Calibration of a Shower Lead-Scintillation Spectrometer by Cosmic Radiation

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Abstract—The results of cosmic-muon calibration of a shower lead-scintillation “sandwich”-type spectrometer of thickness 8.5$X_0$, intended for operation in high-intensity photon and electron beams ($\sim 10^6$ particles/s) with energies of 0.1–1.0 GeV are presented. It is found that the relative energy resolution of the spectrometer depends on the angle of cosmic muon entry into the spectrometer in the vertical plane and is independent of the entry angle into the horizontal plane. The relative energy resolution of the spectrometer is $\delta = 16\%$. Placing of an additional lead-scintillation assembly of thickness 2.2$X_0$ in front of the spectrometer improved its relative energy resolution to $\delta = 9\%$.

Keywords: spectrometer, sandwich, spectrum shifter, cosmic muons, trigger

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In experimental physics, to record electromagnetic decay products (gamma-rays, electrons, and positrons) and to determine characteristics of calibration electron (positron) and photon beams, the problem of combining good time and energy resolution in a single detector remains urgent. The good energy resolution is conventionally achieved using various types crystals (NaI(Tl), CsI, and others), in which, to obtain good time resolution, detectors are partitioned with insert of fast plastic scintillator, or a fast component in the temporal spectrum is separated [1]. Nevertheless, there is an interest in the least-cost multilayer lead-scintillation “sandwich”-type spectrometers featuring significant design potential [2, 3].

In the Nuclear Research Department of the Lebedev Physical Institute at the Pakhra accelerator, a calibration channel of a high-intensity $\sim 10^{10}$ e$^-$/s extracted electron beam with an energy of 250–500 MeV and variable intensity to $\sim 10^3$–$10^5$ e$^-$/s was created, as well as a calibration quasi-monochromatic beam of secondary electrons (positrons) based on a bremsstrahlung photon beam with an energy of 30–300 MeV and an intensity to $\sim 10^2$ e$^-$(e$^+$)/s at a main collimator diameter of 30 mm [4]. To determine characteristics of calibration beams, a two-channel shower lead-scintillation (LS) spectrometer with signal pickup using a single spectrum shifter (Fig. 1) was developed.

When designing the lead-scintillation spectrometer, it was taken into account that the use of photomultipliers (PMs) with short signal shaping time, scintillators with short decay time, and the presence of two channels using which the internal trigger will be formed, and will make it possible spectrometer operation under conditions of high counting rates and to significantly decrease the number of accidental coincidences. It was also taken into account that a decrease in the number of accidental coincidences will be caused by a natural energy threshold existing in the case of the electromagnetic shower development in the spectrometer material. Therefore, to pickup the signal from the lead-scintillation assembly, it was decided to use a spectrum shifter [3, 5].

The LS structure is typical of spectrometers of this type. The spectrometer contains 23 lead plates (2 mm) and a polystyrene plastic scintillator (5 mm) with lateral sizes of 160 × 160 mm$^2$. The total spectrometer thickness was 8.5$X_0$ ($X_0$ is the radiation length). To improve the light collection, aluminized Mylar is placed between lead and scintillation plates wafer. Light is collected simultaneously on three sides of the lead-scintillation assembly by one shifter and is extracted to opposite end faces. The shifter is a plexiglas plate 160 mm wide, 600 mm long, and 3 mm thick with a “surface” shifter deposited on the plexiglas surface (1.5-diphenyl-3 styryl-prazonin). The plate full length from PM to PM is 600 mm, the coating length is 400 mm, the length of transparent inserts between the spectrum shifting coating and output plate
CALIBRATION OF A SHOWER LEAD-SCINTILLATION SPECTROMETER

Fig. 1. Scheme of the two-channel shower lead-scintillation (LS) spectrometer using a spectrum shifter: (1) lead-scintillation assembly, (2) plexiglas spectrum shifter, (3) aluminized mylar, (4) FEU-85, (5) voltage divider, (6) PM housing, and (7) external light-proof case.

end faces to the PM is 100 mm. Light from each plate end face is collected by FEU-85 PMs with standard voltage dividers.

The LS was preliminarily calibrated by cosmic ray muons. The calibration scheme is shown in Fig. 2. The sizes of trigger counters C₁, C₂ and C₃ were 40 × 40 × 5 mm³ and 20 × 20 × 5 mm³, respectively. The thickness of the lead block between C₂ and C₃ was 70 mm. The particle angles of entry into LSs θₓ and θᵧ were varied by moving C₃ along X and Y axes, respectively. The positions of counters C₁ and C₂ remained unchanged. Cosmic muons 1 are minimum ionizing particles and deposit an energy of ~2 MeV/cm in plastic scintillator; therefore, the total energy deposit in LS scintillation plates is ~23 MeV.

Figure 3 shows the dependences of average amplitudes (dependence 1 and 2) and energy resolutions (dependence 3 and 4) of LS channels on divider voltages when muons pass through the spectrometer center (θₓ = θᵧ = 0). We can see that the dependences of average amplitudes of both LS channels within the range of studied divider voltages are linear. The best relative energy resolutions of channels appeared to be δ₁ ≈ 20% and δ₂ ≈ 18% at divider voltages U₁ = 1220 V and U₂ = 1265 V, respectively. Since the signal amplitude in LS channels corresponds to the same energy released by the muon in passing through the LS, the relative energy resolution of channels was determined as δ₁(2) = δ₁(2)/⟨A₁(2)⟩ = ((ΔA₁(2)/⟨A₁(2)⟩)/2.35) × 100%, where δ₁(2) is the standard deviation of the average signal amplitude of the amplitude spectrum of the first (second) channel, ΔA₁(2) is the full width at half maximum of the amplitude spectrum of signals from the PM of the first (second) channel, ⟨A⟩ is the average amplitude in the amplitude spectrum of the first (second) channel, and 2.35 is the proportionality factor defining the relation between ΔE and σ (ΔE = 2σ √2 ln2 ≈ 2.35σ).

Figure 4 shows the dependences of variations in average channel signal amplitudes ⟨A⟩ on the angles θₓ and θᵧ of muon entry into the spectrometer. The angles of muon entry into the spectrometer θₓ and θᵧ with respect to either axis varied from −16° to +16°. We can see that signal amplitudes of both LS channels are almost unchanged with varying θₓ (dependences 1 and 2) in contrast to the signal amplitudes with varying θᵧ (dependences 4 and 5). The same effect is also observed in the comparison of the dependences of total amplitudes of both channels (dependence 3 and 6). This means that three-sided light collection from LS scintillation plates is uniform with varying θₓ. It can be assumed that a decrease in the light collection on the one LS side leads to an increase in the light collection on the other LS side with varying θₓ in such proportion that the total light collection is almost constant. If θᵧ varies, the absence of light col-
Fig. 2. Scheme of LS calibration by cosmic muons: C₁–C₃ scintillation trigger counters, Pb lead block, LS shower lead-scintillation spectrometer.

Fig. 3. Dependence of the average amplitude, relative energy resolution of LS channels, and the relative energy resolution of the composite shower spectrometer consisting of the LS and additional assembly (AA), on the PM divider voltage of LS and AA channels: (1, 2) dependences of the average signal amplitude of LS channels 1 and 2, respectively, (3, 4) dependences of the relative energy resolution of LS channels 1 and 2, respectively, (5) dependence of the relative energy resolution of composite spectrometer LS+AA.
The dependences of the variation in the relative LS energy resolution on the muon entry angles $\theta_x$ and $\theta_y$ are shown in Fig. 5. The relative energy resolution of individual LS channels (dependence $1$ and $2$) with varying $\theta_x$ is not constant and varies within $\pm 10\%$ of values at $\theta = 0^\circ$. The energy resolution of the spectrum of the sum of channel signals (dependence $3$) almost in the entire measured $\theta_x$ angular range is constant and is $\delta \approx 16\%$. The light collection nonuniformity with varying the angle of muon entry into the LS with respect to $\theta_y$ results in that the nonuniformity is also observed in the energy resolution of individual channels and the sum of signals (dependences $4$, $5$, and $6$) in the entire measured $\theta_y$ angular range. In this case, the nonuniformity in the energy resolution is more significant and reaches $\sim 30\%$.

To improve the energy resolution, an additional lead-scintillation assembly AA consisting of 4 lead plates 3 mm thick and a scintillator 5 mm thick was placed in front of the LS. The AA plate size was $100 \times 100 \text{ mm}^2$. Light pickup was performed from four sides of plated by the shifter with light extraction to the FEU-85 [3]. The relative energy resolution of the composite shower spectrometer LS+AA (CSS) on the AA PM divider voltage is shown in Fig. 3 (dependence $5$). The best CSS resolution is achieved at the AA voltage divider $U = 1150 \text{ V}$ and is $\delta = 9\%$. 

Fig. 4. Dependences of the average signal amplitudes of individual channels and the total LS amplitude on the angle of muon entry into the spectrometer: ($1$–$3$) with respect to the horizontal axis ($\theta_x$), ($4$–$6$) with respect to the vertical axis ($\theta_y$); ($1$, $4$) LS channel 1, ($2$, $5$) LS channel 2, ($3$ and $4$) dependences of the total amplitude.

Fig. 5. Dependences of the LS relative energy resolution on the angle of muon entry into the spectrometer: ($1$–$3$) dependences on the muon entry angle with respect to the horizontal axis ($\theta_x$), ($4$–$6$) dependences on the muon entry angle with respect to the vertical axis ($\theta_y$); ($1$, $4$) and ($2$, $5$) dependences for channels 1 and 2, respectively; ($3$ and $4$) dependences of the sum of channels.
Cosmic-muon calibration of the two-channel shower lead-scintillation spectrometer using a spectrum shifter showed that there is a dependence of the average signal amplitude of individual spectrometer channels and the sum signal, as well as the relative energy resolution of individual channels and the total relative resolution on the angles of muon entry into the spectrometer in the studied range of entry angles of ±16°. With varying the entry angles in the horizontal $\theta_x$, the dependence is almost absent. The best relative energy resolution is achieved as muons pass through the spectrometer center at the angle $\theta_x = \theta_y = 0°$ and is $\delta = 16\%$.

Placement of an additional lead-scintillation assembly AA in front of the LS and light pickup using a spectrum shifter on four sides of the assembly improves the relative energy resolution of combined shower spectrometer LS+AA (CSS), which reaches $\delta = 9\%$. Thus, the shower lead-scintillation spectrometer is capable of determining energy characteristics of electron (positron) and photon beams with good accuracy, and can be used as an independent detector in physical experiments. It is planned to study in more detail the time resolution of the spectrometer directly during operation on the high-intensity calibration beam of the Pakhra accelerator.

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