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Cosmic Ray Measurement and Experimental Temperature Analysis with a Muon Detector

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The Basic Atomic Energy Research Institute (BAERI) of Hanyang University in Korea constructed and operates a cosmic ray detection system. In this study, a muon detector composed of a plastic scintillator and a wavelength shifter was used to obtain data over a total of six experimental periods. Using the collected data, we analyzed the response dependence of the developed muon detector on the laboratory's environmental temperature. The detection results showed a correlation coefficient of over 0.7, as well as a negative proportional correlation in the experiments in which the thermostat did not operate. We performed a correction for the laboratory's environmental temperature and analyzed the correlation between the muon count rate and the atmospheric pressure. As a result, we obtained a barometric coefficient of -0.1191 ± 0.0054%/hPa. The analyzed data were compared with data from the eighteen NM64 type neutron monitors at our station. The correlation coefficient between the two detection systems was approximately 0.8046, confirming that the response changes were roughly identical to response of neutron monitors.

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I. INTRODUCTION

In recent times, research on cosmic rays has been actively undertaken because of increasing interest in the origins of cosmic rays, exposure doses from cosmic rays, and changes in the environment of Earth because of changes in space weather [1]. For example, a neutron monitor database was built, and 19 stations in 16 countries participated in this project with the aim of forecasting geomagnetic and radiation events by monitoring solar activity [2]. As regards the detection of muons, a global muon detector network, consisting of 33 muon detector systems, including telescopes, ionization cameras, hodoscopes, and carpets, at on-ground and underground sites is currently being operated.

The Basic Atomic Energy Research Institute (BAERI) of Hanyang University in Korea operates a cosmic ray detection system to analyze the influence of cosmic rays on the climate, monitor solar activity, and estimate the exposure dose from cosmic rays through measurement and analysis. BAERI's cosmic ray detection system consists of a neutron monitor, a muon detector and a data acquisition (DAQ) system. The detection system is installed inside the Korea Research Institute of Standards and Science in Daejeon, Korea (latitude 36.2 °N, longitude 127.2 °E, altitude 200 m, cutoff rigidity ∼11 GV).

This study analyzed the response characteristics of a newly developed muon detection system. Their characteristics are significantly influenced by environmental factors like temperature and pressure. As the response of the muon detector, comprising a photomultiplier tube (PMT) and a scintillator, depends on the temperature in the laboratory environment, temperature dependence analysis and correction was conducted for the experimental data [3]. In addition, for precise monitoring of the cosmic ray modulation, the barometric coefficient at atmospheric pressure was also analyzed.

If the muon detection system discussed in this study is utilized along with post processes to observe and analyze data on long-term modulations similar to the solar cycle (11 years) or short-term modulations such as the Forbush effect, the influence of cosmic rays on Earth's climate change and the effect of the dose from muons, which account for a majority of cosmic rays, can be studied. In addition, if this system is used with an integrated detection system, the responses from muons can be separated from the neutron monitor's cosmic ray detection data. Consequently, this system can contribute to the establishment of a more precise neutron detection system.

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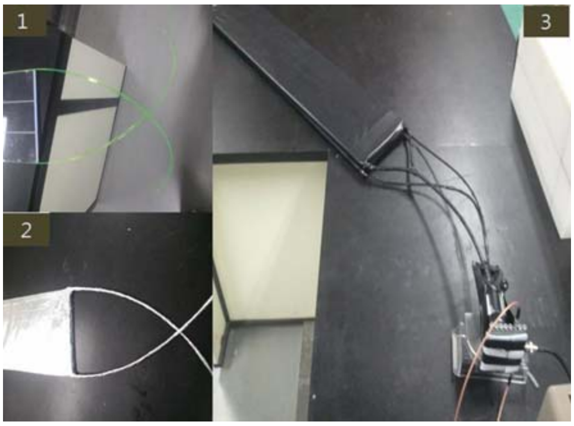

Fig. 1. (Color online) Schematic of the muon detector: (1) WLS attached to the scintillator, (2) scintillator and WLS wrapped with aluminum foil, and (3) detector wrapped with black sheet.

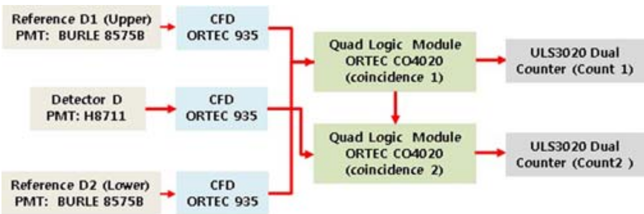

Fig. 2. (Color online) Experimental setup for determining the detection efficiency of the muon detector.

II. EXPERIMENTAL SETUP AND DATA ACQUISITION

The muon detector comprises a 1000 × 200 × 10 mm^3 plastic scintillator, a wavelength shifter (WLS), and a multi-anode photomultiplier tube (PMT) used for large areas and multi-channel detection systems. Data acquisition was performed using the developed detector and the coincidence method. In addition, analysis and correction for the experimental temperature dependence of the detection system and research based on the correlation between the atmospheric pressure and count rate were conducted.

A 1000 × 200 × 10 mm^3 BC-408 plastic scintillator produced by Saint-Gobain was used. The BCF-91 (2 × 2 mm^2 square type) WLS produced by Saint-Gobain for transmission of the induced photons was attached to the side of a scintillator. The plastic scintillator and the WLS were wrapped with aluminum foil as a reflector. A black sheet and tape were used to prevent the entrance of outside light. We used a Hamamatsu H8711 multi-anode PMT for reception of fluorescence.

As Fig. 1 shows, the WLS was attached to both sides of a plastic scintillator in the first step. Then aluminum foil and a black sheet were used to wrap the plastic scintillator for the reflection and blocking of light. Finally, the wrapped plastic scintillator and WLS were connected to the PMT by using a specific WLS holder.

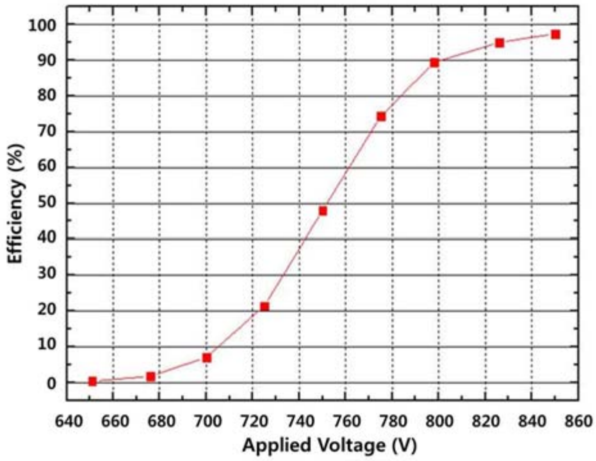

Fig. 3. (Color online) Correlation between efficiency and applied voltage.

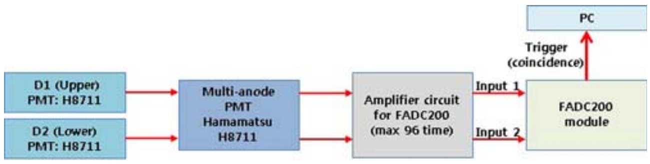

Fig. 4. (Color online) Diagram of setup for data acquisition.

The efficiency of the detector was obtained from the experimental setup shown in Fig. 2, and the change in efficiency caused by the applied voltage is shown in Fig. 3. In the efficiency experiment using the reference detectors with polymethyl methacrylate (PMMA) light guides, the applied voltage ranged from 650 V to 850 V in 25-V intervals. The efficiency of the developed detector is the ratio of the coincidence count rates obtained from all of the detector and coincidence count rates obtained from the reference detectors. The efficiency of the detector at the operation plateau region from 820 V to 840 V was calculated to be around 95% by using

$$\eta = \frac{C_{D \cap D_1 \cap D_2}}{C_{D_1 \cap D_2}}, \tag{1}$$

where η is the efficiency, $C_{D \cap D_1 \cap D_2}$'s the number of muons detected in D, D1, and D2 simultaneously, and $C_{D_1 \cap D_2}$'s the number of muons detected in D1 and D2 simultaneously.

In the detector and the signal process system setup shown in Fig. 4, a trigger process for the signal was performed with the coincidence method (coincidence width of 100 ns). We obtained the response spectrum shown in Fig. 5.

We placed the scintillator on another scintillator and acquired data. For 2 weeks, the mean count rate was approximately 82000 counts/h. In the case of a 1-m^2 area, the result was the same, with a count rate of ap-

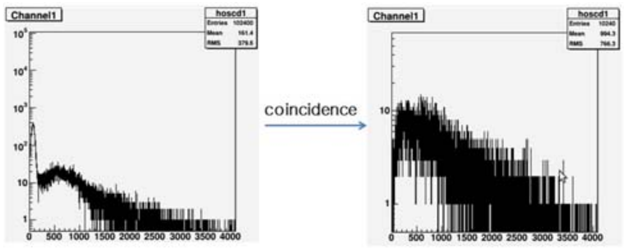

Fig. 5. Change of response spectrum with coincidence method: (x-axis: channel of flash-ADC, y-axis: number of signals).

Fig. 6. (Color online) Picture of the detection system with the prototype neutron monitor.

proximately 7000 counts/min. The expected measurement value of detected muons is approximately 9000 counts/min·m^2, so the obtained value was confirmed to be high enough to monitor muons by using the developed detector [3].

The data thereafter were acquired by placing muon detectors on the top and the bottom of the prototype neutron monitor. The experimental setup is shown in Fig. 6, and the data were collected and analyzed over a total of 6 experimental periods. The prototype neutron monitor consists of a 7.5-cm-thick polyethylene reflector, a 5-cm-thick lead producer, a 5-cm-thick polyethylene moderator and a He-3 proportional counter.

III. DATA ANALYSIS

1. Effect of Various Factors on the Response of the Muon Detection System

The response of the muon detection system is influenced by environmental factors such as the experimental temperature, the atmospheric pressure and humidity, and the noise in the electronics. In this study, the atmospheric pressure and the laboratory environmental temperature dependences of the detection system were analyzed quantitatively, and a data correction for temperature was performed.

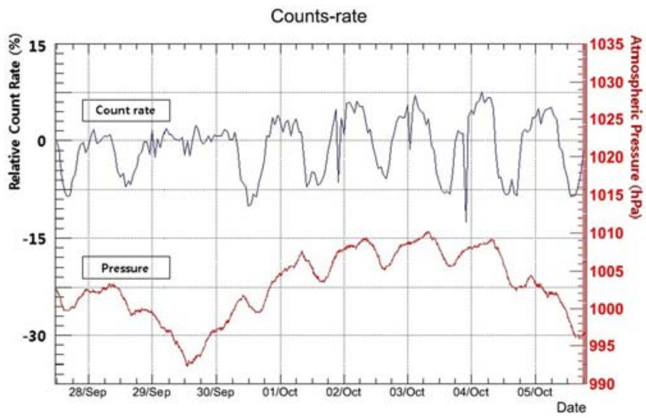

Fig. 7. (Color online) False correlation between count rate and atmospheric pressure from 27 Sep. to 5 Oct. (local time).

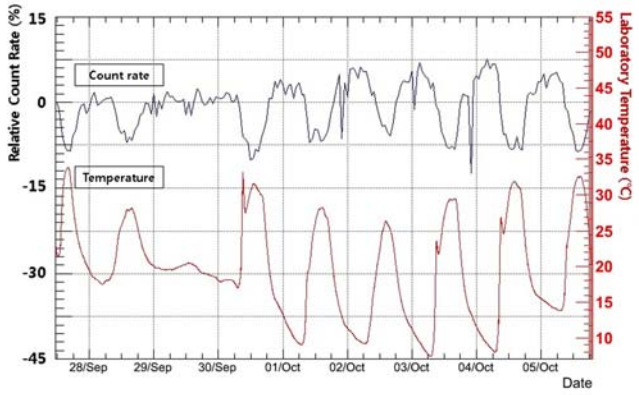

Fig. 8. (Color online) Count rate and laboratory's environmental temperature from 27 Sep. to 5 Oct. (local time).

With regard to a muon detector made of a PMT and a scintillator, a dependence of the response on the laboratory environmental temperature can exist. In the case of a large variation in the temperature, a lower gain of the detection system at relatively high temperatures needs to be addressed [3,4]. In Fig. 7, detection results from 27 Sept. to 5 Oct. show that the count rate was relatively low at low atmospheric pressure. The reason for this effect was a lack of correction for the laboratory environmental temperature. Due to the variation of temperature, a gain change in the detection system was responsible for a direct proportional relationship between the count rate and the atmospheric pressure. We analyzed the correlation between the laboratory environmental temperature and the count rate with the chi-squared test. The p-value for the experimental period was less than 0.01 (significance level 1%), so we confirmed that the correlation between the experimental temperature and the count rate was valid. The dependence of the count rate on laboratory environmental temperature was analyzed quantitatively.

Figures 8 and 9 show a correlation between the count rate and the laboratory environmental temperature. As

Table 1. Dependence of the response of the muon detector on the laboratory's environmental temperature.

Period	Number of entries (hour unit data)	Slope (%/°C)	Correlation coefficient
10 Aug. – 29 Aug.	376	−0.3674 ± 0.01955	0.71
29 Aug. – 05 Sep.	171	−0.4814 ± 0.01036	0.96
05 Sep. – 15 Sep.	238	−1.1050 ± 0.01646	0.97
27 Sep. – 05 Oct.	199	−0.5968 ± 0.02154	0.89
11 Nov. – 25 Nov. (Detector 1)	333	−0.5397 ± 0.02123	0.82
11 Nov. – 25 Nov. (Detector 2)	332	−0.4908 ± 0.02038	0.80

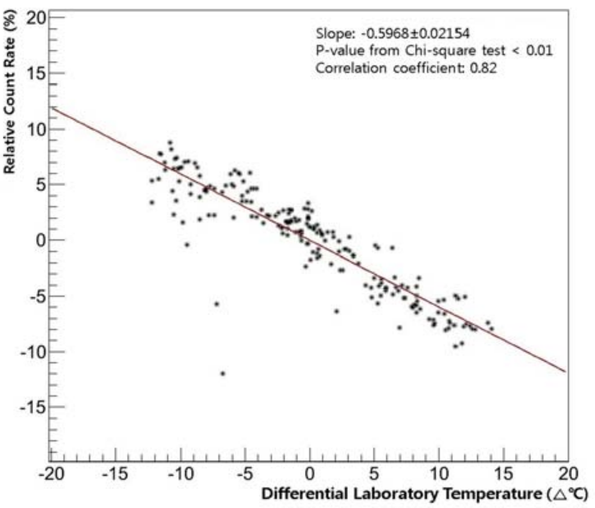

Fig. 9. (Color online) Correlation between count rate and laboratory's environmental temperature from 27 Sep. to 5 Oct. (local time).

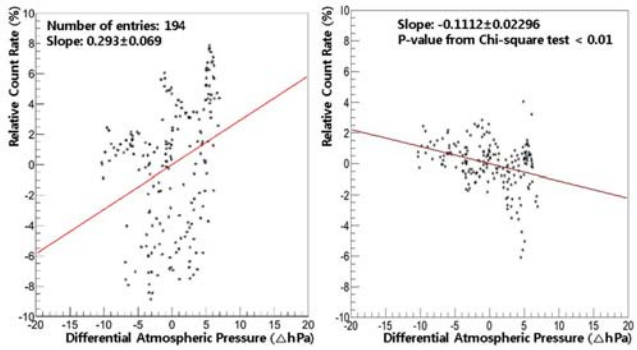

Fig. 10. (Color online) Correlation between count rate and atmospheric pressure (left: uncorrected for temperature; right: corrected for temperature) from 27 Sep. to 5 Oct. (local time).

shown in Fig. 8, the count rate was confirmed to be was lower at higher temperature. For the correction, we plotted the count rate and the temperature. Figure 9 shows that the count rate was inversely proportional to the temperature; the slope of the fitted curve indicates the degree of dependence.

$$\frac{\Delta I}{I} = \alpha \Delta T. \qquad (2)$$

The linear value of α over a total of 6 experimental periods are listed in Table 1 and were used to correct for unstable laboratory environmental temperatures.

The correlation between the count rate and atmospheric pressure is also a very important factor. The reason for an intensity change caused by the atmospheric pressure is simple. Because the atmosphere acts as an absorber for muons, a period of high pressure is associated with more absorption above the detector and a lower count rate [3,5-7]. The barometric coefficient, which is the dependence on the atmospheric pressure, is influenced by the cut-off rigidity because of geological factors such as latitude, longitude, and altitude. This value is usually from −0.1%/hPa to −0.2%/hPa for muon detectors [1,8]. We confirmed the correlation with the atmospheric pressure by using a temperature dependence analysis and correcting the data. Empirically, the value of the barometric coefficient can be found by means of a linear correlation between the intensity and the atmospheric pressure data [9]. Figure 10 shows the response change caused by the temperature correction. The barometric coefficient changed from 0.293%/hPa to −0.1112%/hPa.

In Table 2, the slope from fitting and the mathematically calculated slope of each period are shown. The results from 27 Oct. to 11 Nov. do not need to be corrected because the thermostat operated normally. However, correction was performed for the other 5 results. As a result, the slope from fitting and the mathematically calculated slope were almost the same. We collected all data over all periods and analyzed the correlation between the atmospheric pressure and the relative count rate. The obtained slope was −0.1191 ± 0.0054%/hPa, as shown in Fig. 11.

For the Bess-95 data obtained at cutoff rigidity of 11.4 GV (Tsukuba, Japan), the barometric coefficient was −0.12 %/hPa with a 0.3-GeV/c threshold momentum [10]. This result is almost the same as our result at

Table 2. Barometric coefficients of the muon detector.

Period	Number of entries (hour unit data)	Slope by fitting (%/hPa)	Mathematically calculated slope (%/hPa)
10 Aug. – 29 Aug.	376	−0.1964 ± 0.02326	−0.1965
29 Aug. – 05 Sep.	171	−0.0309 ± 0.00164	−0.0307
05 Sep. – 15 Sep.	238	−0.1646 ± 0.01295	−0.1647
27 Sep. – 05 Oct.	199	−0.1112 ± 0.02296	−0.1113
27 Oct. – 11 Nov.	351	−0.0623 ± 0.01397	−0.0601
11 Nov. – 25 Nov. (Detector 1)	333	−0.1055 ± 0.01004	−0.1055
11 Nov. – 25 Nov. (Detector 2)	332	−0.0875 ± 0.01022	−0.0875

Table 3. Barometric coefficient of the BAERI muon detector and Bess-95 data in Tsukuba.

	Latitude (°N)	Longitude (°E)	Altitude (above sea level, m)	Cut-off rigidity (GV)	Barometric coefficient (%/hPa)
Bess spectrometer	36.2	140.1	30	11.4	−0.12
Developed detector	36.2	127.2	200	∼11	−0.119 ± 0.0054

Table 4. Specifications of the NM 64 type neutron monitor.

NM64 neutron monitor			
BP 28 neutron detector		Structural element	
Diameter (cm)	14.8	Moderator	2-cm thickness polyethylene
Length (cm)	191		
Gas Type	BF_3, 96% enriched ^{10}B	Reflector	7.5-cm thickness polyethylene
Operating Voltage (V)	2800		
Pressure (mmHg)	200	Producer	156 g·cm^{-2} depth lead

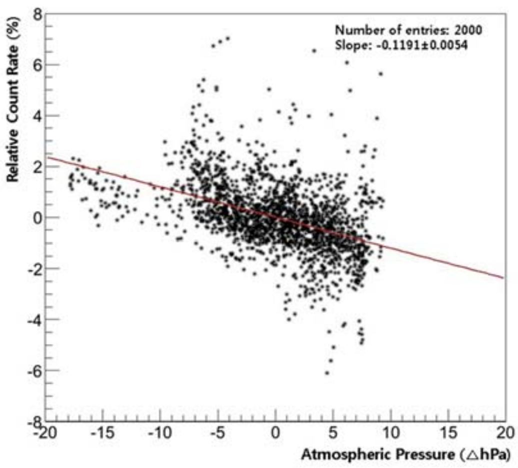

Fig. 11. (Color online) Correlation between count rate and atmospheric pressure over all experimental periods.

around 11 GV (Daejeon, Korea), so we have confirmed that the value obtained by using the developed detector is in agreement with other findings. The barometric coefficient of the developed detector is also similar to that of a muon detector in another region [11].

2. Comparison with the NM64 Type Neutron Monitor

If the data from the developed muon detector are corrected by using the barometric coefficient, the variation of the count rate becomes smaller, confirming that the modulation of muon intensity is difficult. Therefore, we compared uncorrected data for pressure with data from a worldwide eighteen NM64 type neutron monitors at our station. The NM64-type neutron monitor has a higher detection efficiency compared with the IGY-type conventional monitor for cosmic neutron detection. The specifications of the installed neutron monitor are summarized in Table 4.

Figure 12 shows a response comparison of the neutron monitor and the developed muon detector. The count rate of the muon detector became relatively high or low at some points, but the responses of the detectors were roughly identical. The uncertainty of some points of unstable count rate can be reduced by using an improved DAQ system and developing a detector with larger area. The count rates of detectors operating at the same time are plotted in Fig. 13. From these data, we obtained a value of 0.8046 for the correlation coefficient. The correlation coefficient between the neutron monitor and the

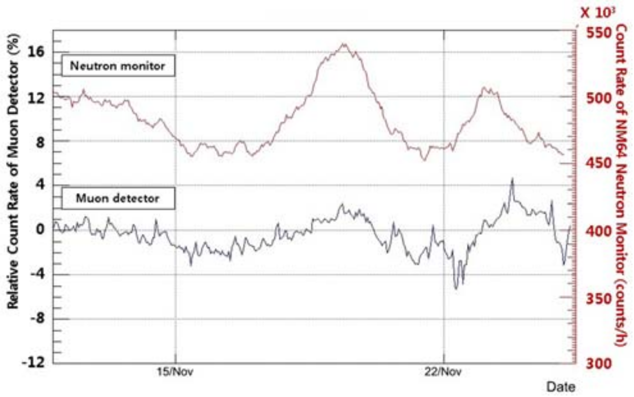

Fig. 12. (Color online) Response changes of the muon detector and the 18-NM64 type neutron monitor.

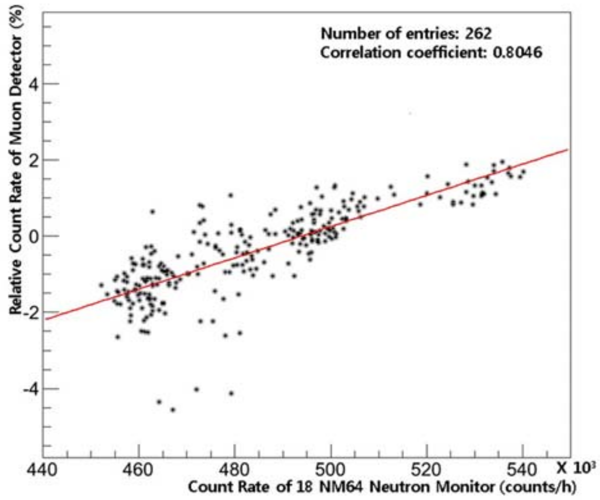

Fig. 13. Response comparison of the muon detector with the neutron monitor from 11 Nov. to 22 Nov. local time.

muon detector is slightly small, so the muon detection system needs to be improved. However we confirmed the feasibility of the developed detection system.

IV. CONCLUSION

In this study, a $1000 \times 200 \times 10$ mm^3 scintillator and a WLS were used to develop a muon detector, and the coincidence method was used to collect data over a total of six periods. Acquired data were used to analyze and correct the temperature dependence of the detection system, and it was confirmed that the erroneous correlation with the atmospheric pressure was confirmed to have been corrected. The correlation between the data collected over a total of six experimental periods and the atmospheric pressure was analyzed, and a barometric coefficient of -0.1191 ± 0.0054%/hPa was obtained. This value could be used to compensate for the cosmic muon intensity that was measured to monitor cosmic rays. The results of using the muon detector for monitoring were compared to those of the eighteen NM64 type neutron monitors installed at the same location. The count rate of the neutron monitors was confirmed to match the count rate of the muon detector with a correlation coefficient of 0.8046. Further improvement seems to be in order. With regard to the muon-detector data, it seems that the uncertainty in the count rate that occurred during the measurement period can be reduced by improving the DAQ system. If a large-area detection system is constructed, the correlation with the atmospheric pressure is expected to be more clearly observable.

Developing the muon detector system, analyzing the temperature dependence, correcting the detection system, and acquiring the barometric coefficient allowed us to assess the detector's applicability to independent monitoring of solar activity. If this system is applied to an integrated detection system to remove the influence of muons on the neutron monitor, it can contribute to the establishment of a more precise neutron detection system.

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