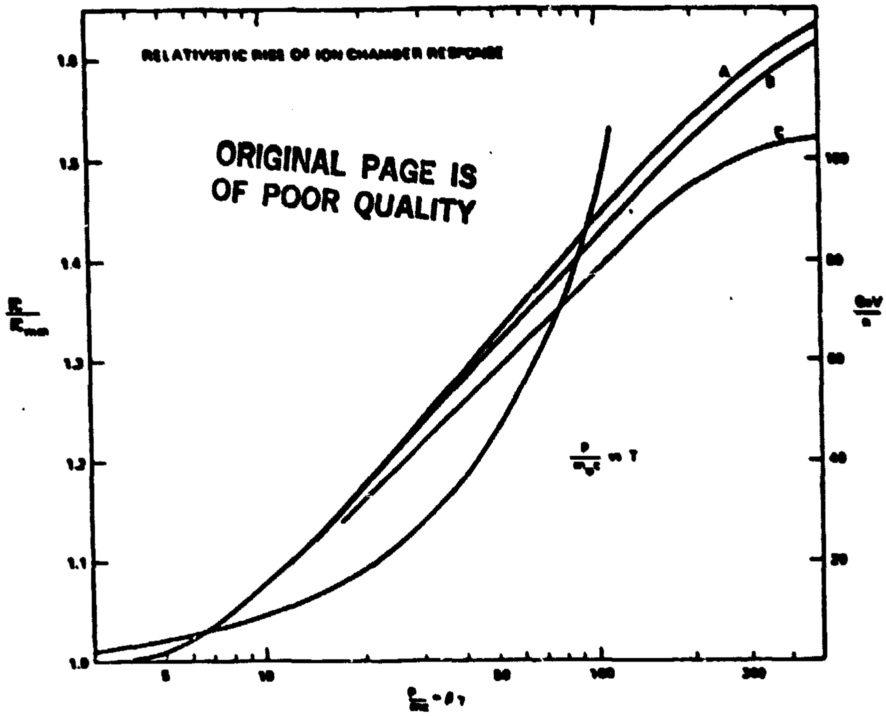

Figure 1: Date from Cobb et. al., A and C are most probably ionisation loss for Xe and Ar. B is truncated mean loss for Xe.

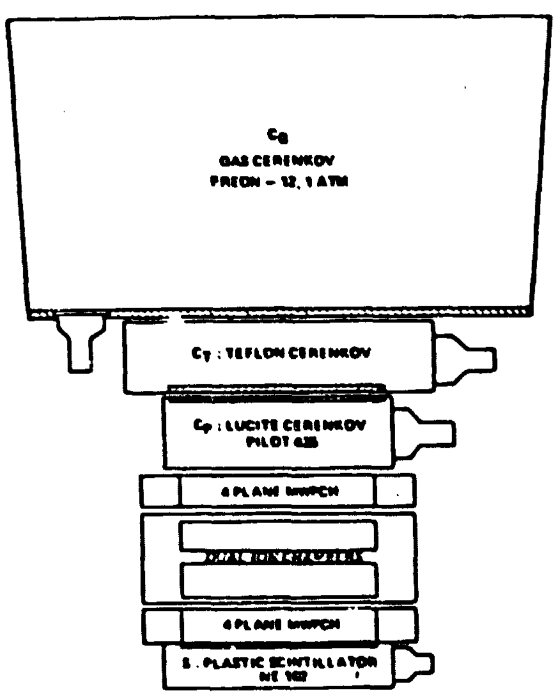

Figure 2: Cosmic Ray Instrument

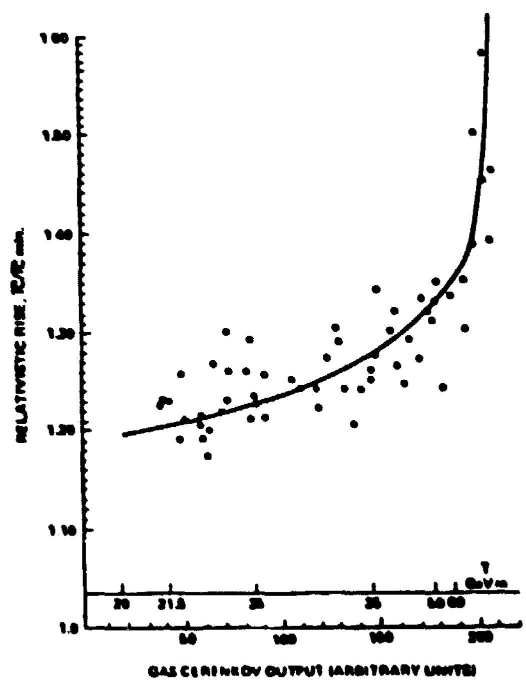

Figure 3: Rise in ion chamber output versus gas Cerenkov output for Fe data above 21.5GeV/n.

RELATIVISTIC RISE MEASUREMENT FOR HEAVY COSMIC RAYS IN XENON

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ABSTRACT

The energy deposit of relativistic cosmic rays from oxygen to iron has been measured in xenon-filled ion chambers. All are consistent with a rise of 39% ± 5% at ∿ 100 GeV/n. A calculation of energy deposit has been made which accounts for energy escaping the gas in the form of delta-rays.

INTRODUCTION

The potential advantages of the use of the relativistic rise of energy loss in gas-filled counters for cosmic ray energy measurement have been noted (1, 2). We have previously reported (2) measurements on the relativistic rise for cosmic ray iron nuclei in parallel plate ionization chambers 8.4 cm thick filled with a xenon and methane mixture. In this paper we examine the observed rise and ionization signal fluctuations for a sample of elements from carbon through iron in the cosmic rays and compare the results with a calculation of energy deposit within the ion chamber.

EXPERIMENT

The balloon experiment which produced the observations reported here was flown from Pierre, South Dakota in September 1978, for 37 hours at an atmospheric depth of $< 5 gm/cm^2$. The experimental apparatus and parameters of observation have been previously described (2). The apparatus contained Cerenkov counters with Teflon and Pilot 425 radiators that measured the charge of the primaries in the energy range considered here with 95% certainty. A proportional counter hodoscope measured the trajectories of the particles. Two parallel plate ionization chambers each 8.4cm thick recorded the ionization energy deposition. The chambers were filled with a 93% xenon 7% methane mixture at one atmosphere. A gas Cerenkov counter containing Freon 12 at 0.90 atmosphere independently measured the velocity of the particle over an energy range of approximately 20 to 60 GeV/amu. The data from the ion chambers reported here cover the energy range up to ∿ 100 GeV/amu where the gas Cerenkov signal is within 4% of saturation.

THE RELATIVISTIC RISE OF IONIZATION LOSS IN GAS-FILLED COUNTERS

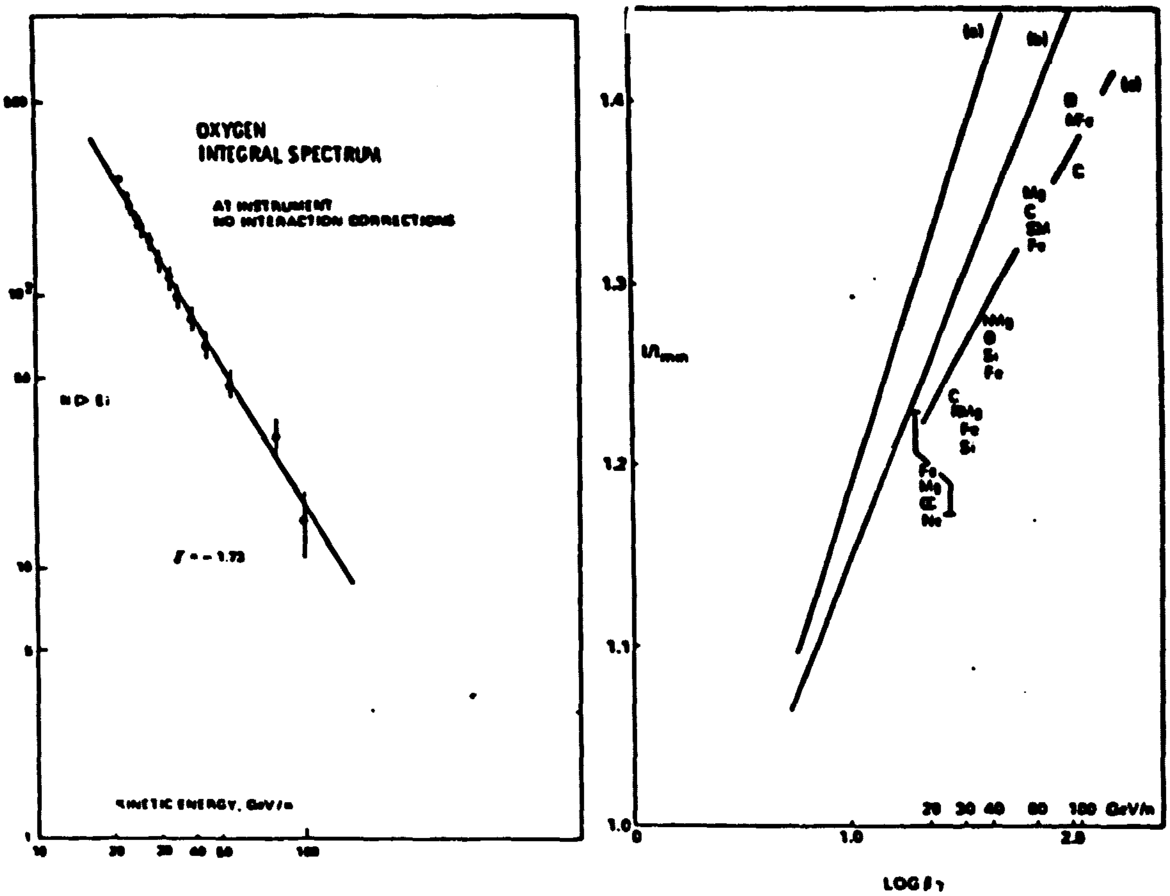
Extensive theoretical and experimental studies of the relativistic increase in ionization energy loss by charged particles beyond about three times the rest energy have been made (3, 4, 5). These studies explained the logarithmic increase in energy loss and its flattening to the Fermi plateau. A significant discrepancy still existed between these works and experimental results for very thin gas counters and z=1 particles until the recent rigorous calculations of Allisón and Cobb (6). These latter calculations took into account the detailed atomic structure of the counter gas; the small number of energy loss collisions in thin gas counters; and the distribution of effective energy transfers to bound electrons when the total energy loss in the counter is not large compared to inner shell electron binding energies. The results fit well the most probable energy loss as a function of energy for z=1 particles in gas filled counters of a few atm-cm thickness and directly predict the correct height of the Fermi plateau.

In order to predict the observed ionization rise in our ion chamber we have assumed that the energy loss due to cosmic ray carbon through iron is sufficiently large that the approach of Allison and Cobb need not be applied and that the Bethe-Bloch energy loss formula with the Sternheimer parameters adequately describe energy loss. It is noted that minimum ionizing oxygen nuclei lose about 3.8 MeV in 8.4 cms of xenon at one atmosphere compared to a maximum binding energy of 34.3 keV for Xe. However, the energy deposition in the ion chamber may not be equivalent to the energy loss due to differences in ionization potential of various materials and the long range of the energetic secondary electrons. To perform the energy deposition calculations a Monte Carlo method was used (7) to transport the more energetic secondary electrons through a detailed mass model of the entire detector system. The energy loss was divided into three parts: 1) Energy transfers to electrons below 0.01 MeV in xenon were assumed deposited in the gas; 2) energy transfers > 140 MeV were ignored; and 3) energy transfers to electrons in the range .01 to 140 MeV. The latter electrons were traced through the instrument by a Monte Carlo method and the energy deposited in the xenon was calculated.

In fig. 4 are shown the energy loss predictions from the Bethe-Bloch-Sternheimer approach (curve a) and that predicted by the Allison and Cobb approach (curve b) for z=1 particles. For the latter we have used their approximate expression for the slope of the rise: $S = 46.4\ (X)^{-0.2}$ Where S = rise compared to minimum ionizing per decade of $\beta\gamma$ and X is the depth of the counter at 1 atmosphere. Curve c is the result of the Monte Carlo energy deposition calculation done at 2, 20, 60 and 100 GeV/nucleon.

RESULTS

Cross-plots of the average ionization deposit in the two chambers versus gas Cerenkov output are shown in figs. 1 and 2 for two of the six elements studied. Minimum ionizing points are taken from other data of IC versus Teflon Cerenkov in the low energy region. A residual light output below the gas Cerenkov threshold of 20 GeV/n is noted for each charge, due to a combination of scintillation and δ-ray Cerenkov and scintillation components. This causes events down to minimum ionizing to appear on these plots. Delta rays in photomultiplier tube windows produce a larger effect.



<u>Figures 1 and 2</u>. Mean ion chamber response versus gas Cerenkov output for oxygen and iron.

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PRIMARY COSMIC RAY PROTON AND HELIUM SPECTRA ABOVE 10^{12} eV*

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Abstract

The chemical composition of primary cosmic rays above 1 TeV per nucleon has been measured in a series of flights of an emulsion chamber. The proton spectrum has been measured from a few TeV to several hundred TeV and the helium spectrum in the range 2-30 TeV per nucleon. Both spectra may be represented by power laws in energy with spectral indices and absolute flux values consistent with projections of previously published values below 1 TeV per nucleon. No significant change in index was observed over the energy range measured for either nucleus.

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A. INTRODUCTION

The intensity and energy spectra of cosmic ray protons, helium, and heavier nuclei in the energy range above 10^{12} eV are of interest because of implications concerning acceleration processes and galactic containment. Various experimental results, both from direct measurements on balloons and satellites, and indirect measurements from air showers have added to this interest. The 'Proton' satellite experiments (Grigorov et al. 1970, 1971) measured proton and helium fluxes using an ionisation calorimeter. Integral spectra for protons were reported over the range 5×10^{10} eV to 2×10^{13} eV and for helium from 5×10^{10} eV to 10^{12} eV per nucleon. The combined or all-particle spectrum was measured up to 10^{16} eV. Whereas the all-particle integral spectrum and helium spectrum from those experiments maintained the same power law as at lower energies, the proton spectrum showed a steepening at 2×10^{12} eV with a change in integral spectral index from -1.7 to -2.3. This change has been attributed (Ellsworth et al. 1971) to backscatter effects from the calorimeter which enhanced the signal in charge-measuring scintillators. Measurements at lower energies than the 'Proton' results have been made (Pinkau et al. 1969, Anand et al. 1965, Ryan et al. 1972), the last reporting measurements on protons up to 2×10^{12} eV and He to about 3×10^{11} eV. These measurements or their extrapolations were consistent with the 'Proton' experiment flux values up to ~ 1 TeV but did not extend to the energy region of the reported proton spectral index change.

In general, the air shower results for the all-particle spectrum (Aseikin et al., 1975; La Pointe et al., 1968) as adjusted by Hillas (1979) and those of Acharya et al. (1981) agree rather well with the all-particle spectrum of Grigorov (1971) in the region around 10^{14} - 10^{15} eV. The situation concerning composition at air shower energies is less clear. At energies around 100 GeV/nucleon, direct measurements indicate that heavier cosmic ray "source" elements have a flatter spectrum than lighter ones (Saito et al. 1974, Simon et al. 1980), but are still steepening with higher energy. Some air shower measurements in the region of 10^{14} - 10^{15} eV total energy indicate a preponderance of iron group nuclei (Goodman et al. 1979; Thornton and Clay 1979; Hillas 1981; see also a review by Yodh 1981), while others report a more normal composition (Acharya et al. 1981). Such a relative enhancement of iron or other heavy nuclei could be caused by flatter spectra of heavier nuclei or a steepening proton spectrum.

Direct measurements of elemental fluxes are needed to advance an understanding of acceleration and propagation of cosmic rays as well as to provide a calibration for the various air shower methods and the underlying models for high energy interactions. The spectra reported here for protons and helium are from the first direct measurements of composition above 10^{12} eV in over a decade.

The large area emulsion chamber technique (R. W.Huggett et al., 1981) was applied by the JACEE consortium in two balloon flights from Palestine Texas: JACEE-1 in 1979 and JACEE-2 in 1980. Each apparatus had lateral dimensions of 80 cm x 100 cm and both were launched inverted and rotated 180° upon reaching float altitude to allow easy discrimination against atmospheric secondaries. These were preceded in 1979 by a flight of a chamber one-fourth the area by the Japanese collaborators. The three flights achieved an accumulated exposure of approximately 100 m^2 sr hr at atmospheric depths between 3.5 and 5.0 gm/cm^2.

The apparatus is both an emulsion chamber, allowing detailed study of nucleus-nucleus interaction processes, and a thin calorimeter which allows measurement of the energy of the electromagnetic portion of the cascade ensuing from the interaction. Shown schematically in figure 1, it consists of three detector systems: (1) the charge module at the top to determine primary atomic number using a variety of emulsions and track recording plastics; (2) the target module consisting of 70 double-sided emulsion plates and 45 thick acrylic plastic plates and (3) the calorimeter which contains 20 layers each of lead, x-ray film and emulsions. An emulsion plate in JACEE consists of a sheet of acrylic plastic 0.8 mm thick, on each side of which is bonded a layer of nuclear emulsion. The type and thickness of these layers is varied depending on the function of the plate.

A nuclear interaction in the light material of the target transfers the energy of the primary nucleus to projectile fragments, charged pions and neutral pions, the last of which decay into a family of γ-rays. The γ-rays develop into electromagnetic cascades in the 7 cascade units of lead in the calorimeter, enabling the energy to be determined by electron-track counting in the emulsions.

Events were detected by scanning with the naked eye for characteristic dark spots produced by electromagnetic cascades on the Sakura (type N) x-ray films in the calorimeter. Using two adjacent films the eye can typically distinguish from background a dark spot produced by $\sim 10^3$ electrons per mm^2, corresponding to a γ-ray energy of 200-300 GeV. All such spots were recorded for each x-ray film from a depth of 1 c.u. to 7 c.u. of lead in the calorimeter. Selection of events for study was made by imposing a higher energy threshold at which the efficiency of detection was estimated by simulation to approach 100%. This energy varies as a function of the Z and zenith angle of the incident particle but for protons and helium nuclei of $\Sigma E\gamma > 1.5$ TeV the efficiency is $\sim$ 100% for all angles used. Selected events were located in the emulsion plates adjacent to the films and traced upwards through the detector using a microscope. Tracing was performed until the first interaction vertex and its primary were found and continued upward beyond the vertex for at least several emulsion layers (and in some cases out of the chamber) to verify that there were no preceding interactions.

After tracing events were separated into 5 groups, (1) primary interactions in the chamber; (2) events having the preceding vertex outside the chamber; (3) single gamma-ray or electron events; (4) events coming from the opposite direction, (incident during ascent or descent); (5) lost events (incomplete tracing). The over-all tracing efficiency is defined by the ratio: ((1) + (2) + (3) + (4) + (5)), and was over 95%.

The primary charge was determined by one or more of the following methods, depending on the charge region:

(1) grain-counting in electron-sensitive emulsion

(2) grain-counting in low sensitivity emulsion

(3) δ-ray counting along the track

(4) etching rate of CR-39 plastic detector for $Z > 6$.

The overall charge resolution from proton to iron was better than $\Delta Z<1$.

Protons and helium nuclei were separated by grain counting in thick electron-sensitive emulsion plates (Fuji 7B) as shown in Figure 2. Resolution for He is $\Delta Z \sim 0.15$. As may be seen in this figure, at smaller zenith angles ($\theta < 5°$), it becomes increasingly difficult to separate p and He because of overlapping of grains as viewed through the microscope. In past emulsion experiments, this problem has resulted in some confusion between p and He events. The effect is avoided in JACEE by the use of plates coated on one side with high sensitivity emulsion (7B) and with low sensitivity emulsion (6B or 2F) on the other. Since the ratio of sensitivities is about 4:1, He tracks in 6B appear similar to those of protons in 7B ($\sim$ 40 grains per 100 μm), while relativistic protons are almost undetectable in 6B emulsion. Grain-counting and gap counting are used to separate He and Li.

In the estimation of total gamma-ray energies, events are divided into two sets; target and calorimeter interactions. Individual γ-rays from target interactions are generally well separated and their energies may be individually determined. Calorimeter interactions, (Pb-jets), on the other hand, contain many overlapping electromagnetic showers and cannot usually be separated into individual showers. Simulations have been made of the longitudinal development of such families of γ-ray showers. Secondary interactions of charged fragments and pions are included.

Well separated showers are measured by counting individual closely-collimated electron tracks within a radius of 50μm in each emulsion layer. The shower development measurements are then fitted to the curves of Nishimura (1964). In our calorimeter of 7 radiation lengths for vertical incidence most γ-ray showers reach maximum before leaving the bottom of the detector.

If the energy dependence of the dispersion of E_γ for a single gamma-ray may be considered to depend only on Poisson fluctuation of the maximum electron number, resolution would improve with energy as $1/\sqrt{E\gamma}$. In practice the fluctuations are larger than one would expect from this and the improvement with energy is offset by the obscuring effect of large electron track densities. The estimate of energy error for a single γ-ray is 40% at 30 GeV to 15% at 1 TeV, with an average value of 22% for the actual data. The error in $\Sigma E\gamma$ for a target jet is less and is governed by the errors in estimation of the few γ-ray showers of the highest energy. Thus the energy error in $\Sigma E\gamma$ might be expected to be better than that for a single γ-ray by a factor of about one-half. In practice, the improvement is rarely achieved above $\Sigma E_\gamma > 5$ TeV because of the offsetting effect of overlapping cores.

Estimation of $\Sigma E\gamma$ for calorimeter interactions has been made by the same method where separation of the cores permits. For heavily overlapping showers the overall development of the family was measured by a total particle count within a larger circle (200 μm) in the emulsions. This was compared with results of a Monte Carlo simulation. Error in the measurement of $\Sigma E\gamma$ for a single event obtained from the curve is 24% and 27% for protons and helium respectively.

Primary cosmic rays were detected by electromagnetic cascade development in the calorimeter, the energy measured being that transferred into γ-rays by π° production. The spectrum of $\Sigma E\gamma$ thus obtained above the selected detection threshold is a convolution of the primary cosmic ray spectrum with the response function of the instrument; in this case the distribution function, $f(k_\gamma)$, where the ratio $\Sigma E\gamma/Eo$ is defined as $k\gamma$. This function was measured by Dake et al. (1979) at FNAL with the 400 GeV proton beam and has been calculated for protons and other elements in the JACEE apparatus by a simulation method. Figure 3 shows a typical result of this calculation. Accelerator measurements with protons at energies up to 400 GeV have indicated that $f(k\gamma)$ does not change with energy but this has not been verified at higher energies or for heavier nuclei.

If the primary differential spectrum is represented by a simple power law:

$$\frac{dN}{dE} = AE^{-\gamma-1}, \quad \text{(where } \gamma \text{ is the integral index)}$$

it may be shown that the measured spectrum of $\Sigma E\gamma$ is a power law with the same index but shifted by a constant normalisation factor provided $f(k\gamma)$ does not change with energy. The energy scale shift at constant integral intensity between the primary E_o spectrum and the measured spectrum of $\Sigma E\gamma$ is given by

$$C(k,\gamma) = \left[\int_0^1 k_\gamma^\gamma \, f(k_\gamma) dk_\gamma \right]^{1/\gamma}$$

Values of $C(k_\gamma,\gamma)$ were determined to be 0.24 (protons) and 0.17 (helium). The reciprocal of $C(k_\gamma,\gamma)$ is the factor by which a measured spectrum is shifted up in energy at constant intensity to yield the spectrum of the primaries.

Since the detection method required a nuclear interaction within the apparatus, the actual response of the detector to the primary cosmic rays is characterised by the geometric-efficiency factor, G. This included the probability for interaction along with the geometric aperture and was calculated for all nuclei of interest by a Monte Carlo method. Edge effects, double interactions and interactions in external portions of the apparatus were taken into account. Calculations of G were made using 30 differential angular bins over all zenith angles and for each of the three flight apparatuses. They were further broken down into separate sub-volumes according to requirements of analysis method and laboratory. The calculations permitted consistency checks to be made between data from different target volumes and at different angular cutoffs as well as checking data sets from the different analysis laboratories for variations in threshold detection efficiency. Cross-sections constant in energy were used in the calculations for all nuclei. A correction for the rising proton cross-section was made later, as described below.

Primary spectra for protons and helium are shown in figure 4. 87 events were used for protons and 34 for helium. While the whole geometric factor for all JACEE was used for the highest energy events (ΣE_{γ}>20 TeV), smaller portions of the data were selected at lower energies. If we adopt a rising cross-section for protons given by $\sigma = s_o E^{\delta}$ (Takahashi, 1979) where E is in TeV and $\delta = 0.03 \pm 0.015$, the spectrum of the primary protons may be steepened by approximately $E^{-\delta}$ since the interaction probability for protons in the instrument is quite low (0.3-0.4).

A convolution of the measured spectrum with a Gaussian error of 25% in ΣE_γ reduced the flux by 14%. Atmospheric interaction corrections of +7% for protons and +12% for helium are included. No allowance was made for production of p and He from heavy primaries but no parallel primary tracks were observed. After these corrections were made to the uncorrected integral spectra shown in figure 4, the best fits were given by:

Protons: $I(\geq E) = (6.9 \pm .07) \times 10^{-6}\ E^{-(1.7-0.03)}$

Helium: $I(\geq E) = (4.19 \pm .42) \times 10^{-7}\ E^{-(1.67\pm.07)}$

Systematic errors are estimated to be about 20%. Both the intensities and spectral indices of protons and helium reported here above 1 TeV/n are consistent with published values (Pinkau et al. (1969), Ryan et al. (1972), Grigorov (1971)) below 1 Tev/n. Above this energy there is no indication of a change in spectral index of protons up to at least 100 TeV, and even though the JACEE results show a mixed chemical composition at the highest energies, 10^{14}-10^{15} eV/nucleus, (Ogata et al., 1981) protons still remain an important component in this region.

Figure 1

Schematic diagram of the JACEE apparatus

Figure 2

Grain counts per unit length of track (100 m) for $z = 1$, 2 and 3 in Fuji emulsions 7B (electron-sensitive) and 6B.

Figure 3

Result of simulations of proton and helium interactions in the JACEE apparatus showing the distribution of energy passing into γ-rays, (k_γ distribution) for about 500 interactions of each nucleus with a Pb target and a zenith angle of 37°. Successive interactions were included. Primary energy per nucleus was varied from 2-50 TeV.

Figure 4

Integral spectra of primary protons and helium nuclei. No correction to fluxes for finite energy resolution or atmospheric losses has been made in this figure nor has the effect of rising cross-section for protons been allowed for. These corrections are included in the expressions for the fluxes given in the text.

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