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Neutron detection using a water Cherenkov detector with pure water and a single PMT

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ABSTRACT

We present the performance of a novel neutron detector based on a water Cherenkov detector (WCD) employing pure water and a single photomultiplier tube (PMT). The experiments presented in this work were performed using ^{241}AmBe and ^{252}Cf neutron sources in different neutron moderator and shielding configurations. We show that fast neutrons from the ^{241}AmBe and ^{241}Cf sources, as well as thermal neutrons from a neutron moderator, despite having different spectral characteristics, produce essentially the same pulse histogram shape. This characteristic pulse-height histogram shapes are recorded as a clear signature of neutrons with energies lower than $\simeq$11 MeV. This is verified in different experimental conditions. Our estimation of the neutron detection efficiency is at the level of (15 ± 5)%, for fast neutrons. Since water is the material employed as active volume, the results of this study are of interest for the construction of low cost and large active volume neutron detectors for various applications. Of special importance are those related with space weather phenomena monitoring as well as those for the detection of fissile special nuclear material, including uranium or plutonium.

1. Introduction

In recent years there has been a growing interest in the measurement of neutrons using WCD with different additives to increase sensitivity. The Super Kamiokande collaboration has been testing different approaches to the use of gadolinium (Gd) in their very large WCD (50,000 ton) [1]. It is worth noting that a ground based space weather oriented experiment that uses neutron monitors to study low energy cosmic ray flux variations can use WCD as an alternative detector. In particular, the LAGO, Auger and HAWC collaborations use WCDs to measure changes in the flux of cosmic rays [2,3] and relate them with solar activity indicators. Non proliferation and homeland security are other possible uses of inexpensive water-based detectors. Fissile elements as uranium or plutonium produce simultaneous emissions of multiple neutrons. The ^{3}He-based neutron detectors, in combination with moderator materials (such as polyetylene), are efficient for the detection of fast neutrons emitted from nuclear fission. This homeland security application of ^{3}He detectors has triggered a crisis in the ^{3}He supply and its price is significantly increasing. Therefore, neutron detectors of large solid angle, inexpensive materials with good noise rejection are desirable. In this context, WCDs employing different materials [4–6] are being studied, however the case of water alone has not been analyzed for this purpose.

In this work we present the first evidence of neutron detection using a WCD containing pure water and a single PMT.

2. The detector

The WCD used at the LAGO experiment at Bariloche [7,8] is an autonomous, reliable, simple and inexpensive detector. It is built using a 0.9 m^3 stainless steel commercial water tank of cylindrical shape, with 1.17 m height and 1 m of diameter. It has 2 mm thick inner coating of *Tyvek*® (UV diffusive and reflective fabric), an 8″ ETL 9353KB PMT, plus a digitizer board of custom design [9]. In Fig. 1, left, a picture of the detector with the PMT placed in the tank lid is shown. The right side of Fig. 1 shows the disposition of the detector and the shieldings configurations used in this work. The PMT has a spectral response, with a maximum at ~350 nm [10], that matches the well known Cherenkov light spectrum produced in water, which is continuously extended in the range of 300 nm to 600 nm [11]. The spectral-directional reflectivity of the employed material used for coating the inner surface of the detector [12].

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Fig. 1. Left: the 0.9 m^3 water Cherenkov detector used in this work. Center: the PMT. Right: Schematic view of the detector-shielding-source configuration.

3. Shielding and configurations

We have used seven configurations of shielding, distances and sources, including background measurements, performed before and after each experiment The position of the wall of paraffin was such that the detector had no direct view of the neutron source. A lead wall was interposed between the paraffin wax shield and the detector to absorb the gamma photons coming from the reaction of neutrons with the hydrogen of the paraffin. The lead shielding consists of a wall 120 cm wide by 40 cm tall and 10 cm deep. Also, a 2 mm thick sheet of cadmium was used in one of the measurements, covering the paraffin wax shield. We employed both ^{241}AmBe and a ^{252}Cf neutron sources. The shielding configurations and the neutron energies detectable for each case, are listed in Table 1.

4. Results

4.1. *^{241}AmBe source*

Fig. 2, top, shows the pulse charge histogram for the background, and for the five measurements performed with the ^{241}AmBe source [13] at 1.5 m distance from the WCD without background subtraction. The units of charge of the recorded events are ADC_q, i.e., the integral of a single, 300 ns-long pulse as a function of time (measured in time intervals of 25 ns) after the subtraction of the signal baseline. A clear difference can be seen between the background measurements and when the source is present. The background, showed in red full circles, is below all configuration curves. The measurements performed using lead shielding, paraffin wax and Cd are below the others in the low energy region, under 30 ADCq. At higher energies two other regions can be seen, one between 30 ADCq and 100 ADCq where configurations 0, 1 and 2 show no difference, and above 100 ADCq the highest energies events mostly due to cosmic rays. This feature can be seen in Fig. 2, bottom, were we show the five configurations after background subtraction, zoomed in the region below this high energy events, for a clear view.

A difference between configurations 1 and 2, and configurations 3 and 4 can also be appreciated. Configuration 1, with paraffin wax and lead, and 2, with only lead, give lower spectra than 3, with only paraffin wax, and 4, without shielding. Configuration 0 uses lead and a Cd shield that absorb neutrons below 0.5 eV, thus giving a lower energy spectrum (it is also shielded with paraffin wax, which thermalizes fast neutrons from the AmBe source). When both paraffin wax and lead are present, the majority of the fast neutrons are moderated, turning them into slow neutrons which can produce gammas of $E_\gamma = 2.22$ MeV after its absorption in H. The lead placed between the paraffin and the detector shields these gamma photons and those of $E_\gamma = 4.44$ MeV emitted by the AmBe source. After this, we have thermal neutrons as well as fast neutrons entering the detector. The latter leave a signal due to the process of moderating in the water of the detector, producing photons of $E_\gamma = 2.22$ MeV. On the other hand, the lead is removed for configuration 3 and 4, giving the chance to all the gamma rays coming from the source to enter into the detector. The difference in the observed counting rate between configurations with (1 and 2) and without (3 and 4) the lead shield is mainly due to gamma rays. Taking this into account, the results of Fig. 2, bottom, for ADCq values lower than 30 the gamma contribution to the observed signal is about 50%, and for values greater than 30 it is about 70%.

4.2. *^{252}Cf source*

In Fig. 3 we show the spectra for configuration 5 (no shield) and 6 (lead) after background subtraction using a ^{252}Cf source [14]. It can be seen that both measurements produce similar results, leading to the conclusion that the lead shielding has no impact on these measurements.

Table 1
Shielding configurations implemented, neutron sources, distance source-detector and the shielding are shown. ('–' means no shield) There is also a mention of the neutron energy detectable under the different shielding configurations.

Configuration number	Neutron source	Distance source-detector [m]	Shielding			Neutron energies after configurations	
			Paraffin wax	Cd	Pb	0 eV to 0.5 eV	0.5 eV to 20 MeV
0		1.5	yes	yes	yes	–	–
1		1.5	yes	–	yes	yes	–
2	^{241}AmBe	1.5	–	–	yes	–	yes
3		1.5	yes	–	–	yes	–
4		1.5	–	–	–	–	yes
5	^{252}Cf	0.22	–	–	–	–	yes
6		0.22	–	–	yes	–	yes

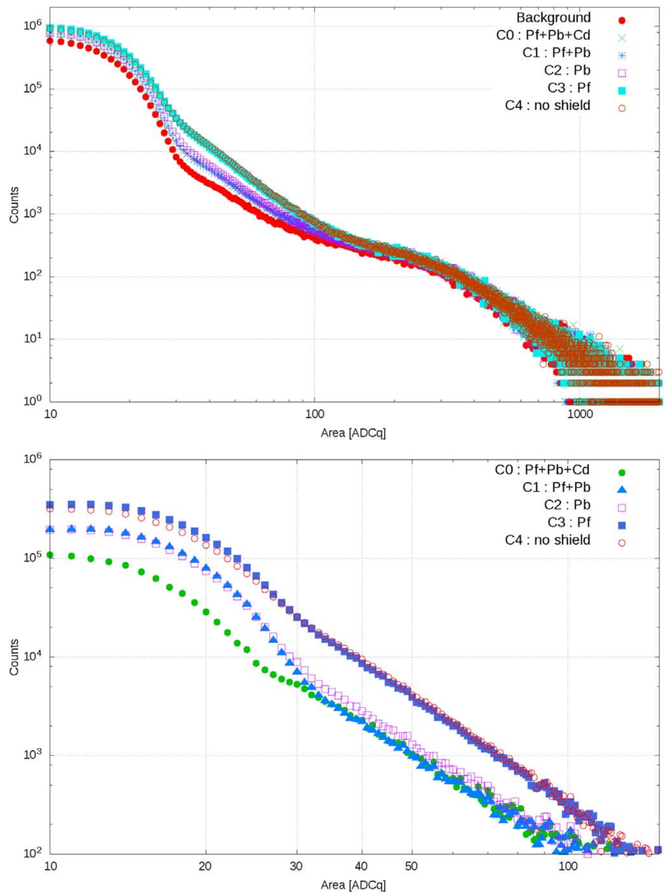

Fig. 2. Charge histogram of the recorded events for background and signals acquired using configurations 0 to 4 (top) and after background subtraction in the region of interest (bottom). 250 ADCq is equivalent to a detected charge signal of 100 pC. Measurements performed using an ^{241}AmBe source.

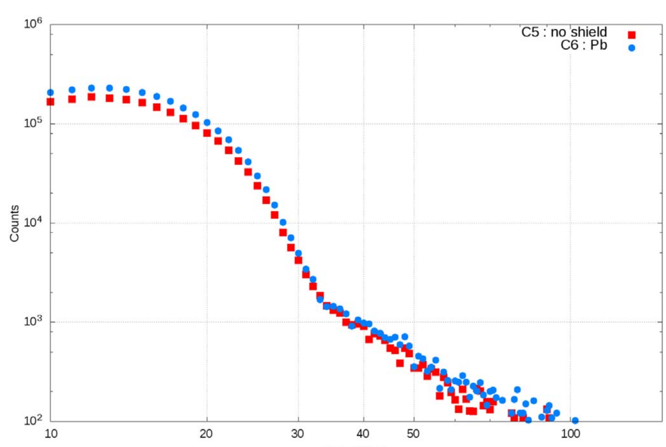

Fig. 3. Charge histogram of the configurations 5 and 6 subtracting the background. They seems to be almost equal (except in the lowest energy region). Measurements performed using an ^{252}Cf source.

5. Neutron detection efficiency

Using the punctual source approximation, and as a first approximation for a detection efficiency calculation, we arrived at the formula:

$$\varepsilon_D \simeq \frac{N_{Pb} - N_{background}}{N_S e^{-\lambda t_d} \frac{\Delta\Omega}{4\pi} t_m}, \tag{1}$$

where $(N_S e^{-\lambda t_d})$ is the neutron emission rate of the source the day of the experiment, N_s is the neutron emission rate at the calibration time, λ the decay probability per time unit, t_d the time difference between the calibration and experiment, $\left(\frac{\Delta\Omega}{4\pi}\right)$ is the solid angle, and the acquisition time t_m (300 s), and the integral of the number of counts (N_{Pb}) subtracting the background ($N_{background}$). We performed both measurements with lead shielding, because it shields the photons emitted by both sources, leaving mainly fast neutrons entering the detector. For the Cf source we get an efficiency of about 20% and for the AmBe source about 10%. Combining both results we estimate a neutron detection efficiency for fast neutrons of (15 ± 5)%. Other works using Gd as dopant quoted an efficiency of ~31% at 1.25 m from the center of the detector using an AmBe source [5]. This is comparable to our ~20% at a distance of 2 m from the center of the detector.

6. Conclusions

We have observed for the first time, using a water Cherenkov detector employing tap water and a single PMT, clear signals due to the detection of neutrons.

The employed detector presents a clear advantage over systems that employ Gd to increase the neutron absorption, and/or more that one PMT. From Figs. 2 and 3 it can be seen that the signal using different neutron sources is always above the background up to charge signals of 40 pC in a 8 in. 12 stage PMT.

In measurements made with an ^{241}AmBe source with Cd shielding, the count rate is seen to diminish with respect to the other shielding configurations, giving us a clear indication that we are detecting gamma photons. When the Cd is removed from the shield we observed signals produced by thermal neutrons in the detector. Since our WCD uses only water as the detector material, the results obtained are of potential interest for the construction of low cost, large active volume neutron detectors for non proliferation enforcement and for "Special Nuclear Material" (SNM) detection for homeland security. These detectors also becomes important as a detector for monitoring space weather [8,15].

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