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A COSMIC-RAY NUCLEAR EVENT WITH AN ANOMALOUSLY STRONG CONCENTRATION OF ENERGY AND PARTICLES IN THE CENTRAL REGION

by

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Abstract

A cosmic-ray induced nuclear event detected in the emulsion chamber is described. The event consists of 217 shower cores with ΣE_γ = 1,275 TeV. In log scale, energy and particles are emitted most densely at the small lateral distance corresponding to 0.5 mm; 77 % of the total energy and 61 % of the total multiplicity are inside the radius of 0.65 cm. The shower cores in the central region show exponential-type energy distribution and non-isotropic azimuthal distribution. This event indicates a possibility that phenomena of large transverse momentum could happen to produce a strong concentration of energy and particles in the very forward direction.

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Key-words: Cosmic ray; Nuclear event; Emulsion chamber.

1. Introduction

Brasil-Japan Collaboration has been studying cosmic-ray induced nuclear interactions in the energy region 10^{13}- 10^{17} eV by means of emulsion chambers exposed at Mt. Chacaltaya.(1) The integrated exposure has been accumulated to be 450 m^2 year up to now, and the main energy region of our concern is moving to the domain, $> 10^{15}$ eV, which has been covered by extensive air shower experiments.

Up to now, 13 events have been observed in the measurable energy region, > 1,000 TeV, by the emulsion chamber experiments at Chacaltaya. 9 events among them are associated with a generally darkened wide area on X-ray films. This area in the central region (*) is called as "halo", and events associated with halos are called as halo events; five halo events (2-4) have been already reported. The experiments at Pamir (5), Mt. Fuji (6) and Kanbala (7) have also observed halo events. Thus it can be said that appearance of strong concentration of energy as a halo is a rather common feature in this energy region.

In this paper, we report a halo event which was detected in the 18th chamber at Chacaltaya. The total measurable energy of individual shower cores is $\Sigma E_\gamma \sim 1{,}300$ TeV. In the very block where this event was detected, nuclear emulsion plates together with X-ray films were set at every layer of the chamber; thanks to the powerful spatial resolution of nuclear emulsion, we can study the details of the event.

(*) The central region on the target diagram corresponds to the very forward angular region in general.

2. Experiment

The present event was detected in the 18th emulsion chamber which had been exposed at Mt. Chacaltaya (Bolivia, 5220 m above sea-level) by the Brasil-Japan Collaboration. The detector consists of an upper chamber (7 cm of Pb), a target layer (23 cm of pitch), an air space (150 cm of air) and a lower chamber (8 cm of Pb). Both the upper chamber (44.2 m^2) and the lower chamber (32.4 m^2) are of multi-layered sandwiches of lead plates and photo-sensitive materials. The details of the experiments at Chacaltaya have been described elsewhere.(1)

The event was detected in the block P06 in the upper chamber and in the block 74 in the lower chamber, where nuclear emulsion plates (Fuji ET7B) were inserted in the sandwiches together with X-ray films (Sakura N-type and RR-type). We call this event here simply "Po6". In the central part of P06, we made a general scan for showers on nuclear emulsion plates under microscope for the area 1.6×1.6 cm^2.

To identify hadron-initiated showers, we apply the following criteria which were also used in the analysis of five halo events (2-4) observed at Chacaltaya: (1) showers which start (*) their cascade process at the deep layer (>4 cu), and/or (2) showers which show a double peaked transition. Taking into account the zenith angle (31^o), detection probability of hadrons above threshold energy is calculated to be 59 % for the event P06.

(*) Showers for which the measured transition curve is >4 cu deeper than average of simulated electro-magnetic showers of same energy.(8)

3. Experimental Results

3.1 Size of Halo

The event P06 contains a large energy deposit in the central region. Its appearance is rather weak and not so impressive at 4 or 6 cu, but the central part develops remarkably in the chamber and a strong concentration of energy is noticed at a glance on the X-ray films at deeper layers. Performing a general measurement of opacity of halo part on N-type films, we can define the lateral size of the halo and estimate its total energy.(2-4)

Fig. 1 shows the lateral distributions of electron density, $\rho(r,t)$, where r and t stand for the lateral distance and the traversed depth, respectively. The electron number at t is deduced from this figure, and its transition reaches the maximum at 14 - 16 cu. We define the halo radius as the lateral distance at the shower maximum where the electron density is 10^6 electrons/cm^2; then the lateral size (radius) of the halo of P06 is obtained to be 0.65 cm. Integrating the electron density, we obtain the total track length to be 1.41×10^8 cu, which gives an estimate of total energy of halo, 1,043 TeV, taking the critical energy of lead as a conversion factor.

It is worth noting that the halo energy, E_{halo}, is nearly equivalent to the sum of energies, ΣE, of shower cores which can be observed individually under microscope and that the depth of shower maximum, t_{max}, is very deep in P06. In case of the event "Andromeda", for example, $E_{halo} \sim 3.5 \Sigma E$ and $t_{max} = 10$ cu.(2,4)

3.2 Individual Shower Cores

We can study individual shower cores even in the halo region thanks to the high spatial resolution of nuclear emulsion.

Fig. 2 shows a correlation diagram between energy, E, and lateral distance, R, of shower cores observed in P06, where showers identified as hadron-initiated are indicated by crosses. The lateral distances are measured from the energy-weighted center of shower cores whose distances from the most energetic core are smaller than 0.65 cm. In the figure, we notice a negative correlation in the halo part, i.e., the decrease of the energy with the increase of the lateral spread up to ~ 1 cm. The dashed line, which corresponds to ER = 7.5 GeV m, is shown as a guide.

In Figs. 3-(a, b and c), we show three kinds of lateral distributions of individual shower cores: (a) number of particles, (b) energy-flow and (c) (energy) × (distance), ER; identified hadrons are indicated. The results of a simulation calculation are also shown for comparison.(*) In these figures we exclude the cut condition, $R \leq 10$ cm, to see the behaviour also at outer region.

It is clearly shown that the halo consists of many shower cores which make a peak in high particle density and energy-flow at the very small lateral distance, 0.5 mm; this high concentration of energy and particles in the central region is one of the most impressive characteristics of this event. One finds that, inside the halo radius (0.65 cm), 77 % of the total energy and 61 % of the total multiplicity are liberated, but it is worth noticing that in the outer region there are also many shower cores with a great ER-flow: it can be said that the event P06 contains a big energy-flow both in the longitudinal and in the transversal directions.

Fig. 4 shows the energy distributions of shower cores in an integral form, with the cut condition of $R \leq 10$ cm in order

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(*) We took the assumption of proton primary, constant interaction cross-section and scaling-type interactions.(9) 119 simulated events were produced in the energy region 1,000 - 2,000 TeV. The cut conditions of $E \geq 1$ TeV, $E(\text{TeV}) \geq R(\text{cm})^{\log 2}$ and $R \leq 10$ cm were put on; the second condition means that the threshold energy increases gradually from 1 TeV at 1 cm to 2 TeV at 10 cm.

to see the behaviour of the lower energy region; the distribution for shower cores inside the halo radius is separately shown. The distribution of P06, especially its halo part, is approximately expressed by an exponential form; the curve of $N \exp(-NE/\Sigma E)$ with $N = 100$ and $\Sigma E = 1{,}000$ TeV is drawn for a reference. The result of simulation calculation is also shown for comparison; its form is almost of power function, indicating how a long passage in air influences the exponential-type energy distributions involved in each local interaction.

In Fig. 5, we show the distributions of (energy) × (distance), ER, for shower cores, in an integral form. The shower cores in the halo are separately shown. A large difference of lateral spread between the halo and the outer region is impressive. The average value of ER in the halo is calculated to be 7.2 GeV m, and that of the outer region is obtained from the slope to be ~ 2 GeV km.

3.3 Structure of Halo

Fig. 6 shows a contour map of opacity in the halo part of P06 on RR-type X-ray film at 14 cu in the upper chamber, where we used a micro-photometer adapted to a microscope with slit size of 113 μm in diameter. In the figure, several contour lines are drawn for the levels of opacity 0.2, 0.3, 0.4, 0.6, 0.8 and 1.0, together with the shower cores with energy greater than 10 TeV. The cores identified as hadrons are indicated by crosses. We notice here that the halo part shows a non-isotropic structure in azimuth in both the distributions of opacity and of the high energy shower cores, and that the distribution also holds for the hadronic shower cores.

Fig. 7 shows the distributions of opacity on RR-type X-ray film at 14 cu in the upper chamber and on N-type X-ray film at 4 cu in the lower chamber, where the measurement was made with slit size $100 \times 100\ \mu m^2$ along the straight line on the films passing through two hadronic shower cores which can be well recognized in both chambers because of their strong and sharp penetration. These two cores (# 40 and # 58) and core, # 1, the highest energy in the event, are indicated especially in the figure. The distribution is not symmetrical, and we notice that the halo part contains at least two peaks.

4. Summary and Discussion

We have described a cosmic-ray induced nuclear event which was detected in the emulsion chamber exposed at Mt. Chacaltaya by the Brasil-Japan Collaboration. The central part of the event is realized in the upper part of the upper chamber as a rather small size dark spot on N-type X-ray films, but it develops remarkably in the lead material of the chamber and appears as a generally darkened wide area (halo). The total energy measurable in the form of electro-magnetic cascade showers of this event is 1,275 TeV, 217 shower cores being observed on the nuclear emulsion plates.

The present event shows several characteristics as follows:

(1) The degree of concentration of energy and particles is very high: 77 % of the total energy and 61 % of the total multiplicity are liberated inside the halo radius (0.65 cm).

(2) Energy and particles are liberated most densely at the very small lateral distance, the peak position being 0.5 mm in log scale.

(3) The energy distribution of this event, especially in the halo part, is approximately expressed by an exponential form.

(4) Many particles are emitted also in the outer lateral region, where a large flow of ER is observed. A large difference in the distribution of ER is seen between the halo part and the outer part (of a factor ~ 30).

(5) A special azimuthal structure is seen in the halo part.

The items, (1) - (3), indicate that this event does not suffer from a large cascade degradation during its passage in the atmosphere. Simulation tells us that a high concentration of energy and particles is associated with high purity of events$^{(9)}$: the item (3) indicates that the original exponential form at the production is almost maintained at the observational level. The general measurement of opacity (sect. 3.1) also supports this consideration.

We could not find any among 119 simulated events which reproduced the strong concentration of energy and particles in the central region and the large lateral spread in the outer region at the same time: only one artificial event showed some similarity in the central region. Since the assumption of our simulation is known (6,10) to be most efficient to produce the high energy concentration because of its slow energy dissipation or strong penetration, the present event seems to be located at the very edge of the fluctuation possible in normal propagation in the atmosphere, but we would like to point out that our event is one of only 8 events so far observed at Chacaltaya in the energy interval 1,000 - 2,000 TeV.

Although the special characteristics of this event should be examined in the higher statistics of the experimental data together with various theoretical (and computational) trials, the event seems to indicate the possibility that phenomena of large transverse momenta could happen to produce a strong concentration of energy and particles in the very forward direction, with small transverse momenta and a large multiplicity.(11,12)

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Figure Captions

Fig. 1 Distributions of electron density $\rho(r,t)$ of the event P06 at 4 - 14 cu in the upper chamber.

Fig. 2 Correlation diagram between energy, E, and lateral distance, R, of all the shower cores observed in P06. The hadronic showers are indicated by crosses. The dashed line stands for ER = 7.5 GeV m.

Fig. 3 Lateral distributions of individual shower cores; (a) number of particles, (b) energy-flow and (c) (energy)× (distance), ER. (-o-) are for γ-rays and hadrons in P06, (-●-) for hadrons in P06 and (……) for 119 simulated events.

Fig. 4 Energy distributions of shower cores in an integral form. The open circles are for shower cores of P06, and the closed circles for only those in the halo. The dashed line stands for the 119 simulated events. An exponential curve, 100 exp(-0.1 E) , is drawn by the solid line.

Fig. 5 Distributions of (energy) × (distance), ER, of shower cores, in an integral form. The open circles are for the shower cores and the closed ones for only those in the halo.

Fig. 6 Contour map of light opacity of the central halo of P06 on RR-type X-ray film at 14 cu in the upper chamber, together with the high energy shower cores (o for 10 - 20 TeV and ● for $>$ 20 TeV), among which the hadronic cores are indicated by crosses. The event center is indicated by large cross. The correction for incident zenith angle is already made.

Fig. 7 Distributions of opacity on RR-type X-ray film at 14 cu in the upper chamber (dotted line) and on N-type X-ray film at 4 cu in the lower chamber (solid line). Measurement was made along the straight line, on the films, passing through two hadronic cores (# 40 and # 58).

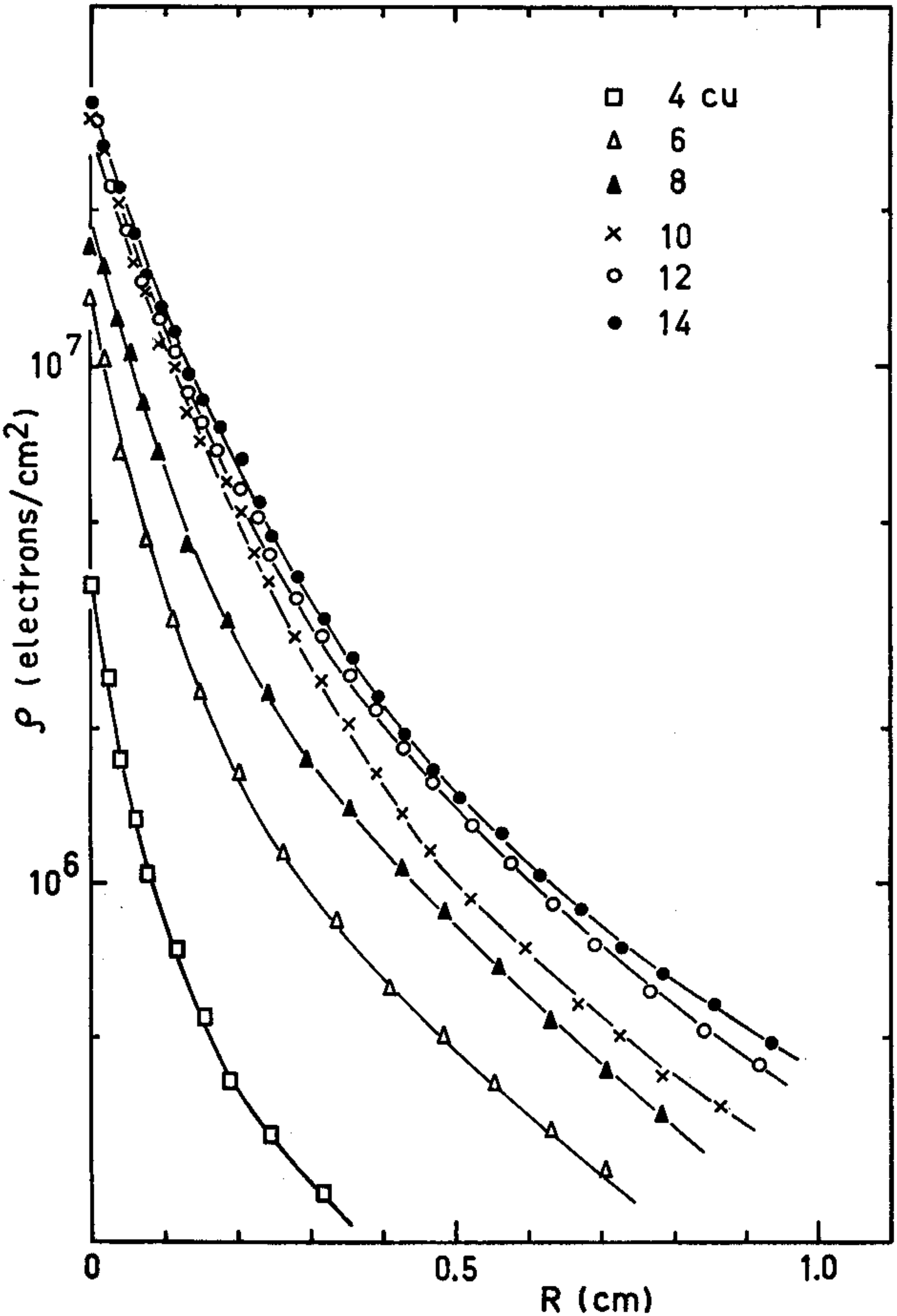

Fig. 1

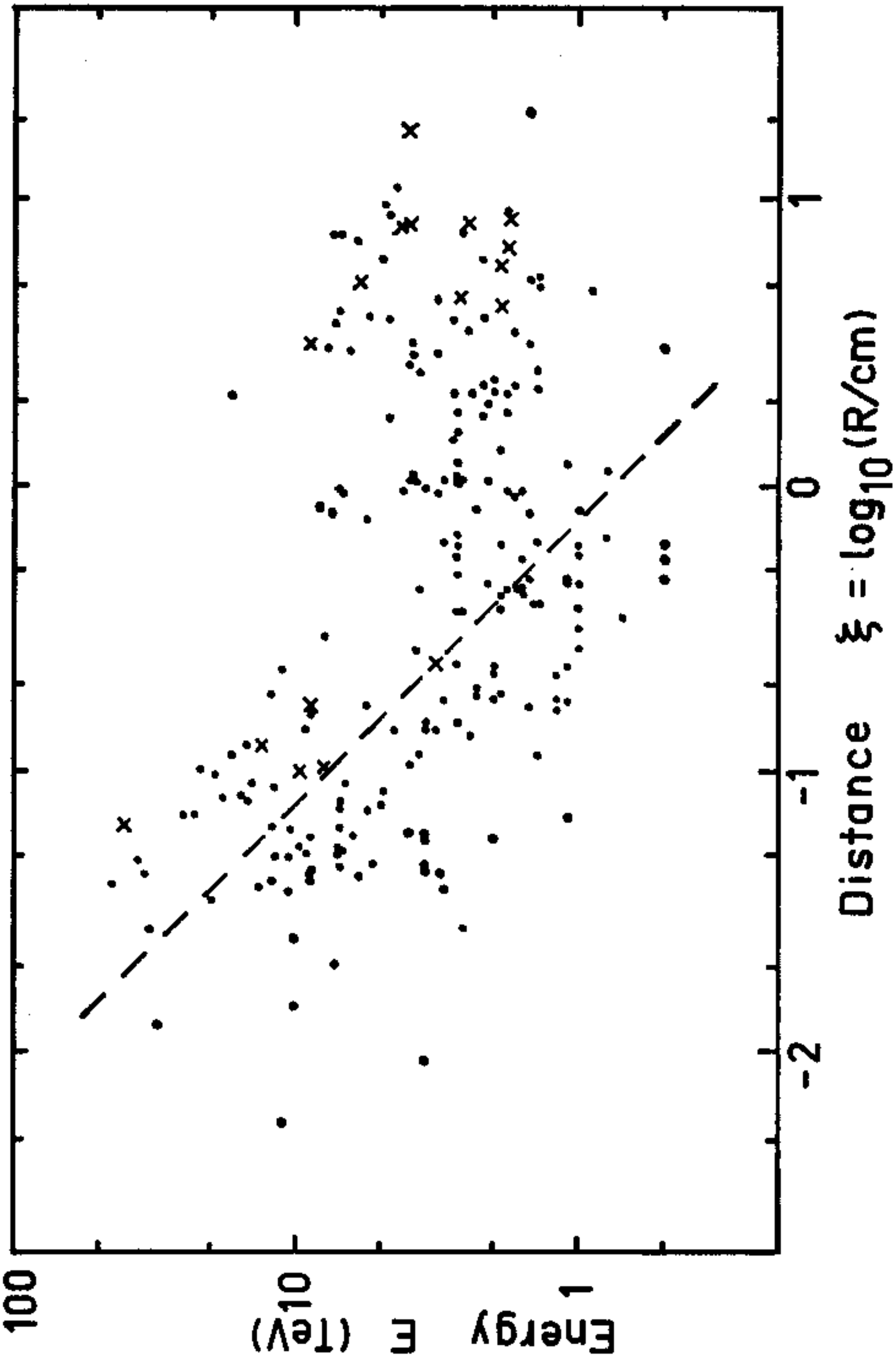

Fig. 2

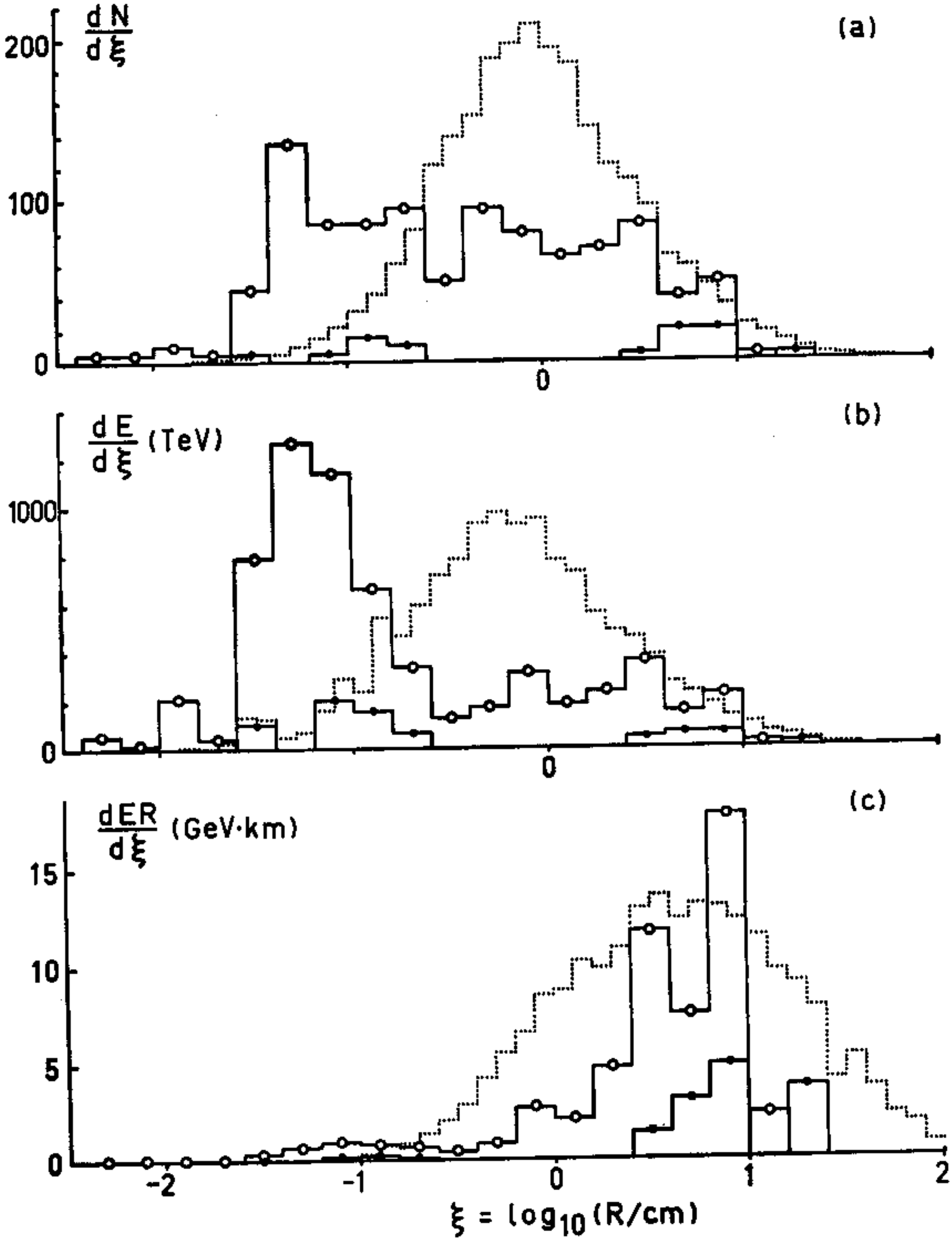
dN/dξ
(a)
200
100
0
0
dE/dξ (TeV)
(b)
1000
0
0
dER/dξ (GeV·km)
(c)
15
10
5
0
-2
-1
0
1
2
ξ = log₁₀(R/cm)

Fig. 3

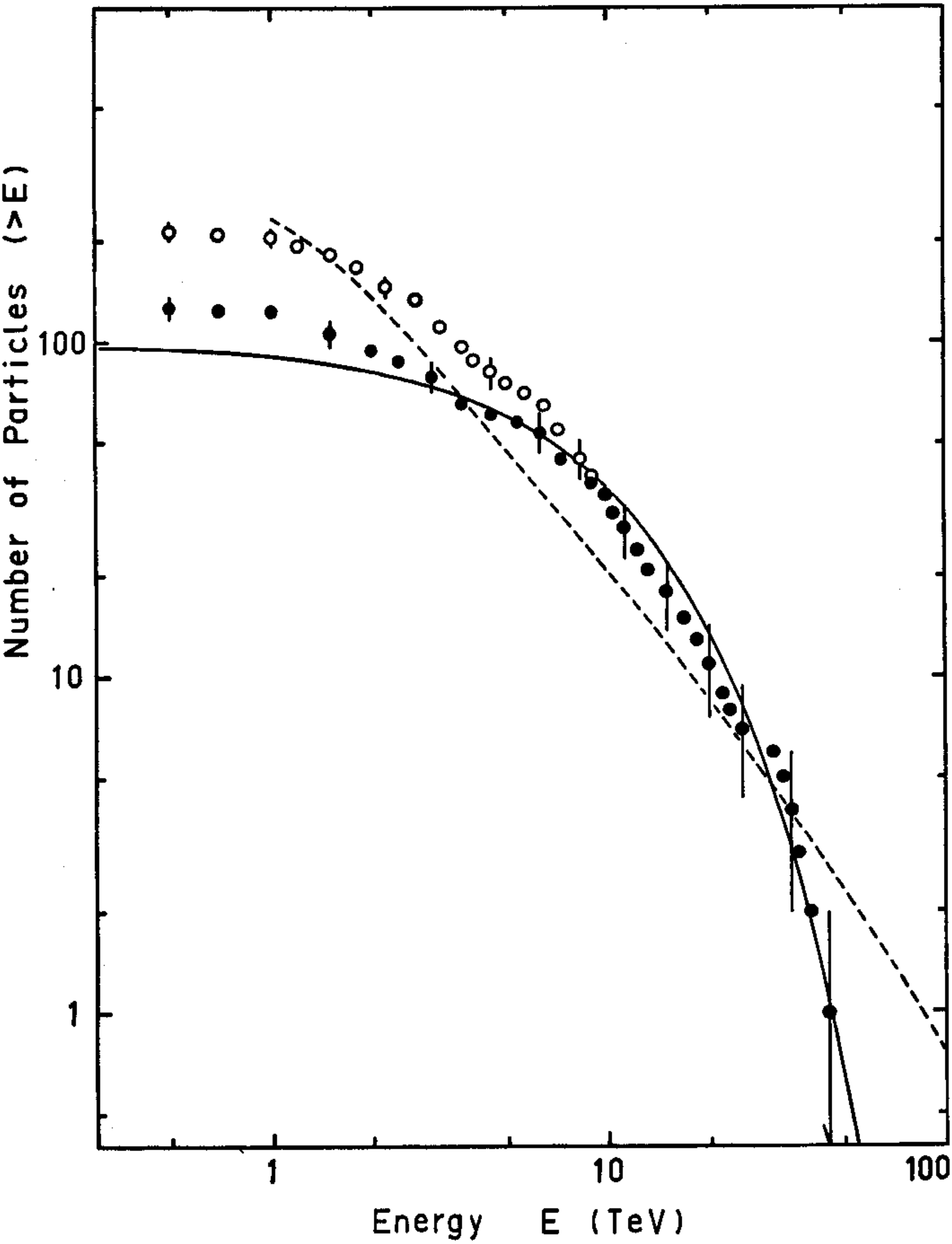

Fig. 4

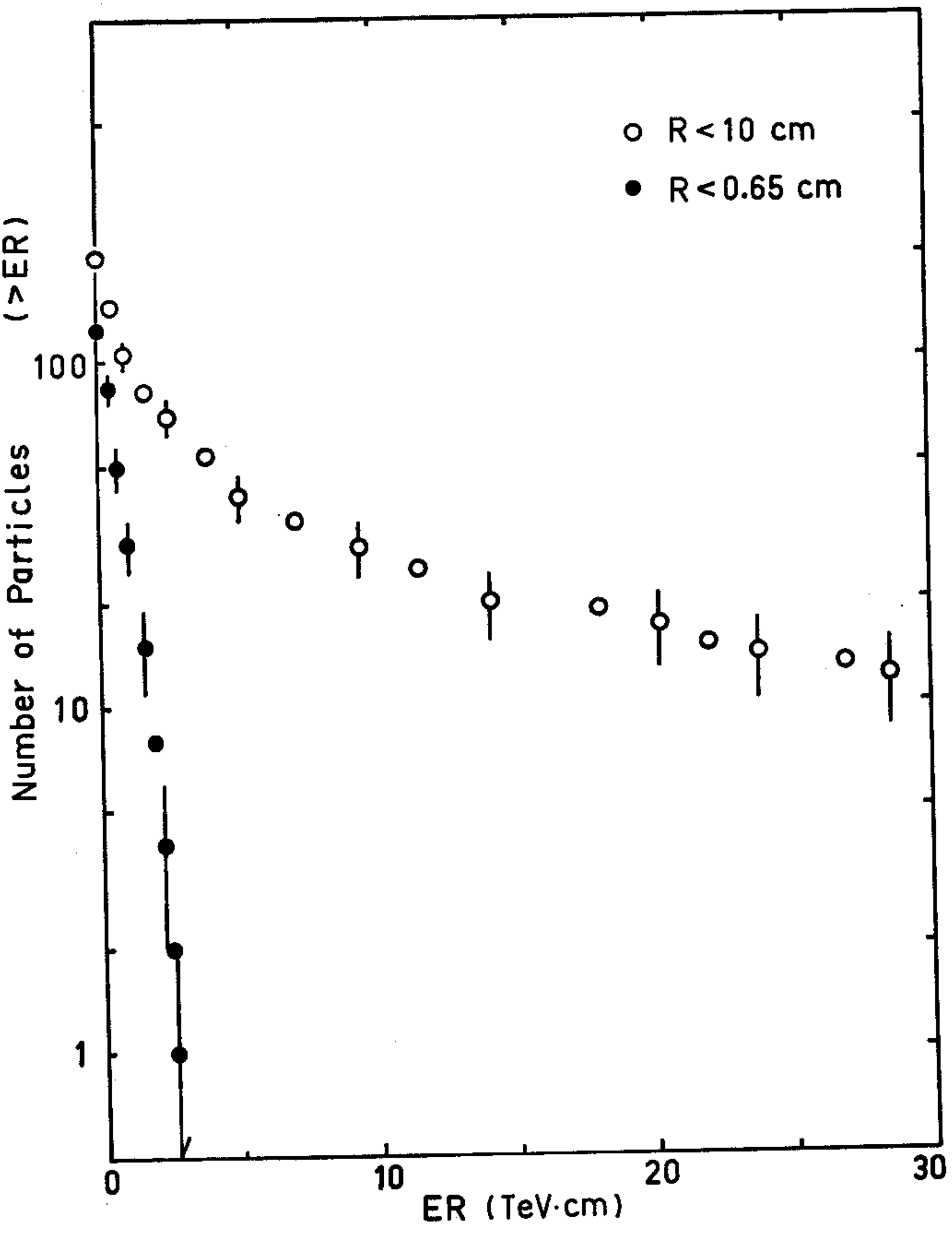
○ R < 10 cm
● R < 0.65 cm
Number of Particles (>ER)
100
10
1
0
10
20
30
ER (TeV·cm)

Fig. 5

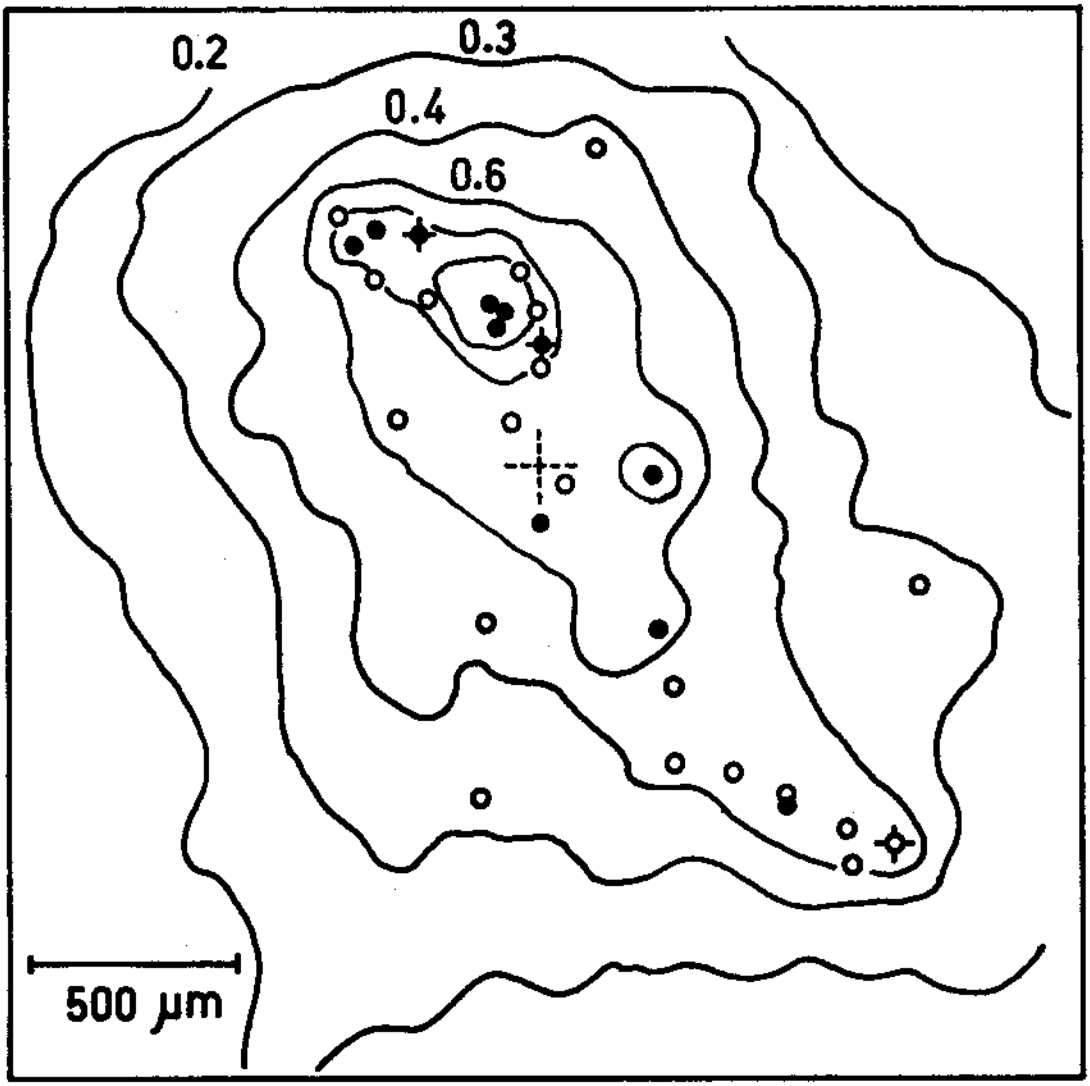

Fig. 6

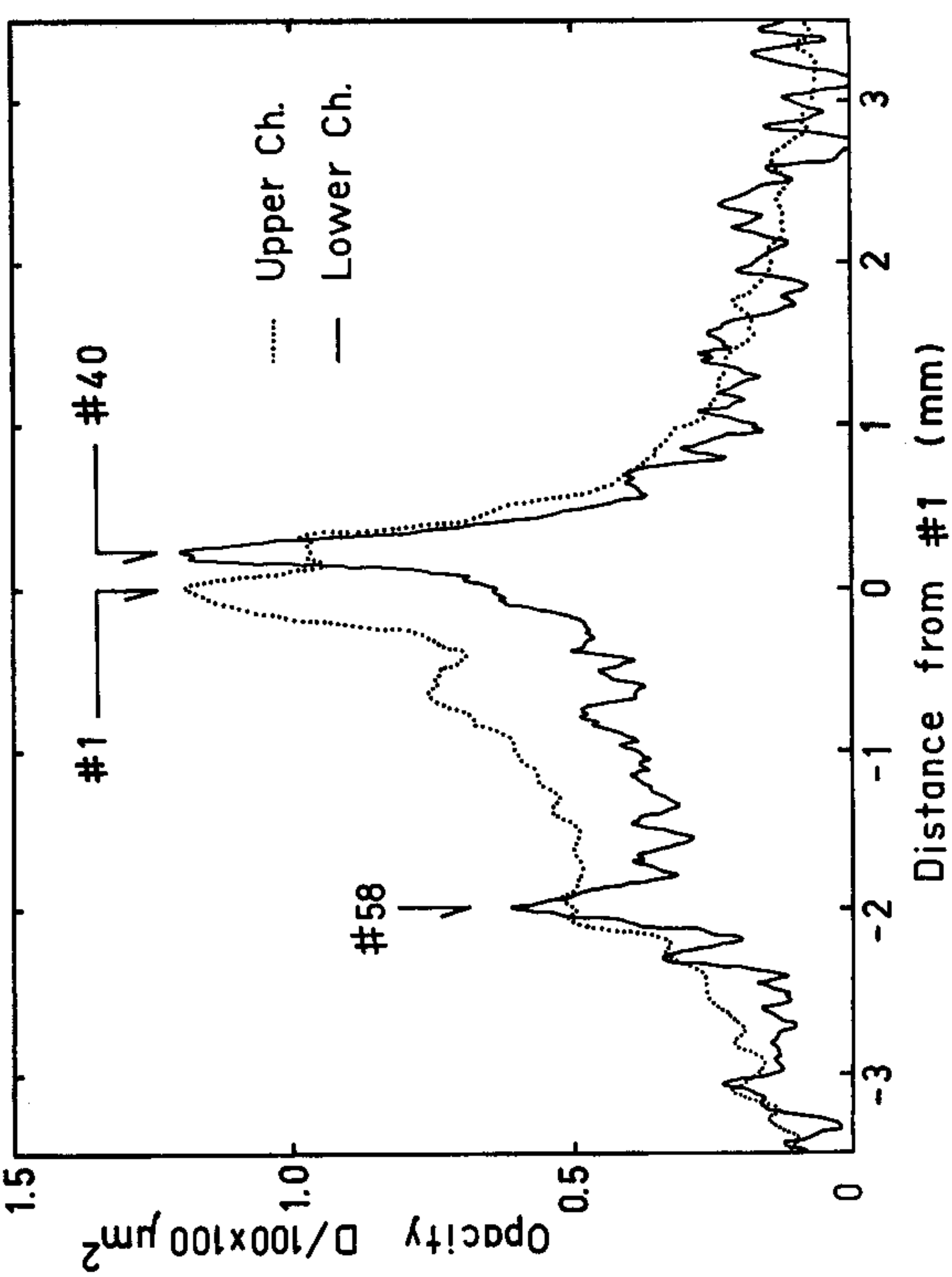
#1
#40
#58
Upper Ch.
Lower Ch.
Opacity D/100x100 μm²
1.5
1.0
0.5
0
-3
-2
-1
0
1
2
3
Distance from #1 (mm)

Fig. 7

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