Calibration of the Veto Detector for the External Target Experimental Terminal of HIRFL-CSR

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Date: 2024-02-26T10:22:23Z

Abstract

The Veto detector of the external target facility (ETF) at the Heavy Ion Research Facility in Lanzhou - Cooling Storage Ring (HIRFL-CSR) was calibrated using cosmic rays. The calibration work was primarily divided into two components: position calibration and time calibration. Position calibration yields the hit position of particles on the detector, while time calibration establishes a unified standard for determining the particle hit time on the detector. This information provides the basis for rejecting charged particle events incident on the neutron wall detector and offers crucial support for realizing the physics objectives of the neutron wall detector. During the calibration process, a position resolution of 2.53 cm full width at half maximum (FWHM) was obtained for the Veto detector, and a time resolution of 1.09 ns FWHM after temporal normalization of all individual strips.

Full Text

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Nuclear Physics Review, Vol. 32, No. 3, February 2024
Article ID: 1007-4627(2024)03-0123-08

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Abstract

Cosmic rays were employed to calibrate the Veto detector at the External Target Facility (ETF) of the Heavy Ion Research Facility in Lanzhou -Cooling Storage Ring (HIRFL-CSR). The calibration work consisted of two main components: position calibration and time calibration. Position calibration determines the hit positions of particles on the detector, while time calibration establishes a unified standard for measuring the arrival times of particles at the detector. This information serves as the basis for rejecting charged particle events incident on the neutron wall detector, thereby providing crucial support for achieving the physics objectives of the neutron wall detector. Through the calibration process, a position resolution of 2.53 cm (FWHM) and a time resolution of 1.09 ns (FWHM) were obtained for the Veto detector after temporal normalization of all strips.

Keywords: Veto detector; calibration; cosmic ray; position resolution; time resolution

1. Introduction

Research on the structure and properties of neutron-rich nuclei far from the - stability line represents one of the frontiers in contemporary nuclear physics. In recent years, with the discovery of unique structures such as neutron halos and neutron skins, significant progress has been made in the study of drip-line nuclei and unbound neutron-rich nuclei, generating tremendous interest in the structural properties of nuclei near the neutron drip line. The complete kinematic measurement method utilizes radioactive beam facilities to produce neutron-rich nuclei in the medium-to-high energy region to bombard reaction targets. Since the fragmentation products are concentrated in the forward angular region, complete measurement of reaction products can be achieved with only a small solid angle coverage. This method reconstructs the pre-fragmentation state of nuclei using coincidence detection information from heavy charged particle fragments, neutrons, and gamma rays, serving as an effective tool for studying nuclear structure. Typical experimental facilities employing this method internationally include MONA at Michigan State University (MSU) in the United States, ALADIN-LAND at GSI in Germany, SUMURAI at RIKEN in Japan, and the External Target Facility (ETF) at the Institute of Modern Physics, Chinese Academy of Sciences in China.

The CSRm (Cooling Storage Ring main ring) at the Heavy Ion Research Facility in Lanzhou (HIRFL) can accumulate and accelerate primary beams to energies of several hundred MeV/u to 1 GeV/u to bombard primary targets, producing radioactive beams through projectile fragmentation reactions. After separation and purification by RIBLL2, the beams are transported to ETF to bombard secondary targets. The ETF detection system performs complete kinematic measurements of reaction fragments, comprising primarily a time-of-flight wall for detecting charged particle flight times, multi-wire drift chambers for tracking charged particles, a large-acceptance dipole magnet for deflecting charged particles, a Veto detector for charged particle anti-coincidence, and a neutron wall for neutron detection. The Veto detector is positioned approximately 10 cm in front of the neutron wall, as shown in Fig. 1(a). Its function is to remove interference from charged particle events incident on the neutron wall detector, ensuring accurate acquisition of neutron event information. Due to the low intensity of radioactive beams and small cross-sections for producing target fragments, the desired neutron event rate is very low and extremely precious. Since the magnetic field strength of the dipole magnet can only be set within a certain range and the angular distribution of outgoing charged fragments can be very broad, charged particle events inevitably contaminate the neutron wall, creating interference for neutron event detection. Medium-to-high energy neutrons are detected through their interactions with nuclei in the detector medium, producing secondary charged particles. The neutron wall alone cannot distinguish between neutrons and charged particles, and misidentifying charged particles as neutrons would severely affect experimental results. The Veto detector employs thin, low atomic number materials as the detection medium. Neutrons in the target energy range deposit very little energy in the Veto detector, producing essentially no effective signal, while the Veto detector exhibits high detection efficiency for charged particles. Therefore, the presence or absence of a Veto detector signal can be used to eliminate charged particle background. The detection efficiency for charged particles is an important performance metric for the Veto detector; higher efficiency corresponds to a lower probability of misidentifying charged particles as neutrons. Related work on efficiency calibration has been detailed in Ref. [12].

In addition to efficiency calibration, position and time calibration are equally essential for the Veto detector to fulfill its function. For instance, in experiments, there is a finite probability that charged particles and neutrons produced in nuclear reactions will simultaneously pass through the Veto detector and strike the neutron wall detector, with their signals being collected as the same event. In such cases, using only the presence or absence of a Veto detector signal as the criterion for charged particle rejection may lead to misjudgment and erroneous elimination of some neutron events. Position calibration provides the hit positions of charged particles on the Veto detector, which, combined with position information from the neutron wall detector, enables accurate removal of charged particle-related fire points while preserving complete neutron event information, thereby improving neutron detection efficiency. Furthermore, secondary charged particles produced by interactions between medium-to-high energy neutrons and nuclei in the neutron wall detector may undergo backscattering. These backscattered charged particles appear to originate from the neutron wall, traverse several neutron wall strips, pass through the Veto detector, and then exit. They cause the Veto detector to fire, leading to erroneous rejection of neutron events. Time calibration provides the arrival time of particles at the Veto detector, and by comparing the firing times of particles on the Veto detector and neutron wall detector, one can determine whether the incident particle is a normally incident charged particle or a backscattering event induced by neutrons, thus providing a basis for correctly retaining neutron events. For these reasons, position and time calibration of the Veto detector are essential prerequisites for subsequent data analysis.

2. Detector System

2.1 Veto Detector The Veto detector at ETF is placed approximately 10 cm in front of the neutron wall detector, as shown in Fig. 1(a). The detector consists of nine strip-shaped detection units. The detection medium for each strip is EJ-200 plastic scintillator produced by Eljen Technology Company. Each strip measures 1500 mm × 180 mm × 10 mm. The inner layer of each strip is wrapped with Tyvek paper as a diffuse reflector to improve light collection performance, while the outer layer is covered with black heat-shrink tubing for light shielding to prevent natural light interference. Similar to the neutron wall detector, the Veto detector strips employ double-ended readout. Considering that using photomultiplier tubes (PMTs) as readout devices would require optical guides for shape transition between the strips and PMTs, and that PMTs and optical guides are relatively expensive, adopting PMTs would increase the overall detector cost and result in excessively large dimensions. In recent years, silicon photomultipliers (SiPMs) have developed rapidly, offering advantages such as high gain, excellent timing performance, compact structure, and low cost. For these design considerations, SiPMs were selected as the readout devices at both ends of each strip, specifically the S13360-6050CS model produced by Hamamatsu Corporation [14]. Since this SiPM model has a sensitive area of 6 mm × 6 mm, nine SiPMs are used at each end of every strip to increase the fluorescence reception area and improve light collection efficiency. The nine SiPMs are connected in parallel, with their signals ultimately merged into a single output. All nine strips of the Veto detector are arranged laterally in a staggered configuration across two layers, with adjacent strips forming a "pin" character structure and overlapping by 10 mm, as shown in Fig. 1(b). This overlapping "pin" structure is adopted primarily because the detection efficiency decreases when incident charged particles pass through the edge regions of strips—the so-called "edge effect" [15]—and this arrangement enhances detection efficiency at strip edges.

2.2 Data Acquisition System and Digitizer Boards The data acquisition system and digitizer boards for ETF detectors were developed by the University of Science and Technology of China. The system is designed based on the industrial PXI (PCI eXtensions for Instrumentation) bus standard, employing a 6U standard chassis.

In cases where detectors have numerous signal channels, the data acquisition system requires multiple chassis—one master chassis plus several slave chassis. The master chassis contains one master trigger board and one master clock board, while each slave chassis contains one slave trigger board, one slave clock board, and several digitizer boards. The master trigger board aggregates slave trigger signals from slave trigger boards to generate the master trigger signal. The master clock board provides a unified clock signal to all slave clock boards, which then fan out the timing signals to slave trigger boards and digitizer boards within their respective chassis, providing a common clock for relevant signal measurements. The slave trigger board is responsible for uploading trigger signals from within the slave chassis to the master trigger board and downloading the master trigger signal to each digitizer board within its chassis. The digitizer boards acquire valid signals.

The data acquisition for the Veto detector and neutron wall detector utilizes three chassis, one of which serves as both master and slave chassis, simultaneously containing one master trigger board, one slave trigger board, one master clock board, one slave clock board, and multiple digitizer boards, as shown in Fig. 2. The digitizer boards used for the Veto detector are Time-of-Flight time-and-charge measurement boards [16] (hereafter referred to as TOF boards), each providing 16 channels. Signals from the detector enter each channel and are split into two paths: one path undergoes leading-edge timing and is fed into a high-performance time-to-digital converter chip HPTDC [17] for time measurement, while the other path is sent to an ASIC chip SFE16 for amplification, shaping, and discrimination before being fed into another HPTDC chip for charge information extraction using the Time Over Threshold (TOT) method [18-19] to obtain energy signals. Additionally, TOF boards can generate trigger signals by grouping the 16 channels into eight pairs, performing a logical AND on each pair, then a logical OR across all groups, and finally outputting an LVTTL-level trigger signal.

2.3 Detection Principle When charged particles traverse a Veto detector strip, they interact with the detection medium, exciting its atoms. The scintillation photons produced during de-excitation propagate toward both ends of the strip, as shown in Fig. 3. The scintillation light enters the SiPMs at both ends of the strip and is converted into electrical signals, which are then transmitted via signal cables to TOF boards for time and amplitude measurement.

The times measured by the TOF boards can be expressed by the following formulas:

$$T_L = T_0 + L/2 + x + \tau_{L0}$$

$$T_R = T_0 + L/2 - x + \tau_{R0}$$

where T_L and T_R are the times measured by the TOF board for signals from the left and right ends of the strip, respectively; T_0 represents the particle hit time on the strip; τ_{L0} and τ_{R0} are the electronic delays of the readout channels corresponding to the left and right ends of the strip; $L/2+x$ and $L/2-x$ are the times required for scintillation light to propagate to the left and right ends of the strip, respectively, where L is the strip length, x is the cosmic ray hit position on the strip, and v_{eff} is the effective propagation speed of scintillation light along the strip length direction. From equations (1) and (2), the expressions for x and T_0 can be derived:

$$x = \frac{v_{\text{eff}}}{2}(T_L - T_R - \tau)$$

$$T_0 = \frac{T_L + T_R - L/v_{\text{eff}} - \tau'}{2}$$

where $\tau = \tau_{L0} - \tau_{R0}$ and $\tau' = \tau_{L0} + \tau_{R0}$.

3. Detector Calibration

To eliminate interference from charged particle events incident on the neutron wall detector and ensure accurate acquisition of neutron physics information and achievement of related physics objectives, calibration of the Veto detector is necessary. The calibration is based on equations (3) and (4), where the values of τ and v_{eff} are specific to each strip and its associated electronics. These parameters vary for three main reasons: First, manufacturing and packaging variations among Veto detector strips cause differences in photon reflection within each strip, leading to different effective propagation speeds and thus different travel times for photons over the same distance in different strips. Second, differences in SiPM gain at the two ends of each strip produce electrical signals with different amplitudes, causing timing variations in the leading-edge discrimination of the TOF boards. Finally, different electronic channels on the TOF boards introduce different electronic delays. However, for each specific strip, the corresponding scintillator strip, SiPM devices, and electronic channels are fixed, making the values of τ and v_{eff} constant. Cosmic rays can be used for calibration experiments to determine these parameters for each strip of the Veto detector. The calibrated parameters can then be applied to future beam experiments.

For Veto detector calibration using cosmic rays, signals from both ends of each strip are connected to adjacent channels on TOF boards. Consequently, signals from the first eight strips are fed into one TOF board, while signals from the ninth strip are fed into another TOF board. The trigger outputs from both TOF boards are sent to the slave trigger board within the chassis, where a logical OR operation is performed, with the final output serving as the system master trigger signal. Thus, a trigger signal is generated when any strip is hit by a cosmic ray.

3.1 Position Calibration During formal experiments, determining the hit positions of charged particles on the Veto detector is essential to prevent erroneous rejection of valid neutron events. Therefore, position calibration must be performed first, as it also forms the basis for subsequent time calibration.

Let $\Delta T = T_L - T_R$. From equation (3), we obtain:

$$\Delta T = \tau + \frac{2x}{v_{\text{eff}}}$$

Equation (5) shows that ΔT is linearly related to the cosmic ray hit position. Based on measured T_L and T_R values, a histogram of ΔT for cosmic ray hits on a strip can be plotted, as shown in Fig. 4(a). Since cosmic rays hit random positions along the strip, the ΔT distribution should theoretically be uniform, approximating a rectangular shape with its lower and upper edges corresponding to positions at the two ends of the strip. However, due to light attenuation length and time resolution effects, tails form on both sides of the rectangle. To identify the positions corresponding to the strip ends in the ΔT spectrum, the differential of Fig. 4(a) is taken to obtain the rate-of-change spectrum shown in Fig. 4(b). Two positions with the fastest rate of change are evident in Fig. 4(b), corresponding to the left and right ends of the strip ($x = \pm L/2$), with their ΔT values denoted as ΔT_{min} and ΔT_{max}. From equation (5):

$$\Delta T_{\text{min}} = \tau - \frac{L}{v_{\text{eff}}}$$

$$\Delta T_{\text{max}} = \tau + \frac{L}{v_{\text{eff}}}$$

Thus, τ and v_{eff} can be obtained:

$$\tau = \frac{\Delta T_{\text{min}} + \Delta T_{\text{max}}}{2}$$

$$v_{\text{eff}} = \frac{L}{\Delta T_{\text{max}} - \Delta T_{\text{min}}}$$

Finally, the cosmic ray hit position x on the strip can be calculated using τ and v_{eff} in equation (3). Table 1 lists the τ values and effective light propagation speeds v_{eff} for each strip of the Veto detector, with an average v_{eff} of 12.14 ± 0.07 cm/ns.

Table 1. τ and v_{eff} values for each strip of the Veto detector.

Strip ID	τ (ns)	v_{eff} (cm · ns ^{1})
0	-0.23	12.18
1	0.15	12.05
2	-0.08	12.20
3	0.42	12.21
4	0.00	12.15
5	-0.31	12.08
6	0.18	12.12
7	-0.45	12.13
8	0.32	12.12

A coordinate system is established with the center of the fourth strip as the origin, the direction parallel to the strips leftward as the positive x-axis, the vertical upward direction perpendicular to the ground as the positive y-axis, and the direction perpendicular to the Veto detector toward the neutron wall as the positive z-axis. Using the τ and v_{eff} values for each strip, the x-coordinate of the particle hit position on the strip is obtained. The y-coordinate of the hit position is taken as the central value of the strip in the y-direction, and the z-coordinate is the installation position of the strip layer. Thus, a particle hit position on different strips of the Veto detector can be expressed as (x_i, y_i, z_i), where i is the strip number ($i = 0, 1, 2, 3, \dots, 8$).

Since the Veto detector has two layers, position calibration is performed layer by layer. First, cosmic ray events that pass through only one layer are selected to calibrate that layer' s strips, followed by calibration of the other layer. Consequently, incident cosmic ray particles can be approximated as moving in the x-y plane, with particle trajectories representable by linear equations:

$$y = kx + b$$

To ensure trajectory validity, events hitting three or more strips are selected. The hit positions (x_i, y_i) are fitted using the least squares method, with the resulting line considered the true cosmic ray trajectory, yielding the coefficients k and b for each track. Substituting the y-coordinate of a hit strip into equation (10) yields the theoretical x-value on the fitted trajectory, i.e., the theoretical hit position. The measured hit position is calculated from equation (3), and the measurement error Δx is obtained as the difference between measured and theoretical values.

Figure 5(a) illustrates a cosmic ray passing through the Veto detector, where white sections represent the first layer strips and gray sections represent the second layer strips. The cosmic ray traverses five strips in the first layer, with red points indicating measured hit positions calculated from T_L and T_R values at each strip' s ends. The straight line represents the cosmic ray trajectory obtained by least-squares fitting of the five measured positions, with the position measurement error Δx for one strip indicated. All events meeting the criteria (single-layer firing with three or more hit strips) are used to populate a histogram of Δx values for hit strips, shown in Fig. 5(b). Gaussian fitting yields a position resolution (FWHM) of 2.53 cm in the x-direction for the Veto detector.

3.2 Time Calibration Time calibration of the Veto detector is performed by calculating flight times between fire points using cosmic ray hit positions and fitted trajectories. As shown in Fig. 5(a), based on the fitted trajectory, the x-direction hit positions x_1, x_2 and y-coordinates y_1, y_2 for two strips can be calculated. The distance between fire points is Δd, and the theoretical flight time is:

$$\Delta T_{\text{th}} = \frac{\Delta d}{v}$$

where v is the cosmic ray velocity, which is approximately equal to the speed of light c given the high energy of cosmic rays. The flight time can also be expressed using measured T_L and T_R values from two strips via equation (4):

$$\Delta T_{\text{exp}} = \frac{(T_L + T_R)_{\text{ref}} - (T_L + T_R)_i}{2} + C_{\text{ref}} - C_i$$

where $C = -(L/v_{\text{eff}} + \tau')/2$ is a constant related to delay time, and subscripts ref and i denote two different strips. ΔT_{exp} represents the flight time of strip i relative to the reference strip, while $\delta_i = C_{\text{ref}} - C_i$ is the relative flight time difference between strip i and the reference strip, caused by structural and electronic differences between the two strips. Due to this relative time difference δ_i, the actual flight time ΔT_{exp} between two strips is not equal to the theoretical flight time ΔT_{th}, which affects the overall performance of the Veto detector. To eliminate the influence of relative time differences δ_i, time calibration is required.

For time calibration, strip ref is fixed as the reference strip while varying strip i to obtain the relative time offset Δt_i for other strips with respect to the reference, such that $\Delta T_{\text{exp}} - \Delta T_{\text{th}} = 0$. More points in the trajectory fitting yield better fitting results, making $\Delta T_{\text{exp}} - \Delta T_{\text{th}}$ closer to the true value. Time calibration proceeds first layer by layer, selecting events that pass through only one layer with three or more fired strips. For the first layer, strip 4 is chosen as the reference, while strip 3 serves as the reference for the second layer. After completing internal calibration within each layer, events simultaneously passing through strips 3 and 4 are selected to obtain the relative time delay parameter between these two strips. Finally, all calibration parameters for the second layer are converted to results relative to strip 4 as the reference.

Figure 6 shows the $\Delta T_{\text{exp}} - \Delta T_{\text{th}}$ values for different Veto detector strips relative to strip 4 before and after calibration, with the horizontal axis representing $\Delta T_{\text{exp}} - \Delta T_{\text{th}}$ and the vertical axis showing strip numbers. Before calibration, different time delay offsets relative to the reference strip cause ΔT_{exp} and ΔT_{th} to be unequal, as shown in Fig. 6(a). After calibration, ΔT_{exp} is corrected to equal ΔT_{th}, as shown in Fig. 6(b).

Projecting Fig. 6(b) onto the x-axis yields a one-dimensional histogram of $\Delta T_{\mathrm{exp}} - \Delta T_{\mathrm{th}}$ values. Gaussian fitting gives a time resolution (FWHM) of 1.09 ns for the Veto detector after temporal normalization of all strips, as shown in Fig. 7.

4. Conclusion

This paper describes the calibration of the Veto detector at the HIRFL-CSR External Target Facility using cosmic rays. In position calibration, particle hit positions on strips were determined using time signals from double-ended readout of EJ-200 plastic scintillator strips and the rate of change in cosmic ray counts at different positions along the strips, completing the position calibration of the detector. The final position resolution (FWHM) of the Veto detector along the strip direction is 2.53 cm.

For time calibration, a scheme of layer-by-layer calibration followed by overall calibration was adopted. By selecting a reference strip and events simultaneously passing through the reference and target strips, the theoretical flight time of cosmic rays between two strips was obtained using position calibration results. The difference between experimental values from the detection system and theoretical values yielded the experimental-theoretical deviation, completing the time calibration of the Veto detector. The resulting time resolution of 1.09 ns (FWHM) represents the overall time resolution of all Veto detector strips after temporal normalization. The calibration of the Veto detector at the HIRFL-CSR External Target Facility ensures correct acquisition of neutron event physics information and is crucial for studying the structure and properties of nuclei far from the -stability line through neutron detection with the neutron wall.

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Note: Figure translations are in progress. See original paper for figures.