High Energy $\delta - ray$ Production by Muons in the BABAR Detector

David N. Brown[a,], Brian Chan[a], Tom-Eric Haugen[a]

[a] *Lawrence Berkeley National Lab*

Abstract

In this note we present a measurement of the $\delta - ray$ production cross section by muons in the BABAR detector [1], for $\delta - rays$ between 50 and 300 MeV. The BABAR experiment recorded over 500M $e^+e^- \rightarrow \mu^+\mu^-$ events near the upsilon resonances over its 7 year run, producing over 1G muons with a lab frame energies between 3 and 9 GeV. These muons produced $\delta - rays$ when traversing the beampipe and other material in the BaBar inner tracker region. We identify $\delta - ray$ candidates by associating a reconstructed low-momentum negatively charged track with a nearby reconstructed high-momentum track in events consistent with the $e^+e^- \rightarrow \mu^+\mu^-$ process, where the two tracks point of closest approach (POCA) is consistent with a known piece of dense material. A detailed simulation predicts the primary $\delta - ray$ background comes from electrons produced in the conversion of photons radiated by the muons, which we measure by applying the same reconstruction algorithm to positively charged tracks. Monte Carlo simulation is used to estimate the remaining backgrounds, which are estimated to be less than 1% of the predicted signal. Simulation is also used to estimate the reconstruction efficiency, the $\delta - ray$ energy resolution, and to predict the mis-identification of the radiator material. We extract a cross-section by normalizing the corrected production rate to the estimated material traversed by the associated reconstructed muon candidate track, as a function of the reconstructed electron candidate track energy. The cross-section errors are dominated by uncertainty in the radiator material mass, which is roughly 5% and coherent across the energy points measured. The resulting cross-section

Preprint submitted to Nucl. Instr. Methods Phys. Res., Sect. A *February 2, 2017*

is found to be consistent with theoretical predictions within errors.

Keywords: Material Interactions

---

1. Introduction

Atomic electrons ejected by high-energy charged particles passing through matter ($\delta-rays$) can be a background for experiments using electrons as signals. An example is the $\mu \rightarrow e$ experiment [2], which will search for muon to electron conversion in the field of an aluminum nucleus. In that experiment the signal signature is the observation of an isolated 105 MeV electron. Simulations of the $\mu \rightarrow e$ experiment based on the Geant [3] Monte Carlo indicate $\delta - rays$ produced by cosmic ray muons mimic the signal process at a rate many times the experimental sensitivity goal, motivating the need for an active cosmic ray veto. Validating the $\mu \rightarrow e$ experiment design and estimating the resulting experimental sensitivity thus depends crucially on understanding the $\delta - ray$ production cross section.

A quantitative theoretical explanation of $\delta - ray$ production was derived in the 1930s from quantum electrodynamics [4], and is incorporated in the $\delta - ray$ production model used by the Geant Monte Carlo [3]. This theory and has been shown to agree with measurements for low energy (< 1 MeV) electrons [5], however it has not been verified experimentally for $\delta - rays$ in the energy range relevant to the $\mu \rightarrow e$ experiment.

2. The *BaBar* Detector and Data Sample

The *BaBar* experiment operated for 7 years at the PEP-IIcollider at SLAC [6]. This provided approximately ** accumulated luminosity at the $\Upsilon(4S)$. Additional off-resonance samples and samples at other Υ resonances were recorded but not used in this analysis. The process $e^+e^- \rightarrow \mu^+\mu^-$ produced a sample of over 10^9 muons between roughly 3 and 9 GeV.

The *BaBar* detector was designed to record the results of *epem* collisions at a center of mass energy near the Upsilon resonances. The *BaBar* beampipe, Silicon Vertex Tracker (SVT) layers , Carbon fiber Support Tube (CST), and Drift Chamber (DCH) inner wall each presented a few % of a radiation length of thin material to normal incident muons, providing radiators for $\delta - ray$ production. A detailed description of the material composition of these structures is given in table **??**, while more general information about the *BaBar* detector can be found in [1].

Charged particles in *BaBar* produced signals in the SVT and DCH, which were reconstructed as tracks using standard pattern recognition algorithms. High transverse momentum ($p_t > 100MeV/c$) were identified primarily in the DCH, while low transverse momentum tracks were found primarily in the SVT. Tracks identified in the DCH (SVT) were extrapolated into the SVT (DCH) to produce complete tracks. Final tracks were fit with a Kalman filter that compensated for the effects of the energy lost in traversed materials and the inhomogeneous *BaBar* magnetic field. Electrons with transverse momentum above 50 MeV/c (100 MeV/c) from the e^+e^- interaction point were reconstructed with > 50efficiency by the SVT (DCH), respectively. Details of the *BaBar* track reconstruction algorithms and its performance can be found in [7].

3. Monte Carlo Simulation

To simulate the $e^+e^- \to \mu^+\mu^-$ process we use the *KK2F* [8] generator, which includes the effects of initial and final state radiation (*** more is needed here). The initial electron and positron 4-momenta are selected randomly according to the distributions observed in the *BaBar* $\Upsilon(4S)$ runs, as described in **??**. Figure **??** plots the lab-frame energy of muons from $e^+e^- \to \mu^+\mu^-$ predicted by the kk2f generator. Only events in which both muons are produced in the active tracking volume are included. Overlaid on figure **??** is the expected momentum spectrum of cosmic ray muons that generate signals in the $\mu \to e$ tracker, as predicted by the Daya Bay experiment (need a real reference here**) [9] generator and the $\mu \to e$ simulation [2]. A reasonable overlap is seen.

The interaction of particles with the *BaBar* detector is simulated using a detailed model built using the Geant4 toolkit [3]. Detector components are modeled assuming the ideal (design) geometry with sim

4. The *BaBar* Detector and Data Sample

The *BaBar* experiment operated for 7 years at the SLAC B factory, which provided approximately ** accumulated luminosity at the $\Upsilon(4S)$. Additional off-resonance samples and samples at other Upsilon resonances were recorded but not used in this analysis. The process $e^+e^- \to \mu^+\mu^-$ produced a sample of over 10^9 muons between roughly 3 and 9 GeV.

The *BaBar* detector was designed to record the results of *epem* collisions at a center of mass energy near the Upsilon resonances [babar]. The *BaBar* beampipe, *Silicon Vertex Tracker* (SVT) layers , *Carbon Fiber Support Tube* (CST), and *Drift Chamber* (DCH) inner wall each presented a few % of a radiation length of thin material to normal incident muons, providing radiators for $\delta - ray$ production. A detailed description of the material composition of these structures is given in table **??**, while more general information about the *BaBar* detector can be found in [1].

Charged particles in *BaBar* produced signals in the SVT and DCH, which were reconstructed as tracks using standard pattern recognition algorithms. High transverse momentum ($p_t > 100MeV/c$) were identified primarily in the DCH, while low transverse momentum tracks were found primarily in the SVT. Tracks identified in the DCH (SVT) were extrapolated into the SVT (DCH) to produce complete tracks. Final tracks were fit with a Kalman filter that compensated for the effects of the energy lost in traversed materials and the inhomogeneous *BaBar* magnetic field. Electrons with transverse momentum above 50 MeV/c (100 MeV/c) from the *epem* interaction point were reconstructed with > 50efficiency by the SVT (DCH), respectively. Details of the *BaBar* track reconstruction algorithms and its performance can be found in [7].

plified shapes, using materials mixtures with relative elemental composition and masses set to agree with measurements made during construction, averaged over the relevant volumes. For instance, the beampipe in the region of the *epem* interaction point is modeled as a cylinder of $2.5cm**$ radius with $2mm***$ wall thickness, as a material mix composed mostly of Beryllium and water, along with trace elements from platings and coatings, as listed in table 1. Detailed features such as the interior vanes used to direct the cooling water flow were not modeled. The material mix was determined by integrating the volume of each components and dividing by the total volume. While the dimensions of the Beryllium components were well measured during detector construction, the coating thicknesses varied spatially, introducing some uncertainty. In addition, the exact composition of one of the coatings [10] was proprietary to the corporation which produced it, and our values were based on oral communication. Similarly, the SVT wafers are modeled as parallelepipeds with dimensions set to the average of those measured during construction [1]. The material composition of the flex circuits was estimated by dissolving a spare circuit in acid, and precipitating out and weighing the metals.

The Geant4 $\delta - ray$ production is simulated based on (more here). Figure **??** plots the $\delta - ray$ spectrum produced in a simple Geant4 Monte Carlo simulation of a mono-energetic 4 GeV muon traversing $2mm$ of pure Beryllium. Overlaid

Table 1: This is a table

A	B	C

is a theoretical calculation based on [4],

showing good agreement in the range covered. Note there are no free parameters in this comparison.

The *BABAR* detector response simulation was tuned to reproduce detailed models of the low-level sensor response measurements, as described in [7] chapter **. Dead channels in the detector were monitored and recorded coherently as a function of time. Simulated data samples were produced suppressing a given set of measured dead channels, with event counts proportional to the luminosity recorded in the period in which that set was dead.

The same reconstruction algorithms were run on simulated data as on *BABAR* data. The efficiency for reconstructing tracks in *BABAR* data and simulation has been found to agree within the measured uncertainties over the range of momentum relevant to this measurement using well-defined test samples [11].

5. $\delta - ray$ Reconstruction

5.1. $e^+e^- \rightarrow \mu^+\mu^-$ *Event Selection*

5.2. $\delta - ray$ *Candidate Identification*

6. $\delta - ray$ Corrections

6.1. Backgrounds

Gamma conversion to electron positron pairs can produce electrons within the energy window. This is an irreducible background to our measurement. The energy spectrum for produced electrons and positrons should be symmetric. Identifying positrons created in the beam pipe region and subtracting them from the electron spectrum allows us to statistically subtract the effects of gamma conversion from our measurement. The Monte Carlo simulated positron distribution agrees with the 7% data sample shown in figure **??**. Other backgrounds to the measurement are much smaller and are largely removed by data cuts. These will be further removed by statistically subtracting the expected amounts from Monte Carlo simulations.

6.2. Acceptance and Efficiency

The BABAR detector has a varying efficiency which changes with energy. The efficiency probability is calculated for each energy bin using the Monte Carlo truth. The number of true detected $\delta - rays$ at each energy is divided by the total number of true $\delta - rays$ at that energy. The efficiency for the beam pipe is shown in figure /refBPeff. This is then used to correct the measured distribution by dividing the energy corrected $\delta - ray$ distribution by the detector efficiency bin by bin.

6.3. Energy Correction

There is a small effect of energy smearing from the detector on the selected $\delta - rays$. This is partially due to smearing effects, and to bremsstrahlung. This effect can be correcting using an unfolding process. This is performed using the ROOT class TSVDUnfold, which uses the Monte Carlo simulation of the true distribution and detected distribution. The energy smearing matrix is inverted with a regularization factor for the Singular Value Decomposition. This process was first tested on the Monte Carlo data. First we separated every other event into a training sample and a test sample. Then we treated the training sample as the Monte Carlo truth and used it to perform the correction on the test samples detected distribution. This Provided a distribution of corrected $\delta - rays$ that agreed with the Monte Carlo truth for the test sample.

6.4. Material Transit

To turn the $\delta - ray$ distribution into a physical cross section we need to scale it to get physical units. The scaling factor is the density of the beam pipe multiplied by the sum of the path lengths for all selected muons that pass through the beam pipe. This is calculated from the 2track sample where selections are placed on the $\delta - rays$, only requirement is two muon tracks. Dividing the thickness of the beam pipe by the dot product of the muon track with the normal vector of the beam pipe provides the path length through the material.

6.5. Material Misidentification

The material of $\delta - ray$ production is identified using the POCA position of the $\delta - ray$ track. This value is calculated using the reconstructed track data and can lead to mislabeling. The values shown in figure **??** show this is a small effect for most regions of the detector. This becomes important in calculating the cross section for the CST and DCH regions of the detector as there is about 20% crossfeed. All other detector regions have crossfeed values at about 1%.

7. $\delta - ray$ Production Cross Section

In section **??** we discussed...."

7.1. Systematic Errors

in this paper we've shown blah blah.

References

[1] ?, The babar detectori, Nucl. Instr. Methods Phys. Res., Sect. A? (?) (?) ? doi:?

[2] ?, Mu2e technical design report, arxiv ? (?) (?) ? doi:?

[3] ?, Geant 4, arxiv ? (?) (?) ? doi:?

[4] H. Bethe, Delta ray theory, arxiv ? (?) (?) ? doi:?

[5] ?, Delta ray experiment, arxiv ? (?) (?) ? doi:?

[6] ?, The babar detectot 2, Nucl. Instr. Methods Phys. Res., Sect. A? (?) (?) ? doi:?

[7] ?, The babar detectot 2, Nucl. Instr. Methods Phys. Res., Sect. A? (?) (?) ? doi:?

[8] ?, Kk2f generator, arxiv ? (?) (?) ? doi:?

[9] ?, Daya bay cosmic ray generator, arxiv ? (?) (?) ? doi:?

[10] ?, Berylium paint, arxiv ? (?) (?) ? doi:?

[11] ?, Babar track finding efficiency, arxiv ? (?) (?) ? doi:?