LPM effect in cosmic-ray electron observations with emulsion chambers

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Introduction

* Bremsstrahlung and pair production:
  * Two of the most important high-energy electromagnetic processes
  * Generally described by Bethe-Heitler (BH) cross sections

* Landau-Pomeranchuk-Migdal (LPM) Effect:
  * Reduction of the interaction cross sections at high energy and in dense media due to multiple scattering
Below a few TeV, reduction of the interaction cross section due to the LPM effect is significantly appeared in bremsstrahlung radiation.
Few tests of the LPM effect

Measurements of bremsstrahlung gamma rays from electron beams of 8GeV — 290GeV traversing thin targets of several % r.l. (Anthony et al. 1997, Hansen et al. 2004)

Example:
Bremsstrahlung gamma ray spectrum from 207GeV electrons on 4% r.l. Ir
Cosmic Ray Electron observations with balloon-borne emulsion chambers

* 14 balloon flights (1968-2001)
* $S\Omega_e T = 8.19 \text{m}^2 \text{sr} \text{day}$ (Total exposures = 11.8 day)

Cosmic Ray Electron Spectrum from 30GeV to 3TeV observed with Emulsion Chambers

(T.Kobayashi et al. 2012)

In addition, electron beam tests at CERN-SPS
Tests of the LPM effect with emulsion chambers

- Electrons measured with emulsion chambers
- Electrons from beam tests at CERN-SPS
- Cosmic-ray electrons up to 3TeV

Our test of the LPM effect
- A different approach from the previous accelerator tests
- Higher energies by using cosmic-ray electrons
Emulsion Chambers (ECC)

- Consisting of nuclear emulsion plates and lead plates, which are stacked alternately
- Typical size: 40cm x 50 cm
- Typical thickness: ~9r.l. (~9cm)

- Measurement of the position of shower tracks with a precision of 1um
  - Inspection of the shower starting points in detail
  - Distinguishing electrons, gamma rays, and other hadronic interaction events
Measurements of the first pairs in ECC

Electron tracks with a position resolution of 1um

Measurements of the first electron pairs

LPM cross section: smaller than Bethe-Heitler cross section

=> The first pairs become deeper than Bethe-Heitler prediction
Analytic calculation of the First Pair distribution

1 gamma ray
\[ e \rightarrow g \]
\[ g + g \]
\[ + \ldots \]

= Probability density of the first electron pair

\[ P(t) = ge^{-gt}(1 - e^{-\sigma t})e^{\frac{g}{\sigma}(1-e^{-\sigma t})} \]

In the case of \( \sigma \) and \( g \), they are constant.

\( g \): Bremsstrahlung gamma-ray emission rate per r.l.
\( \sigma \): Pair creation rate per r.l.
First pair calculations including:

- Effect of complete screening and electron straggling
- Bethe-Heitler or LPM effect

![First Pair Density](chart.png)

- Preliminary first pair distributions
- Electron 100 GeV
- \( P(t) \)
Comparison of the first pair experimental distributions with the calculations

- Experiments
  - Electron beam tests at CERN-SPS
    - 200GeV, 250GeV
  - Cosmic ray electron observations
    - 400GeV — 3TeV (900GeV on average)

- Calculations
  - Analytic calculations with BH and LPM (Preliminary)
  - M.C. simulations with BH and LPM: Geant4, Epics
First pair distributions: Electron 200GeV

Calculation: BH

Calculation: LPM

The number of events = 289, d.o.f. = 8

<table>
<thead>
<tr>
<th></th>
<th>Analytic</th>
<th>$\chi^2_N$ (Prob.)</th>
<th>Geant4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH</td>
<td>3.015 (2.2%)</td>
<td>2.051 (3.7%)</td>
<td>1.814 (6.9%)</td>
</tr>
<tr>
<td>LPM</td>
<td>0.467 (88.0%)</td>
<td>0.801 (60.1%)</td>
<td>1.422 (18.1%)</td>
</tr>
</tbody>
</table>

BH: Rejected
LPM: Accepted
First pair distributions: Electron 250GeV

Calculation: BH

Calculation: LPM

The number of events = 363, d.o.f. = 9

<table>
<thead>
<tr>
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<th>Probs.</th>
<th>Epics</th>
<th>Geant4</th>
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</thead>
<tbody>
<tr>
<td>BH</td>
<td>5.456 (2 \times 10^{-5}%)</td>
<td>4.564 (5 \times 10^{-4}%)</td>
<td>4.462 (7 \times 10^{-4}%)</td>
<td></td>
</tr>
<tr>
<td>LPM</td>
<td>0.791 (62.5%)</td>
<td>0.655 (75.0%)</td>
<td>0.932 (49.5%)</td>
<td></td>
</tr>
</tbody>
</table>

BH: Rejected, LPM: Accepted
First pair distributions: Electron 400GeV-3TeV

Calculation: BH

Electron 400GeV-3TeV

900GeV on average

Calculation: LPM

The number of events = 113, d.o.f. = 5

<table>
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<tr>
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<th>Analytic $\chi^2$</th>
<th>Epics $\chi^2$ (Prob.)</th>
<th>Geant4 $\chi^2$</th>
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<tbody>
<tr>
<td>BH</td>
<td>3.550 (0.33%)</td>
<td>2.591 (2.4%)</td>
<td>2.325 (4.0%)</td>
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<tr>
<td>LPM</td>
<td>0.870 (48.9%)</td>
<td>1.676 (13.6%)</td>
<td>2.103 (6.2%)</td>
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BH: Rejected
LPM: Accepted
Summary

* By using the first pair measurements, we found the direct evidence of the LPM effect in 200GeV, 250GeV, and 400GeV–3TeV (900GeV on average) electrons.

* An another approach different from the previous experiments for verification of the LPM effect

* Verification up to 3TeV => the highest energies so far
Back up
Determination of Electron Energies

* By using the longitudinal development of the number of shower electrons =>
  Track lengths => Electron energies

Transition curve

Energy resolution

17
First pair distributions: Electron 50GeV

The number of events = 225, d.o.f. = 9

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<th>Geant4</th>
</tr>
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<tbody>
<tr>
<td>BH</td>
<td>0.746 (66.7%)</td>
<td>0.694 (71.5%)</td>
<td>0.551 (83.8%)</td>
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<tr>
<td>LPM</td>
<td>0.513 (86.7%)</td>
<td>0.319 (96.9%)</td>
<td>0.371 (94.9%)</td>
<td></td>
</tr>
</tbody>
</table>

BH: Accepted
LPM: Accepted
First Pair Distributions

Gamma rays

Protons

- Experiments (Balloon)
- Expectation

Gamma ray >300GeV

Number of Events

Shower starting point (r.l.)