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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
34 of interest, i.e. in radiation effects on modern electronics, the interest for low energy muons is
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.

45 In this context, we recently developed a muon telescope to measure the cosmic-ray
46 induced atmospheric muon flux at sea level (43°N of latitude) in terms of vertical muon
47 intensity and zenithal angle dependence [19]. However, the energy distribution of the muon
48 flux cannot be measured with the instrument developed in [19]. In the present work, we thus

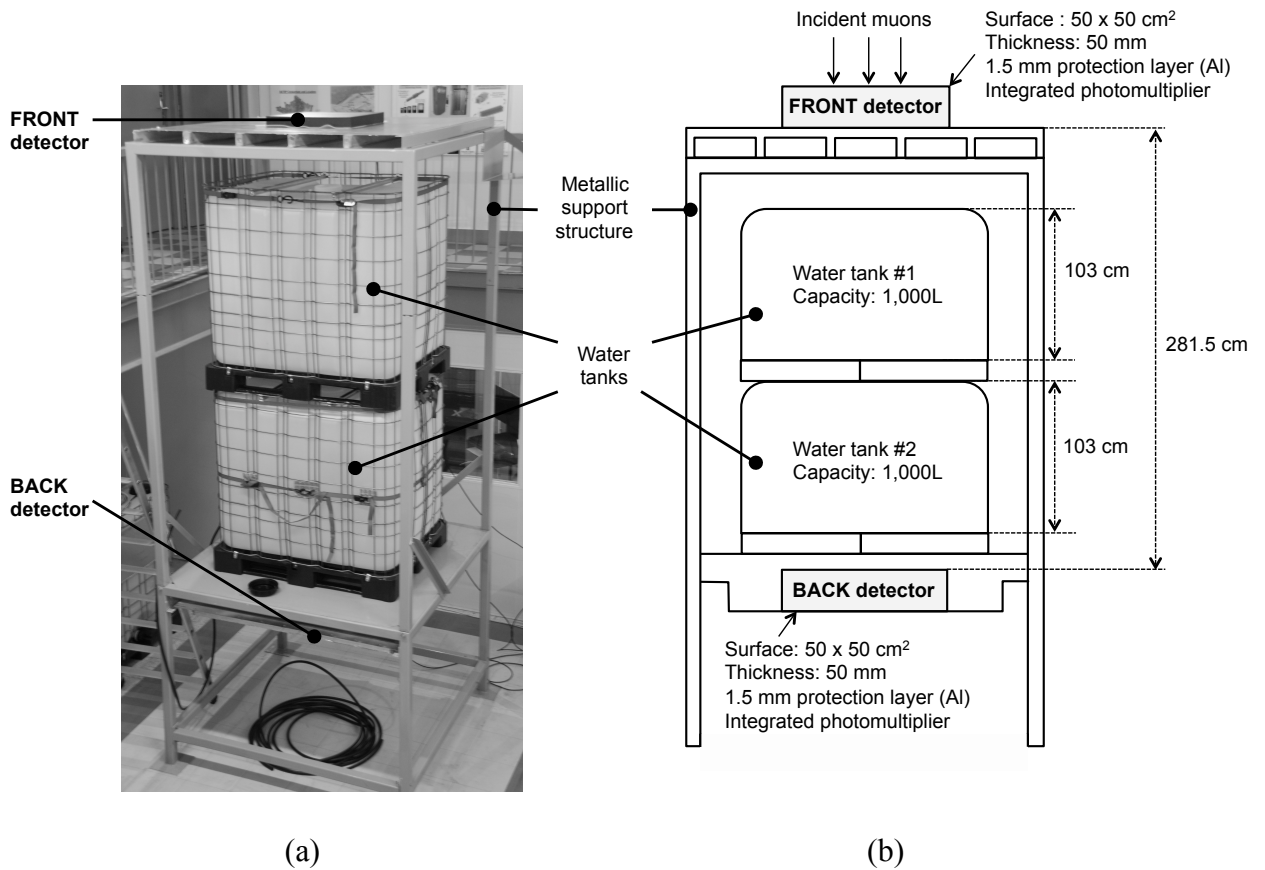
49 developed a new instrument, called “water tank muon spectrometer” to precisely measure the
50 energy distribution of atmospheric muons in the range of hundreds of MeV. The principle of
51 this experiment is to use water as muon moderator sandwiched between two detectors in
52 coincidence to select 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*

60 The experimental setup is presented in Figure 1. The muon spectrometer was developed
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
63 structure. The two detectors are square plastic scintillators (surface of 50x50 cm², thickness of
64 5 cm, housed in 1.5 mm of aluminum plate). The plastic scintillator is made of
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
71 diameter, 25 mm round photocathode and 10-stage photomultiplier. The assembly
72 (PM+scintillator) is mounted in an aluminum housing (thickness 1.5 mm) that ensures a

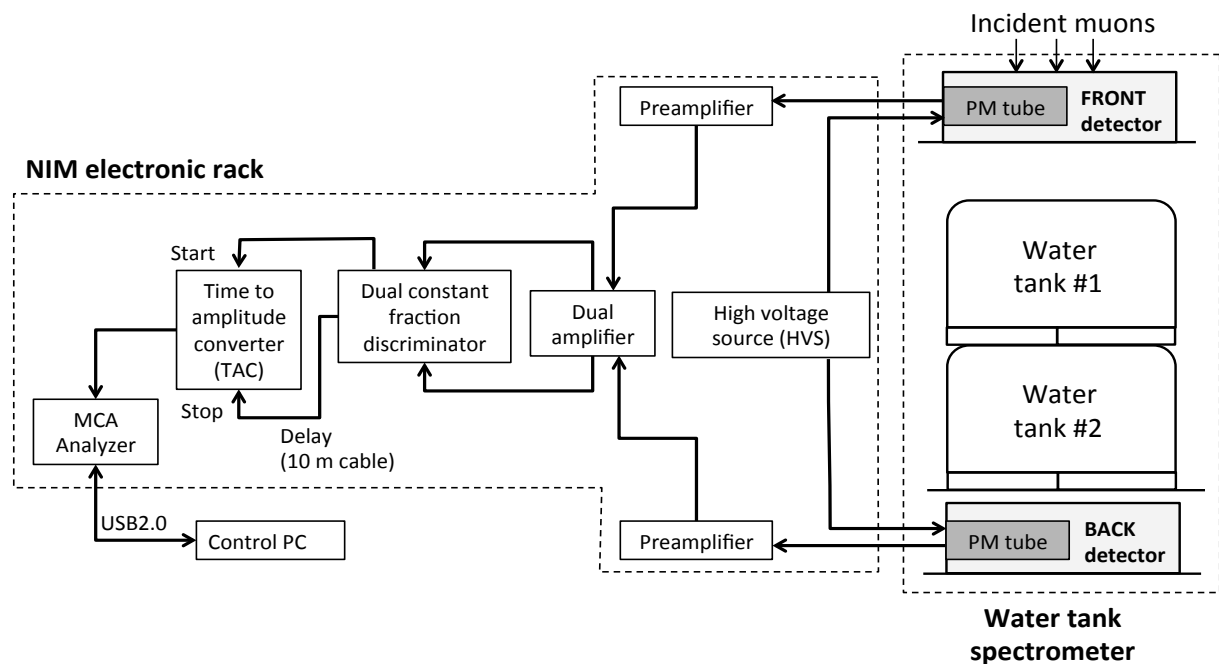
73 permanent light sealing. This solution also offers a simplification of detector design by
 74 eliminating support hardware to maintain contact between the scintillator material and the PM.



75
 76
 77 **Figure 1.** (a) Front view of the water tank muon spectrometer composed from two square
 78 detectors mounted on a metallic support and separated by two water storage tanks made from
 79 blow molded high-density polyethylene. The variation of the water level is carried out
 80 manually by filling or emptying the tanks with an electrical pump. (b) Schematic
 81 representation of the water tank muon spectrometer: the main geometrical parameters and
 82 structure configuration are indicated.

83 The two PMs are connected to the measurement and acquisition chain shown in Figure 2.
 84 Photomultipliers convert scintillation light pulses into electrical signals that are then sent to
 85 the acquisition chain which triggers the muons traversing the front scintillator and measures,
 86 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
 93 thickness of 9 mm. The second tank is installed on a stainless steel plate about 2 mm thick.
 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
 96 thickness of 50 mm was optionally added just below the top detector in order to verify that
 97 low energy gamma rays and electrons are satisfactorily rejected in the detector response.



98

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) ;
- 112 (ii) the nominal value of the supplying voltage (around 1500 V) for each PM has been
113 carefully selected in order to operate in the middle of the plateau of the PM
114 counting rate – voltage characteristics ;
- 115 (iii) a calibration of the electronic acquisition chain has been also conducted to
116 determine the MCA channel number versus time proportionality. The MCA was
117 calibrated to a resolution of approximately 160 bins/ns.

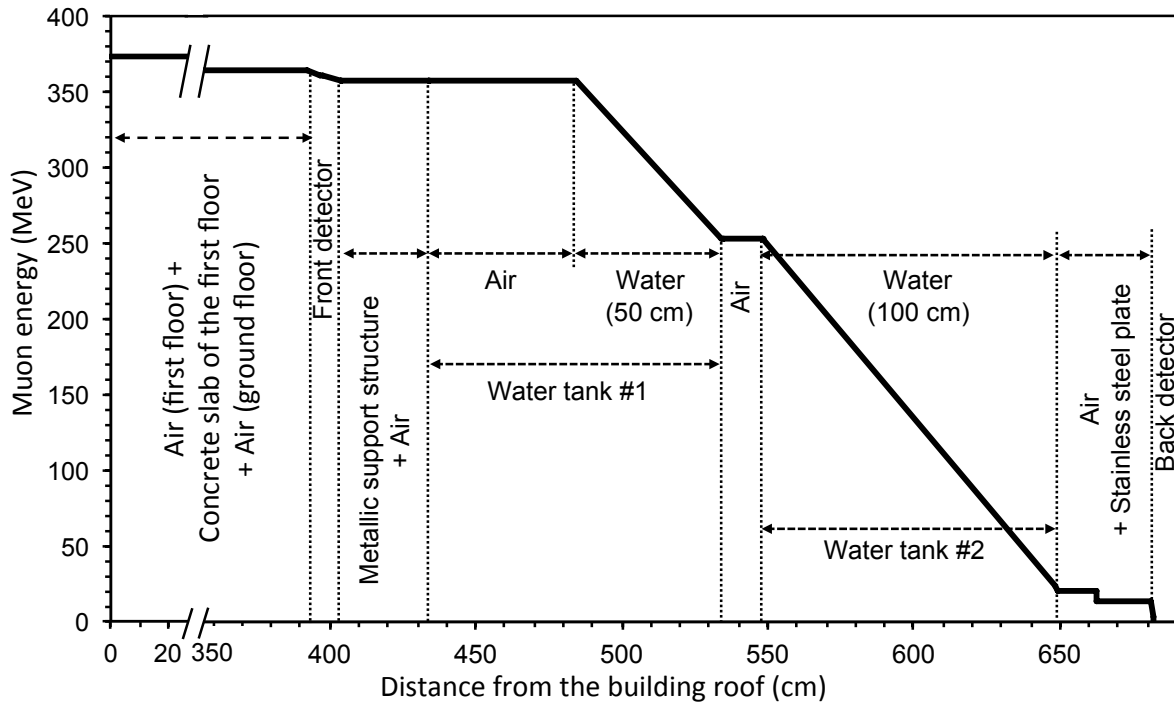
118 Finally, since a detector may sometimes miss (i.e. do not detect) a muon passing through,
119 the efficiency, η , of each detector has been carefully determined using the calibration
120 procedure described in [19]. We found $\eta_F = 99\%$ and $\eta_B = 99\%$ for the front and the back
121 detector, respectively.

122 2.3. Spectrometer modeling and simulation

123 2.3.1. Cutoff energy

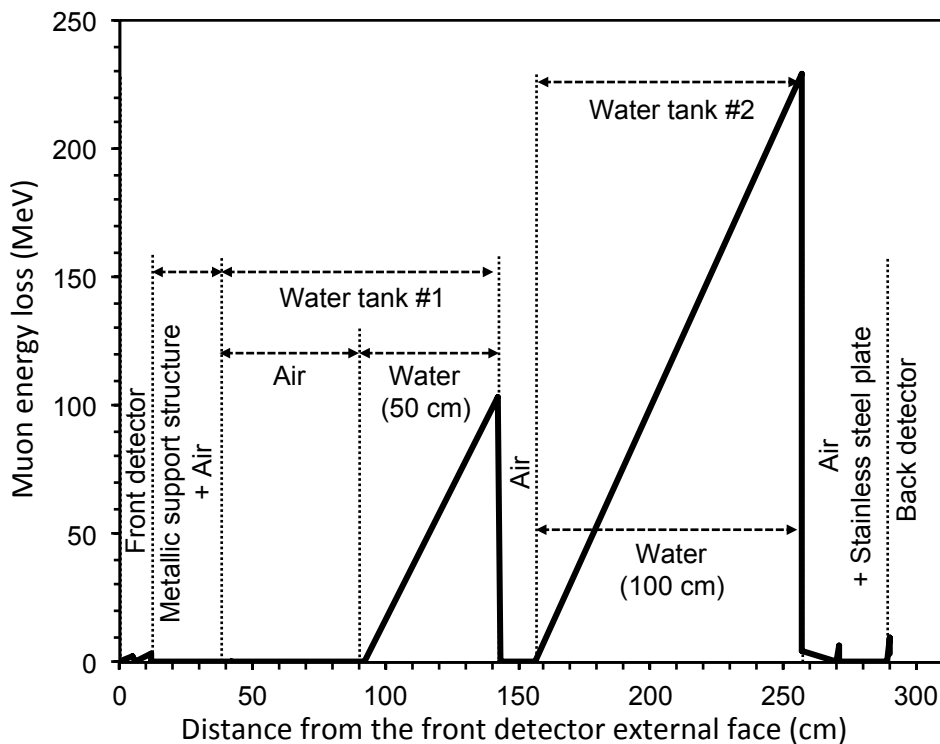
124 To be detected by the back detector, muons must cross the instrument with a minimal energy,
125 depending on the level of water in the tanks, called cutoff energy (E_{\min}). Extensive

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
144 back detector. This means that the cutoff energy of the spectrometer for a water level of 150
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.
149



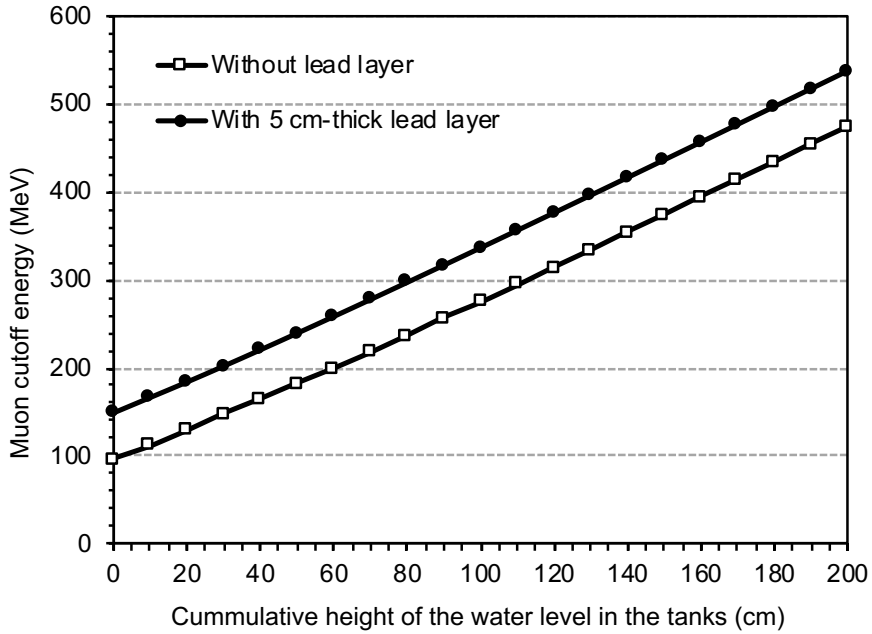
150

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



155

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.



159

160 **Figure 5.** Muon cutoff energy of the spectrometer as a function of the cumulative height of
 161 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*

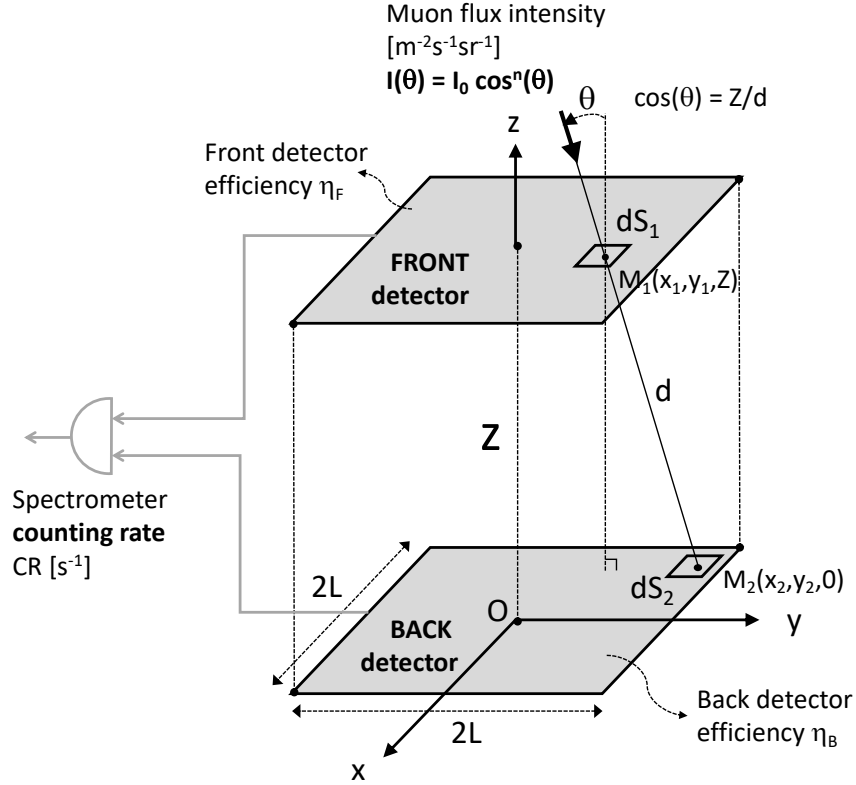
163 The spectrometer counting-rate has been numerically estimated from a model directly
 164 derived from the work of Sullivan [24] and Thomas and Willis [25]. Figure 6 introduces the
 165 notations used in the following. For an anisotropic distribution of incident muons I ($\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}$)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

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

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

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

171



172

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

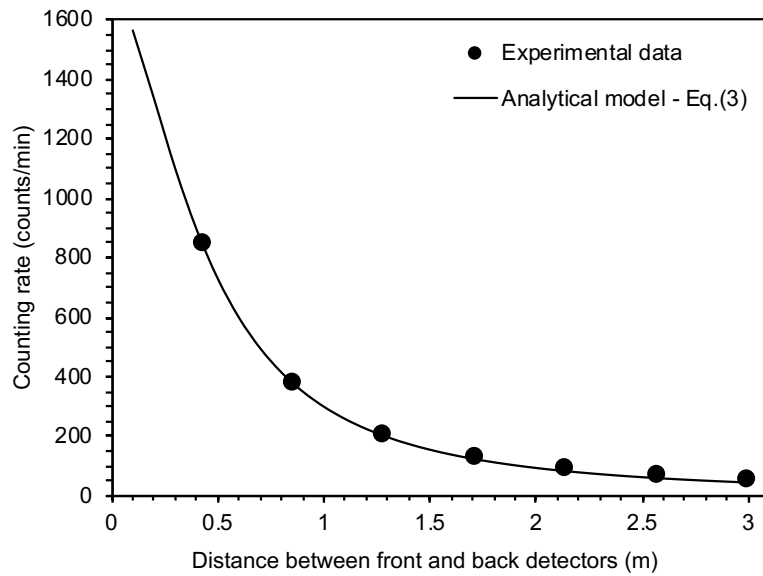
176 where I_0 is the vertical muon flux (expressed in $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}$) integrated over the energy range
 177 of the instrument, η_F and η_B are the front and back detector efficiencies, respectively, and Z is
 178 the distance between the two square detectors of surface $4L^2$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

179 Assuming that the zenith angle distribution of muons follows Eq. (1) with a fixed value of
 180 exponent n in the energy range of interest of the instrument, Eq. (2) directly gives the value of
 181 I_0 for each experimental counting rate CR corresponding to a given water height in the tank,
 182 i.e. to a given cutoff energy E_{min} .

183 For $n = 2$, Eq. (2) can be expressed analytically and the counting rate of the instrument is
 184 then given by:

$$185 \quad CR_{n=2}^a = I_0 \eta_F \eta_B \times 2L \left[\frac{Z^2 + 8L^2}{\sqrt{Z^2 + 4L^2}} \times \arctan\left(\frac{2L}{\sqrt{Z^2 + 4L^2}}\right) - Z \times \arctan\left(\frac{2L}{Z}\right) \right] \quad (3)$$

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

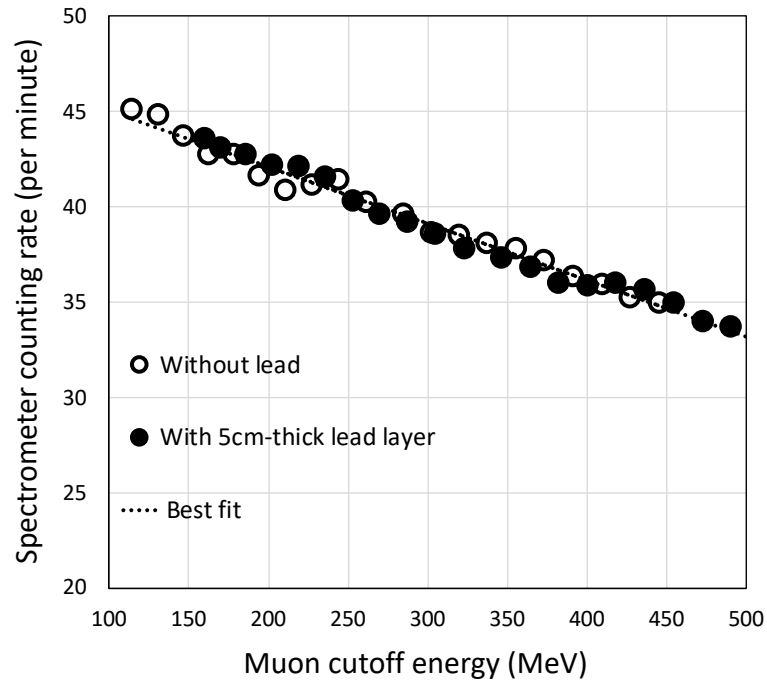


188
 189 **Figure 7.** Counting rate as a function of the distance between the front and back detectors.
 190 The experimental data are obtained using an additional setup based on a plastic shelf
 191 described in [19]. The curve labeled “Model” is obtained from Eq. (3) with
 192 $I_0 = 100 \mu \text{ m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ and $n = 2.0$, as experimentally obtained in [19].

193 3. Experimental results: sea level measurements

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

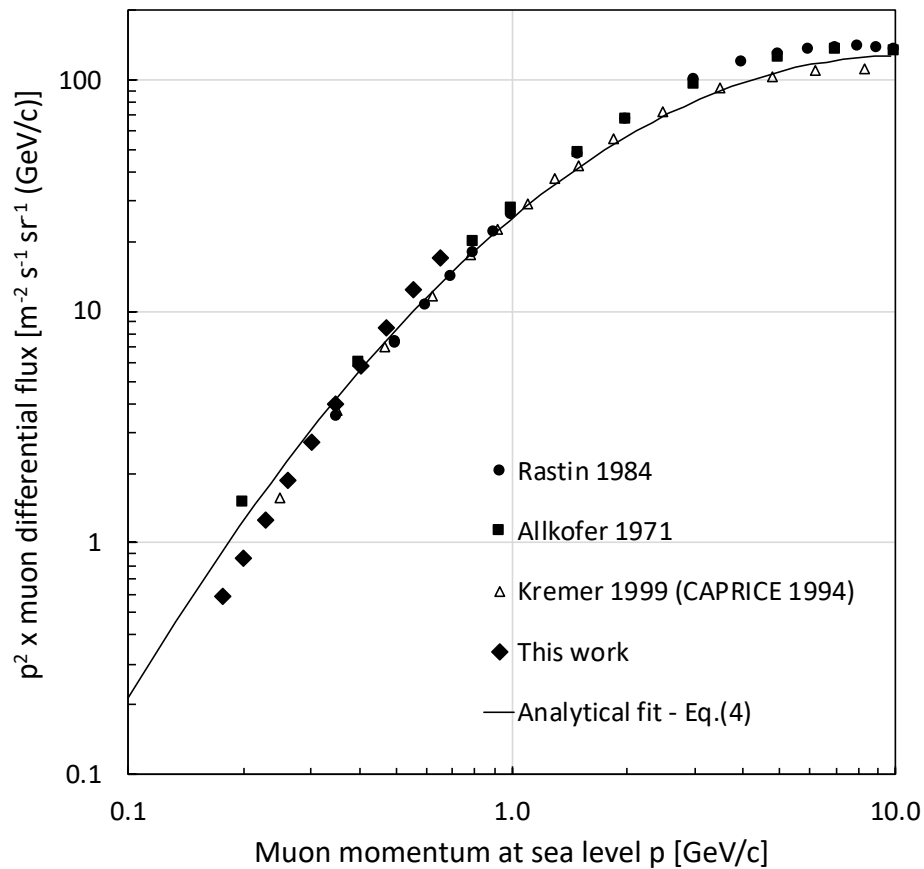
198 To check the validity of the spectrometer counting-rate modeling (Eq. 3), we performed
 199 preliminary measurements by varying the distance Z between the two detectors, using a
 200 plastic resin shelf with seven regularly spaced shelves. In this case, the two detectors were
 201 temporarily removed 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))
 205 presented above, taking values $I_0 = 100 \mu \text{ m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ and $n = 2.0$, as experimentally obtained
 206 in [19].



207
 208 **Figure 8.** Experimental counting rates (with and without the 50 mm-thick lead layer) as a
 209 function of the cutoff energy of the spectrometer. Each point corresponds to a value averaged
 210 over one week (168 h).

211 After this preliminary step, the muon spectrometer was continuously operated for around
 212 nine months for the acquisition of experimental data. Figure 8 shows the variations of the
 213 instrument counting rate as a function of the energy cutoff E_{\min} determined by the height of

214 the water level in the water tanks. Two series of data have been acquired, with and without
 215 the 50 mm-thick lead layer. Each point corresponds to a value averaged over one week (168
 216 hours). These results show a quasi-linear decreasing relationship between the counting rate
 217 and the instrument cutoff energy. They also show that the presence of the additional lead layer
 218 in the instrument material stack does not alter this linear dependency and only shift by ~ 50
 219 MeV the energy domain explored by the instrument.



220
 221 **Figure 9.** Muon spectrum at sea level deduced from data of Figure 8 and measured in other
 222 experiments [3,4,5]. The line refers to the fit of experimental data with Eq. (4) and data
 223 parameter from [26]. The fluxes are multiplied by p^2 , where p is the momentum in GeV/c.

224 From data of Figure 8 and considering the analytical equation (3), the integral vertical
 225 muon flux I_0 above energy E_{\min} can be extracted from the experimental counting rate value
 226 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
228 the first derivative of this $I_0(E_{\min})$ relationship (using the best linear fit on three consecutive
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]:

$$235 \quad \log I(\theta) = a \ln^2 p + b \ln p + c \quad (4)$$

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

237 The analytical fit shown in Figure 9 has been obtained with Eq. (4) considering the values
238 of a , b , and c reported in [26] for a vertical zenith angle: $a = -0.1292$, $b = -0.266$ and
239 $c = -2.600$. We observe that our data satisfactory agree with this analytical fit in the full
240 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.

254

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260

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