# Landau-Pomeranchuk-Migdal Effect on High-Energy Electron Measurements with Emulsion Chambers

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**Abstract:** We have performed high-energy electron observations using balloon-borne emulsion chambers, and derived the cosmic-ray electron spectrum in the energy range from 30 GeV to 3 TeV. For the calibration of the emulsion chambers, we have also carried out beam tests of 50 GeV, 200 GeV, and 250 GeV electrons at CERN-SPS. The Landau-Pomeranchuk-Migdal (LPM) effect predicts the reduction of amplitude for bremsstrahlung photon emission. It affects to the depth of the first electron-positron pair of the electron-induced shower, the so-called shower starting point. In the emulsion chambers, we can measure the shower starting points for high-energy electrons with the position resolution of 1 $\mu$m. From the observations of accelerator-beam electrons of 200 GeV and 250 GeV, and cosmic-ray electrons above 400 GeV, we found the direct evidence of suppression of the bremsstrahlung cross sections due to the LPM effect.

**Keywords:** LPM effect, electron, emulsion chambers, balloon

## 1 Introduction

The interaction cross sections for bremsstrahlung are generally described by the Bethe-Heitler formulas [1]. However, Landau, Pomeranchuk, and Migdal (LPM) predicted that the cross sections are reduced at high energy and in dense media, so called the LPM effect [2, 3]. The LPM effect for bremsstrahlung is the suppression of photon production due to multiple scattering of the electron. If the formation length of the bremsstrahlung becomes comparable to the distance which the multiple scattering becomes important, the probability of bremsstrahlung photon emission is reduced due to the interference of the bremsstrahlung amplitudes from before and after the scattering (e.g. [4, 3]).

Since the LPM effect has a fundamental 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 primary cosmic-ray electrons [5].

Kasahara (1985) [6] studied the behavior of cosmic-ray cascade showers, especially the full width at half maximum (FWHM) of the transition curve in the 100 TeV region observed in lead emulsion chambers, compared with results of a Monte Carlo calculation. By using the assumption that the cascade showers are induced by a single gamma ray or electron, he indicated that 10 showers among 14 cascade showers have the FWHM larger by two standard deviations than the mean FWHM without the LPM effect.

As for accelerator experiments, Anthony *et al.* (1997) [4] conducted their experiments at the Stanford Linear Accelerator Center, which were carried out by using electron beams with thin targets of 0.1 % to several % radiation length (r.l.) and magnets to separate incident electrons from bremsstrahlung gamma rays produced in the targets. They confirmed the LPM and dielectric suppressions from the measurements of 200 keV to 500 MeV gamma rays produced by 8 and 25 GeV electrons.

Hansen *et al.* (2004) [7] presented experimental results for the bremsstrahlung gamma-ray spectra above 2 GeV from 149, 207, 287 GeV electrons in thin Ir, Ta, and Cu targets with the around 4 % r.l. thicknesses. Their experiments were performed at CERN-SPS with the similar setup to Anthony *et al.* [4]. Their measurements showed good agreement with the simulated theoretical gamma-ray spectra based on the LPM theory.

In this work, we have carried out another approach to the LPM effect by using emulsion chambers, in which we use the thick targets of lead and measure the position of the first electron-positron pairs produced by gamma rays from bremsstrahlung of incident electrons. Our measured depths of the first electron-positron pairs directly reflect the suppression of the bremsstrahlung cross section. In this paper, we present quantitative measurements of bremsstrahlung suppression due to the LPM effect with emulsion chambers.

## 2 Experiment

### 2.1 Detector

Emulsion chambers consist of nuclear emulsion plates and lead plates. Nuclear emulsion plates are placed under lead plates. The thickness of one lead plate at the upper layers is 0.5 mm ($\sim$0.09 r.l.) to identify incident parent particles, determine the incident angles, and investigate the initial shower developments. At the bottom layers, the thickness of one lead plate is 5 mm ($\sim$0.9 r.l.) and X-ray films are inserted to detect high-energy cascade showers. The typical size and thickness of the detector are 40 cm $\times$ 50 cm, and $\sim$9 cm ($\sim$9 r.l.), respectively. Detailed configurations are described in Kobayashi *et al.* [5].

#### 2.1.1 Event Identification

Since electron-induced showers start from a single charged track which produces an electron-positron pair, they are identified by the existence of a single and a pair track at the shower starting point. Electron events also give the electro-magnetic shower without core structures. On the other hand, gamma-ray showers start from a pair with no visible primary track above the shower starting point. Since proton-induced showers have many secondaries at the shower starting point and often have multi core structures in the deep layers, proton events are clearly distinguishable from electro-magnetic showers. The proton rejection power is estimated to be larger than $1\times10^5$ [5].

The validity of event identification can be checked by comparison of the measured shower starting points with the expected values. Figure 1 presents the shower starting point distributions of the balloon observations for gamma rays above 300 GeV and protons, compared to the expected distributions. As shown in Fig. 1, the shower starting point distributions within 3.0 r.l. show good agreement with the expectations, whose results suggest the reliability of the particle identification, and the deviation of the proton distribution larger than 3.0 r.l. from the expectation shows the decrease of the proton detection efficiency.

#### 2.1.2 Energy Determination

Electron energies were determined by comparing the number of shower tracks within a circle of 100 $\mu$m 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 structures are slightly different for each flight, we calculated the shower development for each emulsion chamber using Monte-Carlo simulation codes such as Epics [8]. Results calculated using the Monte-Carlo simulation codes were confirmed by emulsion chambers exposed to electron beams of 50 GeV, 200 GeV, and 250 GeV at CERN-SPS. The results of Monte Carlo simulations will be presented in the accompanying paper [9].

#### 2.1.3 Measurements of 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. Since the position of shower tracks can be measured in each emulsion plate with a position resolution of 1 $\mu$m, it is possible to measure the depth of the first electron-positron pair produced by a gamma ray from bremsstrahlung of an incident electron. The depth of the first electron-positron pair of the electron-induced showers directly depends on the cross sections of bremsstrahlung and pair creation. Hence, we can examine the effect of LPM suppression from the measurements of the shower starting points for high-energy electrons.

### 2.2 Beam Tests at CERN-SPS

In order to verify the LPM suppression with high precision, we have carried out the experiments with the emulsion chambers in the H4 beam line of CERN-SPS by using electron beams of 50 GeV and 200 GeV in 2004, and 250 GeV in 2008. The incident directions of electron beams are perpendicular to the surface of emulsion chambers. The structure of emulsion chambers is same as the balloon experiments, and the size is 10 cm $\times$ 12 cm, which is smaller than that of the balloon experiments.

### 2.3 Balloon Observations

We have carried out a series of cosmic-ray electron observations using balloon-borne emulsion chambers from 1968 to 2001, and measured the cosmic-ray electron spectrum in the energy range from 30 GeV to 3 TeV at the top of the atmosphere [5]. Our successive experiments have yielded a total exposure of 8.19 m$^2$-sr-day at altitudes of $4.0-9.4$ g cm$^{-2}$.

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.

## 3 Results

Figure 2 presents shower starting point distributions with electron beams of 50 GeV, 200 GeV, and 250 GeV at CERN-SPS, and cosmic-ray electrons above 400 GeV observed with the balloon-borne emulsion chambers, 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, 289 events for 200 GeV, 363 events for 250 GeV, and 113 events above 400 GeV. 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-$\chi^2$ values of 0.63 for the Bethe-Heitler prediction and 0.42 for the LPM prediction. Above 200 GeV electrons, the difference between the Bethe-Heitler prediction and the LPM prediction becomes more pronounced. The shower starting points of 200 GeV electrons, 250 GeV electrons, and electrons above 400 GeV reject the Bethe-Heitler prediction with reduced-$\chi^2$ values of 2.77, 5.46, and 2.73, respectively. On the contrary, they are well represented by the LPM prediction with reduced-$\chi^2$ values of 0.96, 0.79, and 1.05, respectively. In Table 1, we summarize the results of comparison between the experimental data and the calculations with reduced-$\chi^2$ values and the corresponding probabilities.

## 4 Discussion and Conclusion

In the analysis of the emulsion chambers, the shower electrons within 4 deg from the incident electron are measured. Since electron events start from a single charged track which produces an electron-positron pair within 1 r.l. of the top of the emulsion chamber with about 90 % probability. The mean spreading angle of a parent electron and an electron-positron pair by Coulomb scattering is given by

$$\theta \simeq \frac{1}{\sqrt{3}} \frac{E_s}{E} \left(\frac{x}{X_0}\right)^{1/2},$$

where $E$ is the electron energy, $E_s$ is the scattering constant of $\sim$20 MeV, $x$ is a traversing thickness of the electron in the material, and $X_0$ is a radiation length of the material. In the case of $x = X_0$, that is 1 r.l., the spreading angle of $\theta = 4$ deg corresponds to the electron energy of $E \simeq 2\times10^2$ MeV.

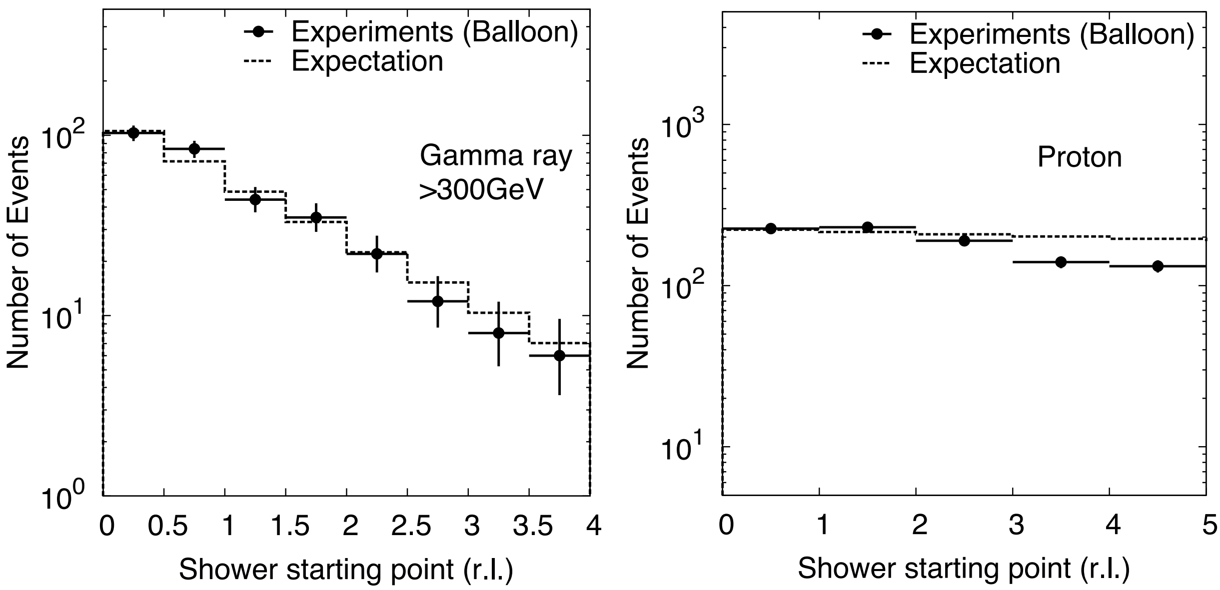


**Fig. 1**: Shower starting point distributions of gamma rays and protons observed with the balloon-borne emulsion chambers, compared to the expected distributions.

**Table 1**: Comparison between experimental data and calculations

| Electron Energy | The number of events | d.o.f. | Bethe-Heitler $\chi^2_\nu$ (Prob.) | LPM $\chi^2_\nu$ (Prob.) |
|---|---|---|---|---|
| 50 GeV | 225 | 9 | 0.63 (77%) | 0.42 (93%) |
| 200 GeV | 289 | 8 | 2.77 (0.50%) | 0.96 (46%) |
| 250 GeV | 363 | 9 | 5.46 ($2\times10^{-5}$%) | 0.79 (63%) |
| $>$ 400 GeV | 113 | 5 | 2.73 (1.8%) | 1.05 (38%) |

The mean square angles between the direction of the incident electron and that of the emitted gamma ray via bremsstrahlung are estimated to be less than $\sim 1\times10^{-2}$ deg in the incident electron energy above 10 GeV [10], which is negligibly small compared to 4 deg. On the other hand, the mean square angles between bremsstrahlung and pair production increase with the decreasing energy of the electron-positron pair. The minimum energy of the produced pair electron (or positron) is 15 MeV at $\theta = 4$ deg [10]. Hence, the minimum energy of the bremsstrahlung gamma ray, which produces an electron-positron pair within 4 deg, is estimated to be 30 MeV for the emulsion chambers.

Although Hansen *et al.* (2004) [7] showed bremsstrahlung gamma-ray spectra for 149 – 287 GeV electrons on targets with $\sim$ 4 % r.l. thicknesses of iridium, tantalum and copper, their measured gamma rays are limited above 2 GeV. We selected the shower electrons within the angle of 4 deg from the direction of the incident electron. Hence, the lower limit of the gamma-ray energies in the measurements of the shower starting points is much lower than 2 GeV.

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 in the electron energies of 50 GeV to several 100 GeV. In addition to the LPM suppression, there is another suppression mechanism, that is dielectric suppression. 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.

From the measurements of the shower starting point, which is another approach different from the previous experiments, we confirmed the bremsstrahlung suppression due to the LPM effect in the electron energies of 200 GeV and 250 GeV. We also found the LPM effect by the measurements in the electron energy above 400 GeV, which is higher than the energy region of the previous accelerator experiments.

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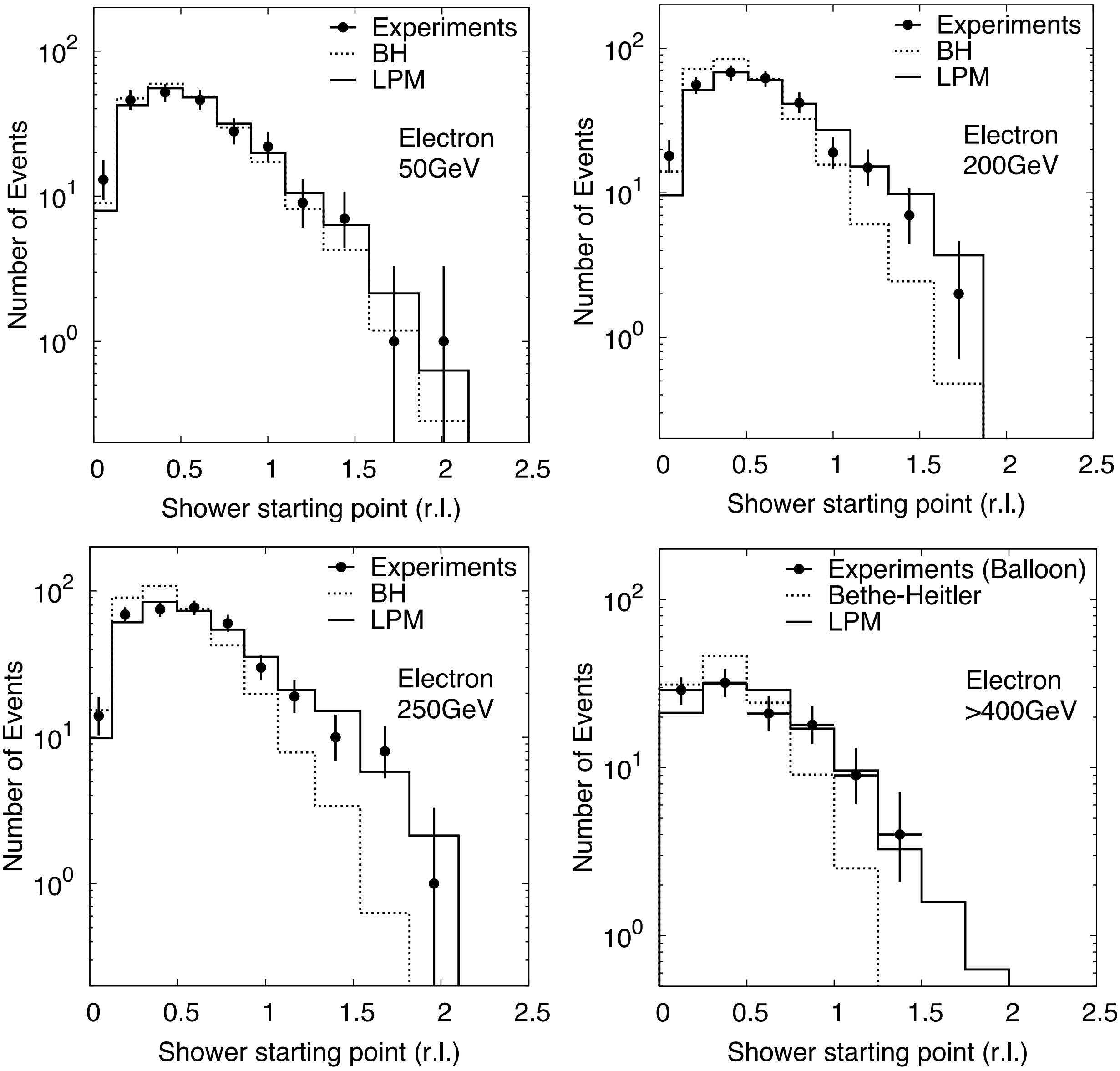


**Fig. 2**: Shower starting point distributions of 50 GeV, 200 GeV, and 250 GeV electrons at CERN-SPS, and electrons above 400 GeV observed with the balloon-borne emulsion chambers, compared to the Bethe-Heitler prediction and the LPM prediction based on Migdal's formula.

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