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Study of the RPC-Gd as thermal neutron detector

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Abstract The BESIII RPC with Gd coating as thermal neutron detector was designed and constructed. Three prototypes were built with different techniques of producing the gadolinium converter. The performance of the cosmic ray test, the signal and the radiation spectrum were discussed in this paper. Lastly, the efficiency of one prototype with the best performance for detecting the thermal neutron was tested as 8.7%.

Key words RPC, Gd, thermal neutron

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1 Introduction

The Resistive Plate Chamber (RPC) is a new type of gas detector developed by R. Santonico (Roma) in the early 1980's[1]. With the development of the new resistive materials, surface treatment, cheap gas mixture required by the new green environment protection and new gap structures, the RPC has been successfully used in several large scale experiments for detecting muons in cosmic rays.

It originated from the research on the RPC sensitivity to neutron/gamma to use a RPC with a thin coating of the special converter material to detect the thermal neutron. Now it is becoming a new research hotspot. Some research groups in INFN[2, 3] have already developed an original technique, using the layer of Gd or B as the converter on the inner surface of the RPC for detecting the thermal neutron.

Our research group has already successfully developed a new resistive material of electrodes without linseed oil in the RPCs for BESIII[4] and the Daya Bay experiment[5]. The main material of our RPC is a special type of phenolic laminates, which is rich in carbon and hydrogen. So the RPC detector is exactly the neutron moderator.

If attached with a suitable converter on the inner surface of this type of RPC, it can be operated in an atmosphere with low gamma-ray sensitivity. Because it is easy to produce, even in a large area, it is suitable to be employed for industrial, medical or security applications.

This paper will focus on the RPC with a Gd converter to detect the thermal neutron, involving the performance of the cosmic ray, the signal and spectrum of this type of RPC-Gd with γ/n radiation sources, and its efficiency of detecting the thermal neutron.

2 The experimental set-up

Since the neutrons are not charged particles, they can not be detected by the RPC directly without converting into charged particles. The converter is a kind of special and suitable material inside the RPC gas gap for interaction with the thermal neutron to generate charged particles. As mentioned in Ref. [6], ^{A}Gd (^{155}Gd and ^{157}Gd), ^{10}B, ^{7}Li are three kinds of material characterized by the highest neutron absorption cross section.

The cross section of the reaction $^{10}\mathrm{B}(\mathrm{n},\alpha)^{7}\mathrm{Li}$ for the thermal neutron is quite high (~3.8 kbarn), but the secondary ionizing α particles with a 3—4 MeV energy have a short range in the high density ^{10}B coat, as described in Ref. [3], the maximum useful thickness for a signal layer of this converter is about 3 μm. It is difficult to produce and test such a thin coating with ^{10}B in a factory.

The cross section of ^{A}Gd to neutron is decreasing

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much more rapidly than others, such as ^{3}He, ^{10}B and ^{7}Li, of which the cross section is decreasing with $1/v$, where v is the velocity of the incoming neutron[7, 8]. Therefore, the gadolinium can be particularly suited to produce detectors specifically designed for revealing thermal neutrons but not fast neutrons. Compared with the 10% abundance of ^{10}B in natural boron, two gadolinium isotopes, namely ^{155}Gd and ^{157}Gd, of which the neutron cross section is at least 12 times larger than that of ^{10}B, have the abundance of more than 30% of the total nature composition. Because the pure metal gadolinium is conductive and too expensive, this kind of material is used in the form of gadolinium oxide, which is a stable white powder in air, and easy to cheaply acquire from the market.

Through the gadolinium oxide converter, without the secondary ionizing particles, the thermal neutron interacts with gadolinium to generate the internal conversion electron in 60% of the cases. The energy spectrum of this conversion electron is a complex one with the range from 30 to more than 200 keV and the main peak around 70 keV[7]. To choose the suitable thickness of the converter, both the conversion efficiency and the escape probability should be considered. For the former, the thicker the better, but for the latter, the thinner the better. A suggested value is around 10—20 μm from the Monte Carlo simulation in Ref. [2].

A research group mixed the gadolinium oxide with the linseed oil, which is the key material to compose a special coating on the inner surface of the electrode in the RPC for improving the surface quality. The detailed process has been described in Ref. [9]. The resistive material of electrodes used in the RPC of BESIII is a special type of phenolic laminates without linseed oil. This type of plate is made of a layer of fine paper impregnated with melamine or phenolic resin hardened in the high pressure lamination press. And the surface of this resistive plate is covered by a layer of specially formulated pre-fabricated plastic film to ensure an excellent surface quality. Three types of these resistive electrodes with the gadolinium oxide coating on the surface were produced in different techniques. Three prototypes of RPC were built to test and verify the feasibility of these methods. The first one using melamine as the standard parting agent is named as the RPC-Gd-coat. The second is RPC-Gd-tungoil, using tung oil as the parting agent. The last one without using a parting agent is RPC-Gd-powder. Besides, another prototype of a standard RPC was also built for controlling experiments.

The prototypes work in streamer mode with the gas mixture as Ar:R134a:Iso-butane=50:42:8. The cosmic ray telescope is composed of three RPCs the same size as the tested prototypes. The signals of the RPC-Gd prototype are divided by the logic Fan-in/out module into several channels, which are validated by a NIM discriminator module with the threshold from 30 mV to 150 mV, then acquired by the CAMAC Scaler and ADC modules, from which the cosmic ray efficiency and counting rate are derived. The environment temperature and relative humidity are detected in real time by the special detectors and recorded automatically[10].

3 The experimental result

3.1 The performance of the RPCs-Gd with cosmic ray

After the four prototypes were built, they were firstly trained with pure argon gas at a high voltage of 10 kV for two days, and then tested with the cosmic ray to check up their manufacture quality, including the production of resistive plates, the assemblage of the chambers, etc. Because of the 30 cm × 30 cm small size of these prototypes, the dark currents were smaller than 1 μA, which is the minimal value of the high voltage system SY127. Only the efficiency and counting rate were tested and their curves are a function of high voltage as shown in Fig. 1 and Fig. 2.

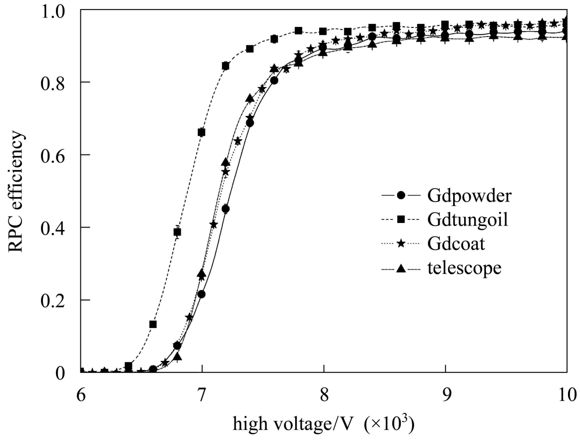

Fig. 1. The efficiency of RPCs-Gd versus high voltage.

The RPC-Gd- tungoil is the prototype with lower high voltage ~7 kV to reach the efficiency plateau for the 100 mV discrimination threshold, but its counting rate is at least 0.15 Hz/cm^{2}at 8 kV, which is higher than the standard value of 0.1 Hz/cm^2 for the RPC used in BESIII. In this prototype, the parting agent tung oil may change the body resistivity and the surface quality. The others have the same efficiency plateau curve versus high voltage, and their counting rates are not as high as the RPC-Gd- tungoil prototype. Especially for the RPC-Gd-coat prototype, the 97% plateau efficiency was measured with an average counting rate always less than 0.06 Hz/cm^2. The lowest counting rate, which means better surface performance and less noise, is very important for the RPC-Gd prototype as a neutron counter to detect the thermal neutron.

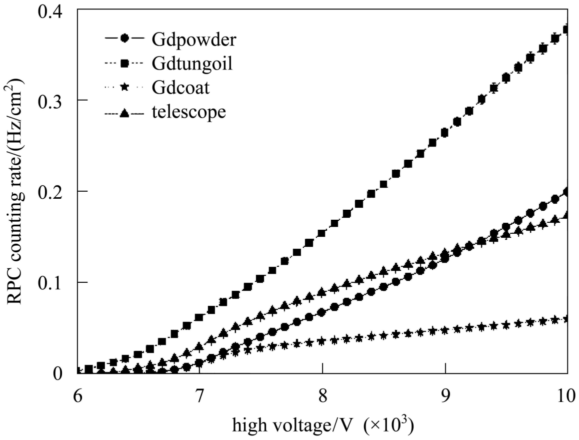

Fig. 2. The counting rate of RPCs-Gd versus high voltage.

3.2 The signal of the RPC-Gd

Figure 3 is the oscilloscope traces of 100 triggered signals registered in the RPC-Gd-coat prototype at 8 kV with 50 Ω input termination of the oscilloscope. The left one shows the signals of the cosmic ray with a 40 ns/div in the horizontal scale and a 200 mV/div in the vertical scale. The signals shown in the right one come from the same prototype with neutron radiation of the Am-Be source, and its horizontal scale is 100 ns/div, and the vertical scale is 100 mV/div. At 8 kV, the amplitude and width of most signals from the cosmic ray were around 270 mV and 100 ns. When the RPC-Gd-coat prototype was radiated by the neutron, its signals would be different from usual. Their amplitude was less than 200 mV and the width was just a little bigger than 60 ns.

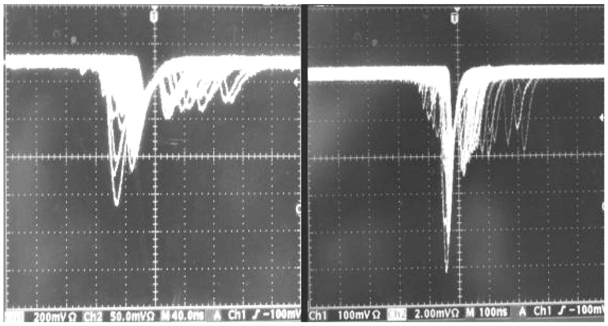

Fig. 3. The signal of RPC-Gd obtained by the oscilloscope.

The amplitude and width of the average signals versus high voltage are shown in Fig. 4. The average data value was obtained by the oscilloscope automatically from 256 triggered signals. With the high voltage increasing from 7 kV to 8.5 kV by 0.5 kV per step, the amplitude of signals from the cosmic ray or neutron is ascending as usual, but the tendency of width is not the same. Compared with the rapidly increasing trend of cosmic ray signals, the width of the neutron signals remains the same at different high voltages.

This abnormal phenomenon happens mainly because of the difference between the two types of sub particles, generated into the RPC-Gd gas gap when the cosmic ray or neutron passes through it. For the former, it will generate one pair of electron-ion, and then the electron will drift to anode and the ion to cathode with the acting force of the electric field from the outside high voltage. Before they arrive at the electrodes, more and more avalanche gains will take place and develop into the avalanche or streamer signal. If the counting rate increases to a high level, the space charge effect (SCE) will generate a reversed electric field to decrease the total electric field in the RPC gas gap. At that moment, the amplitude and width of the average signals would be compressed.

The secondary particles from the nuclear reaction between neutron and ^{157}Gd include Auger electrons, γ rays, X-ray and internal conversion electrons[11]. Such mass particles may cause the SCE in some way. That is why at the same high voltage, the signals of the RPC-Gd with the neutron radiation would be smaller than that with the cosmic ray.

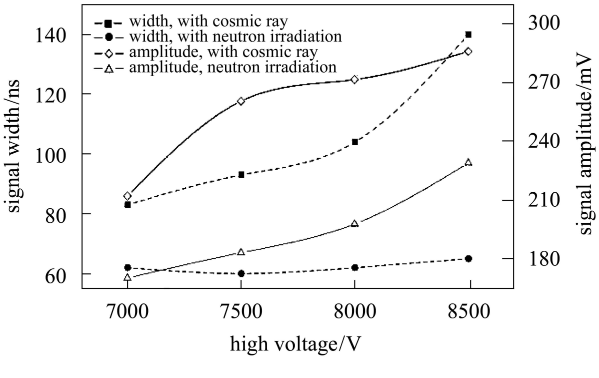

Fig. 4. The amplitude and width of the average signals of the RPC-Gd versus high voltage.

3.3 The spectrum of the RPC-Gd

"Forward incidence/ Backward incidence" are two very important definitions in Ref. [2] to discuss the

Monte Carlo simulation result. As shown in Fig. 5, the isotropical conversion electrons will be generated when a thermal neutron has interacted with a gadolinium nucleus. Only the electrons escaping from the converter and flying into the PRC gas gap could be detected. Once the thermal neutron interacted with the gadolinium oxide converter firstly, the "forward" electrons could enter into the RPC active volume. If the thermal neutron passed through the gas gap before meeting the Gd nucleus, the "backward" electrons, half of the secondary ionizing particles produced by this nuclear interaction, could enter into the active volume without worrying about the thickness of the gadolinium oxide converter, which is proposed to be around 10 μm for "forward" electrons.

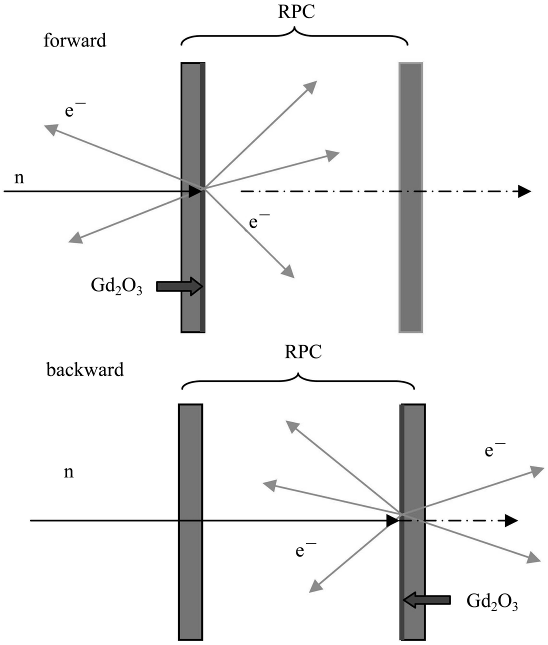

Fig. 5. The "forward/backward" configuration of RPC-Gd detecting thermal neutron.

In this experiment, a gamma radiation source (^{60}Co) and a neutron radiation source (Am-Be) were used to radiate the RPC-Gd-coat prototype for acquiring their amplitude spectrum (charge spectrum) by a CAMAC Q-ADC. There were 5 cm lead and 1 cm oxygen free copper between the neutron source and the prototype for absorbing gamma ray emitting from the Am-Be source. As the hollow and solid circle marks with the right vertical scale shown in Fig. 6, there is no excursion of the gamma spectrum position either in the forward or backward situation. But the results are not the same in terms of the neutron radiation with the left vertical scale. The charge spectrum of the backward neutron radiation (solid triangle marks) is bigger than the forward one (hollow triangle marks). The reason is that, compared with the forward incidence, the backward neutrons generate more secondary particles to develop bigger avalanche or streamer signals in the RPC gas gap.

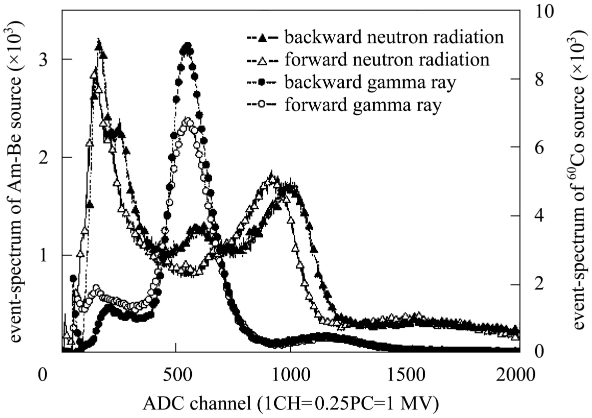

Fig. 6. The Q-ADC spectrum of the γ/ n versus at the "forward/backward" situation.

3.4 The detecting efficiency of RPC-Gd to the thermal neutron

The neutron radiation Am-Be source was set 2 m away from the RPC-Gd-coat prototype in the open air to test the efficiency of this prototype detecting the thermal neutron. The theoretical neutron number has been modified by experience data acquired by the Andersson-Braun Rem Counter in experiment[12]. The environment temperature was 28℃, and the ten channels discriminator threshold was set from 30 mV to 150 mV to discriminate the signals for the CAMAC Scaler at the same time. As shown in Fig. 7, at 8 kV working voltage and 75 mV discriminator threshold, the efficiency value of the RPC-Gd detecting thermal neutron is 8.6%.

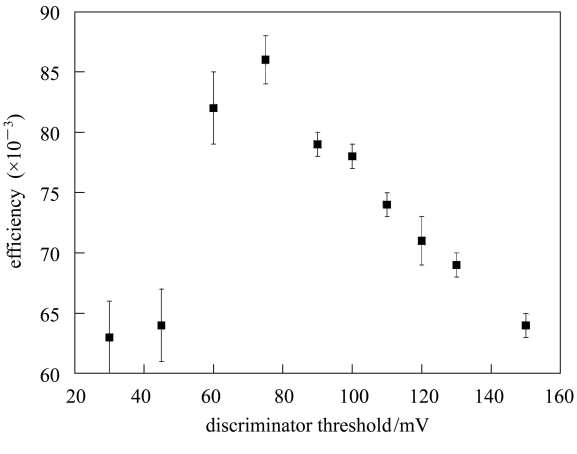

Fig. 7. The efficiency of the RPC-Gd detecting thermal neutron versus the discriminate threshold.

4 Summary

The RPC-Gd-coat prototype has the best performance of cosmic ray test, high efficiency and low counting rate (noise). After the bakelite was attached to the gadolinium converter, the melamine was necessary to be used as the parting agent to keep an excellent surface quality. Without considering the thickness of the gadolinium oxide converter, the backward incidence is the right way to detect the thermal neutron for generating more secondary particles to develop bigger avalanche or streamer signals in the RPC. The spectrum of the RPC-Gd with γ radiation is different from that with neutron. The interaction between the gadolinium and the thermal neutron needs to be studied carefully in the future for a better understanding of the mechanism of generating signals in RPC-Gd.

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