MEASUREMENT OF ACCELERATOR ELECTRON INDUCED CASCADE SHOWERS IN LEAD WITH THERMOLUMINESCENCE SHEET

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(Received September 30, 1987)

ABSTRACT

A new detector, consisting of thermoluminescence [TL] sheets ($BaSO_4$: Eu) and a readout system of TL sheets have been developed to study electromagnetic cascade showers in ultra-high energy interactions. To perform a measurement of showers by using TL sheets the radial and longitudinal development of an electromagnetic cascade shower in lead produced by accelerator electrons has been studied. These calculation of the development of cascade showers were also performed using the EGS Code System (ver.3).

This study is useful to design a thermoluminescence calorimeter [TLC] for the measurements of electromagnetic cascade showers in ultra-high (above 10^{15} eV) energy interactions.

1. INTRODUCTION

For more than 20 years, photosensitive materials such as nuclear emulsions and X-ray films combined with heavy metal plates (iron, copper, lead, etc.) have been used, in an so-called emulsion chamber, to observe ultrahigh energy hadronic and electromagnetic cascade showers. Emulsion chambers have an advantage of high position resolution and easy construction of a large area detector without any use of electronics and power supply. For example, emulsion chambers with an area of several hundreds of square meters have been exposed for one or more years at high mountain altitudes to study heavy cosmic ray interactions at energies of the order of 10^{15} eV, the energies which accelerators have already reached.

In order to observe cosmic rays at ten times higher energy, it is necessary to increase the collecting factor, [area × time] , by about two orders of magnitude because of the steep energy spectrum of cosmic ray particles. It will be difficult to use a conventional passive detector such as an emulsion chamber with an extensively large scale because of the economical limitations and the amount of labor and time required for the analysis afterwards.

Moreover, a detector must cover a wide dynamic range in measuring the energy of the cascade showers due to increase in the energy region. The effective dynamic range of an X-ray film has an order of magnitude of several hundreds at most. The dynamic range of the detector is also important to determine the lateral distribution of high energy showers by measuring the particle density of a highly collimated shower.

A preliminarily report of the measurement of electron induced cascade showers by using the thermoluminescence technique has been reported by T. M. Jenkins et al. [ref.1]. They used LiF powder which was put in a thin walled polyethylene tube. After a beam irradiation, the tube was cut into segments and the thermoluminescence light output was measured with a commercial reader. Therefore it is quite difficult to obtain a two-dimensional continuous distribution of electrons (or photons) in an electromagnetic cascade shower.

A new detector, using a thermoluminescence [TL] sheet ($BaSO_4$: Eu doped), has been developed for studying hadronic and electromagnetic cascade showers [ref.2], [ref.3]. The TL sheet is very suitable for such a study since it has advantages in detecting of cascade showers with a high detection sensitivity and with its wide working dynamic range of over eight orders of magnitude [ref.4] and with easy handling in rooms because of no photosensitivity to the room lights. As TL sheets can be used repeatedly by annealing, it is economic in use in observation of very high energy showers which need a very large collecting area and for a long exposure time. The fading effect of the signals in TL sheets [ref.5] is very small at the room temperature (20℃), but the imaging plate (photostimulable luminescent crystals) [ref.6] is not suitable for a long time experiment.

A large area thermoluminescence calorimeter [TLC] which uses TL sheets is also effective in determination of the energy because no readout electronics system is needed [ref.7]. For the shower counters, the readout electronics system is needed and its volume must be enlarged. To attain the above mentioned aim, by the measurement of an electromagnetic cascade shower using a TLC, a spatial distribution readout system of the TL sheets has been developed [ref. 8] and using the system a two dimensional photon counting method has been introduced also [ref.5].

This paper reports the study of longitudinal and radial development of an electromagnetic cascade shower by using TL sheets; the experiment using electromagnetic cascade showers produced in lead by accelerator electrons, the readout of the signals of these showers and the Monte Carlo calculations by the EGS Code System [ref.9] simulating these showers. These results obtained are discussed by comparing the resuluts of the optical density on developed X-ray films.

2. EXPERIMENTAL METHOD

An apparatus used in this experiment schematically drawn is shown in Fig.1. Beam irradiations to a TL sheet chamber was performed using the Electron Synchrotron [ES] ($\gamma 2$ beam channel) in Institute for Nuclear Study [INS], University of Tokyo. The electron beam energy was 600 MeV and the total beam intensity was 3×10^6 electrons. As shown in Fig.1, the beam profile was measured by the TL sheet stack placed at the same position as shown in Fig.1 and in the same beam situation as this experiment. The beam test (to find the position and the intensity) was performed by using a scintillation counter, an ionization chamber (thin chamber), a total absorption type ionization chamber (thick chamber) and a T L sheet stack.

The TL sheet chamber is, so-called Emulsion chamber type, composed of teflon TL sheets (Teflon-400 ; see Table 1 of Ref.5), X-ray films and lead plates which were assembled as shown schematically in Fig.2. The size is 10cm × 10cm × 7.4cm. Three TL sheets after annealing were packed together into the polyethylene bags. Each X-ray film (Fuji # 100) was also packed into a barrier bag after vacuum sealing. This TL sheet chamber was set vertically to the electron beam

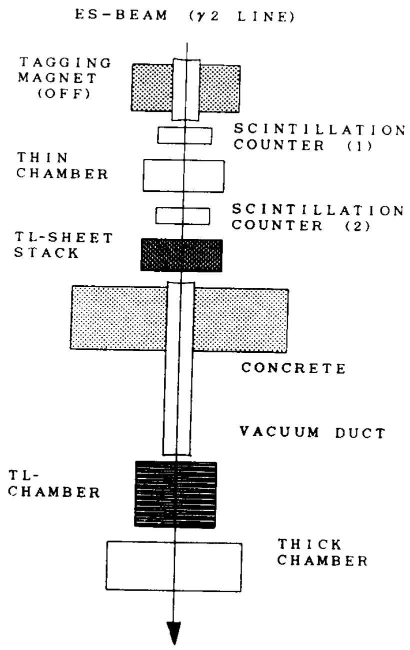

Fig. 1. Experimental arragement for the ES-beam experiment.

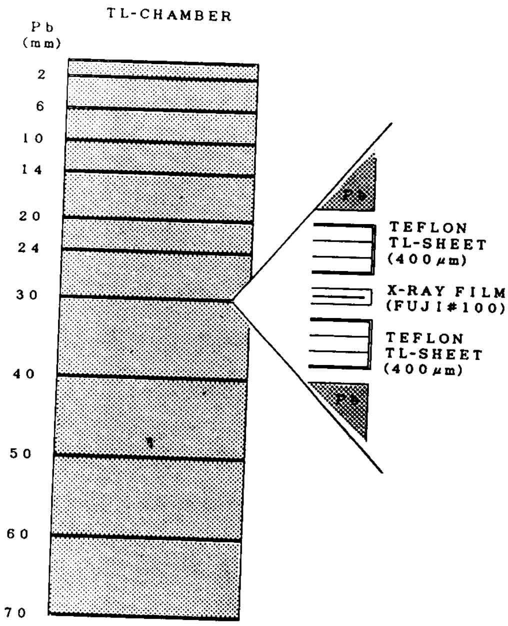

Fig. 2. Cross sectional sketch of the TL sheet chamber and Structure of sensitive layers.

as shown Fig.1.

The spatial distribution of the TL lights from the irradiated TL sheets were measured by using the readout system which has already been developed [ref.8]. The system, which consists of an image intensifier, a CCD-TV camera, a video tape recorder, a video image processor and a host computer, has been developed to observe transient phenomena in the emission of TL signals. By using this system, the two-dimensional [2-D] photon counting was achieved [ref.5]. The basic concept and design considerations of the system to realize the aim were reported in a previous paper [ref.8] [ref.5]. By using the system the spatial distribution of TL signals from the TL sheets are recorded to a video cassette. Each frame picture of TL signals played back from the video cassette is analyzed by using the 2-D photon counting method. The analyzed image is stored in floppy disks as matrices each of which contains 256 × 256 pixcels. An individual pixcel in the image represents a TL signal of an area of 170μm × 130μm on a TL sheet. The digital number read out from one pixcel represents the number of TL photons emitted from the corresponding area of the TL sheet.

X-ray films combined with TL sheets were exposed to the ES-beam electrons and the X-ray films were processed immediately after irradiation. The conditions for the chemical process are given in Table. 1. The optical density of a shower in the processed X-ray films was measured by using Mitaka Image Analysis Microphotometer NGDC 20 × 20 in Institute for Cosmic Ray Research, University of Tokyo. By the measurement the construction of a 2-D optical density map has become possible. The scanning was made with a square slit of 500μm × 500μm.

Process	Chemicals	Temperature(°C)	Time(min)
Development	KONIDOL-X	20±0.5	10
Stopping	Acetic acid(3%)	20±0.5	5
Fixing	KONIFIX RAPID	20±0.5	15
Washing	Water	20±0.5	45

Table. 1. Conditions of the X-ray film processing.

3. . EXPERIMENTAL RESULTS

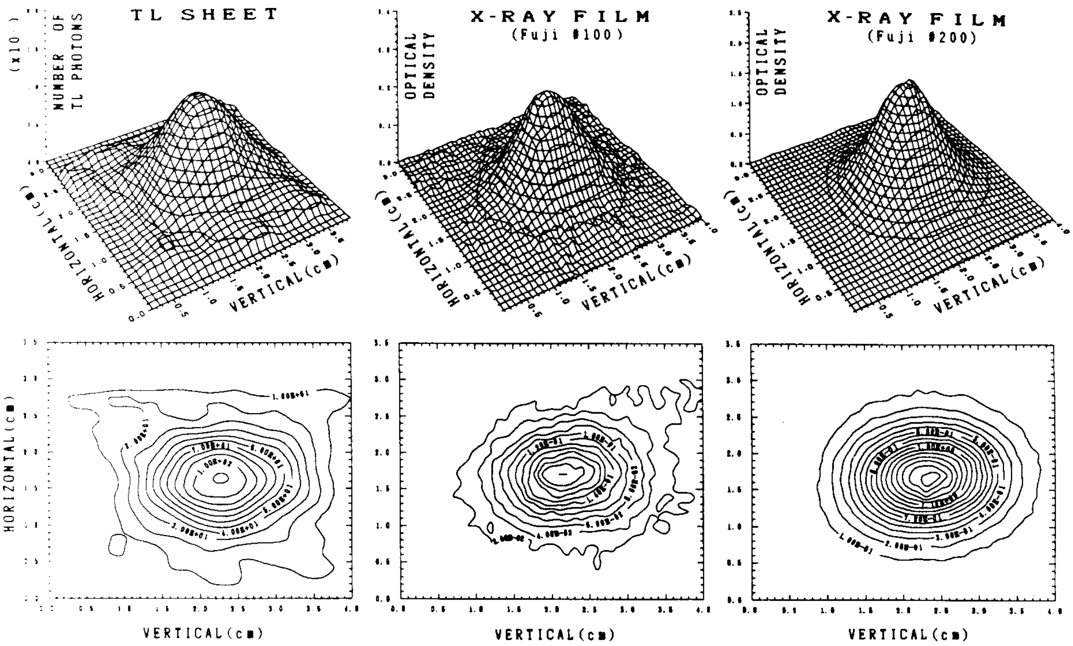

Fig. 3-a Fig. 3-b Fig. 3-c

Fig. 3-a. Beam intensity profile at the first layer of the TL sheet chamber obtained by using TL sheets (Teflon TL sheet 400). The interval of the contour lines is 10 TL phons per unit area of 1.38mm × 1.00mm on the TL sheet.

Fig. 3-b. Beam intensity profile at the first layer of the TL sheet chamber obtained by using X-ray film (Fuji #100). The interval of the contour lines is 0.02 (darkness in an arbitrary unit) per a 500 μm square slit.

Fig. 3-c. Beam intensity profile at the first layer of the TL sheet chamber obtained by using X-ray film (Fuji #200). The interval of the contour lines is 0.01 (darkness in an arbitrary unit) per a 500 μm square slit.

The 2-D distribution of the ES-beam electron density was measured by using the first sensitive layer of the TL sheet chamber. The bird's-eye view together with a contour map of a readout example of the distribution is shown in Fig. 3-a. In the contour map, the interval of the contour lines corresponds to 10 TL photons from an area of 1.38mm × 1.00mm on a TL sheet. The 2-D distributions of the optical density of developed X-ray films Fuji #100 and Fuji #200 respectively are shown in Fig. 3-b and Fig. 3-c. The interval of the contour lines in Fuji #100 corresponds to 0.02 (darkness of arbitrary unit) per square slit of 500μm × 500μm, and that in Fuji #200 is 0.10.

The 2-D distributions of the TL photon density of the TL sheets at various depths in lead have been obtained. The distribution at each depth is shown in Fig. 4 together with the contour maps. In the figure, the interval of the contour lines corresponds to 25 T L photons per an area of 1.38mm × 1.00mm on TL sheets. Using the in-out relation of the TL sheets exposed to a radioisotope, the distribution of the number of TL photons is converted to that of the electron number [ref. 4].

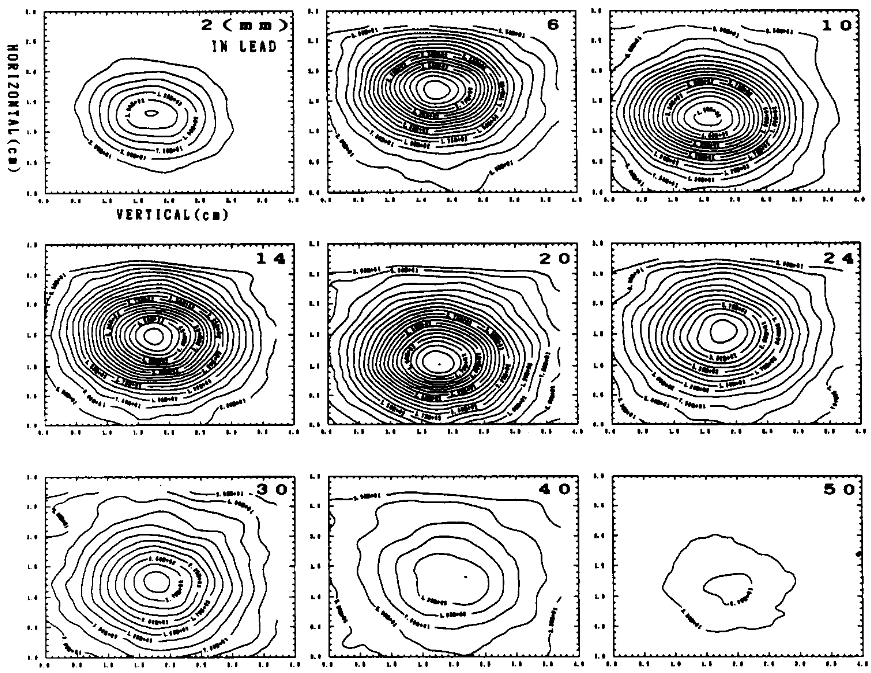

Fig. 4. The radial distributions of TL photon densities in various depths (2, 6, 10, 14, 20, 24, 30, 40 and 50mm in lead.) obtained by using TL sheets. The interval of the contour lines is 25 TL photons per unit area of 1.38mm × 1.00mm on the TL sheet. The TL photon number can be converted into the absolute electron number.

4. ANALYSIS AND DISCUSSION

As a first step in designing TLC, and since the comparison of the 2-D TL distribution from a TL sheet with that from the corresponding X-ray film which has already been discussed in the ref. 4, the ES-beam electrons were irradiated to the TL sheet chamber with such an intensity as to avoid saturation in the optical density of the developed X-ray film.

The 2-D distribution of the TL photon density was converted into that of the electron density by using the in-out relation of the TL sheets exposed to ^{90}Sr β-rays. The relation is given as ;

$$N_e\,(r,\ t) = k \times N_p\,(r,\ t) \qquad (1)$$

where, the k is the sensitivity of a TL sheet to convert the photon numbers to the electron numbers, $N_p(r, t)$ is the 2-D distributions of TL photon density and $N_e(r, t)$ is that of electoron number, the r is a distance from the beam center axis and the t is a depth in lead. The k of the TL sheet used in this experiment is 1/3347 electron per TL photons (see Table 1. in ref. 5.).

Experimental points using T L sheets can be obtained from,

$$\int_0^R Ne(r,\ t) \times 2\pi r dr \qquad (2)$$

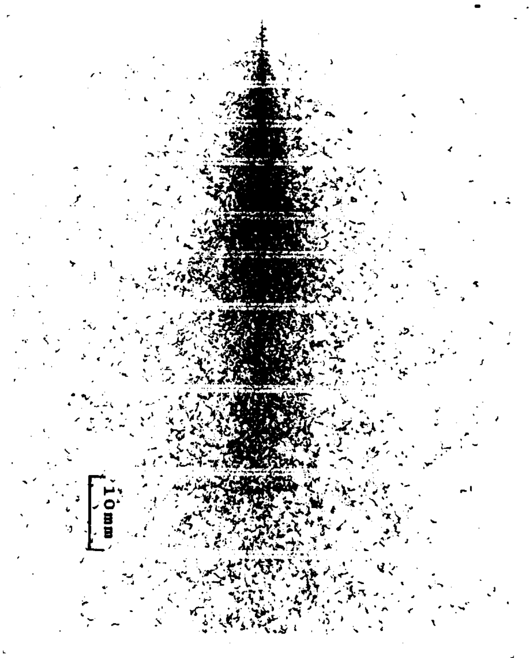

Fig. 5. An example of simulations of the electromagletic cascade showers in the TL sheet chamber. One hundred of 600 MeV electrons are simulated using the EGS Code System. A cutoff energy of secondary particles (electrons and photons) is 1.5 MeV.

where, R is the radius of a cylinder around the beam center axis. The integration was performed graphically. The integrated values at 3cm, 5cm, and 10cm in the radius were plotted in Fig. 6 by using the symbols; ▲, ● and ■, respectively.

The Monte Carlo calculation was performed for lead plates and for TL sheets by the EGS Code System. An example of the simulated electromagnetic cascade showers in the TL sheet chamber is shown in Fig. 5 with a projection drawing.

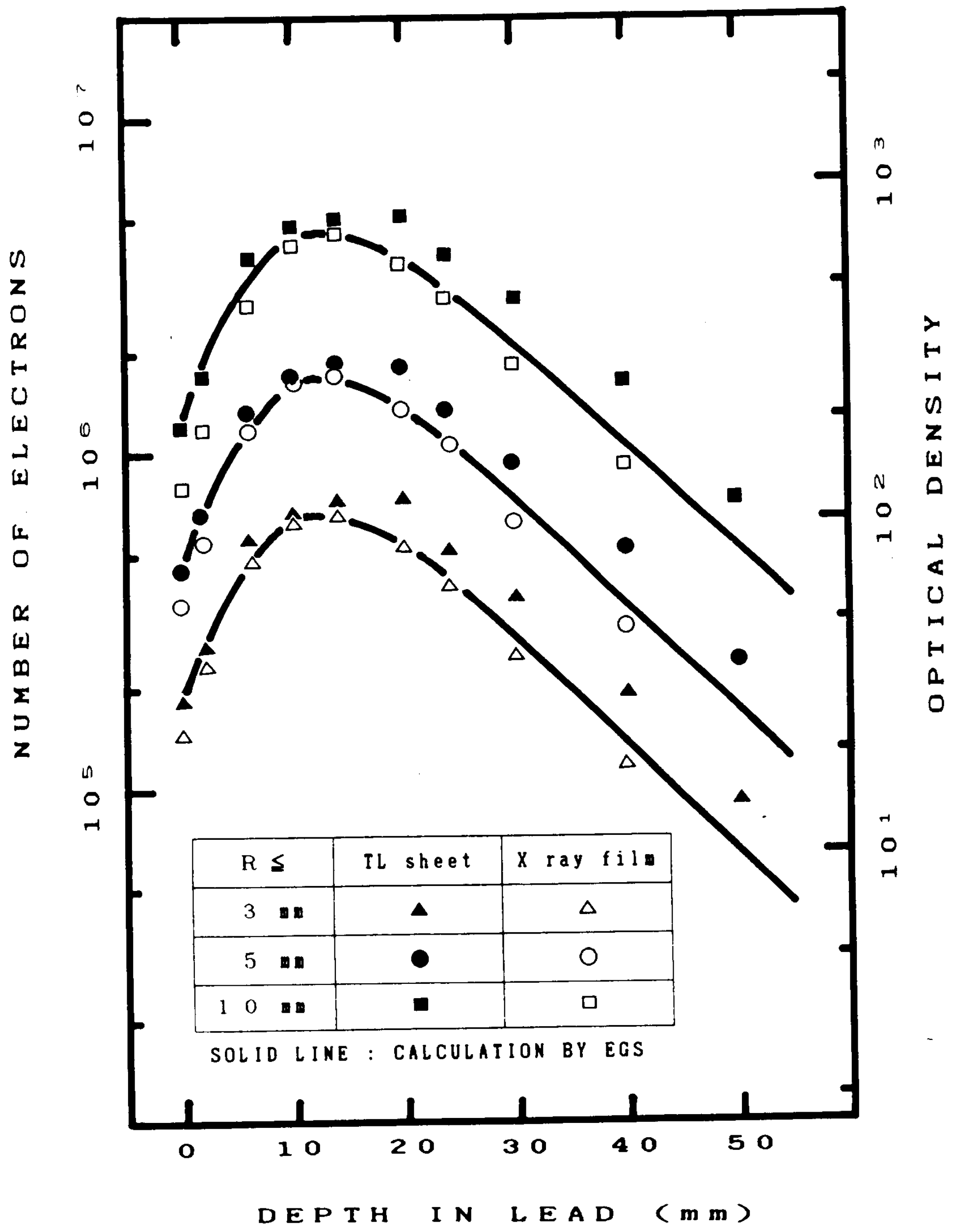

Fig. 6. Experimental points plotted with symbols; ▲, ● and ■ were obtained by the TL sheets. These points can be compared with simulated transition curves (solid curves) in the absolute values. Another points (△, ○ and □) from the optical density of the developed X-ray films were normalized to the shower maximum of the simulated ones.

Energy of the incident electron is 600 MeV and cutoff energy of secondary particles (electrons and photons) is 1.5 MeV. The position of an incident electron was simulated from the 2-D distribution of the TL photon intensity as shown in Fig. 3-a. The number of simulated incident electrons is 2×10^5 and the number is sufficient to reproduce the distribution. It is difficult to simulate 3×10^6 electrons because of a large amoust of CPU time required. The 2-D distribution of the electron numbers in each depth was obatained by multiplying the corresponding distribution of simulated electron density by 15. The simulated transition curves are shown in Fig. 6 In the figure , the curves can be compared with the points obtained from the TL photon density.

On the other hand, experimental points for the electron density using the developed X-ray films is obtained from.

$$\int_0^R D(r,\ t) \times 2\pi r dr \tag{3}$$

where, D(r, t) is the 2-D distribution function for the optical density on the developed X-ray film. The integration was performed graphically. The integrated values are plotted in Fig. 6 by using the symbols ; △, ○ and □ to show different radius. The values are approximately proportional to the density of cascade shower electrons [ref. 10] but the values are in an arbitrary unit. In the figure, the points obtained from the optical density of the developed X-ray films were normalized to the shower maximum of the simulated curves. These points fit well with the simulated curves.

It is well known that in general the number of secondary particles of a cascade shower increases at first and then decreases gradually soon after the maxmum while the energy of the individual particle decreases continuously. To a low energy particle, the minimum detectable energy in the TL sheet is much lower than that in X-ray films. Moreover, the number of TL photons from the TL sheet is linearly proportional to the number of irradiated electrons over eight orders of magnitude [ref. 4] and is independent of read out methods [ref. 5]. To the contrary, the optical density in the developed X-ray film has a narrow working range and depends on processing. In the Monte Carlo calculation, a cut-off energy of secondary particles must be selected to correspond to the minimum detectable energy because the choice of the cut-off energy affects the shape of the transition curve.

5. CONCLUSION

In the transition curves of Figure 6, the electron numbers represented in absolute intensity were obtained by the simulation using the EGS Code System under the condition of the fixed cutoff energy; 1.5 MeV corresponding to the minimum detectable energy of an electron in the X-ray film. The points deduced from the optical density of the developed X-ray films were normalized to the shower maximum of the simulated ones. These points fitted well with the simulation curves. This fact proves that the simulation provides a reasonable method of calculation to obtain the electromagnetic cascade shower curves in the TL sheet chamber irradiated with ES-beam electrons.

On the other hand, a TL photon number read-out from TL sheets can be converted into an absolute electron number. These numbers obtained are plotted in Fig. 6 and can be compared with the simulated curves on the absolute scale. The discrepancy between the plotted points and the corresponding curve occurs at the depth after the shower maximum. This discrepancy would be caused by the sensitivity of the X-ray films, because the TL sheet is more sensitive than the X-ray film to lower energy electrons.

Moreover, in the previous paper [ref. 4], the working dynamic range of the TL sheet detector at extremely high dose has been reported. The relations between the absolute TL photon number and the electron dose were obtained by using the photon counting system [ref. 5]. The in-out relations shows that a TL sheet has a dynamic range of eight orders of magnitude. Furthermore, it was shown in the paper that the important thing was that an electron beam intensity profile, with density range distributed over several orders of magnitude was obtained for an extremely high density of electrons.

A TL-calorimeter using TL sheets has advantages in the detection of cascade showers to study ultra-high energy phenomena like a socalled "halo" and a black core known as an "ANDROMEDA" event [ref. 11] with a high detection sensitivity and a wide dynamic range about which the X-ray films and the nuclear emulsions do not have.

In this paper, the feasibility of the quantitative study of ultrahigh energy phenomena by using the TL calorimeter and the 2-D photon counting system was studied and the comparison between the results obtained by TL sheets and the X-ray films was made and discussed. However, some subjects are remain to be done such as shown as follows: to perform a simulation adopting a lower cut-off energy and to do an experiment which makes it possible to compare the TL sheet results with the nuclear emulsion one.

ACKNOWLEDGMENTS

I would like to acknowledge Prof. K. Imaeda, Prof. T. Tomiyama, Dr. I. Yamamoto, Dr. K. Ninagawa, Prof. T. Wada, Dr. Y. Yamashita and Dr. T. Saito for their helpful suggestions and discussions. I am also thankful to the staff of Electron Synchrotron Division of INS (Institute for Nuclear Study, University of Tokyo) for their assistance in beam irradiations, and to Dr. I. Nakamura for his aid in computer technique in EGS. The TL image data processing and the computer simulation were carried out using computers FACOM-M380 in Okayama University of Science and FACOM-M380 in INS.

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