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A novel 2-dimensional cosmic ray position detector based on a CsI(Na) pixel array and an ICCD camera

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Abstract: A novel 2-D cosmic ray position detector has been built and studied. It is integrated from a CsI(Na) crystal pixel array, an optical fiber array, an image intensifier and an ICCD camera. The 2-D positions of one cosmic ray track is determined by the location of a fired CsI(Na) pixel. The scintillation light of these 1.0×1.0 mm CsI(Na) pixels is delivered to the image intensifier through fibers. The light information is recorded in the ICCD camera in the form of images, from which the 2-D positions can be reconstructed. The background noise and cosmic ray images have been studied. The study shows that the cosmic ray detection efficiency can reach up to 11.4%, while the false accept rate is less than 1%.

Key words: cosmic ray 2-D position, CsI(Na) crystal pixel array, optical fiber array, image intensifier, ICCD camera

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1 Introduction

Cosmic rays are a natural high energy particle source, which not only provide physical information about the Universe, but also offer good methods for studying the performances of various particle detectors, such as track detectors and energy detectors. It is very economical and convenient to use cosmic rays to calibrate the time resolution, spatial resolution and energy resolution of particle detectors. Such a system is called a cosmic ray test system. Its crucial functions are tracking, positioning, and triggering. There are many types of traditional particle detectors used for cosmic ray tracking, such as drift tube, plastic scintillator, and RPC [1, 2]. Recently, the CsI(Na) crystal pixel array has become one of the prospective candidates for particle positioning. In addition, the high performance intensified charge coupled device (ICCD) camera has proven to be a powerful tool in low light detection, even for single photon detection. Therefore, a novel 2-D cosmic ray position detector consisting of one CsI(Na) pixel array and one ICCD camera system has been studied in this paper.

2 Methods

The detector is made of one CsI(Na) pixel array, one optical fiber array, one image intensifier, one ICCD camera, and a triple trigger system, as shown in Fig. 1.

2.1 The CsI(Na) pixel array

CsI(Na) crystal has a relatively high light output (85% of that of NaI(Tl)), which is the most important factor to be considered for an ICCD detection method. In addition, the deliquescence of CsI(Na) in

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air is substantially lower in comparison with that of NaI(Tl). Its decay time varies in the range of 500–700 ns [3]. Fig. 2 shows the CsI(Na) crystal pixel array used in the test.

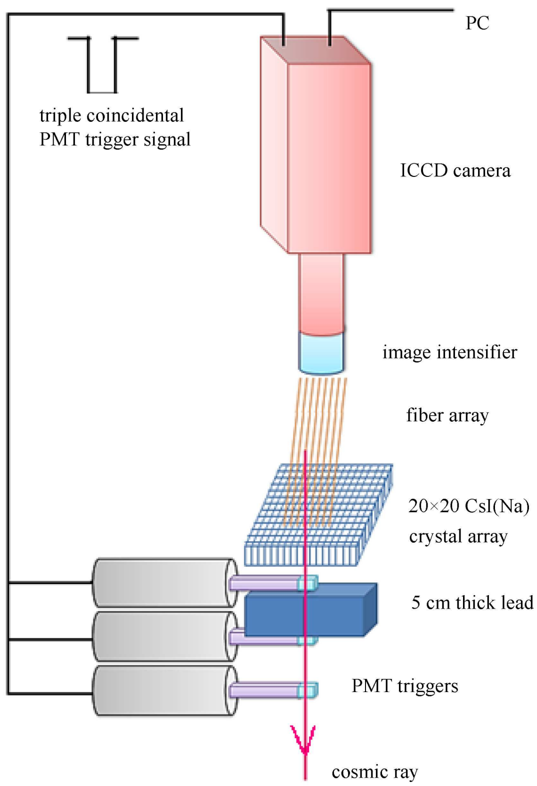

Fig. 1. The cosmic ray test system. The 5 cm thick lead is used to veto cosmic rays of energy lower than 80 MeV.

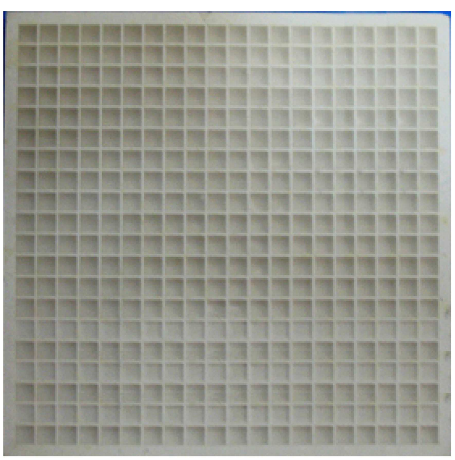

Fig. 2. The 20×20 CsI(Na) pixel array. Each pixel sizes 1 mm×1 mm×2 mm, the adjacent gaps are filled with 0.1 mm thick TiO_2 as the light reflection material.

The CsI(Na) pixel array is 2 mm thick. The energy deposition has been simulated by GEANT4. As shown in Fig. 3, about 1 MeV energy would be deposited, which corresponds to the light yield of about 40000 photons.

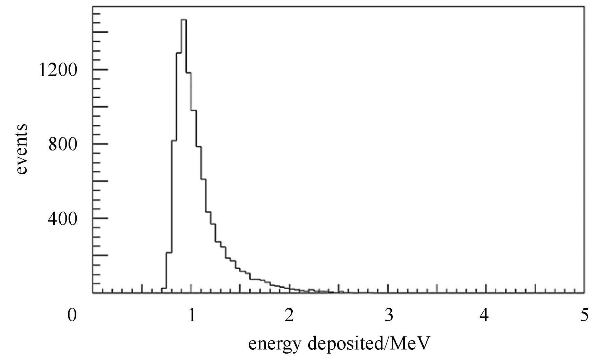

Fig. 3. The energy deposition in a 2 mm thick CsI(Na) pixel, simulated by GEANT4 with 300 MeV incident muons.

2.2 The optical fiber array

The optical fibers are used to deliver the scintillation light from CsI(Na) pixels to the image intensifier. Since the sensitive area of the image intensifier is limited, the diameter of the fiber should be small enough to image all of the pixels on the CsI(Na) array.

Currently, a 30 cm long, 14×14 fiber array has been assembled. One end is coupled to the crystal pixel array by placing each fiber at the center of its corresponding pixel. Thus, the incident position of the comic ray can be reconstructed by the X and Y values of this pixel center. The other end of the fiber is attached to the surface of the image intensifier.

However, there are two restrictions on light collection efficiency when fibers are used as the light delivery media. One is the reduced effective connection area between the crystal and fiber. For the 0.5 mm diameter fiber, the coverage is less than 1/5 of the whole cross-section of one crystal pixel. The other is the small light acceptance angle, which depends on the index of refraction of the fiber core material and cladding material. For the fiber used in this detector, it is 60 degrees. In all, a large part of scintillation light will be lost during fiber delivery.

2.3 The light multiplication

The most important feature of an ICCD camera is the image intensifier, which is placed in front of the CCD chip to enhance its light detection capability. The image intensifier typically comprises three main components: a photocathode, a micro-channel plate (MCP), and a phosphor screen.

In the test, one external image intensifier is placed in front of the ICCD camera lens to further improve the light detection sensitivity of the system. This

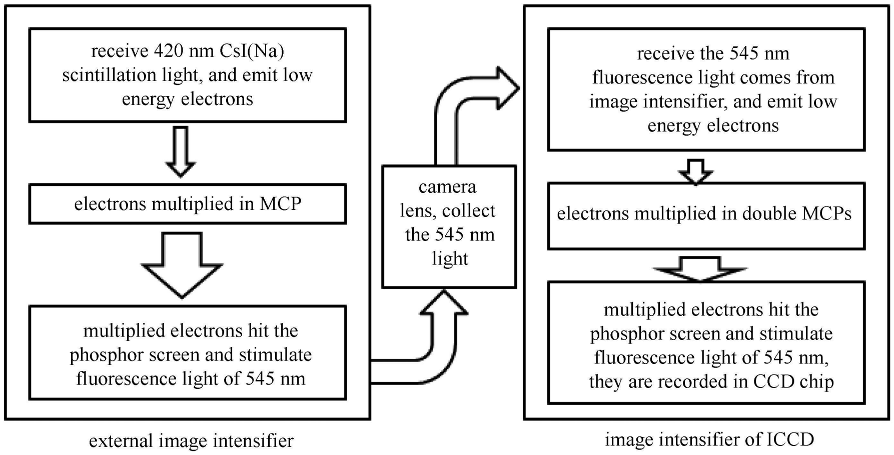

Fig. 4. The scheme of the photon-electron transition and light multiplication inside the two image intensifiers.

external image intensifier has one MCP, while the internal image intensifier inside the ICCD camera has two MCPs. The photocathode of the former is made from S25 material, whose peak sensitivity reaches around 750 nm. The photocathode of the latter inside the ICCD is S20, which has the highest detection efficiency at the wavelength of 450 nm. In addition, both image intensifiers have a sensitive area of 18 mm in diameter.

In such a configuration, the external image intensifier is used to receive and magnify the CsI(Na) scintillation light at the first stage. The ICCD is used to further multiply the light and finally records the light information on a computer in the form of digital images. The photon-electron transition and light multiplication processes are shown in Fig. 4, the total multiplication is about $1000\times1000000=10^9$ times.

2.4 The trigger system

In order to correctly record a cosmic ray, it is necessary to provide a trigger for the ICCD camera shutter. The trigger comes from the coincidence of the three plastic scintillators signals, and gives the incident time of the cosmic ray. Each scintillator has the size of 1 cm×1 cm×0.5 cm, and is coupled with a 10 cm long light guide. The three scintillators are aligned perpendicularly, as shown in Fig. 1.

The CsI(Na) crystal array is placed closely on the surface of the top scintillator. Before opening the shutter, the trigger has already been delayed for about 300 ns, which is the total time spent inside the whole electric device.

Since the size of each plastic scintillator is smaller than the imaging area of the CsI(Na) pixel array, each triggered cosmic ray image in the ICCD must pass through the CsI(Na) pixel array.

3 Results and discussion

3.1 The background noise

The potential noise sources of the detector include the intrinsic shot noise (sometimes called input or photon noise), dark current noise, and readout noise [4]. They can contaminate cosmic ray images. So, it is very important to get a clear understanding of the background noise.

The background noise can be studied through the 3300 images acquired under the ICCD self-trigger mode. In such case, the rate of image acquisition is 33.8fps (frames per second). Each ICCD image contains 780×580 pixels and the energy range for every pixel varies from 0 to 4096 ADCs. All of the analog-to-digital procedures for each image pixel are processed independently through a chip located inside the ICCD camera. Fig. 5 shows the ADC

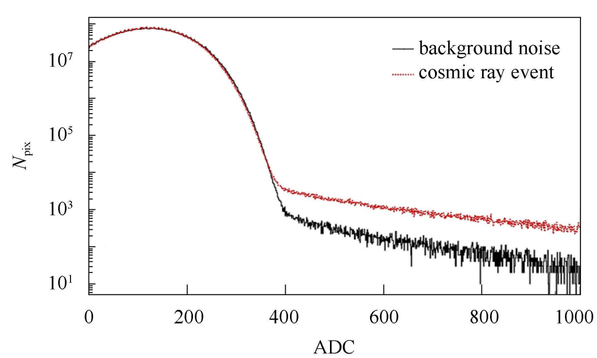

Fig. 5. The ADC distribution of 3300 background noise and cosmic ray images. $N_{\rm pix}$ is the total number of ICCD pixels on 3300 images at a given ADC value. The black bold line represents the background noise signal, and the dashed red line represents the cosmic ray signal.

distribution of all of the ICCD pixels on 3300 images (780×580×3300 pixels in total) for the background noise and the cosmic ray signals separately.

A detailed study of the background noise has been done. At first, the locations and occupation areas of each fiber on the ICCD images have been calibrated. The occupied areas are important for data analysis. The total number of ICCD image pixels covered by one fiber area is about 700. The number of luminous ones of these 700 pixels is defined as $N_{\rm hit}$, which is another important cut besides the ADC threshold. It is found that the ADC threshold has a close relationship with $N_{\rm hit}$, shown in Fig. 6. In it, the ADC varies from 350 to 550, and the $N_{\rm hit}$ changes from 2 to 15. The false event rate (FER) is defined as:

$$\mathrm{FER} = N_{\rm FE}/N_{\rm Total}.$$

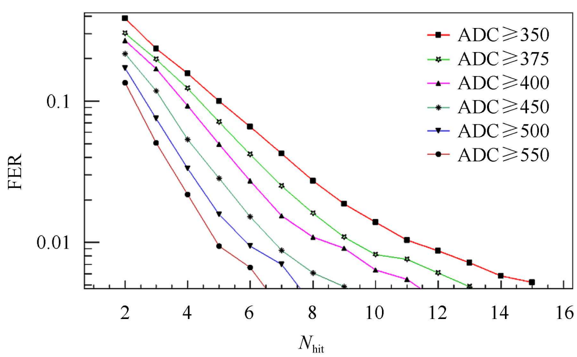

Fig. 6. The FER for various ADC thresholds and $N_{\rm hit}$ values.

The $N_{\rm FE}$ is the number of false events (in this test, one image can also be called one event). That is the number of ICCD background images, each of which contains at least one luminous fiber area, in which the number of luminous pixels with ADC value greater than a given threshold is larger than a cut value $N_{\rm hit}$, therefore, such background images are falsely accepted as cosmic ray images. The $N_{\rm total}$ is the total number of background noise images used in analysis, for this calculation, it is 3300.

From Fig. 6, for a given $N_{\rm hit}$, the FER decreases while the ADC threshold increases. Meanwhile, for a given ADC threshold, FER also decreases while $N_{\rm hit}$ increases. Generally, a low FER is required. In this test, we make it less than 1%. Thus, if the ADC threshold is chosen to be 450, then a suitable candidate for $N_{\rm hit}$ is 7.

3.2 The ICCD light response

It is important to know the light response properties of the image intensifier and the ICCD camera system. The response limitation of such a detector is the minimum number of incident photons onto the image intensifier. Fig. 7 illustrates the test system used to determine the light response threshold. An LED light source powered by pulse generator was applied to provide the 420 nm light, which is the same as CsI(Na) scintillation light.

The pulse generator is modulated in such a way that the number of photons arriving to the image intensifier varies from 4 to 300 (derived from the number of photons detected by XP2020, its quantum efficiency at 420 nm is 24.8%). The experiment shows that when there are less than 40 photons, the ICCD will not give clear signal images. If the number of photons is increased up to 80, the number of luminous pixels is less than 45. When the incident photons are increased up to 300, the number of luminous pixels is no more than 65. Both of the above results are obtained when the ADC threshold is set to 350.

3.3 The Sr-90 test

In order to verify that the deposited energy of 1 MeV in 2 mm CsI(Na) crystal works for ICCD light detection, a ^{90}Sr radioactive source test has been done. One CsI(Na) crystal pixel is wrapped with Teflon on the four side faces, and ^{90}Sr is placed at one end of it. We replace the pulse generator and LED with the ^{90}Sr and CsI(Na) pixel in Fig. 7 and keep the other end of the crystal coupled to the optical fiber.

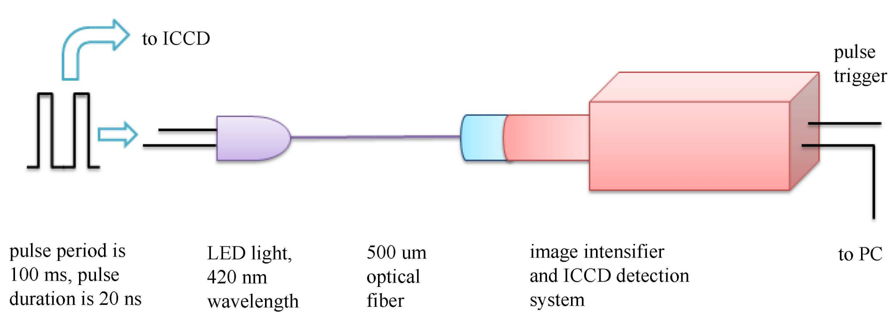

Fig. 7. Scheme of the light response test. The pulse drives the LED and also provides the trigger for the ICCD shutter.

Because the maximum energy of the ^{90}Sr continuous decay is about 2.3 MeV, it is good enough to simulate the cosmic ray due to the similar typical energy deposition in CsI(Na) crystal. Among all the acquired ICCD images, those containing very clear luminous pixels directly demonstrate that the 2 mm thickness of CsI(Na) is capable of light detection. But most of them are less weak signals due to the smaller incident energy of ^{90}Sr.

3.4 The cosmic ray images

The configuration of the cosmic ray detection system is shown in Fig. 1. The ICCD camera is set to output trigger mode. The average image rate is about 0.3/min, and 3300 ICCD images have been acquired during the whole test.

We apply the same methods that have been used for background noise in Section 3.1 in analyzing cosmic ray images. The results of good image selection efficiency are shown in Fig. 8. It is reasonable that the efficiency decreases as $N_{\rm hit}$ increases. Since the FER and efficiency have the similar trend, a low FER will correspond to a low selection efficiency. If the FER is chosen to be 0.88% (obtained when ADC@450 and $N_{\rm hit}$@7 from Fig. 6), the corresponding cosmic ray selection efficiency will be 11.4%.

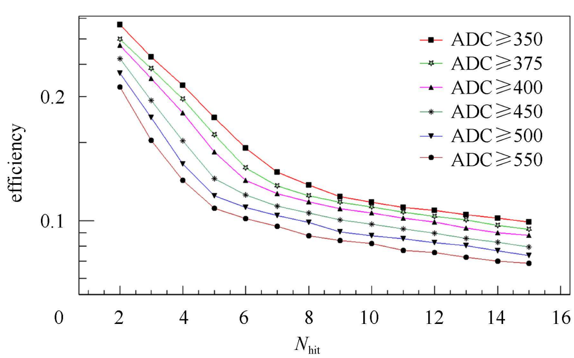

Fig. 8. The cosmic ray selection efficiency for different ADC thresholds and $N_{\rm hit}$ values.

4 Conclusion and discussion

In this paper, we have discussed the performance of a novel cosmic ray detector integrated from an ICCD, an image intensifier, a fiber array, and a CsI(Na) pixel array. The incident cosmic ray position is determined by the location of the fired CsI(Na) crystal pixels. Currently, the position resolution reaches 0.32 mm (crystal size 1.1 mm/$\sqrt{12}$). If further reducing the cross-section size of the CsI(Na) crystal pixel, the resolution would become better. The maximum image rate of this system is 33.8 fps, which is limited by the ICCD camera. By coupling the fiber-optic taper between the fiber array and the image intensifier, the CsI(Na) pixel array can be scaled up to 200×200 or even larger. In addition, it is also possible to reconstruct the 3-D track of cosmic ray by combining two or more CsI(Na) arrays together in the future.

However, the detection efficiency of this novel detector at present is not very high. The main reason is that a large number of scintillation photons have been lost during the fiber delivery. There are two ways to improve this detection efficiency. One is to use a more matched image intensifier which has higher quantum efficiency at the wavelength of 420 nm and lower dark noise performance. The other method is to increase the thickness of the CsI(Na) crystal pixel array. The increased energy deposition in the CsI(Na) pixel will yield more scintillation light. Thus, more photons will be delivered onto the surface of the image intensifier if assuming the light lost keeps the same.

References

1 SHANG Lei, CAI Xiao, WANG Man et al. HEP & NP, 2007, **177**: 182 (in Chinese)

2 Cunningham T J, Mazed M, Holtzman M J et al. SPIE, 1948, **15**: 22

3 SUN Xi-Lei, LÜ Jun-Guang, HU Tao et al. Chinese Physics C (HEP & NP), 2011, **35**: 1133

4 Dussaulta D, Hoess P. Proceedings of SPIE, 2004, **195**: 204