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Nuclear Counter Effect of Silicon PIN Photodiode used in CsI(Tl) Calorimeter *

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Abstract

We investigated the nuclear counter effect of the silicon PIN photodiode mounted on a CsI(Tl) crystal array as a result of the leakage of electromagnetic shower through the rear end of the crystal. Using 1 GeV and 2 GeV electron beams at KEK, we estimated its effect on the energy measurement by the CsI(Tl) calorimeter of BELLE experiment. The results are found to be in good agreement with that of GEANT simulation and the expected effect for the BELLE calorimeter is negligible.

1 Introduction

A high resolution electromagnetic calorimeter made by inorganic crystal scintillators with silicon PIN photodiode read out has been popular in recent high energy physics experiments [1]. In the BELLE experiment [2] at KEK B factory, we plan to use 8736 pieces of CsI(T ℓ) crystals [3] each with two silicon PIN photodiodes [4]. The photodiode has 2 cm² sensitive area and is glued on the rear face of 30 cm long crystal. It has been pointed out that some of the electrons and photons in an electromagnetic shower leaking out from the rear end of the calorimeter hit the photodiode directly and may deposit a significant amount of energy in the photodiode. This “ nuclear counter effect ” of photodiode would cause a deterioration of energy resolution and possibly a systematic shift in the average detected energy. The effect would be significant for the BELLE calorimeter where the length of the crystal is limited and large area silicon PIN photodiodes are used.

2 Experimental Setup

The experiment was performed at the π^2 beam line of KEK Proton Synchrotron (PS). Negatively charged beams from the internal target of PS were momentum analyzed and focussed at the center of a 3 $\times$ 3 array of CsI(T ℓ) counters to be used in the electromagnetic calorimeter of BELLE experiment. The crystals were 30 cm (16.2 X_0) long and the cross sections were 54.5 $\times$ 53.8 mm² on the front and 54.5 $\times$ 66.9 mm² on the rear.

For a crystal at the center of the matrix, two photodiodes (PD1 and PD2) were glued on the rear face with 1 mm thick lucite plate in between. The photodiode used (Hamamatsu Photonix S2744-08) had a photosensitive area of 10 $\times$ 20 mm² and a wafer thickness of 300 μ m. On one of the photodiodes (PD1), however, a sheet of black paper was covered in order to completely block the scintillation light of the CsI(T ℓ) to reach the photosensitive area. Each photodiode, equipped with an identical charge sensitive preamplifier [5], was

attached to the rear end of the crystal (see Fig. 1). In this configuration, PD1 was used to measure the nuclear counter effect when PD2 measured the energy deposit in the CsI(Tl) crystal. We applied a reverse bias voltage of 60 V to both of the photodiodes, which is expected to form a depletion layer of approximately 250 μm thick. The beam trajectory was measured by a set of drift chambers inserted in the beam line and the impact point at the matrix front face was determined with an accuracy of better than 1 mm. A pair of gas Čerenkov counters was used to select electrons in the beam [6].

The output of the preamplifier was shaped by an ORTEC 570 amplifier with a shaping time of 1 μs and digitized by a 12 bit peak hold ADC (Hoshin C008). The gain of electronics for PD1 was calibrated by directly exposing the photodiode to 60 keV γ rays from ^{241}Am source. The spectrum of ^{241}Am is shown in Fig. 2. The peak of 60 keV γ rays is detected with a resolution of 5.5%.

3 Analysis

We exposed the matrix to 1 and 2 GeV beams and approximately 10,000 electron events were collected at each energy. In order to remove the effect of beam halo, we applied a cut on the beam impact point and defined a beam profile of 35 mm (horizontal) by 50 mm (vertical). This profile was found shifted from the matrix center by 2 mm in vertical direction and 10 mm in horizontal direction. The effect of this offset was properly taken into account in the simulation described in the following section.

A scatter plot of energy detected at PD1 (E_{PD}) and energy deposited in the central crystal (E_{CsI}) in units of ADC channel, is shown in Fig. 3 for 2 GeV electron beams. A cluster of events at $E_{PD} = 81$ keV and $E_{CsI} = 355$ ch in Fig. 3 corresponds to μ^- or noninteracting π^- directly passing through PD1. Those events were unavoidably included in the electron samples because of the accidentals and δ ray backgrounds in the Čerenkov

counters. A broad cluster of events due to the nuclear counter effect is clearly seen around $E_{CsI} = 2900$ ch and $E_{PD} > 30$ keV in Fig. 3. A small slope appeared in a band of events for $E_{PD} < 30$ keV was caused by a cross talk between PD1 and PD2 electronics. This effect, a maximum of 18.0 keV in E_{PD} at $E_{CsI} = 3300$ ch (approximately 2 GeV equivalent energy deposit in the central crystal), was corrected in the following analysis.

In order to select electron events well contained in the central crystal and remove the contamination of μ^- and π^- , we required E_{CsI} to be greater than half of the beam energy. After this cut, the events for $E_{PD} > 30$ keV are considered resulting from the nuclear counter effect. The number of events satisfying these conditions are listed in Table 1 and the distributions of E_{PD} are shown in Fig. 4.

A GEANT simulation [7] was made to compare the result with the expectations. A geometry of 3×3 array of CsI(Tl) crystals was set up. Two pieces of silicon plates, each placed on a lucite plate of 1 mm thickness and having a dimension of 10×20 mm² large and 250 μ m thick (simulating the depleted volume of silicon photodiodes), were attached to the rear surface of the central crystal. Monoenergetic electron beams of rectangular spread were projected perpendicularly onto the front face of the central crystal. Electrons and photons in the electromagnetic shower were tracked down to the energy of 10 keV in order to simulate small energy deposits in the photodiode. The same cuts, applied to the data, were assumed for simulated events. The results of GEANT simulation are compared with data in Fig. 4 and Table 1. In Fig. 4 the data are normalized with the simulation in such a way that both have the same number of events for $E_{PD} > 30$ keV. It is seen that the data are well reproduced by GEANT simulation both in terms of rate and energy distribution in the photodiode.

4 Results and Discussion

In order to estimate the effect of nuclear counter in the actual electromagnetic calorimeter of BELLE, we performed a GEANT simulation for 5×5 array of CsI(Tl) crystals. Monoenergetic electrons with energy from 0.1 to 8.0 GeV were injected onto the center of the matrix with a uniform beam profile of 50×50 mm². Each crystal was equipped with a real size lucite plate and two photodiodes at its rear end and the energy deposits in a total of 50 photodiodes were summed up (E_{PD}^{tot}). The rate of nuclear counter effect and average E_{PD}^{tot} with its variance for $E_{PD}^{tot} > 30$ keV are estimated from the simulation and listed in Table 2.

The value of E_{PD}^{tot} can be converted to an equivalent energy deposit in the CsI(Tl) crystal by assuming that (1) 60 keV γ rays from ²⁴¹Am produces 1.64×10^4 electron-hole pairs in the silicon photodiode [8], and (2) 1 MeV energy deposit in BELLE CsI(Tl) crystal is equivalent to approximately 5060 electron-hole pairs detected by two photodiodes [6]. The additional energy by the nuclear counter effect, ΔE^{NC} , is calculated in this way and listed in Table 2.

The simulation shows that 28.7 % of electrons will be associated with the nuclear counter effect at 8 GeV. However 13 MeV of ΔE^{NC} at 8 GeV will cause only 0.16 % shift in the measured energy and it is negligibly small compared to the expected energy resolution at 8 GeV (≈ 2 %). The effect becomes comparable with the energy resolution below 0.5 GeV, but the rate will be less than 1 % in this energy region.

5 Conclusion

The nuclear counter effect of silicon photodiode, caused due to the rear leakage of the electromagnetic shower, has been observed for the 3×3 matrix of prototype CsI(Tl) counters of BELLE electromagnetic calorimeter for 1 and 2 GeV electrons. The observed effect

was well reproduced by the GEANT simulation both in terms of rate and the amount of energy deposit in the photodiode. Based on the good agreement with data and simulation, we estimated the effect for the BELLE calorimeter by simulating the response of monoenergetic electrons on 5×5 matrix for energies from 0.1 to 8.0 GeV. It is found that the performance of the calorimeter will not be deteriorated by this effect.

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Table 1: *Hit rate and average energy deposit in photodiode by the nuclear counter effect measured for 1 GeV and 2 GeV electrons. Expectation by GEANT simulation is also given. Errors for E_{PD}^{tot} is the variance of E_{PD}^{tot} distribution.*

Electron	Number of Events			Average Energy (keV)
	Total	PD Hit	Hit Rate(%)	E_{PD}^{tot}
1.0 GeV	10,325	40	0.39±0.06	165±17
Simulation	50,000	181	0.36±0.03	162±8
2.0 GeV	9,583	146	1.52±0.13	206±16
Simulation	20,000	277	1.38±0.08	177± 9

Table 2: *Expected nuclear counter effect of BELLE calorimeter obtained by GEANT simulation for electrons at different energies. Errors quoted for ΔE^{NC} is the variance.*

Energy (GeV)	Hit Rate (%)	E_{PD}^{tot} (keV)	ΔE^{NC} (MeV)
0.1	0.06±0.01	131±14	7.24±0.78
0.5	0.64±0.06	148±12	8.18±0.67
1.0	1.9±0.1	164±9	9.06±0.50
2.0	4.9±0.2	177±5	9.78±0.28
3.5	10.3±0.4	186±5	10.33±0.28
8.0	28.7±0.6	225±3	12.43±0.16

Figure 1: *Photodiode arrangement on the central crystal.*

Figure 2: *Gamma ray spectrum by ^{241}Am used for the calibration.*

Figure 3: Scatter plot of energy detected by the central crystal (E_{Csl}) and energy deposited in PD1 (E_{PD}).

Figure 4: Energy deposited in PD1 (E_{PD}) by 1 GeV and 2 GeV electrons. Solid points are data and histograms are GEANT simulation.