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An underground cosmic-ray detector made of RPC

Qingmin Zhang[a,b,*], Yifang Wang[a], Jiawen Zhang[a], Jun Cao[a], Talent Kwok[c],
Yuen-Keung Hor[d], Jin Chen[a], Liehua Ma[a,b], Jifeng Han[a,b], Sen Qian[a,b]

[a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[b]*Graduate School of the Chinese Academy of Sciences, Beijing 100049, China*
[c]*Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong*
[d]*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*

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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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[*] Corresponding author. Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China. Tel.: +86 10 8820 0015; fax: +86 10 88233083.

E-mail address: zhangqm@ihep.ac.cn (Q. Zhang).

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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, ^{8}He/^{9}Li 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
^{8}He^{9}Li/signal (%)	0.3	0.2	0.2

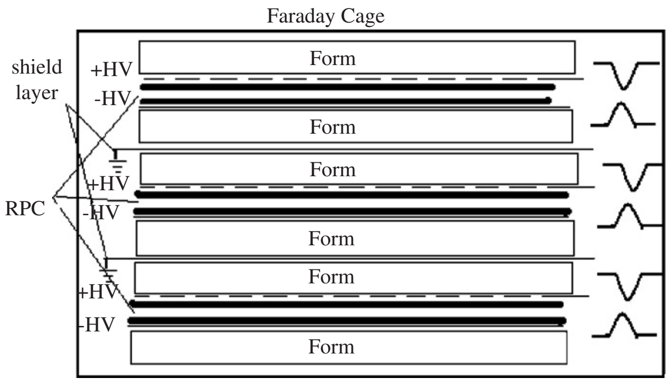

Fig. 1. Sketch of the two-dimensional readout of an RPC module structure.

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

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

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

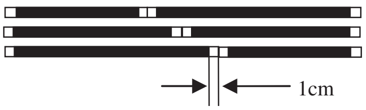

Fig. 2. Sketch of RPC assembly for module. The black is effective area, while the white is dead space.