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1 Simultaneous scintillation light and charge readout of a
2 pure argon filled Spherical Proportional Counter

3 R. Bouet^a, J. Busto^b, V. Cecchini^{a,c,*}, C. Cerna^a, A. Dastgheibi-Fard^d,
4 F. Druillole^a, C. Jollet^a, P. Hellmuth^a, I. Katsioulas^e, P. Knights^{e,f},
5 I. Giomataris^f, M. Gros^f, P. Lautridou^c, A. Meregaglia^a, X. F. Navick^f,
6 T. Neep^e, K. Nikolopoulos^e, F. Perrot^a, F. Piquemal^a, M. Roche^a,
7 B. Thomas^a, R. Ward^e, M. Zampaolo^d

8 ^a*CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France*
9 ^b*CPPM, Université d'Aix-Marseille, CNRS/IN2P3, F-13288 Marseille, France*
10 ^c*SUBATECH, IMT-Atlantique, Université de Nantes, CNRS/IN2P3, France*
11 ^d*LSM, CNRS/IN2P3, Université Grenoble-Alpes, Modane, France*
12 ^e*School of Physics and Astronomy, University of Birmingham, B15 2TT, UK*
13 ^f*IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

14 **Abstract**

15 The possible use of a Spherical Proportional Counter for the search of neu-
16 trinoless double beta decay is investigated in the R2D2 R&D project. Dual
17 charge and scintillation light readout may improve the detector performance.
18 Tests were carried out with pure argon at 1.1 bar using a 6×6 mm² silicon
19 photomultiplier. Scintillation light was used for the first time to trigger in a
20 spherical proportional counter. The measured drift time is in excellent agree-
21 ment with the expectations from simulations. Furthermore the light signal
22 emitted during the avalanche development exhibits features that could be
23 exploited for event characterisation.

24 *Keywords:* Spherical TPC, neutrino, neutrinoless double beta decay,
25 scintillation

26 **1. Introduction**

27 The use of Spherical Proportional Counters (SPC) in direct dark mat-
28 ter searches has been going on for a decade within the NEWS-G collabo-
29 ration [1, 2, 3, 4]. More recently, the possibility to use such a technology
30 to search for $\beta\beta 0\nu$ decay has been investigated [5] and an R&D programme

*Corresponding author
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31 is ongoing [6]. The aim is to tackle the various technical challenges to be
32 faced for the construction of a large SPC, up to 1 m radius, filled with ^{136}Xe
33 at 40 bar and simultaneously to demonstrate that energy resolution of 1%
34 FWHM, and the recognition and radial localization of the two searched-for
35 beta tracks are possible with this very simple setup. The proposed R&D
36 programme addresses the different topics sequentially, before designing the
37 final apparatus optimized for the targeted physics program.

38 So far, very encouraging results on the energy resolution (1.1% FWHM)
39 have been obtained in Ar at 1 bar, and a coarse localization of the inter-
40 actions within the detector seemed possible [6]. In parallel, the NEWS-G
41 collaboration has demonstrated with SPC low-pressure operations that iden-
42 tification and analysis of events initiated by 2 distinct electrons was routinely
43 reached [7, 8]. Likewise, the search for KK axions in their expected di-photon
44 decay channel was carried out [9]. These experimental advances suggests that
45 the identification of double traces induced by a double beta decay would be
46 possible.

47 In this study, our objective is to verify the possibility of using a pure noble
48 gas and to characterise the detector performance obtained at atmospheric
49 pressure before turning to higher pressure. The light emission being one of the
50 distinguishing characteristics of the excitation in a noble gas, we implemented
51 a minimal system to detect scintillation light, and coincidences with the SPC
52 detector signal were observed.

53 In this paper the experimental setup is described with emphasis on the
54 light readout system. We compare between observed data and simulation
55 and discuss the light emitted in the avalanche process. We also evaluate the
56 impact of quencher-free gas on the charge signal shape and resolution.

57 **2. Experimental setup**

58 The detector operating principle consists of a spherical grounded vessel,
59 filled with gas and with a central anode at a positive high voltage as shown
60 in Fig. 1. Particles passing through the gas ionize it and produce electrons
61 which drift under the influence of the electric field to the central anode. When
62 the electrons reach a distance of few mm from the central anode, depending
63 on the high voltage (HV), they create an avalanche leading to the positive
64 ions signal. More details can be found in Refs. [1, 11].

65 The prototype built at CENBG, in the framework of the R2D2 R&D,
66 consists of a spherical stainless steel vessel of 20 cm radius with a central

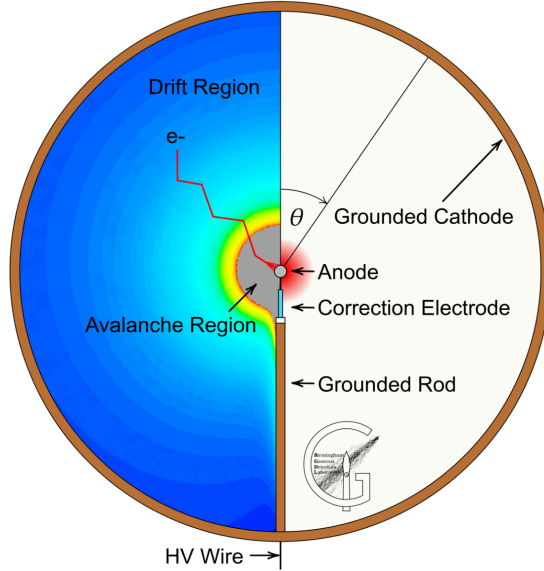


Figure 1: *Operating principle of the SPC detector taken from Ref. [10].*

67 anode of 2 mm diameter. At the bottom of the detector there is an opening
 68 which is used to insert a ^{210}Po source emitting α particles with an energy of
 69 5.3 MeV. This prototype was used to assess the energy resolution in Ar at
 70 different pressures and further details on the setup can be found in Ref. [6].

71 2.1. Light readout system

72 The light yield of Ar gas is 14700 photons per MeV, assuming that elec-
 73 tronegative impurities are kept at the ppm level [12]. In our case the detector
 74 was pumped to a vacuum of 5×10^{-5} mbar, and the use of pure Ar (*i.e.* pu-
 75 rity at the level of 99.9999% given by supplier) allowed to reach a purity
 76 sufficient for light detection and a homogeneous gain, *i.e.* independent of α
 77 track radial distance. No further purification of the gas was attempted. Data
 78 taking was started 6.5 h after filling the SPC to ensure stable operation. The
 79 detector stability was monitored to ensure that the gain response remains
 80 constant over time.

81 To observe argon scintillation light a photodetector sensitive to 128 nm
 82 photons is required. Generally, liquid argon experiments aiming at detecting
 83 scintillation light, exploit Tetraphenyl-Butadiene (TPB) coating of surfaces
 84 to shift the wavelength of the light into a range visible to Photomultiplier

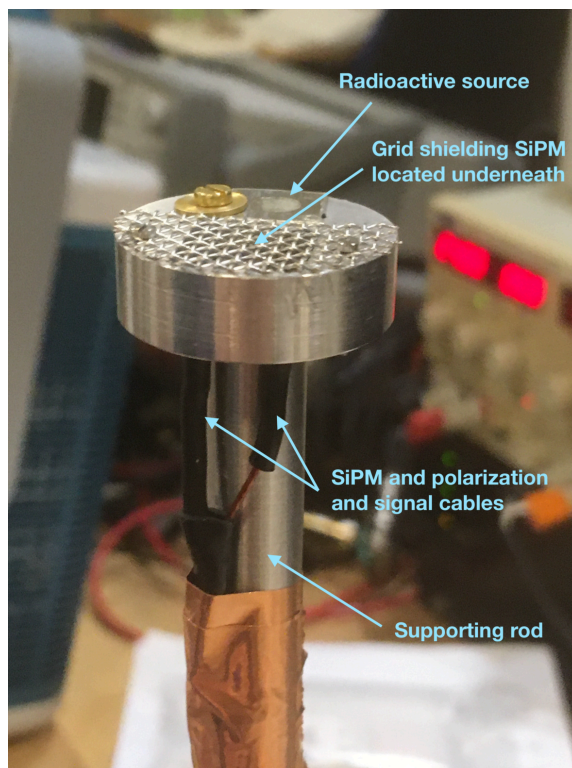


Figure 2: *SiPM setup.*

85 Tubes (PMTs). Such a procedure is however delicate and our chosen solution
 86 was to use commercial VUV silicon photomultipliers (SiPM) from Hama-
 87 matsu. Indeed SiPM S13370, with a size of $6 \times 6 \text{ mm}^2$ is a product of the
 88 VUV4 family with a photon detection efficiency (PDE) of 14% at 128 nm.

89 In the R2D2 setup the SiPM was mounted on the source support as shown
 90 in Fig. 2. Such a position has several advantages including the maximisation
 91 of the number of detected photons emitted by the α track (tracks passing in
 92 front of the SiPM), and the ease of cabling power supply and signal readout
 93 through the feedthrough located at the bottom of the detector. There is,
 94 however, a drawback: the SiPM had to be operated at a voltage of 55 V
 95 and it is located in a region where the electric field was weak, at the level of
 96 0.1 V/cm. Since the SiPM surface was at 55 V most of the electrons from
 97 the α -particle track would have drifted towards the SiPM instead of drifting
 98 towards the central anode. To overcome this issue a grid with holes of 1 mm

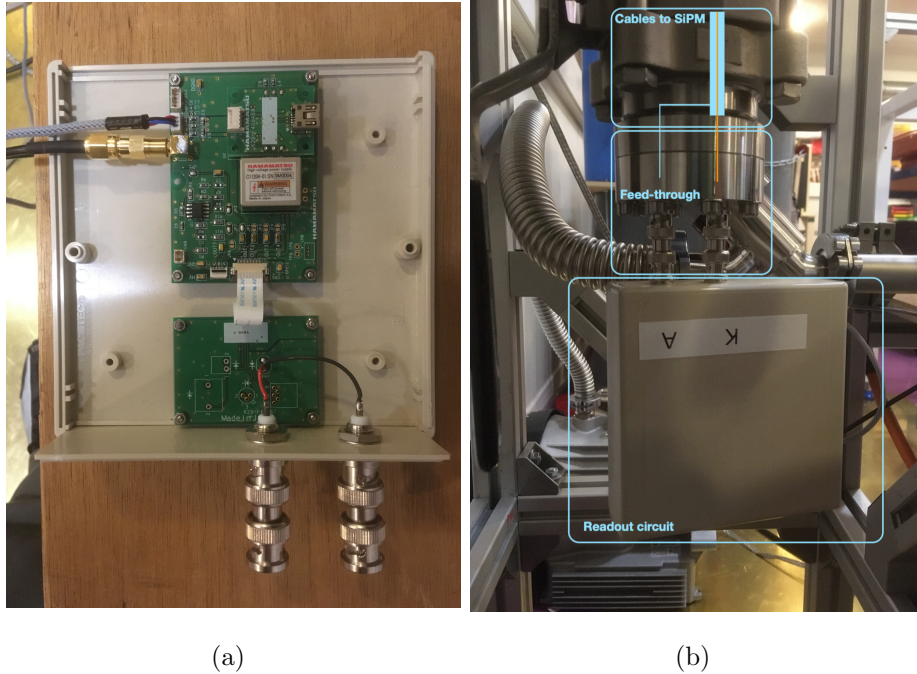


Figure 3: *Picture of the open readout box with the MPPC C12332-01 readout circuit ((a)) and SiPM readout circuit setup ((b)).*

99 and an optical transparency of 65%, was installed in front of the SiPM acting
 100 as a Faraday cage. Dedicated tests showed that turning the SiPM on and
 101 off had no impact on the signal and on the energy resolution proving the
 102 efficiency of the grid in shielding the SiPM field.

103 Since the SiPM is operated at room temperature a self-trigger rate at
 104 the level of kHz is expected for thresholds up to 4–5 photoelectrons (p.e.)
 105 depending on the SiPM. This, however, was not an issue for this application
 106 where the threshold could be raised to about 10 photoelectrons. A further
 107 challenge was related to the electronic noise due to the cables connecting the
 108 SiPM to the Hamamatsu readout circuit. Such a circuit (MPPC C12332-
 109 01), self-regulated with respect to temperature variations, was used to read
 110 out the SiPM signal, but it was located outside the detector, as shown in
 111 Fig. 3(a). This choice was imposed by the requirement to minimize the
 112 presence of material inside the detector. However, to reduce the noise, the
 113 distance between the SiPM and the readout circuit was minimized: the circuit

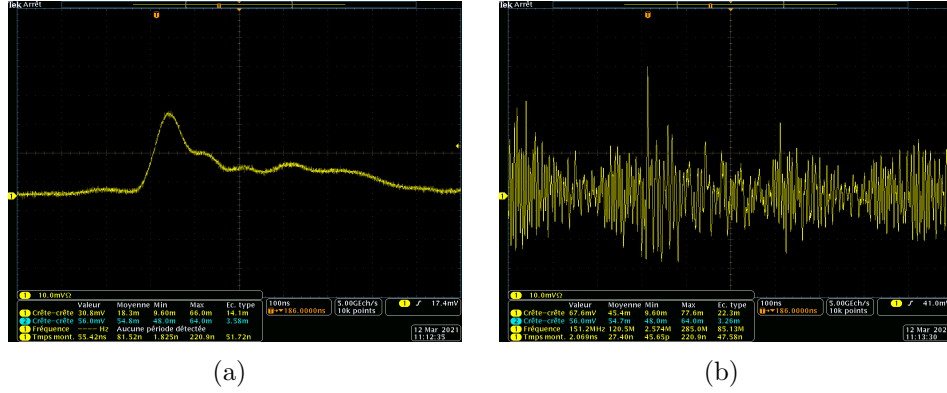


Figure 4: Signal of SiPM with a threshold of about 10 photoelectrons with ((a)) and without ((b)) the CLPFL-0010-BNC CRYSTEK low-pass filter of 10 MHz.

114 was connected directly at the feedthrough as shown in Fig. 3(b). Inside the
 115 detector, between the feedthroughs and the SiPM there was a distance of
 116 about 30 cm which could not be reduced. Several options were explored, but
 117 the solution put forward was to use a single coaxial cable, using the inner
 118 part of the cable for the signal transmission and the outer part for the power
 119 supply of the SiPM.

120 The SiPM signal is relatively fast and its width is of about 200 ns. A high
 121 frequency noise due to the distance between the SiPM and the readout circuit
 122 was observed and eliminated with a low-pass filter of 10 MHz (CLPFL-0010-
 123 BNC) from CRYSTEK (Fig. 4). Such a configuration allowed reaching the
 124 best experimental condition in order to look at the SiPM signal in coincidence
 125 with the SPC signal.

126 3. Data analysis

127 Different runs were taken at different pressures and HV values. For pres-
 128 sures below 500 mbar α -particle tracks are too long (i.e. more than 6 cm) to
 129 give enough detectable light on the SiPM, and therefore the runs used in the
 130 presented analysis were all taken at the maximal allowed detector pressure of
 131 1.1 bar. Two HV regimes were investigated: HV at the level of 1800 V where
 132 the avalanche was not large enough to give detectable light on the SiPM,
 133 and HV of about 2200 V where a clear avalanche light signal was observed as
 134 explained in Sec. 3.3. Those two HV regimes correspond to a detector gain
 135 of about 15 and 50, respectively.

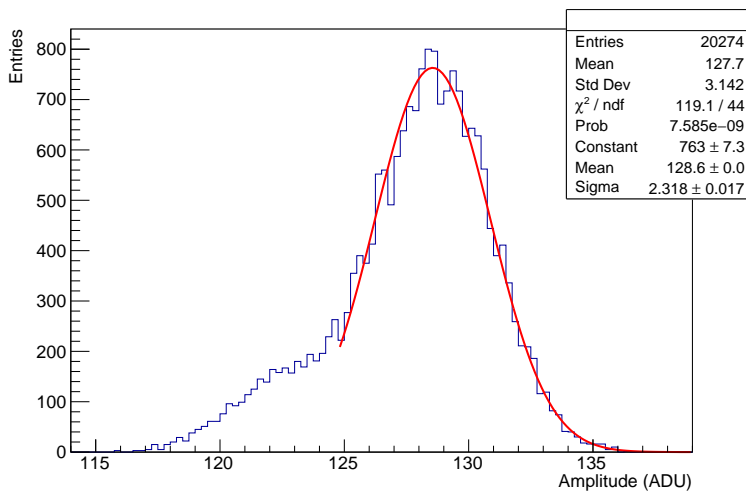


Figure 5: Signal recorded by the same readout electronic chain used for the SiPM for a 10 mV pulse.

137 The first point to be addressed was the SiPM calibration. Considering
 138 that the SiPM was operated in an unusual condition, at a large distance
 139 from the readout card, the noise prevented having the typical SiPM charge
 140 spectrum where the different number of photoelectrons are clearly seen.
 141 Another reason why the typical SiPM charge spectrum was not observed is
 142 that the detector DAQ uses a CALI card [13] at a sampling rate of 2 MHz (i.e.
 143 bins of 500 ns) which records the SiPM signal of ~ 200 ns in a single time
 144 bin. The signal amplitude is therefore smeared by the coarse time sampling
 145 transforming the typical “comb-like” structure of the SiPM readout into a
 146 continuous distribution.

147 To calibrate the SiPM a two-step procedure was therefore applied. First
 148 a defined pulse of 10 mV, from a KEYSIGHT 33600A waveform generator,
 149 was used as input in the same readout electronics chain used for the SiPM.
 150 In order to account for the slow sampling rate of the DAQ with respect to the
 151 signal width, a signal similar to the real one was used, namely a pulse with a
 152 rise-time of 70 ns and a fall-time of 118.8 ns at a rate of 1 kHz. The obtained
 153 distribution shown in Fig. 5 gives a conversion factor of 1 mV equal to 12.9
 154 Data Acquisition Units (ADU). Linearity was also checked and demonstrated
 155 within the input uncertainty between 10 and 30 mV.

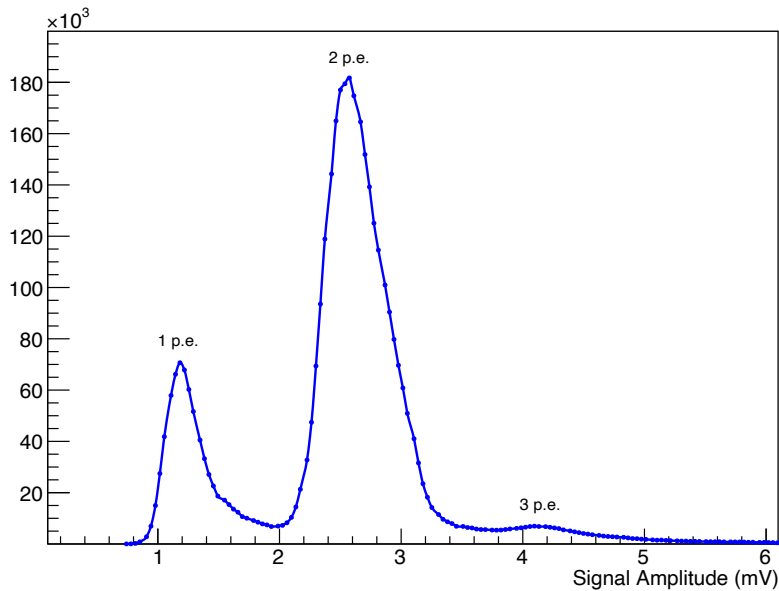


Figure 6: *Amplitude of SiPM dark noise signals. The 1 p.e. and 2 .p.e. peaks are clearly visible.*

156 The second step consisted of removing the SiPM from the detector and mea-
 157 suring its dark noise signal with the same readout electronics but directly
 158 connected to the readout circuit in order to remove the noise due to the
 159 cables. This was done using a Tektronix oscilloscope in order to retrieve
 160 the expected charge readout pattern. A random trigger was used and the
 161 maximum amplitude of the waveform in a window of about 700 ns before
 162 the trigger was recorded. The amplitude of the signal corresponding to a
 163 given number of photoelectrons is not affected by the window width, how-
 164 ever the probability of having a given number of photoelectrons does depend
 165 on it. The larger the window the higher the probability of having a large
 166 signal corresponding to 2 photoelectrons or more. The results is shown in
 167 Fig. 6 where peaks corresponding to 1 and 2 photoelectrons are clearly visi-
 168 ble: the amplitude corresponding to 1 p.e. corresponds to about 1.2 mV. The
 169 pedestal is not seen since it is below threshold. A conversion can therefore be
 170 established between and DAQ units, such that 1 photoelectron corresponds
 171 to about 15.5 ADU.

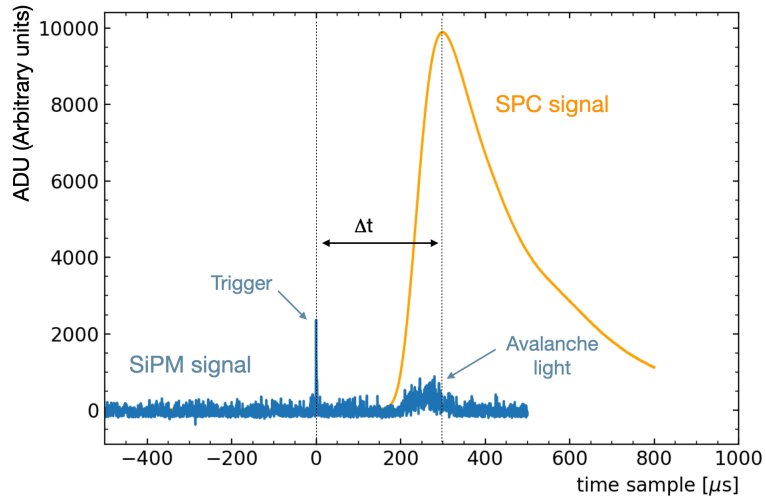


Figure 7: Raw waveforms of SiPM (blue) and anodie signal (orange) for one event taken at 1.1 bar and 2200 V. The Δt of about 300 μs is shown. For illustration purpose the SiPM signal is multiplied by a factor of 5.

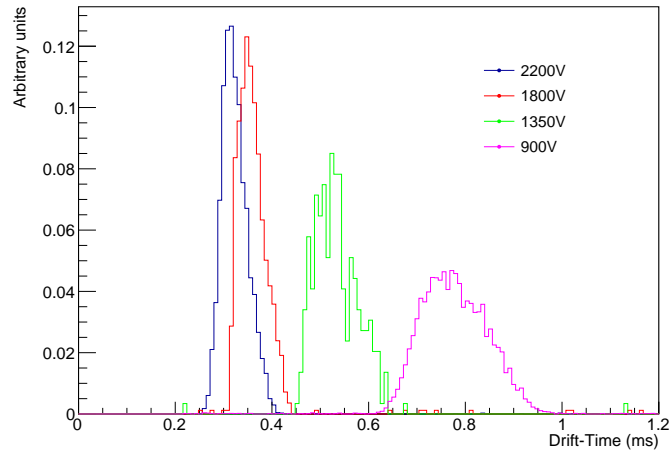


Figure 8: Drift time obtained applying different HV on the central anode. The different histograms are normalized to one for a direct comparison independently on the number of triggered events of the run.

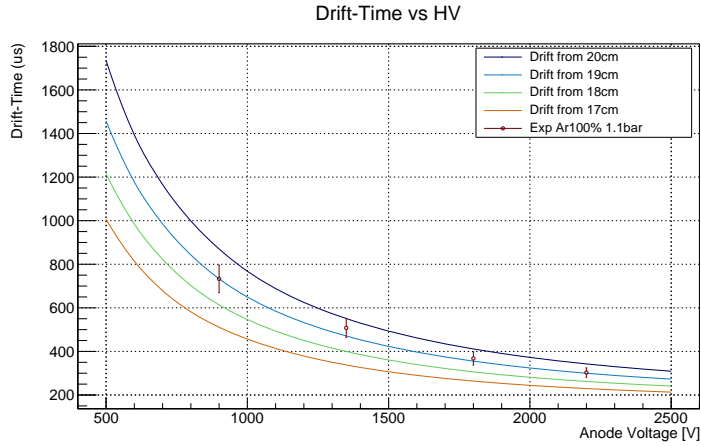


Figure 9: *Drift time from Garfield++ simulations for as a function of the anode HV for different starting radial distances from 17 to 20 cm (colored solid lines). The experimental data are also shown and the bar width corresponds to the RMS of the drift time distributions of Fig. 8.*

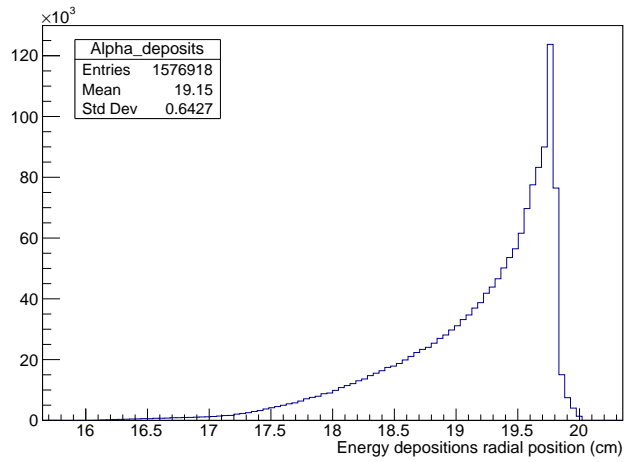


Figure 10: *Radial energy depositions from α -particles simulated by Geant4 at 1.1 bar in argon.*

172 *3.2. Drift time analysis*

173 The first dataset was taken triggering on the SiPM with a threshold of
174 200 ADU which corresponds to about 13 p.e. At the time of measurements,
175 the ^{210}Po source had an activity of 0.4 Bq but only tracks passing in front
176 of the SiPM produced detectable light; selecting this subsample of events
177 reduced the trigger rate by a factor of 10 to 40 mHz.

178 Triggering on the SiPM selects a subsample of α tracks in a specific
179 direction, however all these events should result in a signal on the central
180 anode. This is indeed what we observed and one example of the waveforms
181 for such events is shown in Fig. 7.

182 The time difference Δt between the SiPM signal and the SPC signal was
183 computed and is shown in Fig. 8. The width of the Δt distribution depends
184 on two factors: the spread due to the electron diffusion during the drift, and
185 the α tracks emission angle. Considering that α -particle tracks have a range
186 of about 3 cm at 1.1 bar, the ionization electron distance from the anode
187 spans between 17 cm and 20 cm.

188 A Garfield++ [14] simulation was carried out in order to benchmark the
189 drift velocity of electrons. The drift time for different values of the anode
190 HV was computed starting from radial positions spanning from 17 cm to
191 20 cm with respect to the detector center. The results are shown in Fig. 9
192 along with the measured data, indicating a mean distance of the α -particle
193 tracks of about 19 cm from the detector centre. This was confirmed by a
194 Geant4 [15] simulation of the α tracks: the radial position of the energy
195 depositions exhibits a peak at 19.76 cm with a mean at 19.15 cm as shown
196 in Fig. 10.

197 *3.3. Avalanche light analysis*

198 When the detector is operated at sufficiently high voltage, 2200 V in our
199 case considering the argon gas pressure of 1.1 bar, the light signal emitted
200 during the avalanche is large enough to be detected by the 6×6 mm² SiPM
201 located at the cathode surface. Such a light is emitted at the central anode
202 and is observed also for α tracks which do not pass in front of the SiPM. It
203 is therefore possible to trigger on the avalanche light to have a higher rate
204 of events, at the level of 0.2 Hz expected from the source activity, and the
205 trigger signal is in this case simultaneous with the central anode signal inde-
206 pendently on the drift time.

207 Triggering on the avalanche light is of course not helpful for the radial track
208 reconstruction, but such a signal could potentially be exploited to have an

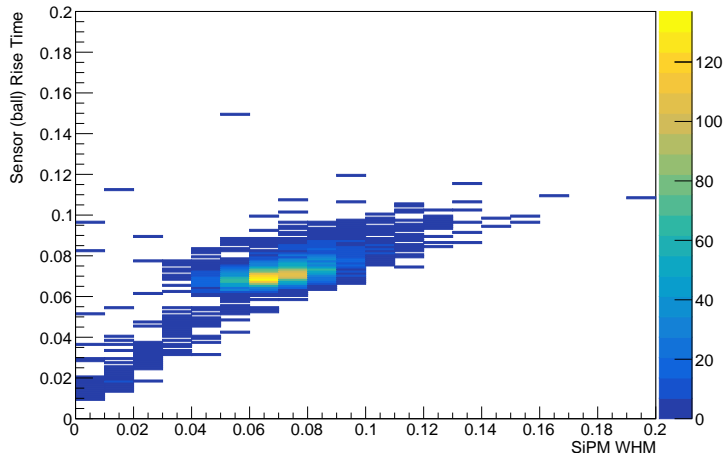


Figure 11: *Width of the avalanche light signal versus rise-time of the central anode signal.*

209 additional handle to reconstruct the topology of the event. The width of the
 210 waveform is indeed proportional to the time between the first and the last
 211 drifted electrons which in turn depends on the radial projection of the track.
 212 To validate such a feature we compared the width of the avalanche light sig-
 213 nal to the rise-time of the central anode signal which is known to provide
 214 information on the radial position of the energy deposits as demonstrated
 215 by the NEWS-G collaboration and previous R2D2 works [4, 6]. The results
 216 shown in Fig. 11 show a clear correlation between the two variables demon-
 217 strating that the avalanche light waveforms contains indeed information on
 218 the event topology. A dedicated analysis to exploit this feature will be the
 219 topic of future work.

220 3.4. Secondary electrons signal

221 The runs taken at 2200 V on the central anode, with a significant amount
 222 of light emitted in the avalanche process, allowed to study another phe-
 223 nomenon, namely the secondary electrons signal.
 224 Photons produced during the avalanche reach the sphere surface and could
 225 eject electrons which would be drifted to the central anode producing a second
 226 signal. A digital deconvolution of the charge preamplifier output waveform
 227 allowed to recover the charge time distribution which was masked by the
 228 RC effect of the charge integrator (see [6] for the method). The resulting

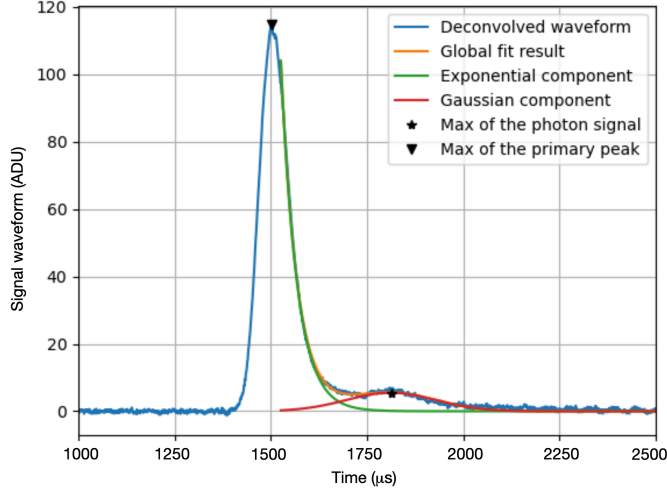


Figure 12: *Waveform, after signal processing (deconvolution), showing the bump due to the secondary electrons. The bump is modelled as a Gaussian function (red curve) over an exponential function (green curve) corresponding to the tail of the primary ionization peak.*

229 deconvolved waveform exhibits a bump on the tail of the primary ioniza-
 230 tion signal, as seen in Fig. 12. . For further analysis, this photon-induced
 231 contribution was modeled with a Gaussian distribution superimposed on an
 232 exponential component describing the tail of the primary ionization peak.
 233 The time difference between the secondary electron signal and the primary
 234 ionization one was computed as shown in Fig. 13(a). The mean value at
 235 about $316 \mu\text{s}$ corresponds indeed to the drift time expected from electrons
 236 starting at the sphere surface (i.e. distance of 20 cm from the anode) for a
 237 central anode at 2200 V as shown in Fig. 9.

238 It is possible to extract the value of the signal time spread due to diffusion
 239 (σ_{dif}). Indeed if the electrons were all produced at the same time the Gaus-
 240 sian width would be completely due to the electron diffusion. This is not
 241 the case and the time spread of the production is given at first approxima-
 242 tion by the time spread of the primary ionization signal. The diffusion can
 243 therefore be evaluated as: $\sigma_{dif} = \sqrt{\sigma_{photon}^2 - \sigma_{ion}^2}$ where σ_{photon} and σ_{ion} are
 244 the widths of the Gaussian fits of the secondary electron signal and of the
 245 primary ionization signal respectively. The mean value of the diffusion over
 246 the full 20 cm drift is $32 \mu\text{s}$ (see Fig. 13(b)).

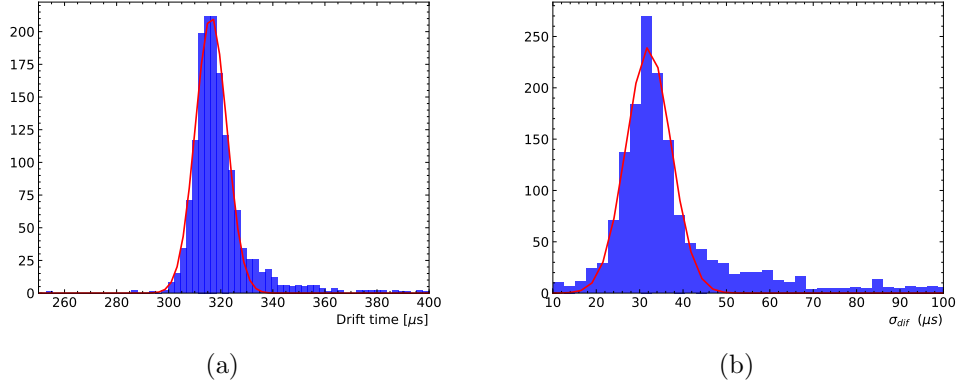


Figure 13: (a) Time difference between the primary ionization signal and the bump due to secondary electron signal. The red is a Gaussian fit. (b) Distribution of the width difference (σ_{dif}) between the peak of primaries and the induced photon peak, fitted by a Gaussian.

247 It is noted that in case of high gain operation, secondary electron emissions
 248 could become challenging since it may bring the detector into a Geiger mode.
 249 The addition of a quencher to the gas allows to mitigate this effect, however,
 250 in a future Xe-filled SPC, the presence of a quencher could result in an ad-
 251 ditional degree of complication concerning xenon purity since the use of a
 252 purifier, such as a hot getter, could modify the quencher fraction over time.
 253 For this reason, considering the foreseen low gain operation, the use of pure
 254 xenon is currently preferred. The impact on the energy resolution of the
 255 secondary electron signal was therefore an important point to be addressed.
 256 The waveform integral was studied, for fully contained tracks, and a reso-
 257 lution of 1.5% FWHM was found at 5.3 MeV as shown in Fig. 14. If the
 258 secondary electron signal is subtracted (modelled with a Gaussian function)
 259 the resolution is degraded to 2.2%.

260 Such a result is of great interest for the development of the future detector
 261 for $\beta\beta 0\nu$ decay search since it suggests that pure xenon may be used also in
 262 proportional mode and the use of a quencher is not mandatory to achieve the
 263 desired energy resolution (at least within our modest gain operating regime,
 264 and the high energy deposits expected with $\beta\beta 0\nu$ search).

265 This is true for what concerns the use of quencher in order to avoid sec-
 266 ondary electrons stripped from the sphere by scintillation light. This result
 267 illustrates the possibility to operate the detector without quencher, but the

268 quencher presence has also an impact on the resolution, affecting the number
 269 of collected electron via Penning effect [16]. Indeed, previous results shown
 270 a better resolution with 98%Ar:2%CH₄ [6] with respect to the resolution
 271 presented here, obtained in pure argon.

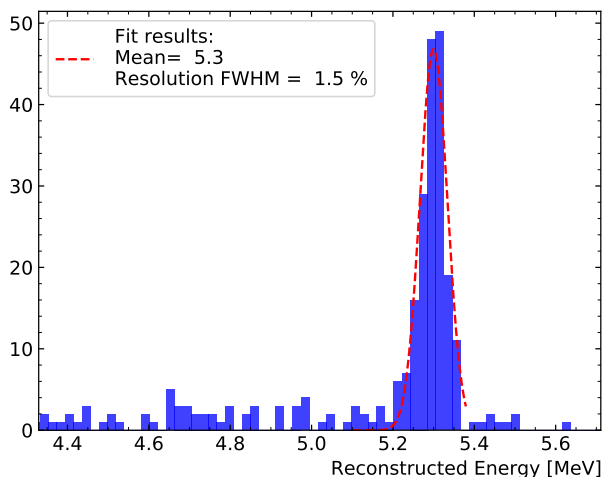


Figure 14: Resolution obtained integrating the waveform over the full range.

272 4. Conclusions

273 For the first time a scintillation light signal is used as trigger in a SPC.
 274 The presented results, although still partial, constitute an encouraging first
 275 step towards the use of an SPC filled with pure noble gas. Studies on the
 276 waveform of the light signal have been carried out and the possibility of cross-
 277 ing information provided by the anode signal was investigated. Observations
 278 showed an excellent agreement between the ionization electron drift time and
 279 the expectation for the GARFIELD++ simulations.

280 An additional important outcome of this study is that, in a suitable regime
 281 of gain, the use of a quencher to avoid secondary electrons is not mandatory,
 282 at least at the tested pressure. The presence of secondary electrons emitted
 283 from the cathode by photons produced in the avalanche, does not spoil the
 284 detector energy resolution.

285 Further work is required to validate these findings for a xenon high pres-
 286 sure detector aiming at the detection of $\beta\beta 0\nu$.

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