An Accurate Measurement of the LPM Effect with Emulsion Chambers

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***Abstract*. We have observed cosmic-ray electrons in the energy range of 30 GeV – 3 TeV by balloon experiments with the emulsion chambers that consist of nuclear emulsion plates and lead plates, stacked alternately. In the emulsion chambers, it is possible to measure the position of shower tracks in each emulsion plate with a precision better than 1 μm. Because of this high position resolution, we can identify the first electron-positron pairs of the electron-induced showers. In our balloon observations, by using this unique capability of our detectors, we have qualitatively found that the depths of the first electron-positron pair in the detector are deeper than the prediction with the Bethe-Heitler cross section, suggesting the bremsstrahlung suppression due to the LPM effect. In order to verify the LPM effect quantitatively, we have carried out our experiments with the emulsion chambers at the CERN-SPS in 2004 – 2008 by using electron beams of 50 GeV to 250 GeV. In this paper, we present the quantitative measurements of the LPM effect by using the first electron-positron pairs of the electron-induced showers.**

***Keywords*: Cosmic-ray electron, LPM effect, Electromagnetic process**

I. Introduction

Bremsstrahlung and pair creation are two of the most important high-energy electromagnetic processes. Although the interaction cross sections are generally described by the Bethe-Heitler formulas [1], Landau, Pomeranchuk, and Migdal (LPM) predicted that the cross sections are reduced at high energy and in dense media due to multiple scattering, so called the LPM effect [2], [3].

Several previous experiments have presented evidence for the LPM effect [2], [3]. As for cosmic-ray experiments, for example, Kasahara (1985) [4] studied the shower development profiles of $\sim$100 TeV cosmic rays in lead/emulsion chambers. He examined fourteen electro-magnetic cascade showers and found that the shower development profiles agreed well with the LPM prediction, but differed from the Bethe-Heitler prediction. Among the previous experiments, Anthony *et al.* (1995) [5] showed the first quantitative result of bremsstrahlung suppression due to the LPM effect by the measurement of the production rate of 5 to 500 MeV photons from 8 and 25 GeV electrons traversing thin gold (0.1% – 6% r.l.) and carbon (6% r.l.) targets. Hansen *et al.* (2004) [6] also presented experimental results for the bremsstrahlung energy loss of 149, 207, 287 GeV electrons in thin Ir, Ta, and Cu targets (around 4% r.l.). Hansen *et al.* showed good agreement between simulations with the LPM bremsstrahlung suppression and data from the experiment. Both the accelerator experiments, conceptually similar to each other, has been carried out by using electron beams with thin targets of several % radiation length (r.l.) and magnet to separate incident electrons from gamma rays produced in the targets.

On the other hand, we have carried out a different approach to the LPM effect by using the emulsion chambers, in which we use the thick targets of lead (10% – 30% r.l.) and measure the first electron-positron pairs produced by gamma rays from bremsstrahlung of incident electrons. In this paper, we present a quantitative measurement of bremsstrahlung suppression due to the LPM effect with the emulsion chambers.

II. Experiment

A. Detector

We have observed cosmic-ray electrons in the energy range of 30 GeV – 3 TeV with balloon-borne emulsion chambers in many flights between 1968 and 2001 [7]. The total cumulative effective exposure $S\Omega T$ for electrons is 7.7 m^2-sr-day, which is larger than any other electron observations with balloons. Emulsion chambers consist of nuclear emulsion plates and lead plates, which are stacked alternately. Nuclear emulsion plates sample the development of electro-magnetic showers produced in the lead plates. X-ray films are also inserted to allow rapid, naked-eye scanning for high-energy showers. Figure 1 shows a typical emulsion chamber structure. The typical size and thickness of the detectors are 40 cm $\times$ 50 cm, and $\sim$9 cm ($\sim$9 r.l.), respectively.

In emulsion chambers, it is possible to measure the position of shower tracks in each emulsion plate with a precision better than 1 μm. Because of this high position

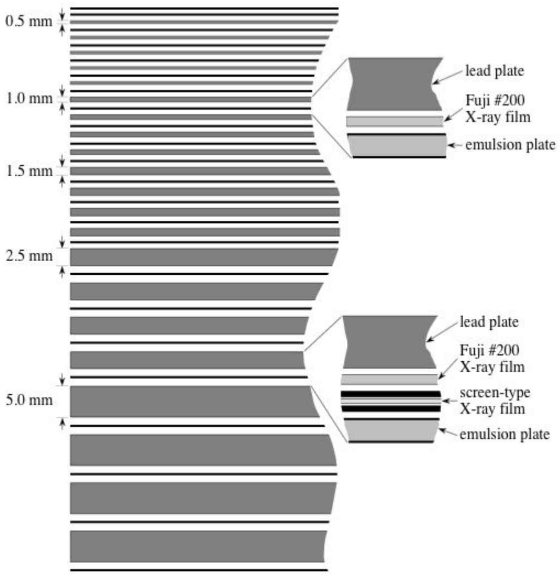


Fig. 1. The typical structure of emulsion chambers.

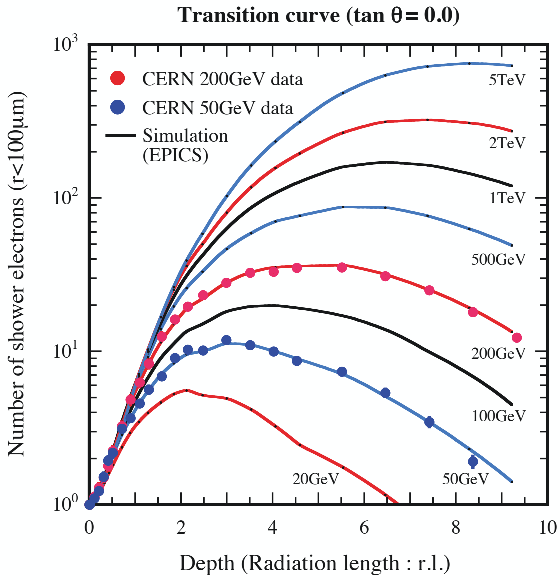


Fig. 2. Longitudinal development of the averaged number of shower tracks within a radius of 100 μm, compared to the simulations.

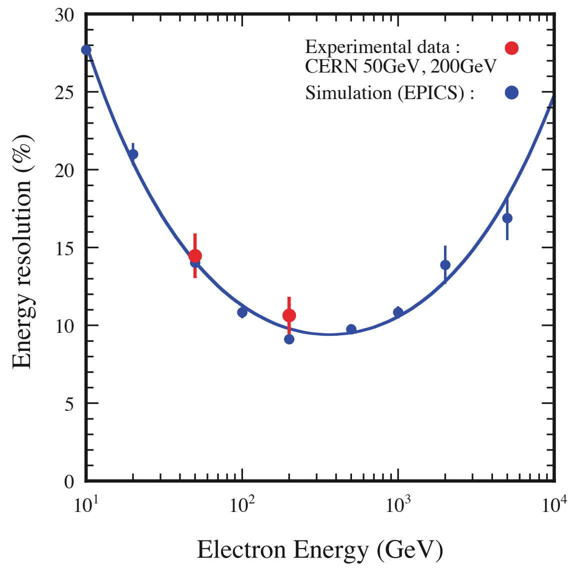


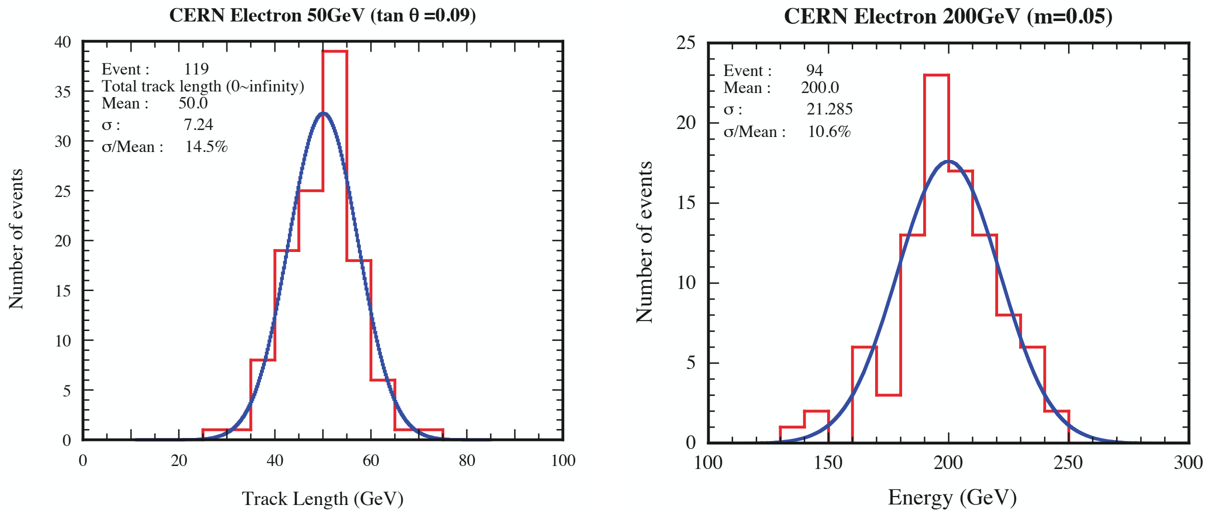
Fig. 3. Energy dependence of energy resolutions with the emulsion chambers for electrons of 50 GeV and 200 GeV, compared to the simulations.

resolution, we can inspect the shower starting points in detail and unambiguously distinguish showers due to electrons, gamma rays, and other hadronic interaction events. By inspecting various specific features of those events, the rejection power for protons misidentified as electron candidates is found to be as large as 10^5 [7].

Electron energies were determined by comparing the number of shower tracks within a circle of 100 μm radius from shower axis at various depths with the theoretical transition curves, and fitting to the integrated track length, used to estimate total ionization in the cascade. As the chamber structure is slightly different for each flight, we calculated the shower development for each emulsion chamber using a Monte-Carlo simulation code Epics [8]. Results calculated using the Epics code were confirmed by emulsion chambers exposed to electron beams of 50 GeV and 200 GeV at CERN-SPS. Figure 2 shows longitudinal developments of the averaged number of shower electrons within a radius of 100 μm with 50 GeV electrons and 200 GeV electrons, compared to the simulated transition curves. Figure 3 shows the energy dependence of energy resolution for electrons of 50 GeV and 200 GeV, compared to the simulations. As shown in these figures, the simulations well represent the experimental data, and the energy resolutions are 15% at 50 GeV and 11% at 200 GeV. Figure 4 shows the energy distribution of the experimental data for 50 GeV and 200 GeV electron beams at CERN-SPS.

B. Measurements of the LPM effect

As an electron enters into the emulsion chamber, a gamma-ray photon is produced by the bremsstrahlung radiation in the lead plates, and then the gamma-ray photon generates an electron and a positron by pair production. As described in the previous subsection, the position of shower tracks can be measured in each emulsion plate with a precision better than 1 μm. By using this unique capability of our detectors, it is possible to measure the position of the first electron-positron pair produced by a gamma ray from bremsstrahlung of an incident electron. Since the depth of the first electron-positron pair of the electron-induced showers directly depends on the cross sections of bremsstrahlung and pair creation in dense and thick targets with lead material of 10% – 30% r.l. thickness, we can measure the effect of LPM suppression from the distribution of the depth of the first electron-positron pair.



(a) 50GeV electrons

(b) 200GeV electrons

Fig. 4. Energy distributions of the experimental data for 50 GeV and 200 GeV electron beams at CERN-SPS.

In the balloon observations, we identify electron events among incoming cosmic rays, determine electron energies, and measure the depth of the first electron-positron pair of the electron-induced showers, so called the shower starting point. Figure 5 presents a shower starting point distribution of the balloon observation in 1996, compared to the Bethe-Heitler prediction and the LPM prediction based on Migdal's formula including the dielectric suppression. We selected electron events with energies above 400 GeV, in which the number of electrons is 25 events. As shown in Fig. 5, although the results of the balloon observations qualitatively indicate that the depths of the first electron-positron pair in the detector are deeper than the Bethe-Heitler prediction and consistent with the LPM prediction, the measurements of the shower staring points with high statistics are required for quantitative verification of the LPM effect.

In order to verify the LPM suppression with high precision, we have carried out the experiment with the emulsion chambers in the H4 beam line of the CERN-SPS by using electron beams of 50 GeV to 250 GeV in 2004 – 2008. We have analyzed the experimental data of 50 GeV and 200 GeV electron beams, and are now analyzing the data of 250 GeV electrons. The structure of emulsion chambers is same as the balloon experiments, and the size is 10 cm × 12 cm, which is smaller than that of the balloon experiments.

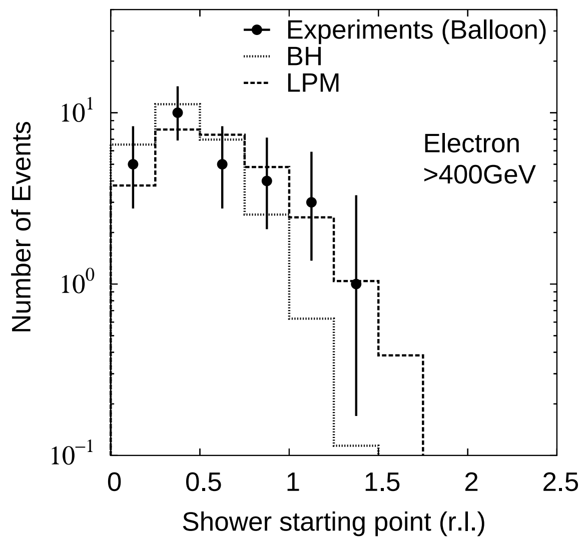
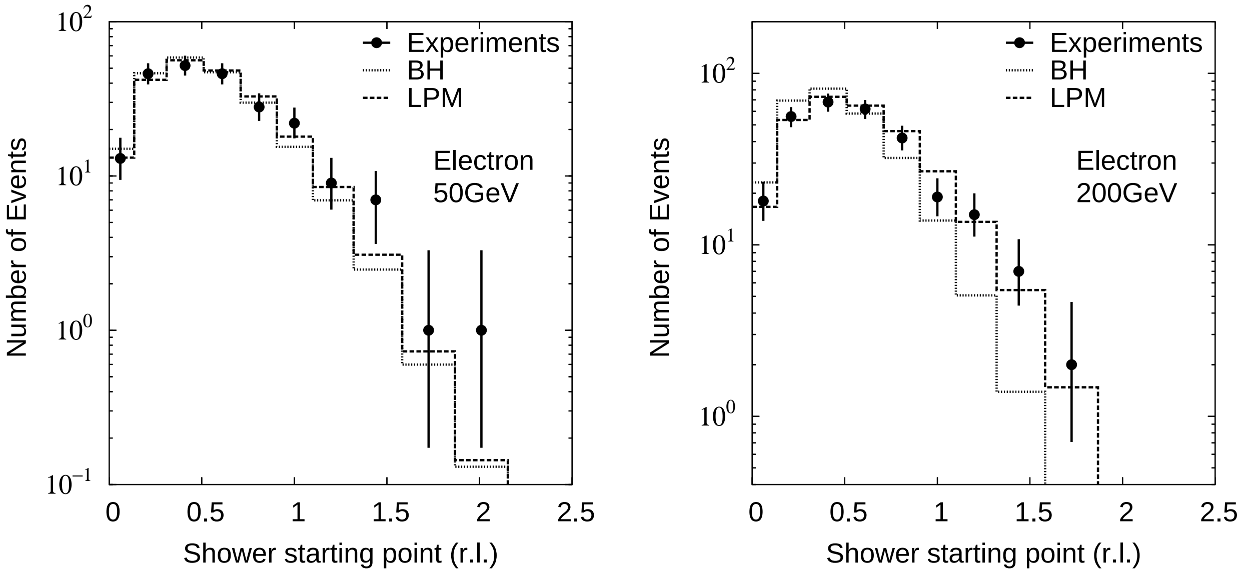


Fig. 5. Shower starting point distribution of electrons above 400 GeV with the balloon observation in 1996, compared to the Bethe-Heitler and LPM prediction. The number of electrons is 25 events.

III. RESULTS AND DISCUSSION

Figure 6 presents shower starting point distributions with electron beams of 50 GeV and 200 GeV at CERN-SPS, compared to the calculations from the Bethe-Heitler cross section and the LPM cross section based on Migdal's formula including the dielectric suppression [2]. The number of electrons is 225 events for 50 GeV electrons and 289 events for 200 GeV electrons. As for 50 GeV electrons, since there are almost no differences between the Bethe-Heitler prediction and the LPM prediction, the shower starting distribution of 50 GeV electrons is well represented by both the cross sections with reduced-χ^2 values of 0.75 for the Bethe-Heitler prediction and 0.51 for the LPM prediction. As for 200 GeV electrons, the difference between the Bethe-Heitler prediction and the LPM prediction becomes more pronounced. The shower starting point of 200 GeV electrons reject the Bethe-Heitler prediction with a reduced-χ^2 value of 3.01 for d.o.f. of 8, which corresponds to a probability of 0.41%, and is in good agreement with



(a) 50 GeV electrons

(b) 200 GeV electrons

Fig. 6. Shower starting point distribution of 50 GeV and 200 GeV electrons, compared to the Bethe-Heitler prediction and the LPM prediction based on Migdal's formula including the dielectric suppression.

the LPM prediction with a reduced-χ^2 value of 0.47. In Table I, we summarize the results of comparison between the experimental data and the calculations with reduced-χ^2 values and the corresponding probabilities.

Since the pair production suppression due to the LPM effect requires gamma rays above several TeV for lead [2], the effect of the pair production suppression is negligible for 50 GeV and 200 GeV electron beams. Our targets are relatively thick lead plates of 10% – 30% r.l., the suppression due to thin targets is practically irrelevant for this experiment. Although the dielectric suppression for bremsstrahlung is included in our calculations, the suppression due to the dielectric effect is much smaller than that of the LPM effect for this experiment. Thus, we can conclude that the major mechanism for this measured suppression is the bremsstrahlung suppression due to the LPM effect.

Since the LPM effect has a valuable role in the development of electromagnetic cascade showers initiated by high-energy electrons in a calorimeter, the study of the LPM effect is important to derive the accurate energy spectrum of cosmic-ray electrons. We are now analyzing the experimental data of 250 GeV electron beams, and will report the result in the near future publication.

TABLE I
COMPARISON BETWEEN EXPERIMENTAL DATA AND CALCULATIONS

Electron Energy	Events Number	d.o.f.	Bethe-Heitler χ^2_ν (Prob.)	LPM χ^2_ν (Prob.)
50 GeV	225	9	0.75 (67%)	0.51 (87%)
200 GeV	289	8	3.01 (0.41%)	0.47 (88%)

IV. ACKNOWLEDGEMENTS

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