The LPM Effect: Comparing SLAC E-146 Data with Experiment

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The suppression of photon bremsstrahlung due to a variety of in-medium effects is discussed. Different electrodynamic suppression effects are discussed, and compared with the related color analogs. Higher order effects are considered, and found to be important. Data from SLAC E-146 is discussed, and compared with theory. The effect of finite thickness targets is emphasized, since nuclear size is such an important limiting factor for the chromodynamics effects.

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1 Introduction

Originally, the LPM effect referred to the suppression of electron bremsstrahlung or pair production due to multiple scattering. More recently, it has been applied to the effects of the nuclear medium on quark and gluon interactions. This subject is of interest because calculations predict that quark or gluons should radiate increased energy in traversing a quark gluon plasma, compared to normal nuclear matter.

This talk will consider the electrodynamic version of the LPM effect. I will discuss recent experimental results from SLAC E-146, and compare these results with theory. This might seem like an odd choice for a conference devoted to quantum chromodynamics. However, electrodynamics can be an important point of comparison for the chromodynamics calculations. For electrodynamics, it is possible to identify a variety of different kinematic regimes, with significantly different photon spectral indices. And, the electrodynamics calculations can be tested experimentally, over a broad range of target thicknesses.

2 Suppression Mechanisms

The LPM effect stems from the formation length, the distance over which an interaction such as pair production or bremsstrahlung occurs. For bremsstrahlung
from an isolated atom, this distance is

\[ l_f = \frac{2\hbar E(E - k)}{m^2 k} \]  

where \( E \) is the incoming electron energy, \( k \) is the photon energy and \( m \) the electron mass. This distance can be very long; for a 25 GeV electron emitting a 1 MeV photon, \( l_f = 1 \text{ mm} \). Classically, if the electron is disturbed while traversing this distance, then the emission can be disturbed. In field theoretical language, other interactions within \( l_f \) can interfere with the bremsstrahlung, reducing its amplitude. In dense media, the Bethe-Heitler \( 1/k \) bremsstrahlung photon spectrum is suppressed by a factor \( S \):

\[ S = \frac{\sigma}{\sigma_{BH}} = \sqrt{\frac{kE_{LPM}}{E(E - k)}} \]  

where \( E_{LPM} = \frac{m^4 X_0}{E_s^2} \) where \( X_0 \) is the radiation length of the material, and \( E_s = m\sqrt{4\pi/\alpha} \).

In 1956, Migdal used the Boltzmann transport equation to model multiple scattering, calculating the emission for each path. He used a simple model for the potential, and found results good to logarithmic accuracy.

One limitation of Migdals result is that neglected surface effects, which are important for targets of finite thickness. This is important for QCD, where the target size is limited to a nuclear diameter. Gol’dman and Ternovskii extended Migdals calculation to include finite thickness targets. In the limit \( T \ll l_f \), the Bethe-Heitler \( 1/k \) spectrum is recovered, albeit at a reduced intensity, proportional to \( \ln T \). Since E-146, there have been several new calculations; since several of the authors are speaking here, I will not further discuss them further.

One interesting aspect of the QED is that it allows for a variety of different suppression mechanisms. In dielectric suppression, the produced photon interacts with the electrons in the medium. This bulk interaction, mediated by forward Compton scattering, is best expressed in terms of the dielectric constant of the medium, \( \epsilon(k) = 1 - (\hbar\omega_p)^2/k^2 \), where \( \omega_p \) is the plasma frequency. This interaction gives the photon an effective mass \( \omega_p c^2 \), which shortens the formation length, and produces a suppression that scales as \( k^2 \):

\[ S = \frac{k^2}{k^2 + (\gamma\hbar\omega_p)^2} \]  

where \( \gamma = E/m \). A similar effect can occur when a radiated gluon undergoes further interactions. Although these interactions are included in current
calculations, the specific effects of these diagrams have not been considered separately.

Another mechanism occurs when the $l_f$ is longer than the radiation length. Then, the nascent photon can interact before it is fully created. This limits $l_f$ to $X_0$, suppressing photon emission. Similarly, bremsstrahlung can also suppress pair production when a produced lepton radiates a photon in the formation zone. For electrodynamics, this effect only occurs at extremely high energies. For QCD however, the interaction length inside a nucleus can be smaller than $l_f$, so multiple interactions in a single formation length are likely. This higher order effect is not considered in current calculations. Unfortunately, this ‘correction’ is likely to be very large, and numerical predictions of quark $dE/dx$ in nuclear media should be used with great caution. This problem will greatly complicate the interpretation of energy loss measurements planned for RHIC.

Suppression can also occur when bremsstrahlung or pair production occurs in an external magnetic field. In the absence of a bulk color magnetic field, this effect is unlikely to be important in QCD. These different suppression mechanisms are summarized in Table 1.

### Table 1: Bremsstrahlung photon spectral indices.

| Region        | Dominant Mechanism     | Photon Spectrum | Importance in QCD |
|---------------|------------------------|-----------------|-------------------|
| none          | -                      | $k^{-1}$        | ?                 |
| LPM Pair      | Multiple Scattering    | $k^{-1/2}$      | yes               |
| Production    | Pair Production        | $k^0$           | very              |
| Dielectric    | Compton Scattering     | $k$             | ?                 |
| Magnetic      | Magnetic Field         | $k^{-1/3}$      | no                |

3 E-146 Data and Analysis

The SLAC E-146 collaboration has studied LPM and dielectric suppression by observing 200 keV to 500 MeV photons produced by 8 and 25 GeV electrons passing through a variety of targets. For most materials, two different thickness targets were studied. Since the experiment is well described elsewhere, here I will focus on the data and its implications for theory. The photon flux is histogrammed in logarithmic bins in $k$, $1/X_0 dN/d \log k$. This binning allowed the histograms to cover many orders of magnitude in $k$. It also flattened out the $1/k$ Bethe-Heitler spectrum.

Figures 1-3 show the E-146 data for carbon, uranium and thin gold targets. These targets cover a wide range in density, and also in $l_f/T$. Figure 1
Figure 1: Data from SLAC-E-146 compared with MC predictions for 200 keV to 500 MeV photons from 8 and 25 GeV electrons passing through 2% and 6% $X_0$ carbon targets. The cross sections are given as $dN/d(\log k)/X_0$ where $N$ is the number of events per photon energy bin per incident electron, for (a) 2% $X_0$ carbon and (b) 6% $X_0$ carbon targets in 25 GeV electron beams, while (c) shows the 2% $X_0$ carbon and (d) the 6% $X_0$ carbon target in an 8 GeV beam. Three Monte Carlo curves are shown. The solid line includes LPM and dielectric suppression of bremsstrahlung, plus conventional transition radiation. Also shown are the Bethe-Heitler plus transition radiation MC (dashed line) and LPM suppression only plus transition radiation (dotted line). Adapted from Anthony et al. (1997).
compares the carbon \((T \gg l_f)\) data with predictions based on Bethe-Heitler, LPM suppression only, and LPM plus dielectric suppression; both mechanisms are clearly required to match the data. However, the 25 GeV data shows a significant disagreement in the region \(k \approx E^2/E_{LPM}\). Figure 2 shows uranium data, compared with curves based on LPM plus dielectric suppression. The data and theory agree for \(k > 10\) MeV, but the data rises above the theory for \(k < 10\) MeV. The difference can be attributed to the small thickness of the targets. For these target thicknesses, when \(k < 10\) MeV, \(T \approx l_f\), so surface effects are likely to be important. Several early calculations of the surface effects, shown in the figure, fail to reproduce the data. Newer calculations do appear to reproduce the surface terms, but are not easily comparable with data because they do not localize the emission, and hence cannot be easily included in a simulation.

Figure 3 shows the E-146 data for electrons passing through a 0.7 \(X_0\) (23 \(\mu\)m) thick gold target. Here, \(l_f > T\) for \(k < 7\) MeV. In this regime, the target interacts as a coherent whole, and the Bethe-Heitler \(1/k\) spectrum is recovered, albeit at a reduced intensity. This flattening is also predicted by newer calculations, such as those by Blankenbecler and Drell. In this case, the target is thin enough that multiple interactions by a single electron are unlikely, and so the calculation can be directly compared with the data.

The systematic error for these measurements are small, ranging from 3.3\% at the higher photon energies, up to 17\% for \(k < 5\) MeV in a 25 GeV beam. The systematic errors are smaller than the discrepancy between the carbon data and theory.

4 Conclusions

I have discussed several mechanisms which can suppress electron bremsstrahlung. Different mechanisms are important in different kinematic regions. At current accelerators, for electrodynamics, suppression due to multiple scattering is the most important, followed by dielectric suppression.

At much higher electron energies, pair production can suppress bremsstrahlung in the regime \(l_f > X_0\). In this regime, in fact, the concept of individual interactions in an electromagnetic shower break down, leaving an (so far) unsolvable complex Feynman diagram containing multiple steps in a shower. For colored interactions in dense media, \(X_0\) is much smaller, and these higher order diagrams are likely to be very important, even at near-future colliders.

The accuracy of the electrodynamics calculations is shown by data from SLAC E-146. The data generally matches the theory to within 10\%. The one
Figure 2: SLAC E-146 data and Monte Carlo for 3% $X_0$ and 5% $X_0$ uranium targets in 8 and 25 GeV electron beams. The solid line shows the LPM and dielectric suppression, conventional transition radiation Monte Carlo prediction. The other lines include simulations based on calculations of transition radiation due to Pafomov (dashed line) and Ternovskii (dotted line). Adapted from Anthony et al. (1997).
exception to this is with the light (low $Z$) targets, where the data is somewhat below the theory around $k = E(E−k)/E_{LP}$). The reason for this is unknown, but may stem from an inadequate treatment of atomic effects.

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