LPM effect in cosmic-ray electron observations with emulsion chambers

Kenji Yoshida¹, Tadashi Kobayashi², and Jun Nishimura³

¹ Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama 337-8570, Japan
² Aoyama Gakuin University, 5-10-1 Fuchinobe, Chuo, Sagamihara 252-5258, Japan
³ ISAS, JAXA, 3-1-1 Yoshinodai, Chuo, Sagamihara 252-5210, Japan
E-mail: yoshida@shibaura-it.ac.jp

Abstract. We have performed a series of cosmic-ray electron + positron observations using balloon-borne emulsion chambers since 1968, together with electron beam tests at CERN-SPS. In emulsion chamber experiments, we can measure the location of shower tracks in each emulsion plate with a precision of 1 µm. Because of the high position resolution, we can identify the first electron-positron pairs of electron-induced showers. The LPM effect predicts a reduction of amplitude for bremsstrahlung photon emission by a high-energy electron. It causes the optical depth of the first electron-positron pair to increase. From the measurements of the first pair depths with 200 GeV and 250 GeV beam electrons at CERN, and cosmic ray electrons + positrons from 400 GeV to 3 TeV (on average at 900 GeV), we found direct evidence of suppression of the bremsstrahlung cross section due to the LPM effect. In this work, we present the experimental results compared to analytic approximations and Monte-Carlo simulations.

1. Introduction

Landau, Pomeranchuk, and Migdal (LPM) predicted that the interaction cross sections of bremsstrahlung and pair creation by the Bethe-Heitler formulas [1] are suppressed at high energy and in dense media [2, 3, e.g.]. The LPM effect for bremsstrahlung is the suppression of photon production due to multiple scattering of the electron. In multiple scattering of an electron while traversing the formation zone, the probability of bremsstrahlung photon emission is reduced due to the interference of the bremsstrahlung amplitudes from before and after the scattering [3, e.g.]. A similar suppression of the cross section occurs for pair creation.

The existence of the LPM effects affects high energy phenomena involving electro-magnetic showers in thick targets with bremsstrahlung radiation and pair creation when the energy of the incident electron is in high enough on transversing material. If the LPM effect does exist, the phenomena involving such processes would look very different from those without such an effect. Therefore, it is important to verify the LPM effect in high energy region. Since the LPM effect will cause the elongation of high-energy electromagnetic showers with large fluctuations of the number of shower particles. In fact, Konishi et al. (1991) demonstrated that such behaviors are observed in their Monte-Carlo simulations [4].

Below a few TeV region, although the reduction of the pair creation cross section due to the LPM effect is expected to be negligible small, the LPM effect of the bremsstrahlung radiation is expected to be significantly appeared. So far, the experimental verification of the LPM effect have been achieved only by few accelerator experiments, which measure bremsstrahlung gamma
rays from electron beams of 8 GeV − 290 GeV traversing thin targets of several % r.l. [5, 6]. In this paper, we present the results of the verification of the LPM effect with emulsion chambers by using electron beams of 50 GeV, 200 GeV and 250 GeV, and cosmic ray electrons of 400 GeV to 3 TeV that is 900 GeV on average. We confirmed that the experimental results were consistent with the expected results from the LPM effect by means of analytical calculations and Monte-Carlo simulations.

2. Cosmic ray electron observations

We have carried out fourteen balloon flights from 1968 to 2001 for cosmic ray all-electron (electrons + positrons) observations with emulsion chambers. The geometrical factor is \( S\Omega_eT = 8.19 \, \text{m}^2 \, \text{sr} \) day and the total exposure is 11.8 day. Figure 1 shows the cosmic ray all-electron spectrum from 30 GeV to 3 TeV observed with emulsion chambers [7], compared to our SNR model [8]. In Fig. 1, the recent electron + positron spectra observed with H.E.S.S. on the ground [9, 10] and AMS-02, Fermi-LAT, DAMPE, and CALET in space are also plotted [11, 12, 13, 14]. Our all-electron spectrum is in good agreement with the recent spectra from the experiments in space.

In addition to the balloon observations, we have performed accelerator beam tests at CERN-SPS with electron beams of 50 GeV, 200 GeV and 250 GeV.

3. Verification of the LPM effect

3.1. Emulsion chambers

Emulsion chambers consist of nuclear emulsion plates, X-ray films, and lead plates, which are stacked alternately. The typical size and thickness are 40 cm × 50 cm and about 9 cm (~9 r.l.),
respectively. A left panel of Fig. 2 shows a schematic side view of emulsion chambers. In emulsion chambers, it is possible to measure the location of shower tracks in each emulsion plate with a precision of 1 \( \mu \)m. The high position resolution enables us to inspect the shower starting points in detail, which are used for identification of electrons, gamma rays, and other hadronic interaction events.

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 calculated transition curves, and fitting to the integrated track length, used to estimate total ionization in the cascade [15].

3.2. Measurements of the first electron-positron pairs
An incident electron generates gamma-ray photons through bremsstrahlung radiation, and these gamma rays generate electron-positron pairs in emulsion chambers. Because of the high position resolution, we can identify the location of the first electron-positron pair that is produced by a gamma ray from bremsstrahlung of an incident electron. A right panel of Fig. 2 shows the conceptual diagram of the first pair creation in emulsion chambers. The first pair depths directly depend on the cross sections of bremsstrahlung and pair creation. Since the LPM effect predicts the suppression of the Bethe-Heitler cross section, the first pair depths are expected to become deeper than that of the Bethe-Heitler cross section. We derived the distributions of the first electron-positron pair depths from the electron beam tests at CERN-SPS and the electron observations with balloon-borne emulsion chambers.

3.3. Calculations of the first electron-positron pairs
Monte-Carlo simulations can represent the distributions of the first electron-positron depths in emulsion chambers, which have the complicated structure of nuclear emulsion plates, X-ray films, and lead plates. We derived the distributions of the first electron-positron pair depths by using two completely different Monte-Carlo simulation codes of Epics [16] and Geant4 [17, 18]. All essential cross sections of the electromagnetic processes are implemented in Epics and Geant4, respectively.

In addition to the Monte-Carlo simulations, we derived analytic approximations of the distributions of the first pair depths. Not only do the analytic approximations allow a good
4. Results

We compared the experimental distributions of the first pair depths with the calculations. Figure 3, 4, 5 and 6 present the first pair depth distributions with electrons of 50 GeV, 200 GeV, and 250 GeV at CERN-SPS, and cosmic-ray electrons + positrons from 400 GeV to 3 TeV, which is 900 GeV on average, compared to the calculations with the analytic approximations, Epics, and Geant4 Monte-Carlo simulations. In Table 1 the comparisons among the experimental and calculated results are summarized with reduced-$\chi^2$ values. As for 50 GeV electrons, since there are almost no differences between the Bethe-Heitler predictions and the LPM predictions, the first pair depth distribution of 50 GeV electrons is well represented by both the cross sections. Above 200 GeV electrons, the differences between the Bethe-Heitler predictions and the LPM predictions become more pronounced. As shown in Fig. 4, 5, 6, and Table 1, the first pair depth distributions of 200 GeV electrons, 250 GeV electrons, and electrons from 400 GeV to 3 TeV reject the Bethe-Heitler cross sections for the all calculations. On the contrary, they are well represented by the LPM predictions for the all calculations.

5. Conclusions

For the verification of the LPM effect, we applied the different approach from the previous accelerator experiments [5, 6]. By using the first pair measurements with emulsion chambers, we found direct evidence of the LPM effect in 200 GeV, 250 GeV, and 400 GeV−3 TeV (on average at 900 GeV) electrons. This verification of the LPM effect up to 3 TeV is the highest energies so far.

| Table 1. Summary of comparisons between the experimental and calculated results |
|-----------------------------------------------|
|                                | Analytic | $\chi^2$ (Prob.) | Geant4 |
|-----------------------------------------------|
| 50 GeV (225 events, 9 d.o.f.)     |          |        |        |
| BH                              | 0.746 (66.7%) | 0.694 (71.5%) | 0.551 (83.8%) |
| LPM                             | 0.513 (86.7%) | 0.319 (96.9%) | 0.371 (94.9%) |
| 200 GeV (289 events, 8 d.o.f.)    |          |        |        |
| BH                              | 3.015 (2.2%)  | 2.051 (3.7%)  | 1.814 (6.9%)  |
| LPM                             | 0.467 (88.0%) | 0.801 (60.1%) | 1.422 (18.1%) |
| 250 GeV (363 events, 9 d.o.f.)    |          |        |        |
| BH                              | 5.46 (2×10^{-5}) | 4.56 (5×10^{-4}) | 4.46 (7×10^{-4}) |
| LPM                             | 0.791 (62.5%) | 0.655 (75.0%) | 0.932 (49.5%) |
| 400 GeV−3 TeV (113 events, 5 d.o.f.) |          |        |        |
| BH                              | 3.550 (0.33%) | 2.591 (2.4%)  | 2.325 (4.0%)  |
| LPM                             | 0.870 (48.9%) | 1.676 (13.6%) | 2.103 (6.2%)  |
Figure 3. First pair depth distributions of 50 GeV electrons at CERN-SPS, compared to calculations of the Bethe-Heitler cross section (left) and the LPM effect (right). The calculations are carried out with the analytic approximations, Epics and Geant4.

Figure 4. First pair depth distributions of 200 GeV electrons at CERN-SPS, compared to calculations of the Bethe-Heitler cross section (left) and the LPM effect (right).

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References
[1] Tsai Y S 1974 Rev. Mod. Phys. 46 815
[2] Klein S 1999 Rev. Mod. Phys. 71 1501
[3] Baier V N & Katkov V M 2005 Phys. Rep. 409 261
[4] Konishi E, Adachi A, Takahashi N, and Misaki A 1991 J. Phys. G: Nucl. Part. Phys. 17 719
[5] Anthony P et al. 1997 Phys. Rev. D 56 1373
[6] Hansen H et al. 2004 Phys. Rev. D 60 032001
Figure 5. First pair depth distributions of 250 GeV electrons at CERN-SPS, compared to calculations of the Bethe-Heitler cross section (left) and the LPM effect (right).

Figure 6. First pair depth distributions of all cosmic ray electrons from 400 GeV to 3 TeV (on average at 900 GeV), compared to calculations of the Bethe-Heitler cross section (left) and the LPM effect (right).

[7] Kobayashi T et al. 2012 Astrophys. J. 760 146
[8] Kobayashi T et al. 2004 Astrophys. J. 601 340
[9] Aharonian F et al. 2008 Phys. Rev. Lett. 101 261104
[10] Aharonian F et al. 2009 Astron. Astrophys. 508 561
[11] Aguilar S et al. 2014 Phys. Rev. Lett. 113 221102
[12] Abdollahi S et al. 2017 Phys. Rev. D 95 082007
[13] Ambrosi G et al. 2017 Nature (London) 552 63
[14] Adriani O et al. 2018 Phys. Rev. Lett. 120 261102
[15] Nishimura J et al. 1980 Astrophys. J. 238 394
[16] Kasahara K 2018 http://cosmos.n.kanagawa-u.ac.jp/EPICSHome/index.html
[17] Agostinelli S et al. 2003 Nucl. Instrum. Methods Phys. Res. A 506 250
[18] Allison J et al. IEEE Trans. Nucl. Sci. 53 270