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Resistive Plate Chambers with Gd-coated electrodes as thermal neutron detectors

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Abstract

Resistive Plate Chambers (RPCs) are wide spread, cheap, easy-to-build and large size detectors, used mainly to reveal ionising particles in high-energy physics experiments. Here a technique, consisting in coating the inner surface of the bakelite electrodes with a mixture of linseed oil and Gd_2O_3 is reported. This allows to make RPCs sensitive also to thermal neutrons, making them suitable to be employed for industrial, medical or de-mining applications. Thermal neutron-sensitive RPCs can be operated at atmospheric pressure, are lightweighted, have low γ-ray sensitivity and are easy to handle even when large areas have to be covered. This paper reports the results of the first test of this detector, performed at the Geel Linear Accelerator (GELINA) in Belgium.

Keywords: RPC; GdO_3-coated

1. Introduction

Resistive Plate Chambers (RPCs) basically consist of two bakelite plates kept at a 2 mm distance by a grid of plastic spacers [1]. An appropriate gas mixture is circulated in between and a 4–5 kV/mm electric field is applied. When an ionising particle crosses the gas gap, subsequent avalanche or streamer processes induce a detectable signal on external readout strips.

Even if this device has been mainly employed to reveal ionising particles, its possible use to detect neutrons could lead to interesting practical applications like, for instance, the spotting of explosive materials contained in anti-personnel and anti-tank mines underground. A possible detection technique, accurately studied in the context of the DIAMINE project, uses a ^{252}Cf source placed near the mined ground, which, undergoing fission processes, emits neutrons ranging in energy from about 1 to 4 MeV. Going through the layer of soil

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overhanging the mine and hitting materials compounding it (mainly H and N), neutrons lose energy in multiple scatterings till termination [2].

The goal is to reveal the backscattered thermal neutrons directing upwards, since an intense enhancement in their number is a precise signature of the presence of the mine. RPCs are very good candidates to fulfill the requirements of an ''on-field'' application of this technique because they are cheap and mechanically robust.

2. The choice of the converter

Neutron detection can only be achieved after interaction with a suitable material, called converter, which has the role of generating ionising particles. Two gadolinium isotopes, namely ^{157}Gd and ^{155}Gd, present in absolute, have the largest cross-section to thermal neutrons (of the order of 10^5 barn) which is more than 20 times greater than other usual converters, like ^{3}He, ^{10}B and ^{7}Li.

Cross-section for these converters follows the same typical behaviour, decreasing with $1/v$, where v is the velocity of the incoming neutron; in the case of Gd the cross-section slope is much steeper, starting from an energy around 40 meV to become comparable to others for $E_k \approx 1$ eV. This means that Gd can be particularly suited to produce detectors specifically designed to reveal thermal neutrons (and not fast neutrons); this is an advantage, since fast neutrons coming directly from the ^{252}Cf source could constitute a sort of undesirable background.

In this work, natural Gd, which is composed of a mixture of many isotopes, of which ^{157}Gd and ^{155}Gd constitute about 30% of the natural composition, has been chosen. This material was actually used in the form of Gd-oxide (Gd_2O_3), which presents itself as a white inert powder, with granules 1–3 μm in diameter. This is inert, very easy to handle, poses no problem of gas contamination and is very cheap (100 $/kg). Gd-oxide powder was put in suspension inside the linseed oil normally coated on the inner surface of the bakelite electrodes, so that the usual method for its polymerisation allows to trap the granules of converter in a solid layer. Since Gd-oxide is not conductive the electric properties of the electrodes are not altered.

3. The expected performance

To estimate the possible performance of this kind of detector, suitable calculations have been carried out. In particular, a Monte Carlo program has been developed, taking into account the basic interesting processes, i.e., the interaction of the incident thermal neutron, the emission of the secondary electron with the correct energy spectrum, its travel in a Gd-oxide sheet up to its surface and the eventual entering into the detector active volume.

As a consequence of the capture process of a thermal neutron, natural Gd produces, in 60% of the cases, an electron from internal conversion, with a complex spectrum ranging from 30 to more than 200 keV and a main peak around 70 keV. The range for the produced electrons in Gd starts from about 5 μm up to 20–30 μm, which dictates the useful converter thickness. While electrons are produced isotropically they can be conveniently classified as ''forward'' or ''backward'' in relation with their direction with respect to the direction of the incoming neutron, which in turn determines the converter surface from which they escape.

The results of the Monte Carlo program are summarized in Fig. 1, where the detection efficiency, defined as the probability that the incident thermal neutron produces an electron which escapes the Gd sheet, is reported; the contributions of ''forward'' and ''backward'' electrons are evidenced here. Total detection efficiency rapidly reaches a maximum of around 10–15 μm of about 35%, and after that it decreases slowly. When the Gd-oxide thickness is lower than 10 μm, the probability of an electron stopping inside the Gd sheet is negligible, and the fast rise in efficiency reflects the increasing number of neutron interactions as the Gd thickness increases. When Gd thickness becomes comparable with electron range, one has to take into consideration the fact that neutron flux decreases exponentially inside Gd-oxide; this means that only a surface layer of Gd mostly contributes to the conversion processes.

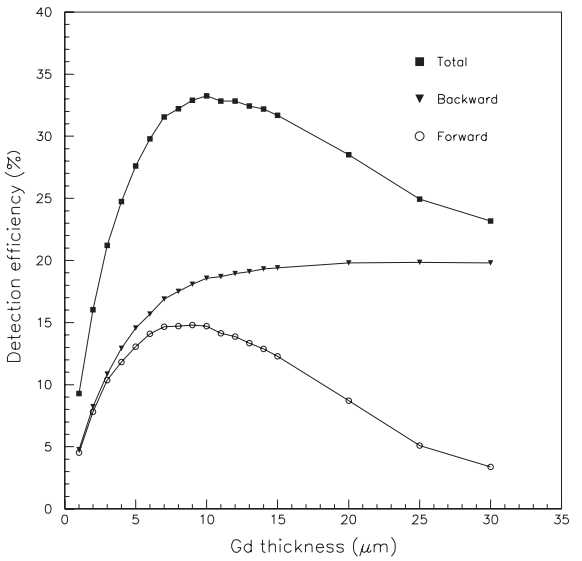

Fig. 1. Detection efficiency vs. Gd thickness; the contributions of "backward" and "forward" electrons are shown.

Once produced, "forward" electrons have to cross more and more Gd-oxide to exit the sheet, as Gd thickness increases, while "backward" electrons have just a, more or less, fixed thickness to cross (Fig. 2). This causes two different behaviours for the curves representing the contributions to the total detection efficiency. In this configuration, one can choose to reveal "forward" or "backward" electrons, depending where the detector active volume is located. Fig. 1 shows that, revealing "backward" electrons, one has not to worry much about the layer thickness, which may be difficult to control, provided it is greater than 10 μm.

4. Experimental set-up

This new technique was applied to build three RPCs, $10 \times 10\,cm^2$ in dimension, of which one without Gd_2O_3 and the others coated, on the inner surface of one of the two electrodes, with different Gd_2O_3 concentrations.

Signal readout was made by two copper pads on which a signal was induced and sent as input for a NIM discriminator, with a 30 mV threshold.

The test was performed at Geel where the neutron beam produced by the Geel Electron

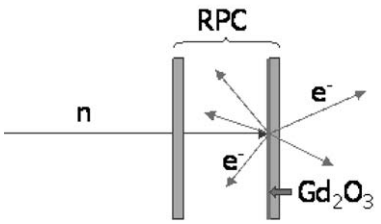

Fig. 2. Layout showing the "backward" configuration.

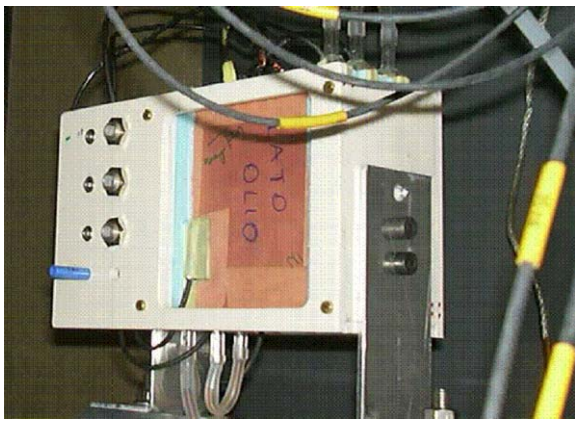

Fig. 3. Picture of the RPCs in their plastic frame at Geel.

Linear Accelerator (GELINA) was available. It was produced by means of an electron beam which, hitting an uranium target, generated γ-rays by bremsstrahlung which, in turn, by photonuclear reactions, yielded neutrons, in an energy range from few meV to 20 MeV.

The system worked in the following way, sketched in Fig. 3: photons (and other particles) produced by the uranium target were collimated through a suitable diaphragm and the charged component was eliminated by a magnetic field. This assured that only neutrons reached the experimental zone, after going through different absorption filters. There, in addition to the RPCs, an Ionisation Chamber (IC), equipped with two 0.35 μm ^{10}B layers, was used as reference detector.

The acquisition system was composed of two multihit TDCs, one for the IC and the other for one of the RPCs at a time. They received the start signal at the moment t_0, when the electron beam hits onto the uranium target, and the stop signals

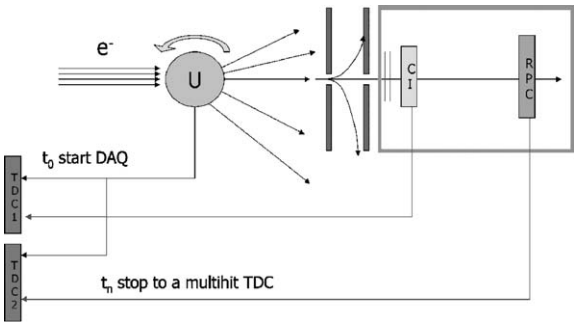

Fig. 4. Acquisition system of GELINA.

t_n at the moment when detectors generated an over-threshold signal.

During the test a gas mixture of $C_2H_2F_4$–isobutane–SF_6(97%–2.5%–0.5%) was used and an operation voltage of 10–11 kV was applied, so as to work in streamer mode. No amplifier was needed since the signal amplitude for ionising particles was already much larger than the threshold and distinguished from chamber noise.

The RPCs were mounted inside a plastic frame (Fig. 4) and exposed to the beam in the "backward" configuration.

5. Data analysis

The data analysis shown later refers to the RPC with the highest Gd_2O_3 concentration. The experimental data are collected from spectra taken at same time, for the IC and the RPC, and referred to as the leading variable to the Time Of Flight $t_n - t_0$.

In Fig. 5, two of these spectra in the region of TOF $t_n - t_0$ from about 50 to 800 μs are shown. The evident holes in Fig. 5 are due to the presence of different filters (W, Na, Ag, S, Co), placed upstream the detectors. These ones are characterised by an absorption cross-section for neutrons which presents resonances at known energy values, by means of which we can calibrate the system, i.e. pass from the time to the energy domain. If we fix the energy of the W resonance for the RPC as E_{rif} at 5.19 eV, which corresponds to TOF $t_{\mathrm{rif}} = 482\,\mu s$ (determined by removing the filter from the beam), we can derive the energy E of particles arriving at a

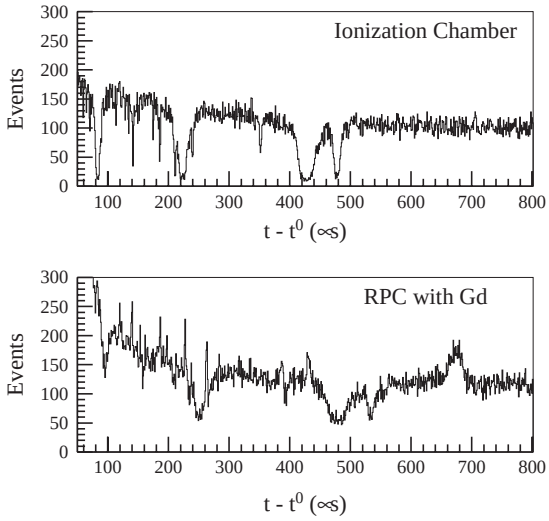

Fig. 5. Experimental spectra in resonances region.

generic t_n by means of the following formula:

$$E = \left(\frac{1}{\sqrt{E_{\mathrm{rif}}}} + \frac{\Delta t}{s}\sqrt{\frac{2}{m}}\right)^{-2}$$

where $\Delta t = t_n - t_{\mathrm{rif}}$, s is the flightpath from the uranium target to the detectors and m is the neutron mass. Note that, since both s (13.5 m for the IC and 15 m for the RPC) and the electronics delays were different for IC and RPC, the procedure has been performed separately for the two devices.

Let us consider now the thermal neutron region; this is shown in Fig. 6, where the experimental spectra obtained with the RPC and the IC are reported. These spectra were corrected to account for any possible source of background; an effective technique to perform this task was to put a Cd filter, opaque to neutrons with energy $E < 0.5$ eV, upstream the detectors. In these conditions the acquired events can be due to intrinsic noise of the chambers or due to higher energy neutrons, which, scattering somewhere around the detectors, arrive on them "out of time".

To check that the background was correctly subtracted, a simulation of the RPC answer to neutrons was performed, using a Maxwellian spectrum and the Gd cross-section as input. The distribution obtained is also reported in Fig. 6, and

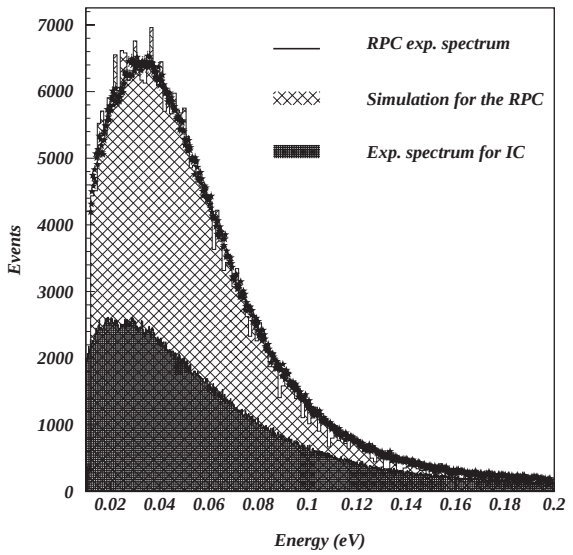

Fig. 6. Simulation results for the RPC in the thermal neutron region.

the agreement between the experimental and simulated plots demonstrates that all sources of background were correctly taken into account and only thermal neutrons are contained in the spectra of Fig. 6.

Now we can evaluate the relative efficiency of the RPC with respect to the IC, by simply dividing the number of events contained in the two distributions. This relative efficiency in the energy region between 11 and 200 meV results to be about 2.5, with a maximum around 3 if we consider only neutrons with an energy of 70 ± 15 meV. Taking from the literature the detection efficiency for two layers of ^{10}B of the IC, we can derive an absolute value for the Gd-RPC detection efficiency of about 9.5% up to 60 meV, followed by a decrease to about 3% at 160 meV, as expected by the Gd cross-section behaviour. This result puts our detector among the most performant in absolute for the detection of thermal neutrons.

6. Conclusions

In this article, the feasibility of a new approach to build RPC coated with Gd for the detection of thermal neutrons has been demonstrated. The obtained experimental efficiency is already larger than the theoretical maximum efficiency reachable with the most currently used neutron converters. In addition, this technique can be easily applied to cover large surfaces at low cost.

Finally, Gd-RPCs are still far from the reachable theoretical maximum efficiency. So, there is space to think about improvements, like the optimisation of the Gd concentration and the linseed oil polymerisation, or the use of more layers of Gd.

Acknowledgements

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[2] DIAMINE Technical Annex, October 2000.