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An underground cosmic-ray detector made of RPC

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Abstract

Owing to its high efficiency, low cost and low sensitivity to environmental gamma-rays, resistive plate chamber (RPC) is a good candidate for large area underground cosmic-ray detectors. We report in this paper such a design for the Daya Bay reactor antineutrino experiment based on calculations and simulations for the efficiency, dead space control, noise and gamma-ray backgrounds. Experimental tests are performed, and good agreements with calculations and simulations are obtained, showing that the design is appropriate.

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Keywords: RPC; Cosmic-ray; Muon detector; Daya Bay experiment

1. Introduction

Resistive plate chamber (RPC), which is composed of two resistive plates with gas flowing between them, has been originally developed by Santonico in the early 1980s [1] and has been widely used in many particle physics experiments. The typical structure is that there is a 2-mm-thick gap ensured by the spacers between two 2-mm-thick resistive plates [2]. It has been used in the recent B-factory experiments (BaBar [3], BELLE [4]) and adopted in the trigger system of the LHC experiments (ALICE [5], ATLAS [6], CMS [7]), and it was also chosen by BESIII MUON [8] system as its active detector, operated in streamer mode [9–11].

Low background particle physics experiments are often required to be underground to shield cosmic-rays. Remaining muons passing through rocks sometimes need to be further shielded actively by a large area cosmic-ray detector. Such a detector should consider cost issues since the area is large, noise issues since cosmic-muon rate is low in underground lab and special environmental issues including humidity, gamma-ray backgrounds from rock and radon, etc.

RPC is a good candidate for large area underground cosmic-ray detector since it has a high efficiency, low cost and is insensitive to environmental gamma-rays from nearby rocks. Plastic scintillator is a possible choice, but it is relatively expensive and more sensitive to gamma-rays. While liquid scintillator has a low cost, its high sensitivity to gamma-rays and mechanical difficulties prevent it to be chosen as the candidate. For above reasons, the Daya Bay reactor antineutrino experiment chooses RPC as the muon veto detector [12], with design considerations to be discussed in the following.

The goal of the Daya Bay reactor neutrino experiment is to determine the neutrino mixing angle $\sin^2 2\theta_{13}$ with a sensitivity of 0.01 at 90% CL, an order of magnitude better

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than the current limit. Since most of the backgrounds come from the interactions of cosmic-ray muons with nearby materials [12], it is desirable to have a very efficient active muon detector coupled with a tracker for tagging the cosmic ray muons. Hence, RPCs and water Cherenkov detector are planned to efficiently detect cosmic-muons and cross check with each other.

According to the design, the experiment employed at the near (far) site two (four) antineutrino detector modules with a radius and half height of 2.5 m. The neutrino signal events of inverse beta decay reactions have a distinct signature: a prompt positron signal followed by a delayed neutron-capture signal. However, there are three important sources of backgrounds: fast neutrons produced by cosmic-muons in materials surrounding the antineutrino detector modules, $^8He/^9Li$ produced by cosmic-muons in the antineutrino detector modules and accidental coincidence of natural radioactivity. Simulation and calculation show that the background-to-signal ratio will be less than 0.6% (0.4%) at near (far) site, assuming a muon efficiency of 99.5%, as shown in Table 1 [12].

2. Design of RPC veto detector

In order to satisfy the requirements of Daya Bay experiment, the RPC muon detector should have high efficiency, low noise, low backgrounds and few dead spaces. The coverage area of RPC for the far (near) site is 18 m × 18 m (12 m × 18 m). A modular structure is planed with a dimension of 2 m × 2 m as shown in Fig. 1.

Table 1
Neutrino event rate, cosmic ray flux and background

	DYB site	LA site	Far site
Overburden (m)	98	112	350
Antineutrino rate (/day/module)	930	760	90
Cosmic-muon flux (Hz/m^2)	1.16	0.73	0.041
Accidental/signal (%)	<0.2	<0.2	<0.1
Fast neutron/signal (%)	0.1	0.1	0.1
$^8He^9Li$/signal (%)	0.3	0.2	0.2

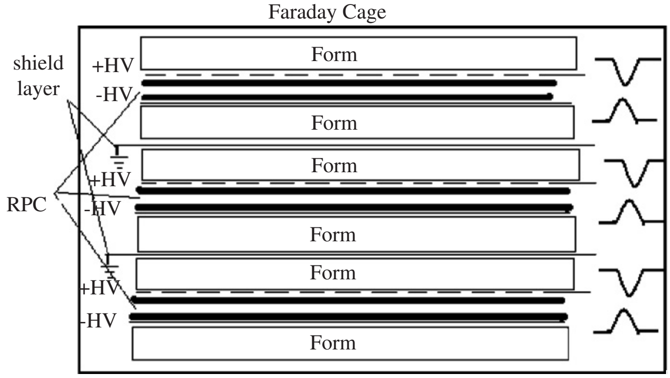

Fig. 1. Sketch of the two-dimensional readout of an RPC module structure.

The RPCs that we plan to adopt are developed by Institute of High Energy Physics (IHEP), Chinese Academy of Sciences, for the BESIII detector and are made of a new type of bakelite plate without linseed oiled coating [9–11]. The efficiency can reach up to 98% and the noise is about 0.08 Hz/cm^2. The RPCs work in the streamer mode at a high voltage of 8 kV (one side +4 kV and the other side −4 kV) with a gas mixture of argon:freon (F134a): isobutane = 50:42:8 [9]. In order to track muons with a reasonable position precision while keeping the cost low enough, we adopt two-dimensional readout for each layer as seen in Fig. 1. There are three layers in one module, and each layer has one single-gap RPC.

A majority coincidence of two fired layers out of three layers is defined as a muon hit, which has a right balance among the muon detection efficiency, the accidental coincidence and gamma-ray backgrounds, the cost and the reliability. In the following sections, we discuss the expected performance of RPC for such a design.

2.1. Efficiency

The efficiency of a single layer of RPC, $\varepsilon_{\mathrm{eff}}$, can typically reach 98% [9]. Here we assume it to be 95%, the coincident efficiency of two fired layers out of three is

$$\varepsilon = \varepsilon_{\mathrm{eff}}^3 + C_3^2 \varepsilon_{\mathrm{eff}}^2 (1 - \varepsilon_{\mathrm{eff}}) = 0.95^3 + 3 \times 0.95^2 \times (1 - 0.95) = 99.3\%.$$

Associated with water Cherenkov detector (the efficiency is more than 95% [13]), it can satisfy the efficiency requirement discussed above.

2.2. Dead space

Owing to edge sealing strips, gas feedthroughs, high voltage cables, etc., the RPCs have 3 cm (1 cm)-wide dead space in the side with (without) gas feedthough. In order to minimize the dead space, the sizes of RPCs in three layers of a module are designed to be 1.1 m × 2 m, 0.9 m × 2 m, and 1.0 m × 1.0 m, respectively. They are staged as shown in Fig. 2. Modules are also staged with an overlapping width of about 3 cm as shown in Fig. 3.

In order to find out optimum overlap between modules, we simulate efficiencies of different module arrangements. Assuming the single RPC efficiency of 95%, the combined efficiency as a function of overlapping width is shown in

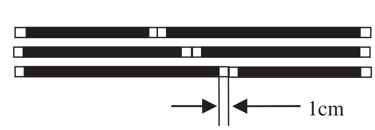

Fig. 2. Sketch of RPC assembly for module. The black is effective area, while the white is dead space.

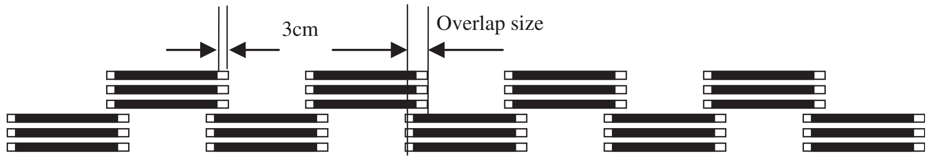

Fig. 3. Sketch of modules assembly in one axis. In other axis, all modules have a small slope in order to keep the overlap. In the figure, black area is effective while the white is dead space.

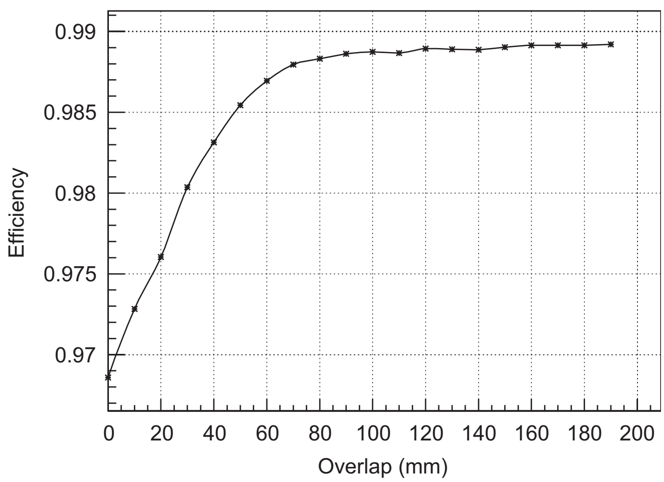

Fig. 4. The combined efficiency of two out of three as a function of the overlap size.

Fig. 4 from a Monte Carlo simulation, taking into account the angular distribution of cosmic-rays at far site. The maximum combined efficiency of two out of three can reach up to 98.9% for an overlap more than 10 cm.

2.3. Noise

The noise rate of a single layer RPC is typically less than 1000 Hz/m^2 [9]; the random coincidence of two out of three layers can be expressed as

$$R = \frac{1}{T}\sum_{m=2}^{3} mC_n^m (kAT)^m (1-kAT)^{n-m}$$

where the time coincidence window T can be taken as 100 ns, k is the single counting rate of RPC (Hz/m^2), A is the area of a module (m^2). Ignoring the higher order items, the accidental coincidence is 0.6 A^2 Hz/module, or 9.6 Hz/module.

In addition, the three-fold accidental coincidence is

$$R = \frac{1}{T} \times 3C_3^3 (kAT)^3 = 3 \times 10^{-5}\ \mathrm{A}^3\ \mathrm{Hz/module},$$

or 0.00192 Hz/module.

2.4. Gamma-ray backgrounds

Rocks are usually very radioactive. Typical granite at the Daya Bay site contains 10 ppm of ^{238}U, 30 ppm of ^{232}Th and 5 ppm of ^{40}K. In order to estimate the gamma-ray background, a GEANT4 simulation with geometry that there are three layers of RPC under granite rock is performed. Since the attenuation length of rocks to typical gamma-rays is ~7 cm, the thickness of rock in the simulation is chosen to be 50 cm, while the RPC is made of two bakelite plates with a thickness of 2 mm and a gas gap of 2 mm.

Gamma-rays from ^{238}U, ^{232}Th and ^{40}K are generated uniformly in the rock and a signal is an electron reaching the gas gap of RPC. The total gamma-ray background from the simulation is 3.5 Hz/m^2, 14 Hz/module for the criteria of two fired layers out of three, mainly due to double Compton scattering, and less than 0.008 Hz/m^2 or 0.03 Hz/module for three layers in coincidence due to multiple Compton scattering, while the average rate of only one single layer is about 236 Hz/m^2, or 2830 Hz/module for all the three layers.

Since the accidental coincidence rate for two out of three is 9.6 Hz/module, while the gamma background is 14 Hz/module, and the muon flux is 0.16 Hz/module at far size, the total trigger rate of 81 modules at far site is about 2 kHz, which can be easily handled by our data acquisition system. For cross check with water, Cherenkov detector, a more clean muon signal, adopting three-fold coincidence with a muon purity of 83% can be used.

3. Test results

In order to check the results from previous calculations and simulations, the coincident noise and gamma background of an RPC module has been measured at IHEP and at an underground lab in the Aberdeen Tunnel of Hong Kong. This tunnel has similar granite with that of Daya Bay and an overburden of about 250 m of rock.

During the test, the configuration has been modified using the available RPCs in order to have fast results before the designed modules are built. Results have been compared with corresponding Monte Carlo simulations and calculations, and the level of agreement shows the precision and adequacy of the design discussed above.

3.1. Efficiency and noise test

A total of six RPCs with a dimension of 0.3×1.0 m^2 in two groups are used to test the efficiency at IHEP. One

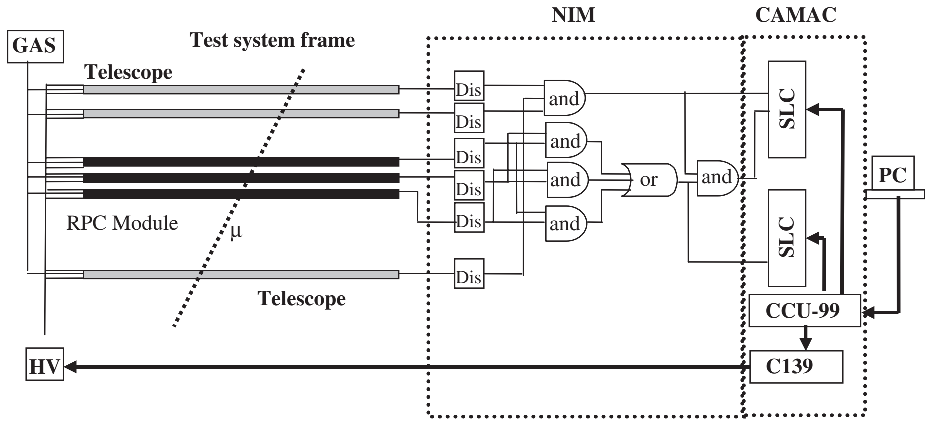

Fig. 5. Setup for the test of RPC module efficiency. The two RPCs at the top and the one at the bottom are used as the telescope, while the three RPCs in the middle as a module are for testing. The gap between chambers in the testing module is 1 cm.

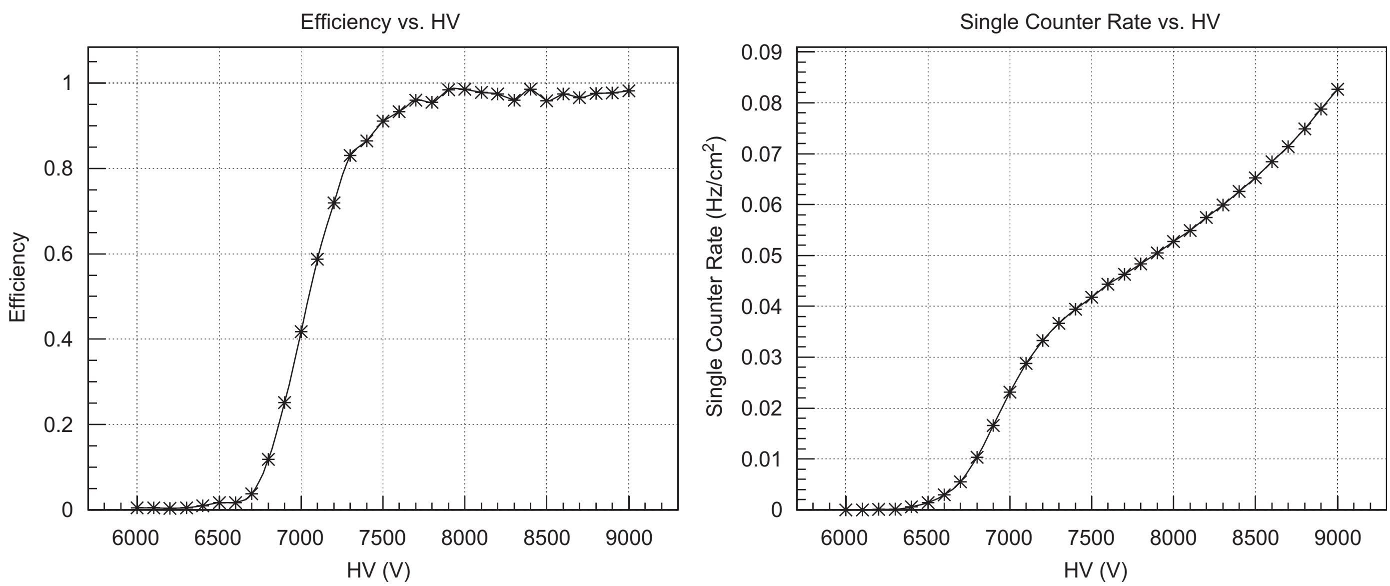

Fig. 6. Performance of a typical RPC. Left: efficiency; right: the single counter rate.

group is a telescope system for the cosmic-ray trigger, and the other one is to be tested, as shown in Fig. 5. In order to test the accidental coincidence, three RPCs are arranged side by side.

Performance of a typical RPC is shown in Fig. 6. The efficiency of all the six RPCs is more than 95%, and the noise rate less than 0.1 Hz/cm^2 at 8 kV.

For a module with three RPCs, the average efficiency of two fired layers out of three with a high voltage from 7600 to 9000 V is found to be $99.5 \pm 0.25\%$, as shown in Fig. 7. It is quite consistent with the prediction of 99.3%, as discussed in Section 2.1.

The measured accidental coincidence rate of a typical module at IHEP is about 10 Hz/m^2 at 8000 V on surface, much more than expected noise of about 0.6 Hz/m^2, as shown in Fig. 8. This is mainly due to cosmic-ray air showers which may extend to a large area as three RPCs. The same test in Aberdeen Tunnel results in a coincidence rate of 0.696 Hz/m^2, consistent with the

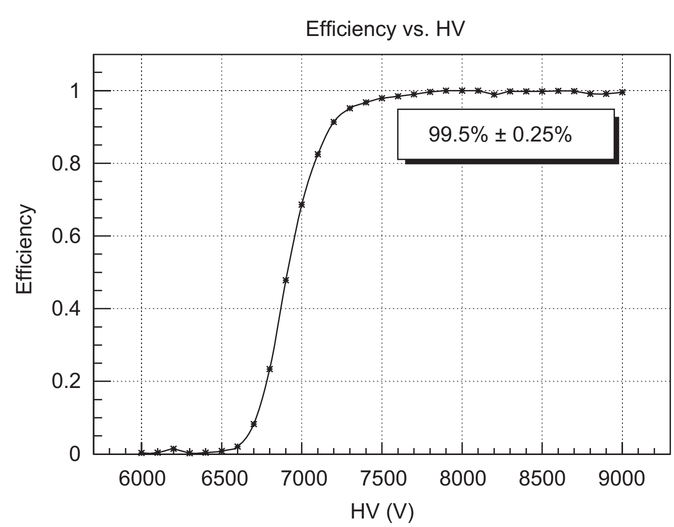

Fig. 7. Performance of a typical module for the scheme of two fired layers out of three.

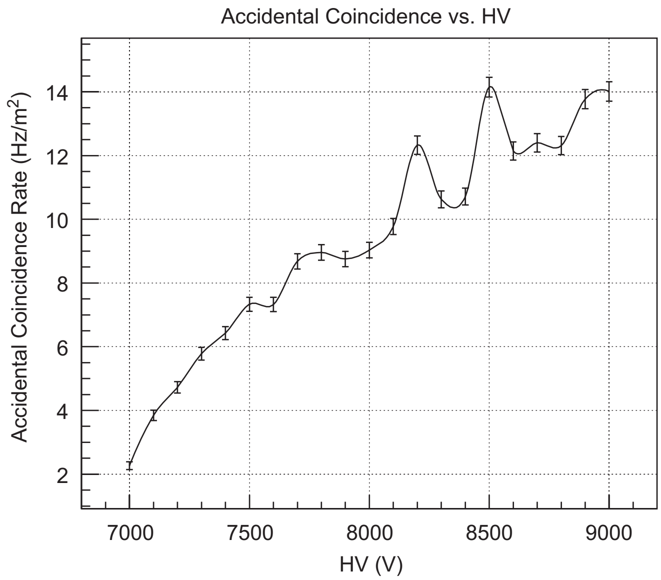

Fig. 8. The accidental coincidence rate of an RPC module.

previous calculation of 0.6 Hz/m^2 for accidental noise in Section 2.3.

3.2. Gamma-ray background test

In order to estimate the gamma background in the underground lab, we performed a test in the Aberdeen Tunnel with a configuration similar to that in Fig. 5. In addition, each RPC module is covered by two 1-mm-thick Al plates to simulate the module box as it would have in real case.

The test result shows that coincidence rate for two out of three layers of RPC is 15 Hz/m^2 which comes mainly from the following sources: Compton scattering of gammas from surrounding rocks, cosmic-rays and accidental coincidence. The cosmic-ray flux at an overburden of 250 m rock is 0.0915 Hz/m^2 from MUSIC simulation [14], consistent with the observed triple coincidence of 0.4 Hz/m^2, by taking into account the difference on solid angle. Although there are others sources of triple coincidence, such as triplex Compton scattering, and triplex accidental coincidence, they are estimated to be 0.008 and 3×10^{-5} Hz/m^2, respectively, negligible as compared to 0.4 Hz/m^2. The accidental coincidence of two fired layers out of three is estimated to be about 0.6 Hz/m^2 as discussed in Section 2.3. Hence, the Compton scattering of gamma-rays from surrounding rocks has a rate of approximately 14 Hz/m^2.

Since the test setup does not have water underneath to shield gamma-rays from rocks, its rate is different from what was estimated in Section 2.4. Using the same simulation code as in Section 2.4 but the new geometry setup for this test, the gamma rate for a coincidence of two out of three layers is estimated to be 4.74 Hz/m^2 and three-fold coincidence rate less than 0.0026 Hz/m^2. The agreement between the test results and simulation is within a factor of three. Since the concentration of radioactive isotopes in the rock has a very high variation in the tunnel, such an agreement is reasonable and confirms the adequacy of the simulation and design in Section 2.

3.3. Radioactive source test

In order to fully understand the sensitivity of RPCs to gamma rays, particularly the probability of double Compton scattering, a test using Co-60 gamma-ray source at IHEP is performed. The two RPCs are arranged vertically on the ground, as shown in Fig. 9, to reduce the influence of cosmic-rays. The size of readout pad is 12 cm × 12 cm and the source strength of Co-60 is 219.2 μCi.

Initially, a total of more than 100 runs, 50 s each, are taken without the Co-60 source. Such tests are repeated after the Co-60 is in place. A comparison of the test results for the two cases is shown in Fig. 10.

After the subtraction of noise, gamma-rays from Co-60 are clearly seen by RPC as single hit via single Compton scattering, as shown in Fig. 10 (left). Similarly, we get the increased coincidence counts with the presence of Co-60 source after the subtraction of noise as shown in Fig. 10 (right). The sensitivity of RPC to gamma-rays is obtained after normalizing the observed single and coincidence counts by the total incident gammas, as listed in Table 2. The same geometry has been simulated and results are also shown in Table 2.

The observed coincidence of two RPCs is mainly from the following three sources: double Compton scattering, accidental coincidence and two single Compton scatterings from cascade gammas of one Co-60 decay. The accidental coincidence of two RPCs is estimated to be 0.68×10^{-6}, taking the same normalization into account. The contribution of cascade gammas is estimated to be 0.02×10^{-6} after normalization, taking into account the single counting rate of the two RPCs with Co-60 and the effective solid angle, etc. Subtracting these two factors, the contribution of double Compton scattering is obtained as shown in Table 2.

Taking the single Compton scattering from RPC no.1, the ratio of double to single Compton scattering is determined to be 0.00245 (0.00923) for simulation (test)

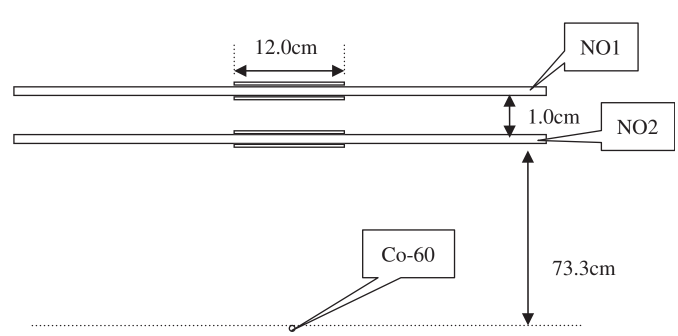

Fig. 9. Top view of the arrangement for the Co-60 test at IHEP.

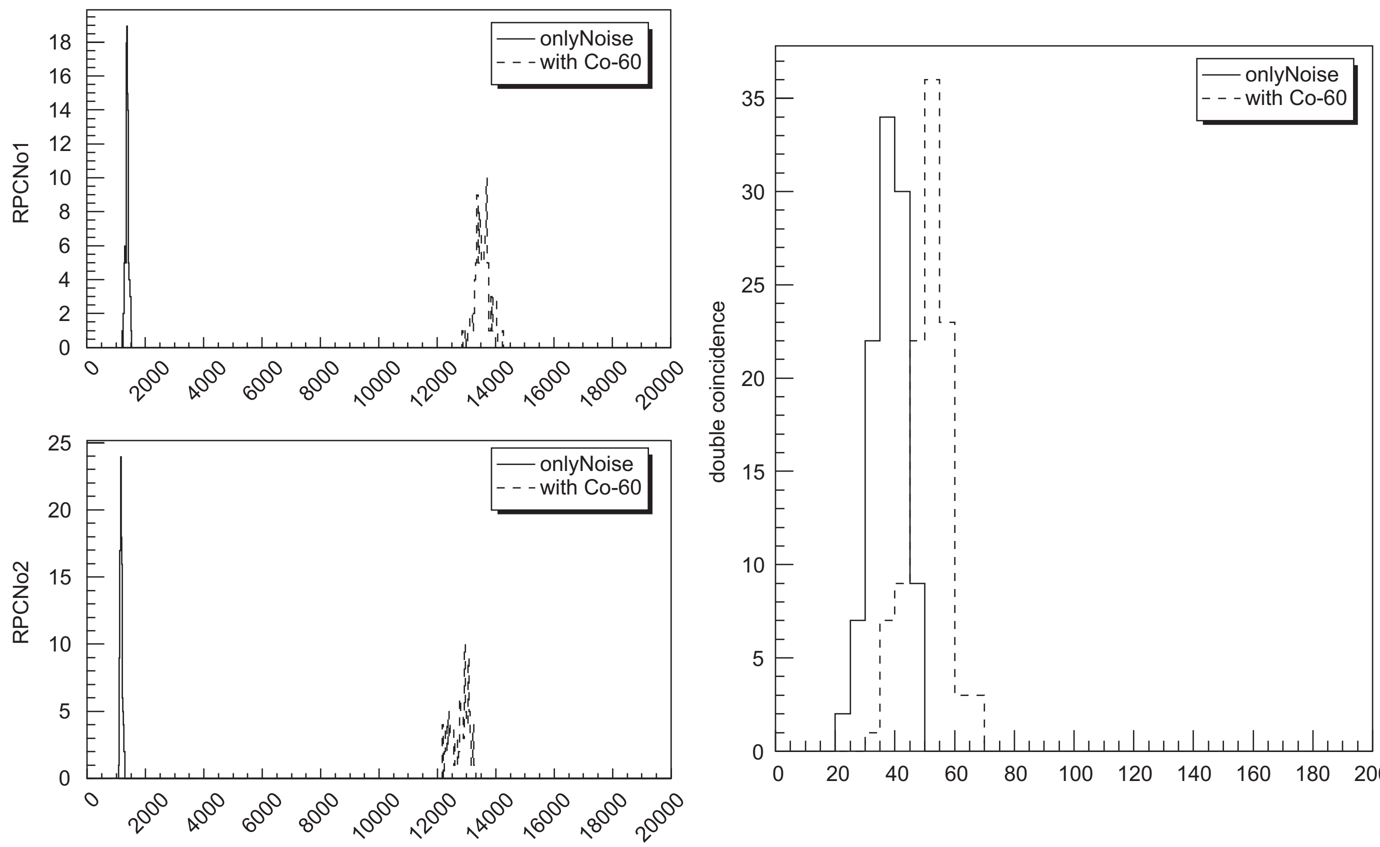

Fig. 10. Histograms of signal counts for single hit (left) and coincidence counts with Co-60 (right).

Table 2
RPC sensitivities to gammas of Co-60 from simulation and test

	RPC no. 1: single Compton scattering (%)	RPC no. 2: single Compton scattering (%)	Observed double coincidence ($\times 10^{-6}$)	Double Compton scattering ($\times 10^{-6}$)	Double-to-single ratio of Compton scattering
Simulation	1.046	1.006	–	25.67	0.00245
Test	0.576	0.531	6.016	5.316	0.00923

as shown in Table 2. The results from simulation and test are consistent within a factor of four, which is mainly due to the definition of RPC being fired in the simplified simulation.

4. Conclusion

Owing to its advantages on efficiency, cost, and sensitivity to gamma-rays, the RPC is an attractive candidate for the cosmic-ray detector of Daya Bay reactor neutrino experiment. Successful experience of the RPC muon detector for BESIII is helpful for the design and construction although more R&D and improvements are needed. A detailed design of RPC layout is present, Monte Carlo simulations and experimental tests shows that such a design is adequate and satisfies the requirements.

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