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1	A water tank muon spectrometer for the characterization
2	of low energy atmospheric muons
3	
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8	
9	Abstract
10	In this work, a water tank muon spectrometer was designed, assembled and operated to
11	measure the energy distribution of low energy atmospheric muon flux induced by cosmic-rays
12	at sea level in the energy range 100-500 MeV. The principle of this experiment is to use water
13	as muon moderator inserted between two coincidence detectors to select the cutoff energy
14	below which muons can no longer be detected. The differential and integral muon spectra are
15	then derived from successive measurements by varying the liquid height within the water tank.
16	The instrument was entirely characterized and modeled in terms of detector efficiency, cutoff
17	energy and counting rate. Experimental data are reported for the energy distribution of muon
18	flux at sea level (43°N of latitude) and finally compared with literature survey.
19	
20	Keywords: Atmospheric muons, low energy muons, cosmic rays, muon flux, muon
21	spectrometer, sea level muon intensity, differential spectrum, integral spectrum
22	
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25 1. Introduction

26 Muons are the most abundant energetic charged particles at sea level where they arrive 27 with an average flux of about ≈ 1 muon per square centimeter and per minute and with an 28 average energy of about 4 GeV [1]. Their characterization provides important information on 29 the physics of primary cosmic rays and on the production mechanisms of atmospheric 30 cascades. An abundant literature exists for muons at ground level and underground but the 31 overwhelming majority of works rather concerns high-energy physics with energy ranges 32 above a few GeV and beyond [2]. Literature surveys on atmospheric muons [2-7] show that 33 there is a clear lack of experimental data typically below a few hundred MeV. In another field of interest, i.e. in radiation effects on modern electronics, the interest for low energy muons is 34 35 rapidly growing due to the potential role that they can play in failure mechanisms of 36 nanoscale digital integrated circuits [8, 9]. Even if the research effort has so far focused 37 mainly on the errors induced by atmospheric neutrons in electronics [10-14], the effects of 38 muons can no longer be neglected. Indeed, recent investigations demonstrated the importance 39 of these particles in the production of soft errors in the most advanced CMOS technologies 40 [15-18]. The probability of memory upsets was shown to increase near the energy region 41 corresponding to muon stopping in the circuit semiconductor material, indicative of direct 42 ionization effects [16]. The characterization of low energy muon distributions at ground level 43 is thus a challenging issue for the prediction of radiation effects in microelectronics; this 44 corresponds to the initial motivation of the present work.

In this context, we recently developed a muon telescope to measure the cosmic-ray induced atmospheric muon flux at sea level (43°N of latitude) in terms of vertical muon intensity and zenithal angle dependence [19]. However, the energy distribution of the muon flux cannot be measured with the instrument developed in [19]. In the present work, we thus 49 developed a new instrument, called "water tank muon spectrometer" to precisely measure the 50 energy distribution of atmospheric muons in the range of hundreds of MeV. The principle of 51 this experiment is to use water as muon moderator sandwiched between two detectors in 52 coincidence to select the cutoff energy below which the muons will no longer be detected. It 53 is then possible to determine the energy distribution of muon flux by varying the water height 54 in the water reservoir. This paper details the main characteristics of this instrument including 55 its complete characterization and modeling and reports our first measurements of the muon 56 differential and integral flux in the range 100-500 MeV conducted at sea level in Marseille 57 (43° N of latitude).

58 2. The water tank muon spectrometer

59 2.1. Experimental setup

The experimental setup is presented in Figure 1. The muon spectrometer was developed 60 61 using a dedicated metallic tower structure capable to support heavy load (two metric tons of 62 water in storage tanks) between the two detectors installed at the top and the bottom of the structure. The two detectors are square plastic scintillators (surface of 50x50 cm², thickness of 63 5 cm, housed in 1.5 mm of aluminum plate). The plastic scintillator is made of 64 65 polyvinyltoluene (PVT) and fabricated by Eljen Technology (EJ-200) [20]. This plastic is 66 highly sensitive to charged particles: its typical stopping power for 1 GeV muons is 2.132 67 MeV/cm [21]. Each scintillator has a photomultiplier tube (PM) directly integrated in the 68 assembly; the tube is placed in a housing positioned in the bulk material and optically coupled 69 using a high refractive index optical coupling medium at the bottom of the housing (polished 70 surface with an optical quality). The PMs are Hamamatsu model R6427 with 28 mm tube diameter, 25 mm round photocathode and 10-stage photomultiplier. The assembly 71 72 (PM+scintillator) is mounted in an aluminum housing (thickness 1.5 mm) that ensures a

73 permanent light sealing. This solution also offers a simplification of detector design by

reliminating support hardware to maintain contact between the scintillator material and the PM.



75 76

Figure 1. (a) Front view of the water tank muon spectrometer composed from two square detectors mounted on a metallic support and separated by two water storage tanks made from blow molded high-density polyethylene. The variation of the water level is carried out manually by filling or emptying the tanks with an electrical pump. (b) Schematic representation of the water tank muon spectrometer: the main geometrical parameters and structure configuration are indicated.

The two PMs are connected to the measurement and acquisition chain shown in Figure 2. Photomultipliers convert scintillation light pulses into electrical signals that are then sent to the acquisition chain which trigs the muons traversing the front scintillator and measures, using a coincidence detection procedure in a time window of 10 ns, their time-of-flight 87 between the front and back detectors separated by a distance of 2.815 m. PM signals as well 88 as time-of-flights converted in voltage pulses using a time-to-amplitude converter (TAC) are 89 digitized using multi-channel analyzers (MCAs based on 16k ADCs). For piloting the 90 experiment, we have developed dedicated Visual Basic software that allows the acquisition of 91 the muon count rate as function of the water level in the water tank. The two polyethylene 92 water tanks have a thickness of about 3 mm except the bottom of the tanks, which has a thickness of 9 mm. The second tank is installed on a stainless steel plate about 2 mm thick. 93 94 The variation of the water level was carried out manually by filling or emptying the tanks by a 95 step of 100 L, which corresponds to a water height of 9 cm. An additional layer of lead with a thickness of 50 mm was optionally added just below the top detector in order to verify that 96 97 low energy gamma rays and electrons are satisfactorily rejected in the detector response.



- 99 Figure 2. Schematics of the electronics acquisition chain for measuring the time-of-flight of
- 100 coincidence muons between the two detectors of the spectrometer.

101

102 2.2. Spectrometer calibration

103 In order to optimize the spectrometer operation and to be sure that the spectrometer detects 104 and counts only atmospheric muons, a careful calibration of the instrument has been 105 performed, very similarly to that carried out in [19] for the cosmic ray telescope. The 106 calibration procedure consists in the following three steps:

- 107 (i) the detection threshold of the pulses coming out of each PM has been fine-tuned
 108 (around 130 mV), which ensures that the low-energy peak (due to the PM noise and
 109 the contribution of ambient gamma radiation) is well rejected, the counting rate
 110 thus only corresponding to the contribution of the sole charged atmospheric muons
 111 (see Fig. 3 in [19] for details) ;
- (ii) the nominal value of the supplying voltage (around 1500 V) for each PM has been
 carefully selected in order to operate in the middle of the plateau of the PM
 counting rate voltage characteristics ;
- (iii) a calibration of the electronic acquisition chain has been also conducted to
 determine the MCA channel number versus time proportionality. The MCA was
 calibrated to a resolution of approximately 160 bins/ns.
- Finally, since a detector may sometimes miss (i.e. do not detect) a muon passing through, the efficiency, η , of each detector has been carefully determined using the calibration procedure described in [19]. We found $\eta_F = 99\%$ and $\eta_B = 99\%$ for the front and the back detector, respectively.

122 2.3. Spectrometer modeling and simulation

123 2.3.1. Cutoff energy

To be detected by the back detector, muons must cross the instrument with a minimal energy, depending on the level of water in the tanks, called cutoff energy (E_{min}). Extensive

126 simulations using TRIM (Transport of Ions in Matter) Monte Carlo simulation code [22] have 127 been performed to determine the cutoff energy of the spectrometer for each water level in the 128 tanks. In these simulations we have taken into account the exact 1D stack of materials that the 129 muons pass through from the metal roof of the building to the back detector, including the 130 first floor (air and concrete slab) and the different materials of the spectrometer. Muons have 131 been emulated in TRIM by applying a simple "mass scaling" to protons, as suggested in [23]. 132 We estimate that signal pulses produced by a particle depositing around 2 MeV in the 133 scintillator material of the detector can pass the constant fraction discriminator. Figure 3 and 4 134 illustrate TRIM simulations used to determine the cutoff energy for a cumulative water level 135 in the tanks of 150 cm. We consider an incident muon arriving in perpendicular incidence on 136 the building roof with an incident energy of 374 MeV. The muon pass through the successive 137 layers from the metallic roof to the back detector and its energy decreases until going to zero 138 in the back detector where it definitely stops and is detected by the coincidence detection 139 procedure. The variation of the muon energy and the energy lost in each layer are shown in 140 Fig. 3 and 4, respectively; the different layers crossed by the muon are also indicated in these 141 figures. Our simulations show that muons with lower incident energies are stopped in the 142 spectrometer layers before reaching the back detector (i.e. they will not be detected by the 143 spectrometer), while muons with higher incident energies are systematically detected by the back detector. This means that the cutoff energy of the spectrometer for a water level of 150 144 145 cm is $E_{min} = 374$ MeV. This value should be slightly higher for oblique tracks. The same 146 procedure was used to determine the cutoff energy of the spectrometer for each level of water 147 in the water tanks. Figure 5 shows the calculated cutoff energy of the spectrometer as a 148 function of the cumulative height of the water level in the two water tanks.



Figure 3. TRIM simulation showing the muon energy variation through the water tank spectrometer for an incident energy of 374 MeV (particle track perpendicular to the detector surfaces). The water height is 50 cm in the first water tank and 100 cm in the second tank. The cutoff energy of the spectrometer for a water level of 150 cm is $E_{min} = 374$ MeV.



156 Figure 4. TRIM simulation showing the muon energy loss through the water tank 157 spectrometer for an incident energy of 374 MeV. The water height is 50 cm in the first water 158 tank and 100 cm in the second tank.



160 Figure 5. Muon cutoff energy of the spectrometer as a function of the cumulative height of161 the water level in the two water tanks with and without the optional 50 mm-thick lead layer.

162 *2.3.2. Modeling of the spectrometer counting rate*

159

163 The spectrometer counting-rate has been numerically estimated from a model directly 164 derived from the work of Sullivan [24] and Thomas and Willis [25]. Figure 6 introduces the 165 notations used in the following. For an anisotropic distribution of incident muons I ($m^{-2}s^{-1}sr^{-1}$) 166 following a power cosine law with the zenithal angle θ :

167
$$\mathbf{I} = I_0 \cos^n(\theta) \tag{1},$$

168 the counting rate CR (s^{-1}) of the spectrometer fixedly pointing in the vertical direction can be 169 easily expressed as [25]:

170
$$CR = I_0 \eta_F \eta_B \int_{-L}^{L} \int_{-L}^{L} \int_{-L}^{L} \int_{-L}^{L} \frac{Z^{n+2}}{[Z^2 + (x_2 - x_1)^2 + (y_2 - y_1)^2]^{n+1}} dx_1 dx_2 dy_1 dy_2$$
(2)



172

Figure 6. Schematics of the front and back detectors, and definition of axes, angles and different quantities used in the modeling of the spectrometer counting rate. For the setup shown in Fig. 1, main dimensions are Z = 2.815 m and L = 0.25 m.

where I_0 is the vertical muon flux (expressed in m⁻² s⁻¹ sr⁻¹) integrated over the energy range of the instrument, η_F and η_B are the front and back detector efficiencies, respectively, and Z is the distance between the two square detectors of surface $4L^2$ (see Figure 6).

Assuming that the zenith angle distribution of muons follows Eq. (1) with a fixed value of exponent n in the energy range of interest of the instrument, Eq. (2) directly gives the value of I_0 for each experimental counting rate CR corresponding to a given water height in the tank, i.e. to a given cutoff energy E_{min} . For n = 2, Eq. (2) can be expressed analytically and the counting rate of the instrument is then given by:

185
$$CR_{n=2}^{a} = I_{0}\eta_{F}\eta_{B} \times 2L \left[\frac{Z^{2}+8L^{2}}{\sqrt{Z^{2}+4L^{2}}} \times \arctan\left(\frac{2L}{\sqrt{Z^{2}+4L^{2}}}\right) - Z \times \arctan\left(\frac{2L}{Z}\right)\right]$$
(3)

where the superscript "a" is for "analytical" and the subscript "n=2" indicates that this
expression is restricted to this particular value of parameter n.



188

Figure 7. Counting rate as a function of the distance between the front and back detectors. The experimental data are obtained using an additional setup based on a plastic shelf described in [19]. The curve labeled "Model" is obtained from Eq. (3) with $I_0 = 100 \ \mu \ m^{-2} \ s^{-1} \ sr^{-1}$ and n = 2.0, as experimentally obtained in [19].

3. Experimental results: sea level measurements

The muon spectrometer has been assembled indoors, on the ground floor of the experimental hall of a steel-frame industrial building with a single floor (concrete slab, thickness 10 cm) and a metal roof. The building is located on the Aix-Marseille University campus of Saint-Jérôme (Marseille, France, +43.337732°N, +5.412108°E, altitude 118 m).

198 To check the validity of the spectrometer counting-rate modeling (Eq. 3), we performed 199 preliminary measurements by varying the distance Z between the two detectors, using a 200 plastic resin shelf with seven regularly spaced shelves. In this case, the two detectors were 201 temporarily removed from the spectrometer setup and aligned vertically on two shelves of this 202 complementary characterization setup. Figure 7 shows the results of the model 203 characterization: the experimental data are in very good agreement in a distance range 204 between 40 cm and 3 m with the results of simulation using the analytical model (Eq. (3)) presented above, taking values $I_0 = 100 \ \mu \ m^{-2} \ s^{-1} \ sr^{-1}$ and n = 2.0, as experimentally obtained 205 206 in [19].



207

Figure 8. Experimental counting rates (with and without the 50 mm-tick lead layer) as a function of the cutoff energy of the spectrometer. Each point corresponds to a value averaged over one week (168 h).

After this preliminary step, the muon spectrometer was continuously operated for around nine months for the acquisition of experimental data. Figure 8 shows the variations of the instrument counting rate as a function of the energy cutoff E_{min} determined by the height of the water level in the water tanks. Two series of data have been acquired, with and without the 50 mm-thick lead layer. Each point corresponds to a value averaged over one week (168 hours). These results show a quasi-linear decreasing relationship between the counting rate and the instrument cutoff energy. They also show that the presence of the additional lead layer in the instrument material stack does not alter this linear dependency and only shift by ~50 MeV the energy domain explored by the instrument.



220

Figure 9. Muon spectrum at sea level deduced from data of Figure 8 and measured in other experiments [3,4,5]. The line refers to the fit of experimental data with Eq. (4) and data parameter from [26]. The fluxes are multiplied by p^2 , where p is the momentum in GeV/c.

From data of Figure 8 and considering the analytical equation (3), the integral vertical muon flux I_0 above energy E_{min} can be extracted from the experimental counting rate value for each value of E_{min} varying from ~100 to ~500 MeV (for a muon rest mass of 105.659

227 MeV, the corresponding muon momentum ranges from 0.176 to 0.596 GeV/c). Considering the first derivative of this $I_0(E_{min})$ relationship (using the best linear fit on three consecutive 228 229 points delimiting a small energy interval), we deduced the muon differential flux values 230 reported in Figure 9. Experimental data measured in other published works [3,4,5] are also 231 shown for comparison. Our values ideally complete the muon spectrum in an energy domain 232 where only a few and sparse data were previously reported, especially below 200 MeV. These 233 data are also consistent with previously published data and fits, in particular with the 234 parabola-fitting model on a log-log scale given by [26]:

$$\log I(\theta) = a \ln^2 p + b \ln p + c \tag{4}$$

where p is the muon momentum in GeV/c and a, b, and c are three fitting parameters.

The analytical fit shown in Figure 9 has been obtained with Eq. (4) considering the values of a, b, and c reported in [26] for a vertical zenith angle: a = -0.1292, b = -0.266 and c = -2.600. We observe that our data satisfactory agree with this analytical fit in the full energy domain covered by the instrument.

241 **4.** Conclusion

242 In this work, we developed an original setup, called "water tank muon spectrometer", to 243 measure the energy distribution of low energy atmospheric muon in the energy range 100 to 244 500 MeV (momentum range 0.176 to 0.596 GeV/c) not yet covered by other ground-level 245 instruments. The instrument use water as muon moderator and a controllable water height up 246 to 2m to vary the muon cutoff energy. The differential flux for vertical muons at sea level 247 (43°N of latitude) has been deduced from experimental measurements combined with the 248 numerical modeling of the instrument. Differential flux values obtained between 100 and 500 249 MeV are consistent with previously published data and parabola fitting model available in 250 literature. A short-term development will automate the filling and emptying of the water tanks,

251	in order to make the measurements fully controllable by computer. With such an automated
252	instrument, middle-term work will consist in a continuous muon flux monitoring to evidence
253	possible flux variations as a function of various environment parameters.

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- 260

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