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Cosmic Ray Studies With a Gas Cherenkov Counter in Association With an Ionization Spectrometer

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ABSTRACT

The results from a balloon borne gas Cherenkov counter (threshold 16.5 GeV/nucleon) and an ionization spectrometer are presented. The gas Cherenkov counter provides an absolute energy calibration for the response of the calorimeter for $5 \leqslant Z \leqslant 26$ nuclei of cosmic rays. The contribution of scintillation to the gas Cherenkov pulse height has been obtained by independently selecting particles below the gas Cherenkov threshold using the ionization spectrometer. Energy spectra were derived by minimizing the χ^2 between a Monte Carlo simulated data and flight data. Best fit power laws ($dN/dE = AE^{-\gamma}$) were determined for C, N, O, Ne, Mg, and Si. The power laws, all consistent with $E^{-2.7}$, are not good fits to the data. A better fit is obtained using the spectrum derived from the spectrometer. The data from the ionization calorimeter (Simon, et al., 1980) and the gas Cherenkov are thus completely self-consistent.

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INTRODUCTION

The study of the energy dependence of the composition of cosmic rays above 10GeV/nucleon has resulted in several interesting results. The energy spectra of secondary cosmic ray nuclei (Li, Be, B) were steeper than those of primary nuclei (C, O) indicating that the interstellar matter traversed by cosmic rays decreased with energy. Even amongst primary nuclei such as C, O and Fe spectral differences were detected. Using models of propagation of cosmic rays in the interstellar medium, composition of cosmic rays in their source regions were deduced (Shapiro, et al., 1975). The leaky box model for the propagation of cosmic rays based on the available experimental results on composition of cosmic rays up to 100GeV/nucleon (Ormes and Freier, 1978) appeared to be consistent with the results in a general way. The available precision in the experimental results of C, O, and Fe spectra could, however, not rule out the possibility of some energy dependent source composition of cosmic rays. An extension of the study of the composition of cosmic rays to energies > 100GeV/nucleon would help clarify our ideas regarding the propagation of cosmic rays.

Many of the cosmic ray composition experiments have been performed with the use of gas Cherenkov counters and a few of them using ionization calorimeters or magnet spectrometers, (Juliusson, 1974; Lezniak and Webber, 1977; Caldwell, 1977; Balasubrahmanyan and Ormes, 1973; and Orth, et al., 1978). In order to compare two of the techniques and to extend the available measurements to beyond 100GeV/nucleon a balloon borne instrument, using both a gas Cherenkov counter and ionization calorimeter, was built and flown in a balloon on October 11, 1976.

For the more abundant nuclei such as C and O, these new measurements extend up to 1000GeV/nucleon. The use of both the gas Cherenkov counter and ionization calorimeter results in measurements which have been independently checked against each other. The experiment is not affected by the systematic effects peculiar to either one of these two techniques and their consistency provides a powerful method for confirming and extending results in this area of cosmic ray studies. The details of the operation of the instrument have been published (Arens, et al., 1979) and the results from the analysis of the ionization spectrometer data are being published (Simon, et al., 1979). In this paper the role of the gas Cherenkov counter in the experiment is described and results from the analysis of its data are presented.

The Instrument

A schematic diagram of the instrument is shown in Figure 1. It consists of the following detectors:

(1) A gas Cherenkov counter for determining the energy of the incident particles in the range 16.5 GeV/nucleon to 50 GeV/nucleon.

(2) A module consisting of five scintillators and an acrylic Cherenkov counter was used to determine the charge of the incident particles. In addition, the scintillators were used to determine the position of the incident particle. This was done by recording the scintillation light from the opposite ends of the scintillator by separate photomultiplier tubes (Arens, et al., 1979).

(3) An ionization calorimeter was used to determine the energy of the incident particles by studying the nuclear–electron cascades generated in the iron slabs. The calorimeter had $170 g/cm^2$ of iron absorber and was divided into three modules. Each module had two scintillators sandwiched between the iron slabs. The response of the calorimeter was determined by Monte Carlo simulation (Jones, 1969) based upon accelerator calibrations.

The geometric factor of the telescope for particles traversing the gas Cherenkov counter and the iron calorimeter was $0.280 m^2 ster$. A detailed description of the functioning of the instrument, testing of the detectors before flight and their response to flight data has been published (Arens, et al., 1979).

The balloon floated at an altitude of 6–7 g/cm^2 giving an exposure factor of 5.9 m^2sr hours.

The Gas Cherenkov Counter

The gas Cherenkov counter was filled with Freon 12 at 20 p.s.i. corresponding to a refractive index of 1.00143 with a threshold energy of 16.5 GeV/nucleon. The light from the chamber was viewed by six 5″ PM tubes (R.C.A. 4525) through acrylic plastic windows. The inside of the counter was painted with $BaSO_4$ paint (Schutt, et al., 1974) which has high reflectivity extending into the ultraviolet. The windows were coated with β-terphynl, a wavelength shifter which converts near ultraviolet photons into the optical range to match the cathode response of the photomultiplier tubes. The enhancement of the signal due to the wavelength shifter was 1.6. The six photomultiplier tubes were divided into two banks of three tubes each. Each bank was separately pulse height analyzed in order to detect events in which a large signal was present due to a knock-on electron passing through a tube window or other effects.

The counter was calibrated with cosmic ray muons on the ground and the pulse height distribution is shown in Figure 2. The width of this distribution corresponds to a peak of 2 photoelectrons and so for a relativistic carbon nucleus about 70 photoelectrons are expected.

Data Analysis

The charge of the incident particle was determined using the scintillators S_{1x}, S_{1y} and the acrylic Cherenkov counter using a multi detector correlation technique. For details see paper by Simon, et al., (1979). For energies $>$ 50 GeV/nucleon, the gas Cherenkov counter response would saturate and so could be used to identify the charge of the incident particles. Figure 3 shows a cross plot of the gas Cherenkov counter response and the charge as determined from the scintillators and the solid Cherenkov for particles with energy $\geqslant$ 64 GeV/nucleon.

A comparison of the response of the gas Cherenkov counter and the calorimeter is shown in Figure 4. The calorimeter response at the gas Cherenkov threshold calibrates the calorimeter. This agrees well with the expected response based upon a Monte Carlo cascade simulation program for the response of the calorimeter. These simulations were used to determine the energy as a function of the calorimeter response (Simon, et al., 1979, and Jones, 1976). The only free parameter needed to find the response curve shown on this plot is the asymptotic level of the gas Cherenkov saturation pulse height. See Figure 7 for how well the asymptotic level can be determined from the experimental data. Similar plots are used to determine the response for other nuclei. In Figure 5 it can be seen that the calorimeter response at the gas Cherenkov threshold is independent of charge between carbon and iron.

For particles below the gas Cherenkov threshold, there is a contribution due to the scintillation of the Freon gas. This contribution has to be taken into account in interpreting the gas Cherenkov signal. By using the calorimeter, oxygen nuclei with energy much below the threshold of the counter ($\leqslant 5$ GeV/nucleon) were selected and their response in the gas counter is shown in Figure 6. The curve has a long Landau tail due to fluctuations in ionization loss in the gas detector. All other nuclei have similar ionization responses and their curves scale as Z^2 as expected.

Energy Spectra Determination

The technique used to determine the energy spectra of incident cosmic rays was to compare the flight data with a Monte Carlo generated simulation of the instrument. In the Monte Carlo program a particle of specified charge was assigned an energy on a randomly selected basis from an assumed input spectrum. Then a pathlength through the gas counter was assigned based on an isotropic incidence of nuclei and the acceptance geometry of the telescope. The scintillation contribution was obtained from the known response and the Cherenkov light collected for the appropriate energy. Note that there will be a contribution by low energy particles (1–16.5 GeV/nuc) to the Cherenkov pulse height distribution due to the Landau tail of the ionization loss distribution (see Fig. 6). This has been taken into account. The two banks of tubes were treated independently and the photoelectron fluctuations were simulated based on Poisson statistics.

The input parameters to the program were obtained from flight data and ground calibration data. The saturation response of the Cherenkov counter scaled as Z^2 up to $Z = 20$ and was consistent with the ground muon calibration. Above $Z = 20$, a malfunction of an electronic gain switching circuit prevented data from being obtained. In this analysis no data beyond $Z = 14$ was considered.

From the flight data particles which passed, the following criteria were selected for comparison with the Monte Carlo simulated data.

(1) The trajectory indicated the particle passed through the gas Cherenkov counter.

(2) The charge assigned by the scintillators S_{1x}, S_{1y}, and the solid Cherenkov should have a $\chi^2 < 36$. This criterion has been found to be effective in rejecting background.

(3) The two banks of the PM tube signals of the gas Cherenkov counter agree within 50%.

The pulse height distribution of Monte Carlo simulated data and flight data were compared on a χ^2 basis. The simulated spectra of the incident nucleus were assumed to be a power law of the form $\frac{dN}{dE} = AE^{-\gamma}$. The values of A and γ for which χ^2 is a minimum gives the most likely fit.

In Figure 7 a comparison of the simulated data and flight data is shown for input spectra with $\gamma = -2.7$ and $\gamma = -2.5$. There is a considerable difference between the fits, which indicated the sensitivity of the method between the Monte Carlo simulation and data. Figure 8 shows the reduced χ^2 values as a function of γ for oxygen nuclei.

The observed intensity at the balloon altitude was corrected for nuclear interactions in the matter of the telescope and the atmosphere. The criterion demanding consistency within 50% of the two sets of photomultipliers viewing the gas Cherenkov necessitated a correction of 2% for the flux. The χ^2 criterion for identifying charge resulted in an uncertainty in the absolute flux of 10%.

Results and Discussion

The results for carbon, nitrogen, oxygen, neon, magnesium, and silicon are shown in Table I. Due to poor statistics and uncertainty in charge resolution, odd Z nuclei other than nitrogen were not analyzed. Though the χ^2 minima obtained for power law spectra are quite pronounced (see Fig. 8), indicated fits are poor. For example, for carbon and oxygen the probability of the power law hypothesis being correct is less than 1%.

In order to test the consistency of the results of the gas Cherenkov detector with those of the ionization calorimeter, the actual fluxes measured (Simon, et al., 1980) in the latter were used as the input for the Monte Carlo simulation program. When this was done, the reduced χ^2 decreased to 0.88 for carbon and 0.93 for oxygen for 40 degrees of freedom. These are good fits and confirm that the gas Cherenkov detector reflects the deviations of the cosmic ray spectra from power laws as determined using the calorimeter data. Figure 9 shows the experimental data for oxygen and the Monte Carlo simulated data for the input spectrum obtained from the calorimeter analysis.

For these nuclei, slowly steepening energy spectra are expected due to increasing importance of escape relative to nuclear interactions as energy increases (see discussion in Ormes and Freier, 1978). The observed steepening is consistent with such an effect.

The gas Cherenkov counter technique has been used by Juliusson (1974), Lezniak and Webber (1977), and Caldwell (1977). A comparison of their intensities with ours is shown in Figure 10. The integral intensity at 16.5 GeV/nucleon is in agreement within errors with the previous measurements and with the results from the calorimeter section of the experiment (Simon, et al., 1980).

The results of composition measurements up to 100 GeV/nucleon seem to be quite consistent amongst the several experiments and with the leaky box model of cosmic ray propagation. However, recent results of Goodman, et al., (1979) seem to require an energy spectrum for iron nuclei as flat as 2.36 ± 0.06 and would suggest sources richer in iron at higher energies. It will be important to get the spectrum of iron nuclei by direct methods in the TeV/nuc energy region. With this objective in mind the Goddard cosmic ray group is developing a large area experiment using a very low pressure gas Cherenkov counter with a threshold of 200GeV/nucleon. When detailed results in that energy region become available the question of the energy dependence of cosmic ray source composition can be answered with greater rigor.

We would like to thank Dr. F. B. McDonald and Dr. R. Pinkau for their support and encouragement. Mr. C. R. Greer, Mr. G. Cooper and Mr. A. Puig helped to build and test the detectors under the able supervision of Mr. J. Laws who provided electrical engineering support. This experiment was also supported by the Bundesminister fur Forschung and Technologie of The Federal Republic of Germany under the title WRK244 and WRK0275:5. Also thanks are due to the excellent launch and support provided by the crew of the National Scientific Balloon Facility at Palestine, Texas for launching this payload which set a record for weight carried above 100,000 feet on a balloon.

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Table I

(1) Energy Spectra for Power Law Hypothesis

$$\frac{dN}{dE} = AE^{-\gamma} \quad \text{(Intensity-Particles/m}^2\text{-sr-sec-GeV/nuc)}$$

(E--Energy in GeV/nucleon)

Nucleus	γ	A	χ^2_ν min
Carbon	-2.8 ± 0.2	6.0 ± 0.4	1.8
Nitrogen	-2.8 ± 0.25	1.3 ± 0.5	1.4
Oxygen	-2.7 ± 0.2	6.4 ± 0.3	1.8
Neon	-2.65 ± 0.25	1.2 ± 0.3	2.1
Magnesium	-2.6 ± 0.15	1.1 ± 0.4	2.2
Silicon	-2.6 ± 0.15	0.9 ± 0.3	2.1

(2) Fits Using the Energy Spectra from the Calorimeter

χ^2_ν for Carbon 0.88 for 40 d.f.

χ^2_ν for Oxygen 0.93 for 40 d.f.

FIGURE CAPTIONS

Figure 1 Schematic diagram of the Cosmic Ray Telescope Experiment.

Figure 2 Pulse height distribution obtained in the gas Cherenkov counter for sea level cosmic ray muons.

Figure 3 Cross plot of charge determined by the charge module vs. charge obtained by gas Cherenkov counter signal for particles with energy >64 GeV/nucleon.

Figure 4 Correlation of the gas Cherenkov counter signal with the calorimeter signal for oxygen nuclei. The curve is the calculated response.

Figure 5 The calorimeter signal at gas Cherenkov threshold for different charges.

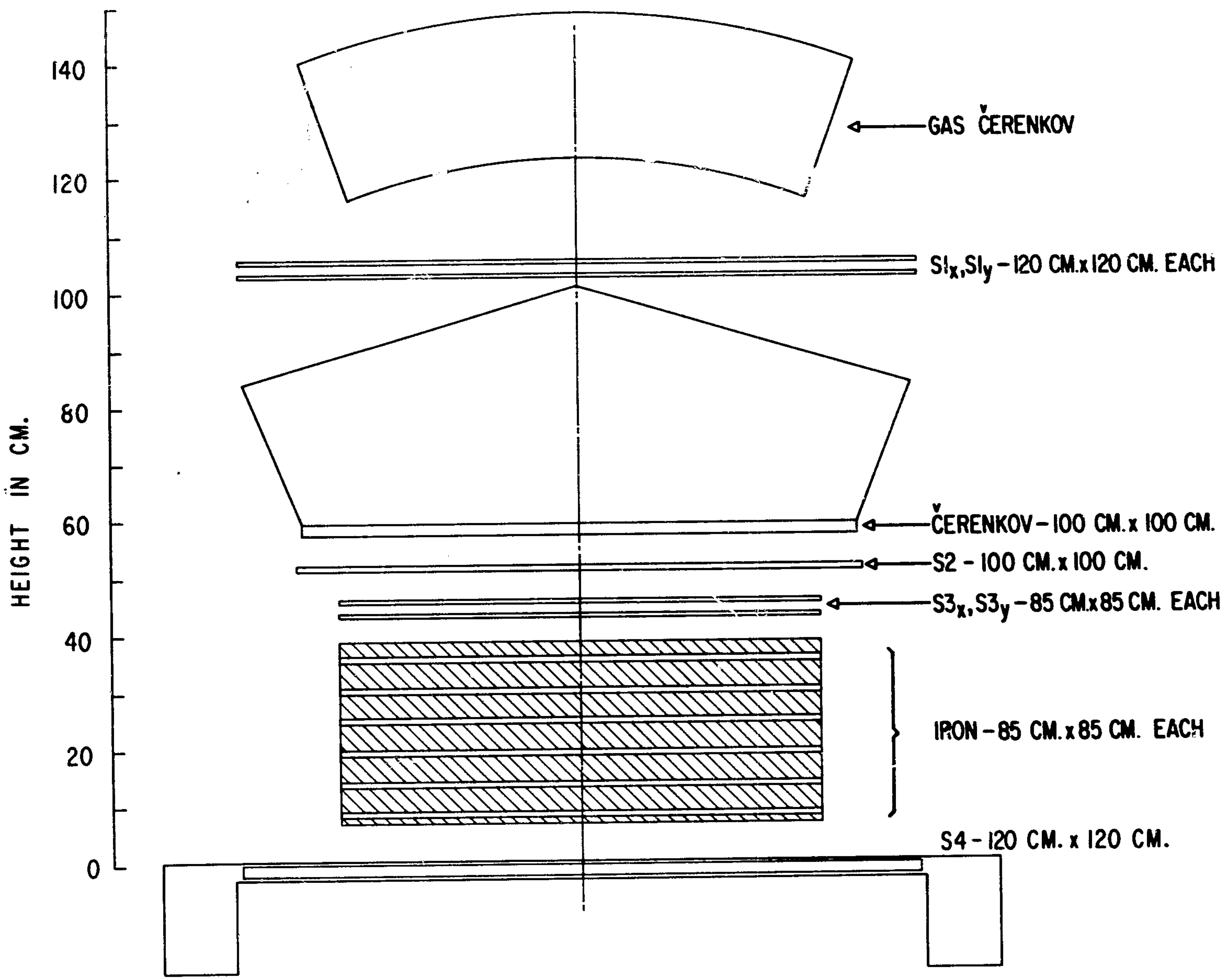
Figure 6 Pulse height distribution of oxygen nuclei of energy $\leqslant$5 GeV/nucleon as determined by the calorimeter. The result of the Monte Carlo calculation for particles below the Cherenkov threshold is also shown in the figure.

Figure 7 Monte Carlo simulation power law spectra compared with data for oxygen nuclei. The power law corresponding to $\gamma = -2.7$ can be seen to be a better fit.

Figure 8 Variation of the reduced X^2 between data and Monte Carlo simulation for power hypothesis.

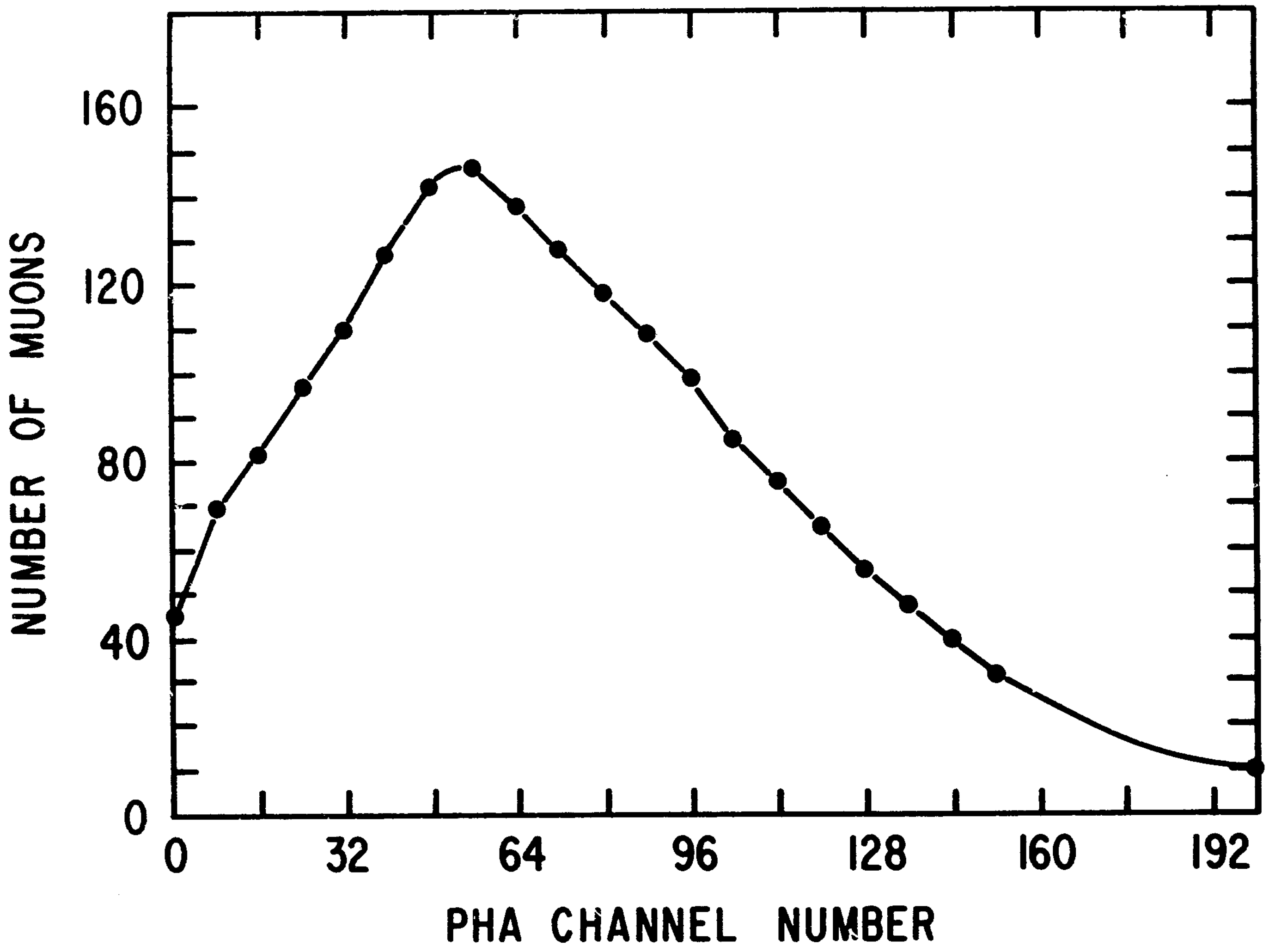
Figure 9 Fit of data and Monte Carlo simulation when input spectrum is same as obtained from the calorimeter.

Figure 10 Integral energy spectrum of oxygen nuclei. The point at 16.5 GeV/nucleon represents the number of particles above the Cherenkov threshold.



GERMAN-AMERICAN HIGH ENERGY COSMIC RAY TELESCOPE

Fig.1



CALIBRATION OF GAS CERENKOV COUNTER
WITH COSMIC RAY MUONS

Fig. 2

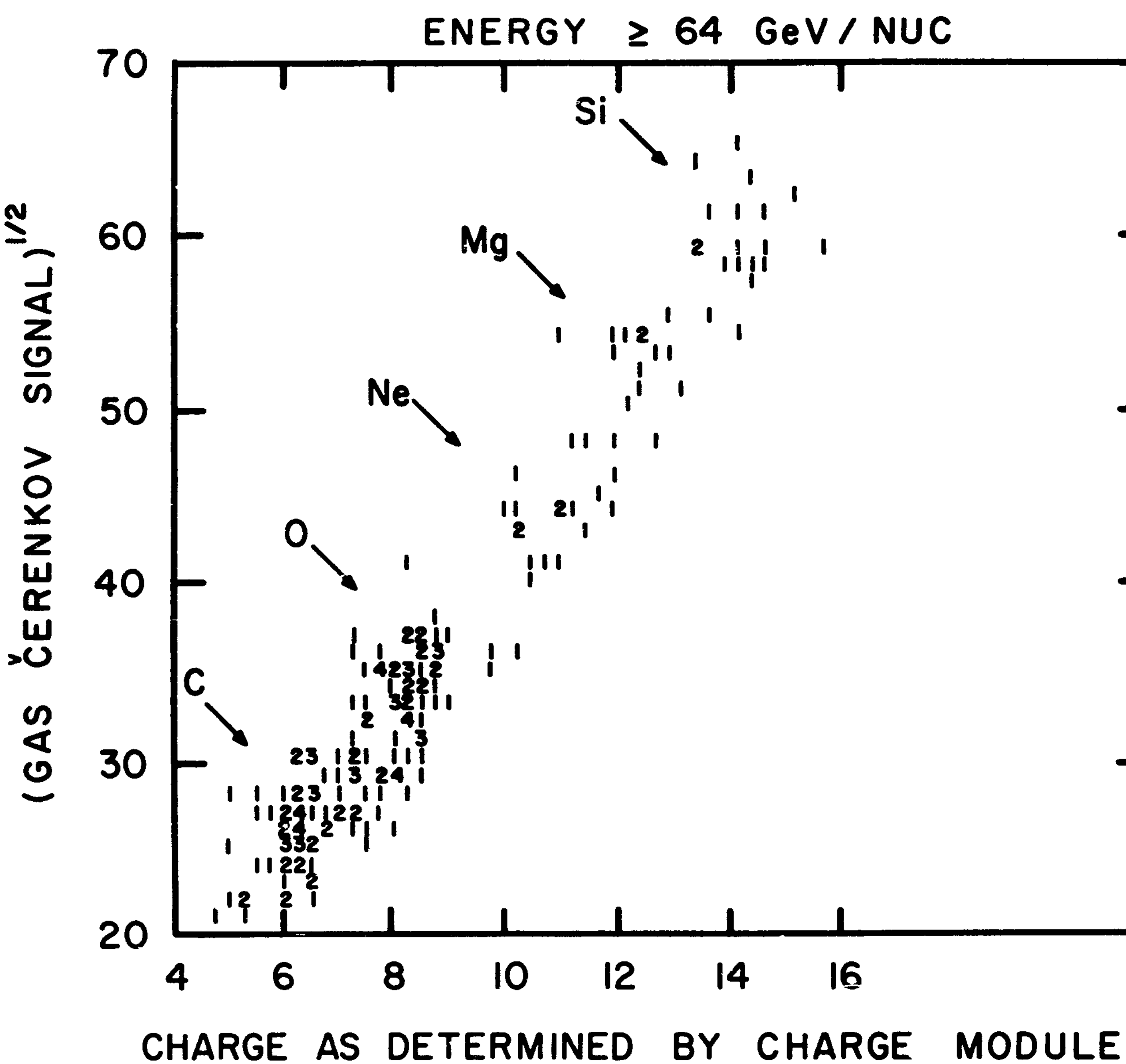

ENERGY ≥ 64 GeV / NUC
(GAS ČERENKOV SIGNAL)$^{1/2}$
CHARGE AS DETERMINED BY CHARGE MODULE
Si
Mg
Ne
O
C
70
60
50
40
30
20
4
6
8
10
12
14
16

Fig. 3

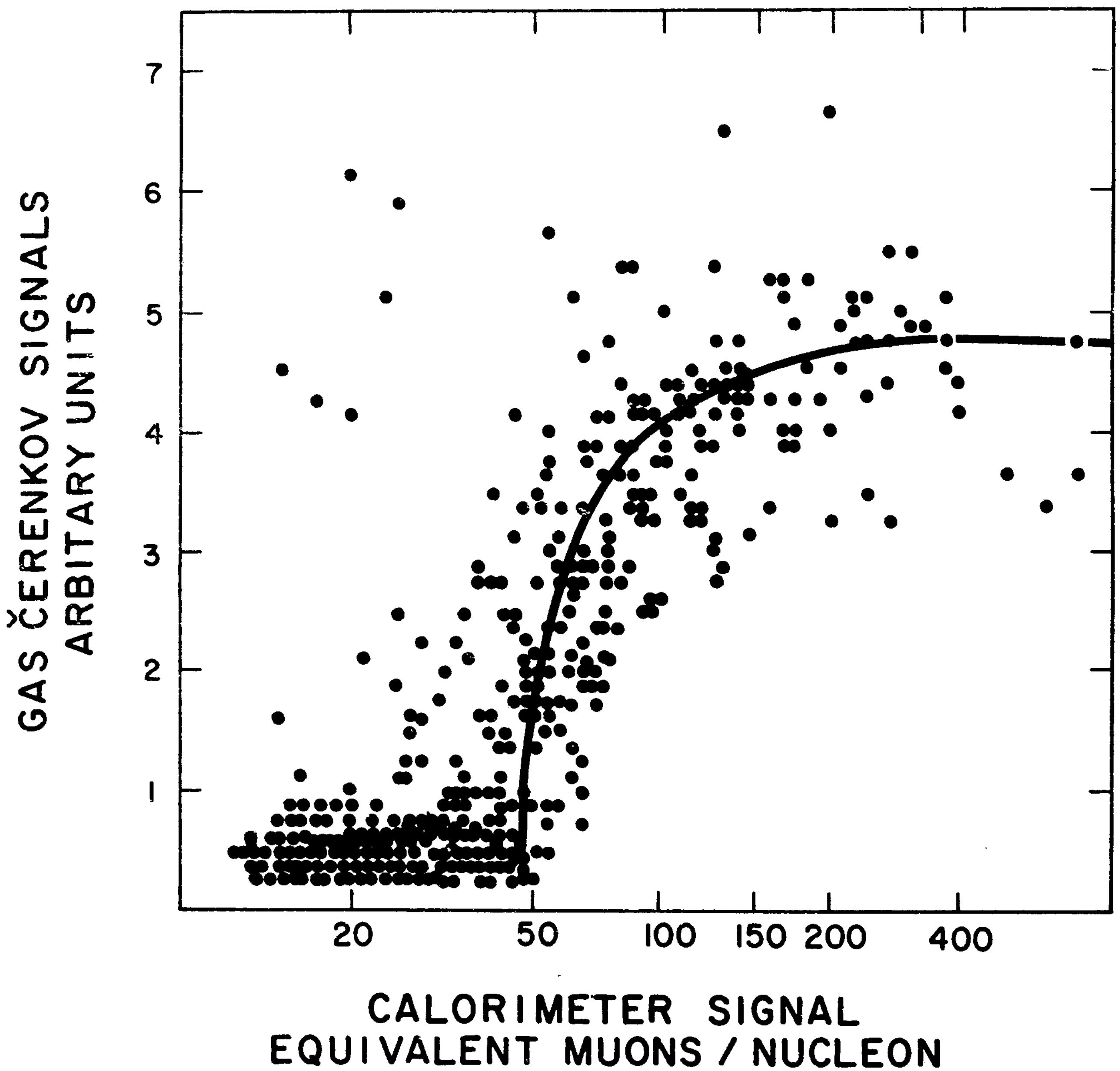

GAS ČERENKOV SIGNALS
ARBITARY UNITS
7
6
5
4
3
2
1
20
50
100
150
200
400
CALORIMETER SIGNAL
EQUIVALENT MUONS / NUCLEON

Fig. 4

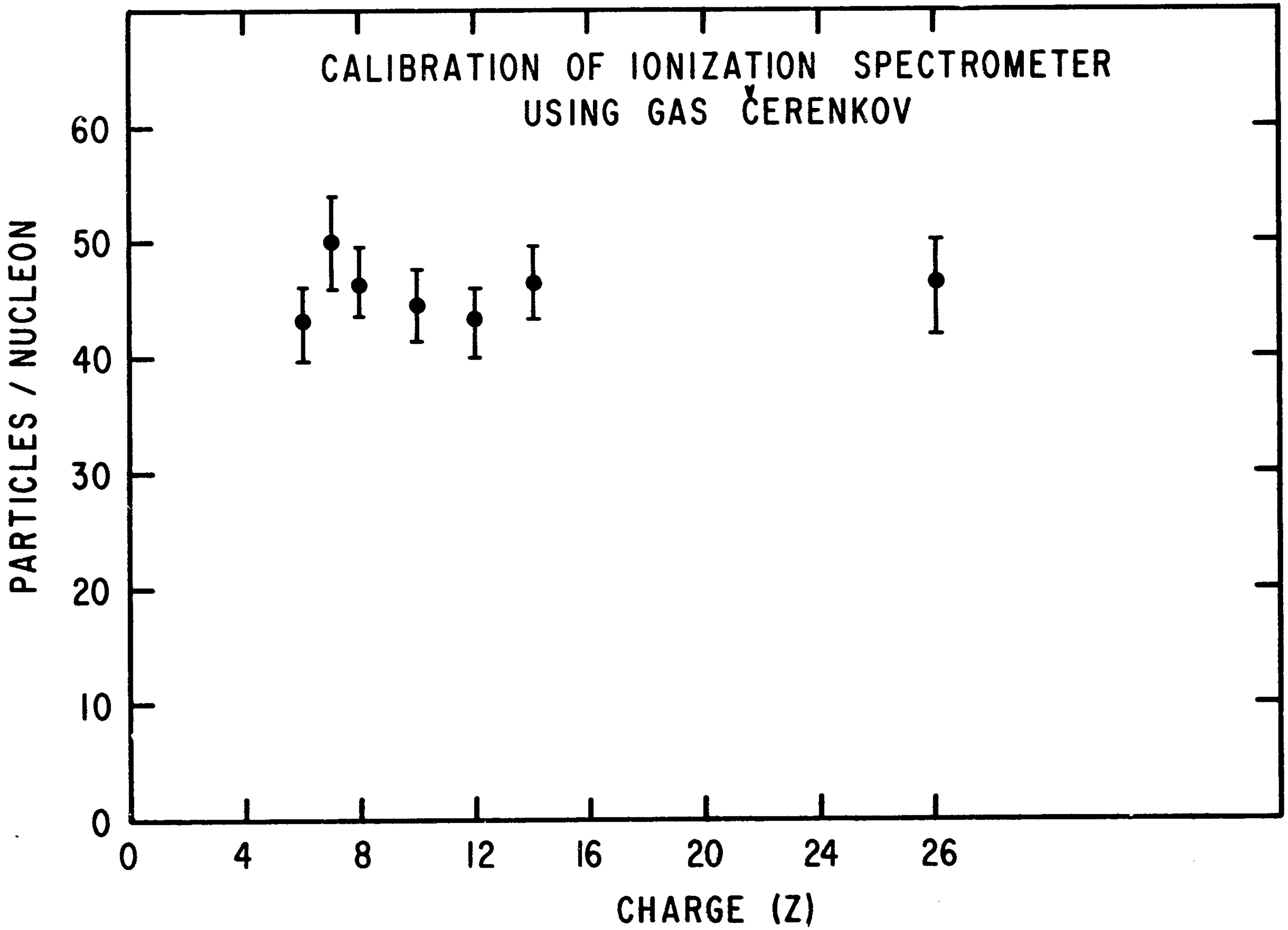

CALIBRATION OF IONIZATION SPECTROMETER
USING GAS ČERENKOV
PARTICLES / NUCLEON
0
10
20
30
40
50
60
0
4
8
12
16
20
24
26
CHARGE (Z)

Fig.5

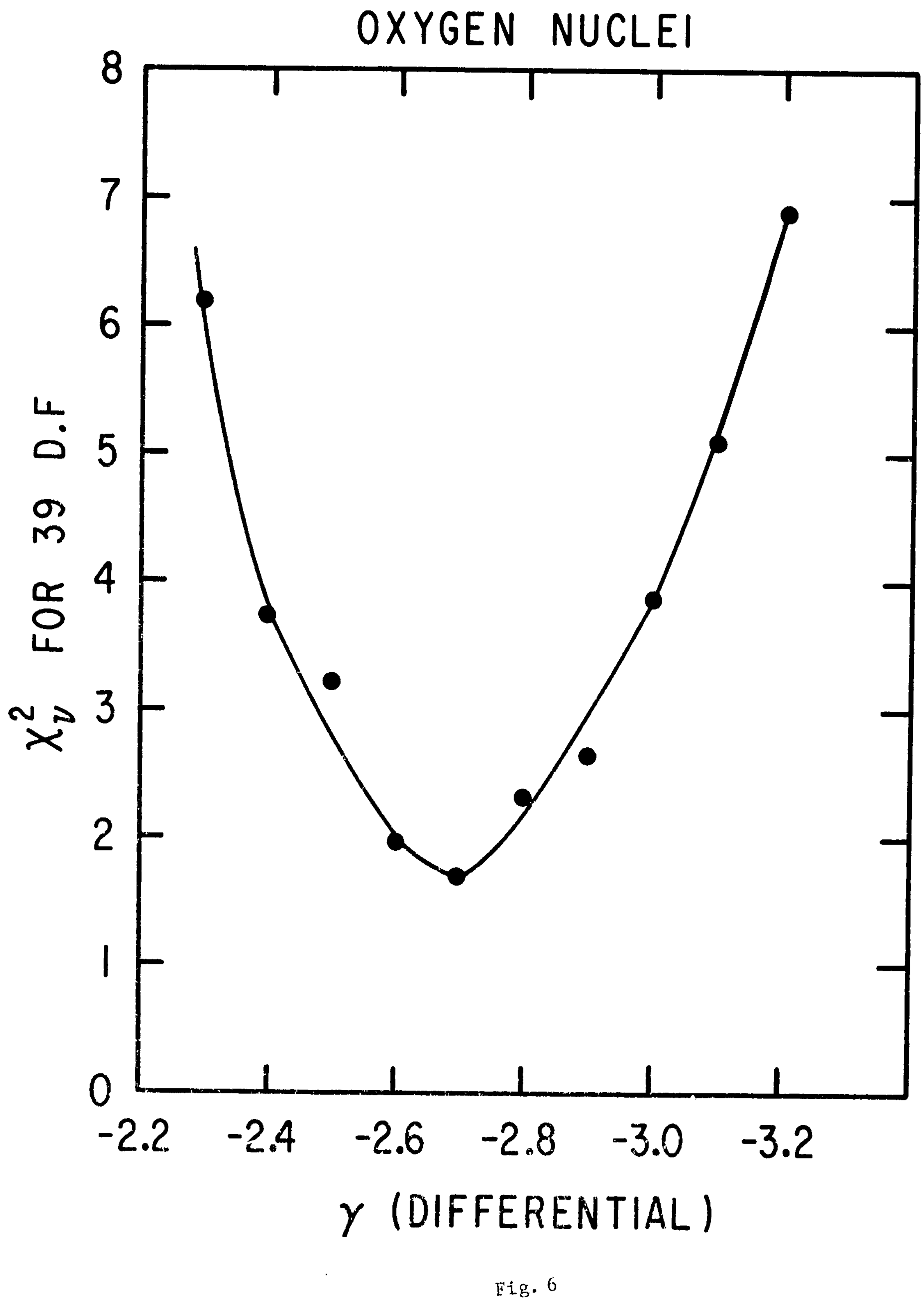
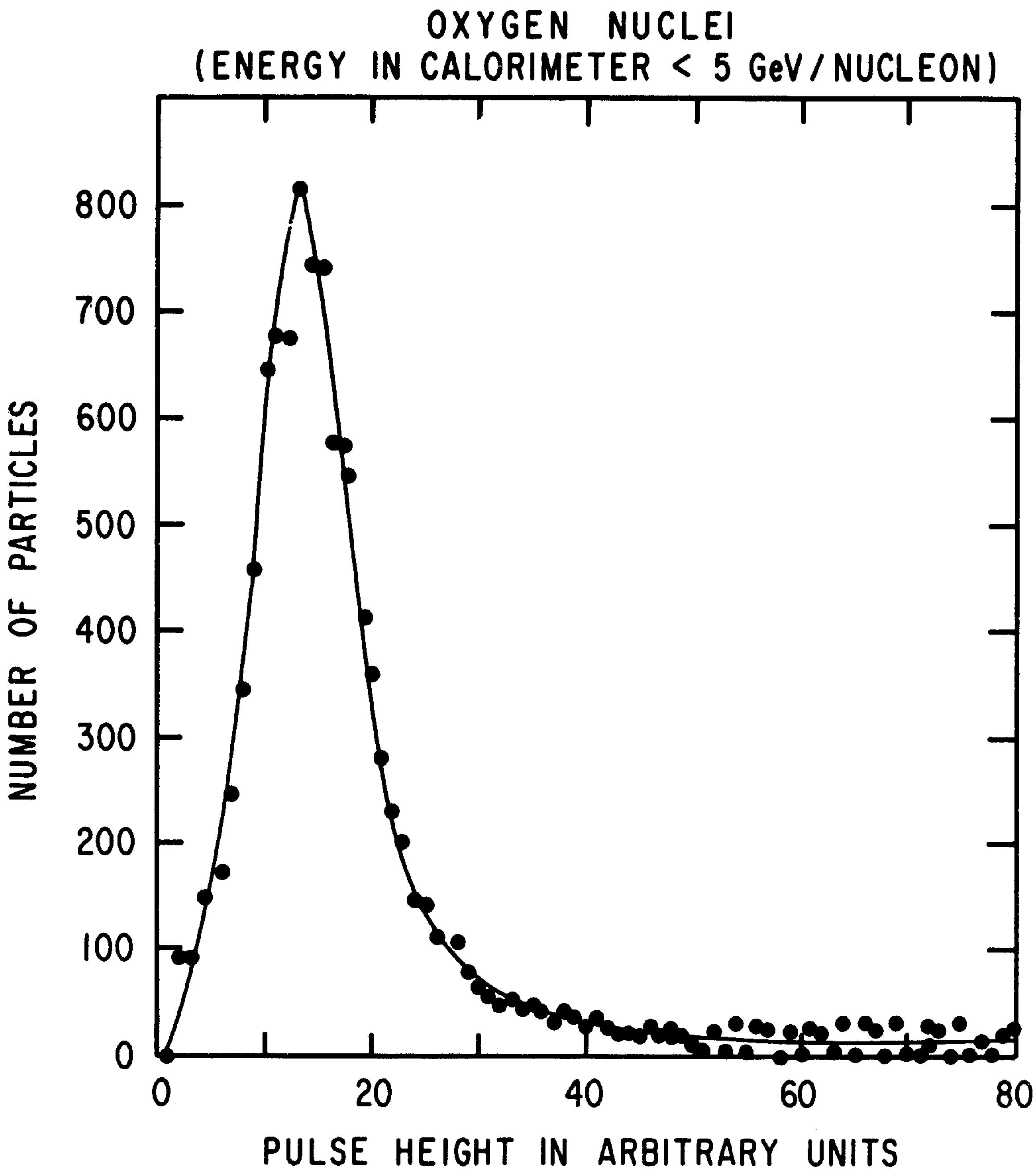
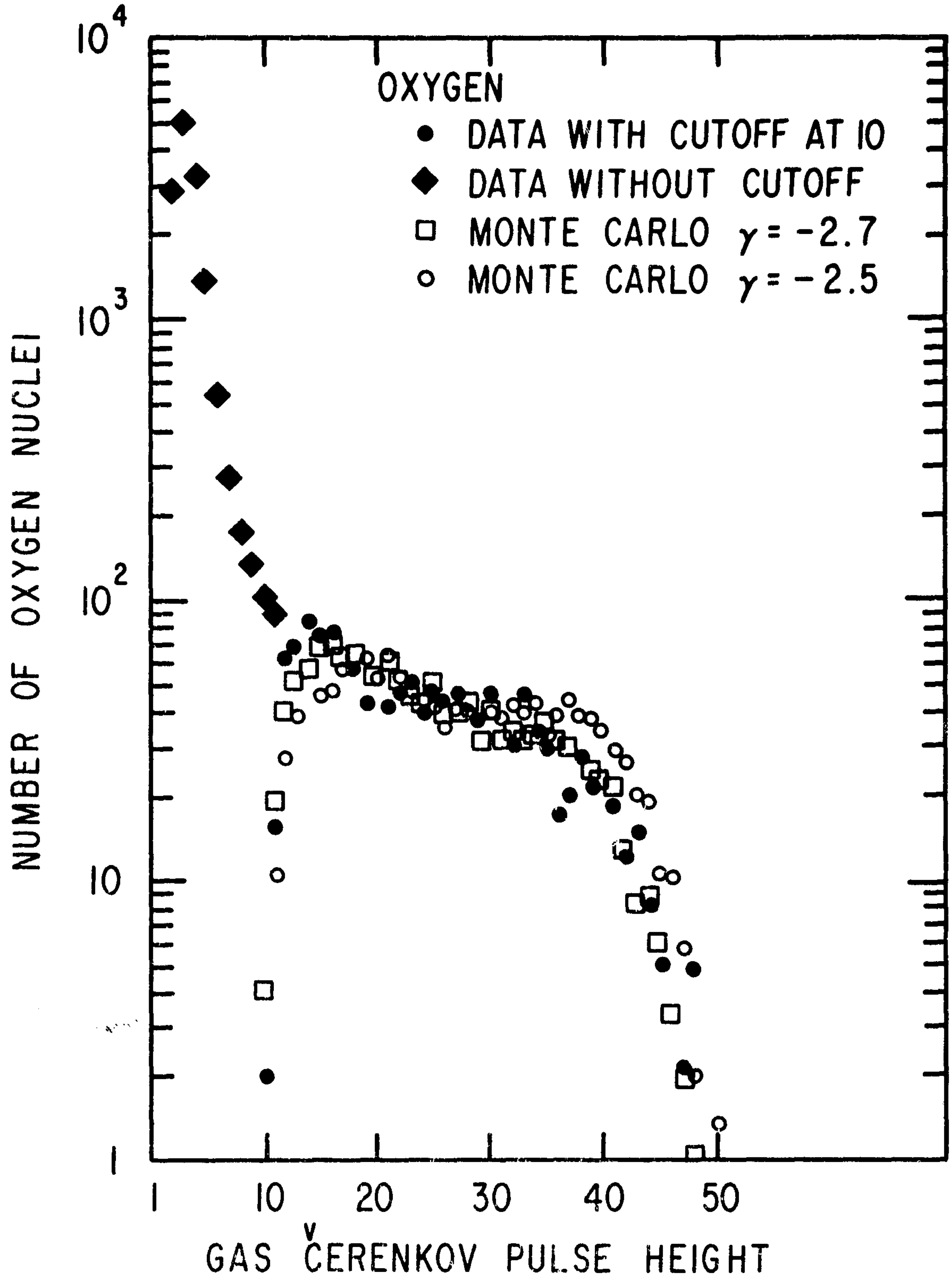

OXYGEN NUCLEI
8
7
6
5
4
3
2
1
0
χ_ν^2 FOR 39 D.F
-2.2
-2.4
-2.6
-2.8
-3.0
-3.2
γ (DIFFERENTIAL)

Fig. 6



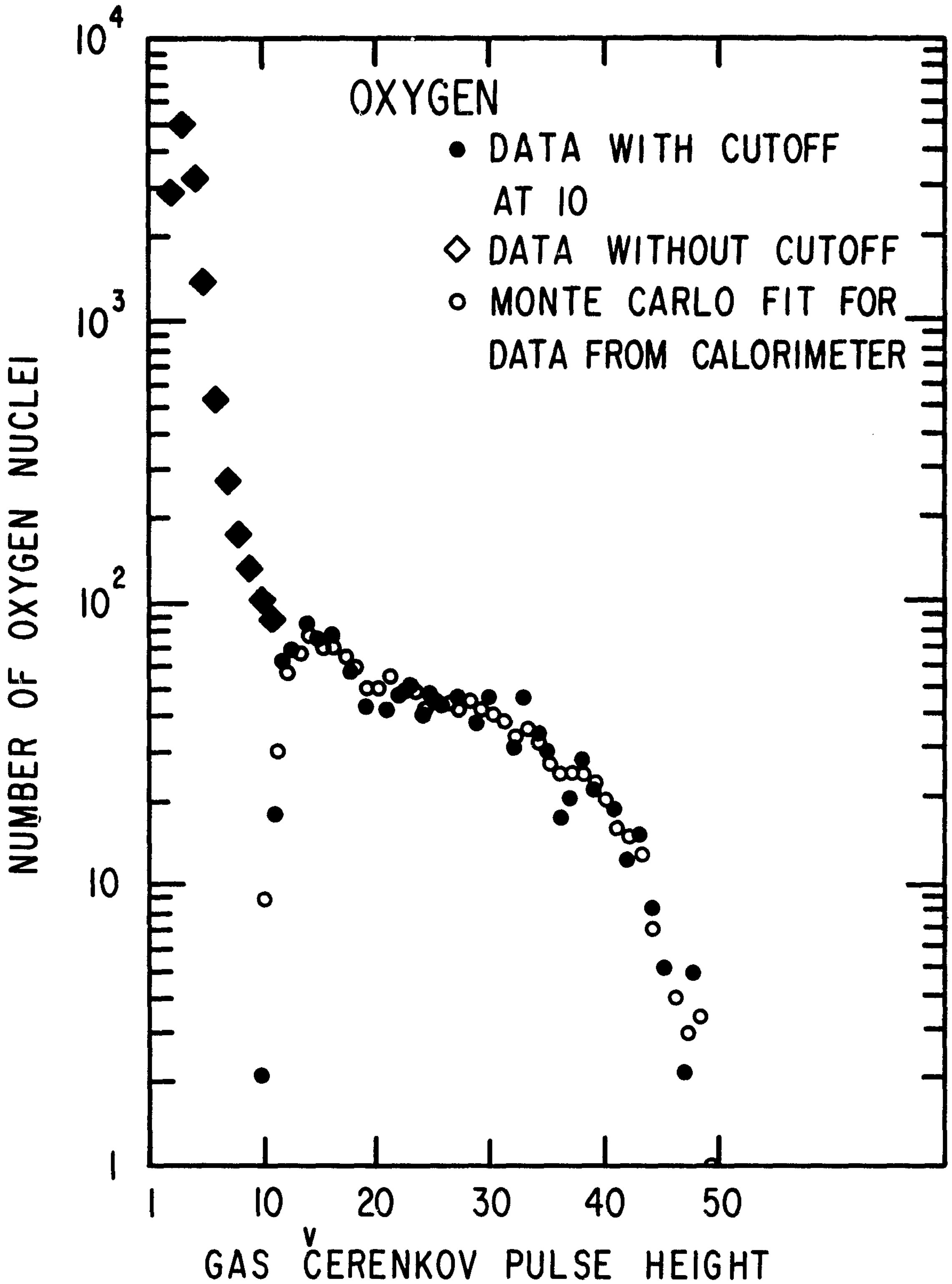
OXYGEN NUCLEI
(ENERGY IN CALORIMETER < 5 GeV/NUCLEON)
NUMBER OF PARTICLES
800
700
600
500
400
300
200
100
0
0
20
40
60
80
PULSE HEIGHT IN ARBITRARY UNITS

Fig.7



OXYGEN
DATA WITH CUTOFF AT 10
DATA WITHOUT CUTOFF
MONTE CARLO γ = −2.7
MONTE CARLO γ = −2.5
NUMBER OF OXYGEN NUCLEI
10⁴
10³
10²
10
1
1
10
20
30
40
50
GAS ČERENKOV PULSE HEIGHT

Fig.8



OXYGEN
DATA WITH CUTOFF AT 10
DATA WITHOUT CUTOFF
MONTE CARLO FIT FOR DATA FROM CALORIMETER
NUMBER OF OXYGEN NUCLEI
GAS ČERENKOV PULSE HEIGHT
10^4
10^3
10^2
10
1
1
10
20
30
40
50

Fig. 9

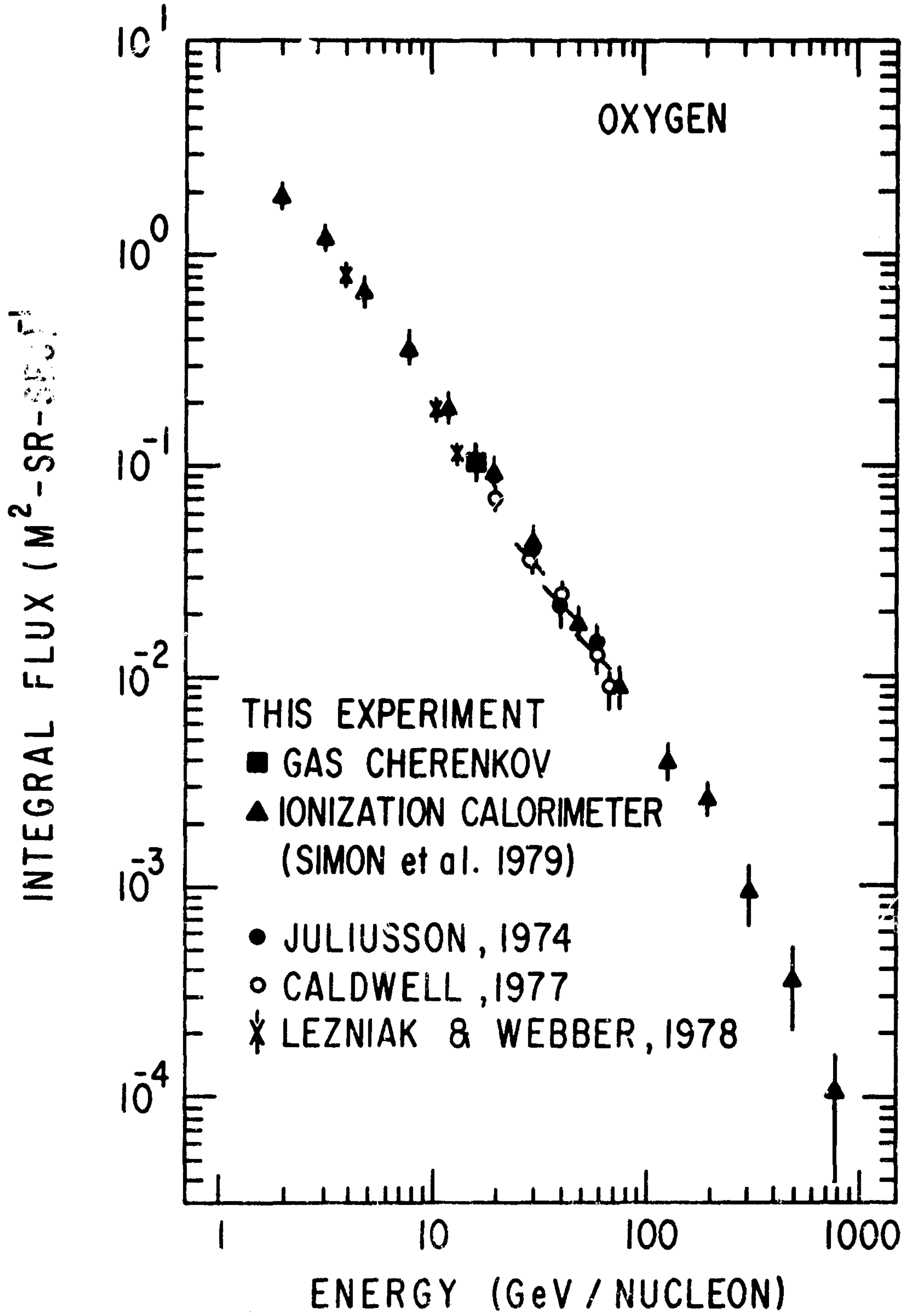

OXYGEN
THIS EXPERIMENT
GAS CHERENKOV
IONIZATION CALORIMETER
(SIMON et al. 1979)
JULIUSSON, 1974
CALDWELL, 1977
LEZNIAK & WEBBER, 1978
INTEGRAL FLUX (M2-SR-SEC)-1
ENERGY (GeV / NUCLEON)
1
10
100
1000
10 1
10 0
10 -1
10 -2
10 -3
10 -4

Fig. 10

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17. Key Words (Selected by Author(s))
Cosmic radiation-composition at high energy, Gas Cherenkov and calorimeter combination technique

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