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An R&D program for the research of $2\beta 0\nu$ decay with a SPC

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Abstract. The objective of the R2D2 R&D is to test the concept of a spherical proportional counter (SPC) for the search of the neutrinoless double beta decay ($2\beta 0\nu$). For this, we built a small prototype (40 cm in diameter), which was filled with an argon-based gas mixture at pressures up to 1.1 bar, and irradiated with a ^{210}Po alpha source. We report on results obtained in terms of directional, volume, and energy responses. We performed time measurements by combining the charge readout from the SPC with the light detection provided by a SiPM. We also studied the possibilities of localizing tracks in the detector and of discriminating multiple tracks.

1. Introduction

The determination of the nature of the neutrino mass is a missing critical piece of information in our knowledge for neutrino physics and for cosmology. The observation of the double beta decay without emission of neutrinos (the so-called $2\beta 0\nu$ decay) is today the most sensitive way to assess the Majorana nature of neutrino. Experimentally, the $2\beta 0\nu$ decay consists in the emission of only two electrons. The sum of the energy of these electrons must be equal to the transition energy (typically 2-3 MeV depending on the isotope). Such a process, if it exists, is extremely rare (periods larger than 10^{26} years) and its half-life is inversely proportional to the neutrino mass squared. Few events per year are expected for a target of 10^{26} nuclei, hard to distinguish from background induced by natural radioactivity. Next generation experiments, aiming at measuring periods at the level of 10^{27} years, envisage detector masses of several tons. Extremely low radioactive background, excellent energy resolution, tons of candidate emitters, and probably unambiguous identification of the $2\beta 0\nu$ decay, added to an optimal control of the detector operation will constitute extraordinarily difficult constraints to reconcile [1, 2].

To meet this challenge, we envisage to exploit a single-channel gaseous detection technique based on the spherical proportional counter (SPC) [3], filled with ^{136}Xe gas at 40 bars [4]. The very simple mechanical structure should make it possible to reach an ultimate radioactive background due to the very low material budget, and to size the detector up to one ton of isotopes. Indeed, preliminary calculations [5] indicated that a 1 m radius SPC filled with enriched Xe could stand as an efficient device. Today, SPC technology is used in the NEWS-G experiment for the search for rare events in the keV range (for low mass dark matter [6] and KK-axions [7]) up to 3 bars. In particular, detection of single primary electrons are now routinely exploited [8, 9], suggesting that the recognition of double traces induced by a double beta decay would also be possible. These developments have provided valuable starting points for the R2D2 R&D program.

Our aim is to assess the various technical challenges related for the construction of a 1 m radius SPC and to demonstrate that an energy resolution of 1% FWHM can be reached, while having the ability to identify the two β -tracks (thanks to the gas density). We approach these pitfalls step by step, starting with a small SPC of 0.2 m radius, filled with an Ar gas (pure or with 2% of CH₄) up to 1.1 bar. We report here some of the results obtained.

2. SPC principle

The spherical proportional counter consists of a grounded spherical vessel (cathode), filled with gas, and a central anode (a few mm of diameter) biased at high voltage. Its operation has similarities to that of a TPC. Thanks to the electric field going as $1/r^2$, the primary electrons produced by an interaction in the gas volume drift toward the anode. At a few mm from the anode, the electric field becomes high enough to initiate a multiplication. The avalanche produces ions that slowly drift towards the cathode, which induces the SPC signal. The latter is pickup by a charge-sensitive preamplifier, then digitized in the form of a wave. The transient shape depends on both the amount of the energy deposited and the spatial distribution of the primary ionization. Since the amount of scattering depends on the drift distance, some sensitivity of the signal to the localization of the interaction is expected. By cons, noise plays a critical role because data interpretation relies on a single channel. Therefore, the requirements in terms of signal, grounding, vibrations, HV stability and gas purity are relatively stringent.

From a practical point of view, our SPC is equipped with a custom-made low-noise resistive-feedback charge-sensitive preamplifier designed to provide a high gain but a frequency band limited to a few hundred MHz [10]. Regarding signal processing, the waveform is first numerically filtered in order to attenuate possible RFIs using different composite filters. Then, a deconvolution of the RC introduced by the integrator allows extracting observables corrected for the ballistic deficit.

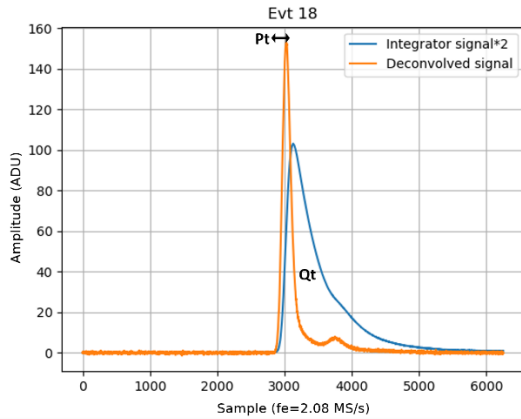


Figure 1. Example of an alpha interaction in pure argon seen through the raw integrator signal (in blue) and the associated deconvolved signal (in orange). The small peak corresponds to a secondary avalanche induced by the emission of photons from the main avalanche (see section 5). The Qt and Pt annotations concretize the observables used.

This report will refer to two of them (see figure 1):

- The area of the transient Qt, calculated from the beginning of the pulse to its end, and which measures the energy deposit;
- The peaking time Pt, defined as time between a threshold crossing and maximum amplitude of the deconvolved transient.

3. Experimental setup

Our SPC prototype consists of a 20 cm radius sphere built in aluminum (at this stage of R&D, the use of radio-pure materials was not necessary). The central anode consists of a stainless steel ball (1 mm radius), connected to an insulated wire (150 μ m in diameter), itself inserted into a grounded rod. The upper pole of the cathode holds this part. The internal wire connects to the readout electronics.

Below 10 bars, to detect energies of the same order of magnitude as the ^{136}Xe $Q_{\beta\beta}$ value, we did not use β sources because of the mean free path required for complete calorimetry. Instead, we used a ^{210}Po

source of alphas (5.3 MeV, rate of 1 Bq). The latter is attached on the internal surface of the cathode at its bottom pole. Simulations showed that, for pressures of 1.1 bar down to 0.2 bar, the maximum lengths of the interactions varied from 3.5 cm to 16.5-17 cm respectively from the source spot (figure 2).

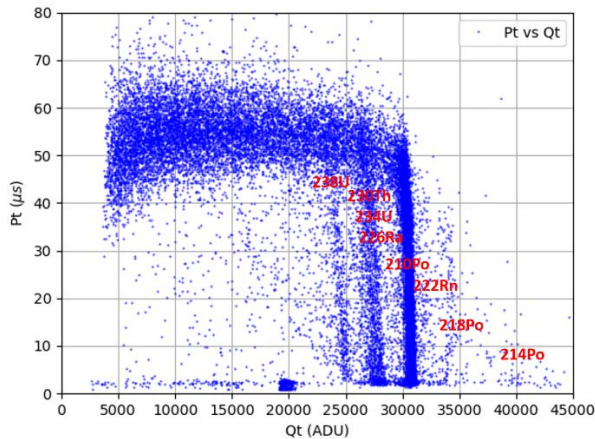


Figure 2. Diagram of events in the observable space (Qt, Pt) as observed with a ^{210}Po source in ArP2 gas at 0.2 bar. The 3 main vertical lines correspond to alphas penetrating the volume, including the main emission of ^{210}Po (31000 ADU), and residual contaminations of ^{230}Th , ^{234}U , ^{226}Ra (27000 ADU) and ^{238}U (25000 ADU). The horizontal bar around $Pt = 55 \mu\text{s}$ is associated with tangential α emissions, which stop at the cathode. The spot around 20000 ADU and $Pt < 5 \mu\text{s}$ is associated to calibration pulses.

Operating in sealed mode, we have imposed strict gas sealing requirements to prevent contamination from outside. Before each data taking, we pump the detector to about 10^{-6} mbar. We use an ArP2 mixture (98% Ar + 2% CH₄) certified (by the manufacturer) for contamination of less than 1 ppm in oxygen at the bottle outlet. With pure argon, a purity of 99.9999% is guaranteed (by the manufacturer) at tank outlet.

Being sensitive to acoustic, electronic noise and temperature variations, we paid a particular attention to stabilize the operating conditions. Temperature of the laboratory is kept constant within 1°C and human activity is reduced as much as possible. Silent blocks are inserted under the detector chassis to dampen mechanical vibrations as they affect the baseline stability of the waveforms (and therefore the energy resolution). Meticulous grounding and cable electromagnetic screening results also in a substantial reduction of low frequency noise. Finally, a non-negligible noise reduction was obtained (about a factor of 3 below 100 Hz). For all the results presented in this report, the multiplication gain of the detector was set to 20, by adjusting the high voltage bias to the correct level.

In addition to this initial setup, for measurements with pure Ar, we positioned a Silicon Photomultiplier (SiPM) near the Po source (see the conference slides). The argon excitation light radiates at 128 nm. We implemented a 6×6 mm² S13370 Hamamatsu VUV4, given for 14% photon detection efficiency at 128 nm. Its electronics are installed outside the tank.

4. Energy measurements

The energy resolution has been measured first with the ArP2 gas from 0.2 to 1.1 bar, and then according to the track length effect and to the track direction effect. Reference [10] presents a detailed discussion of these results. At pressure of 0.2 bar, the energy resolution reaches 1.1% FWHM for the most penetrating 16.5 cm tracks. At 1.1 bar, corresponding to a maximum track length of 3.5 cm, the detector exhibits an energy resolution of 1.2% FWHM. Those results indicate that neither the track length, nor the pressure, affect sizably the energy resolution.

To complete the previous results in terms of the directional response of the detector, we then sought an estimator of the emission angle (because of our source location, this also reflects the penetration distance to the detector center). This motivated simulations (based on Garfield and Magboltz) to determine if certain observables (such as total duration, width at half height, or peaking time) could be related to direction. With our source positioning, simulations showed that the total signal duration linked to the angle of emission of the source. The directions extracted from the simulation were expressed by

the cosine of the angle between the track and the vertical of the detector (-1 corresponds to the track going towards the anode, 0 for alphas emitted tangentially). Figure 3 presents the evolution of the energy resolution as a function of this angle, after sorting the real waveforms versus their duration. We concluded that the direction of the trajectory did not affect strongly the energy resolution (taking into account statistical uncertainties).

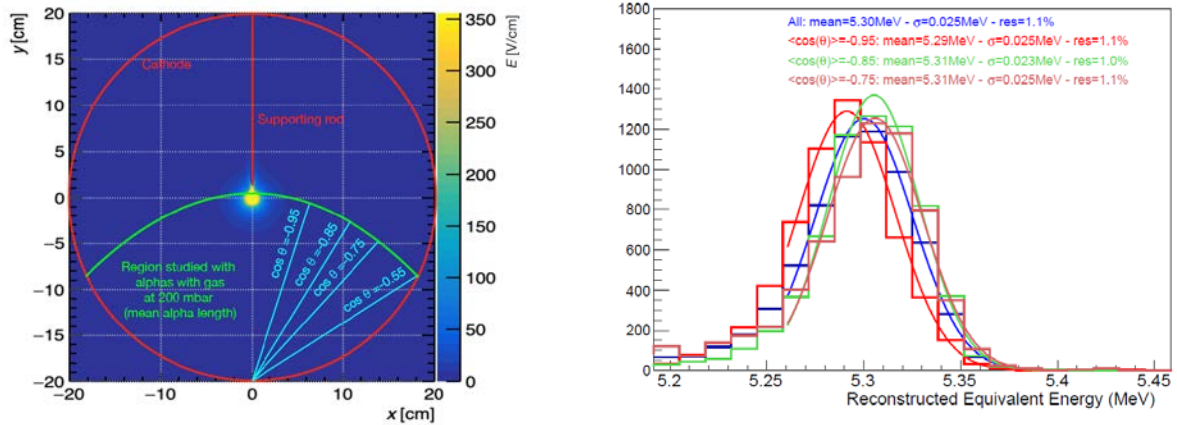


Figure 3. (a) Sketch of trajectory topologies according to angular cuts with ArP2 at 0.2 bar. (b) Energy distributions for different angular selections. These are based on the sorting of events according to the duration of the signal.

We also took advantage of the residual contamination of our ^{210}Po source to refine the response of the SPC to different deposited energies. We first selected source events (figure 4-a) pointing toward the anode using an identification plot (Q_t , P_t) of figure 2 and with the cuts ($Q_t > 23000$ ADU and $P_t < 50 \mu\text{s}$). After correction (green dots in figure 4-a) of the attachment effect which manifests itself by a slight inclination of the lines (blue dots), we then constructed by projection the energy deposition distributions. These are then adjusted using Gaussians whose averages are used in figure 4-b. As can be seen, the energy resolution make it possible to identify most of the different α emitters of the ^{238}U decay chain to estimate a preliminary energy response of the detector.

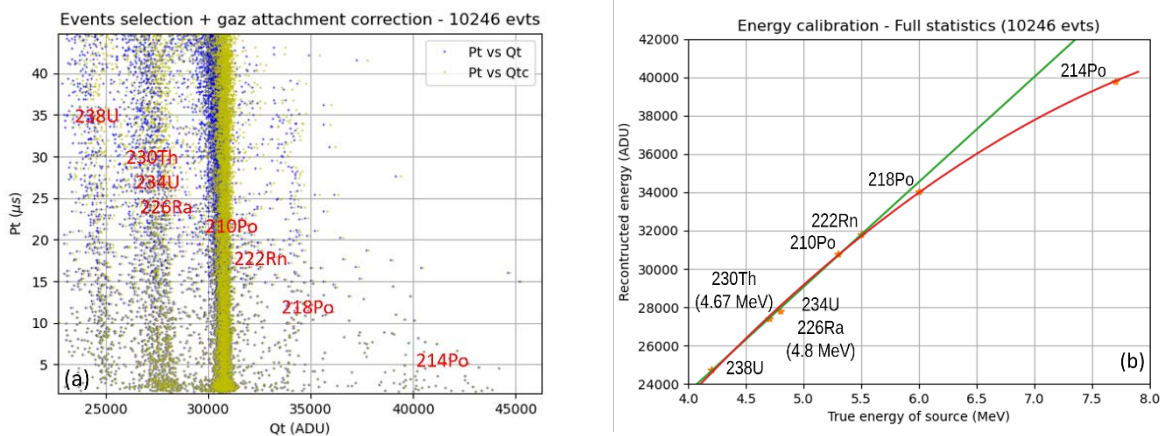


Figure 4. (a) Identification diagram (Q_t , P_t) obtained at 0.2 bar with the ArP2 gas and the ^{210}Po source. (b) Response in energy of the SPC for the same operation conditions. A slight deviation from linearity can be observed, probably due to incomplete calorimetry for the longer tracks.

5. Time measurements

Operation of a SCP alone would be a considerable asset in minimizing radioactive background noise. In addition to calorimetry, this presupposes having other observables to characterize the interactions, in terms of localization and discrimination of multiple tracks. Knowledge of the characteristic time scales of the processes driving the detector (drift time, signal formation, etc.) then becomes essential. With this aim, we used a pure Ar gas and a SiPM (see section 3) to detect the scintillation light produced during the primary ionization and the avalanche. To infer the counterpart SPC signal, both sensors are recorded in coincidence. Sufficient geometric acceptance of the primary ionization light was only achieved for tracks closest to the SiPM, and by operating the detector at 1.1 bar. This limitation turns out to be of no consequence for our study: the detected light fraction was sufficient for our purpose.

Initially, we have measured the drift time by calculating the time elapsed between the primary ionization seen by the SiPM and the maximum of the avalanche signal from the SPC. Measurements made for various high voltages showed good agreement with the simulations (see [11] for detailed discussions).

By exploiting, with the SPC only, the first and the second avalanche signals due to photons re-interaction, it turns out to be also possible to establish another independent estimation (figure 5) of the maximum drift time and its dispersion (for the maximum drift distance of 20 cm) [11].

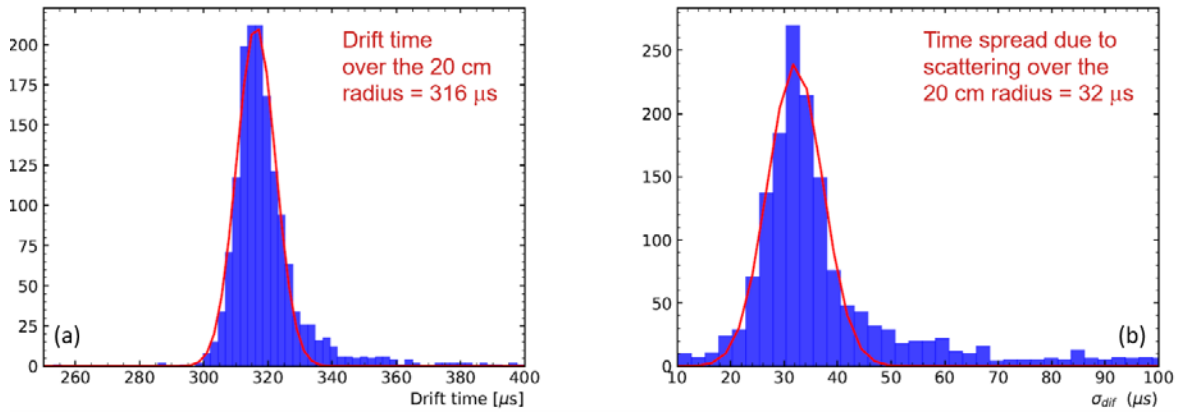


Figure 5. (a) Time difference (i.e. drift time for 20 cm) between the peak induced by the primaries and that due to the photons produced during the avalanche and interacting on the cathode. (b) Distribution of the width difference (σ_{dif}) between the two peaks (see also figure 1). The red lines show the results of the Gaussian adjustments.

Subsequent analysis revealed several other aspects. For instance, a third method, using the SiPM signal alone (time interval between the light of the ionization signal and the light produced by the main avalanche) has been implemented. All approaches produced consistent results. Being an observable completely independent of the SPC, this method was chosen for all subsequent analyses.

A next step in the analysis was to look for correlations between the drift time (deduced from the light measurements) and SPC observables. Several correlations appeared between the drift time and some of the SPC observables, in particular the correlation (Drift-time, Pt). To put in evidence this correlation, ^{210}Po 's emissions pointing to the anode were first selected, according to the qualitative information deduced from the identification plot (Qt, Pt). The observed dependency (figure 6) allows a direct interpretation. It suggests that observable Pt is related to the distance from the track to the anode. More events be welcome, but this is already encouraging, given that the tracks are short (3 cm) at this pressure (1.1 bar).

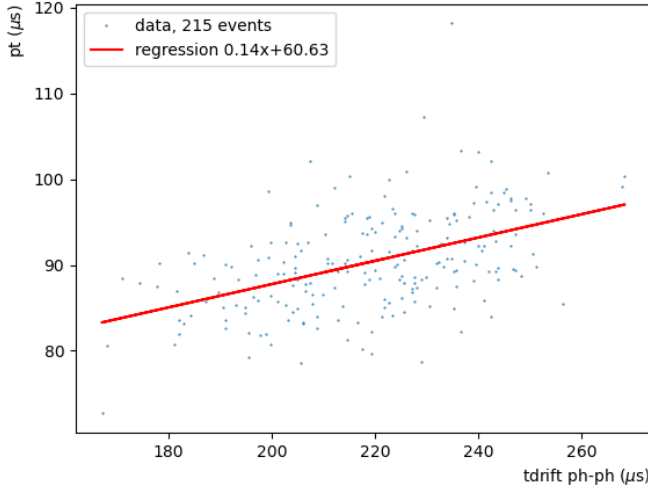


Figure 6. Distribution of the Pt according to the drift time between the 2 scintillation peaks (noted tdrift ph-ph), obtained after selection of the α -tracks of the ^{210}Po pointing towards the anode.

6. Radial localization of the tracks

One of the significant consequences of the previous observation is that it opens up the possibility of locating interactions, event by event, by exploiting the SPC in stand-alone mode. To check the latter hypothesis, we went back to the data obtained with ArP2 gas at 200 mb, for which the ionization tracks can extend up to 16.5 cm. In this configuration, no light was detected, only the SPC signal was usable. We relied our development on two additional observations. First, the deconvolved waveform is the experimental counterpart of the Garfield+Magboltz simulation signal induced at the anode (including ions diffusion and motion). Second, by analogy with the observed dependence in the simulation between the drift time (and the diffusion contribution) and the distance R to the anode, we assumed that a similar relationship would persist between the experimental observable Pt (maximum of the deconvolved signal) and R. At the time of writing, recent developments have shown that Pt is in fact strongly related to diffusion during drift and to the minimum approach distance from the track to the anode (publication in preparation). Therefore, we used a dependency of the form:

$$Pt = Pt_{max} \cdot \left(\frac{R}{R_{max}} \right)^\alpha$$

R is the searched distance to the anode (in cm); Pt_{max} is the maximum peaking time (experimental value in μs) at R_{max}, which is the maximum drifting distance. This pair of values corresponds to the tracks close to the cathode. The power term α is determined from the experimental values extracted from the identification 2D plot (Qt, Pt) presented in figure 2. It shows that Pt_{max} = 55 μs for R_{max} = 20 cm, when Pt = 2.2 μs is associated to the simulation value R = 3 cm. These last two quantities correspond to the most penetrating tracks, those pointing towards the anode. A value α of 1.7 is then deduced.

Once all the parameters are established, the final transformation (peak time $P_t \Rightarrow$ distance R) is obtained by inversion of the relationship. Figure 7 shows the results. As expected, the nonlinear transformation mainly affects the distribution of events near the cathode. It provides greater selection sensitivity in this region compared to the original diagram (Q_t , P_t). This preliminary development is a first attempt to localize interactions within an SPC working in stand-alone mode. The achievable spatial resolution has to be specified, in particular by imagining a simple experimental trick allowing this estimation. To complete, figure 8 shows the results of a similar processing for detection for the ArP2 gas at 1.1 bar, where the maximum radial extend of the ^{210}Po tracks is 3.5 cm.

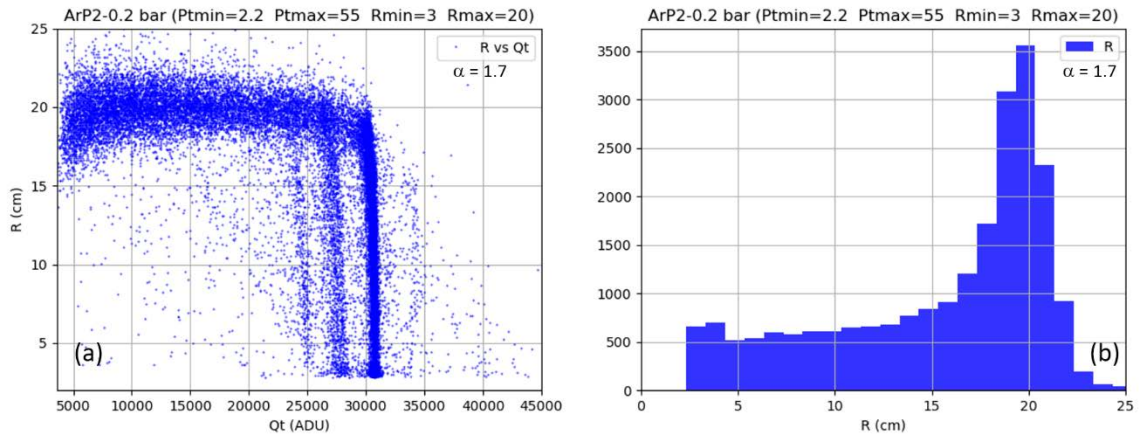


Figure 7. Resulting distribution (Q_t , R) (a) and histogram of R (b) for ArP2 gas at 0.2 bar.

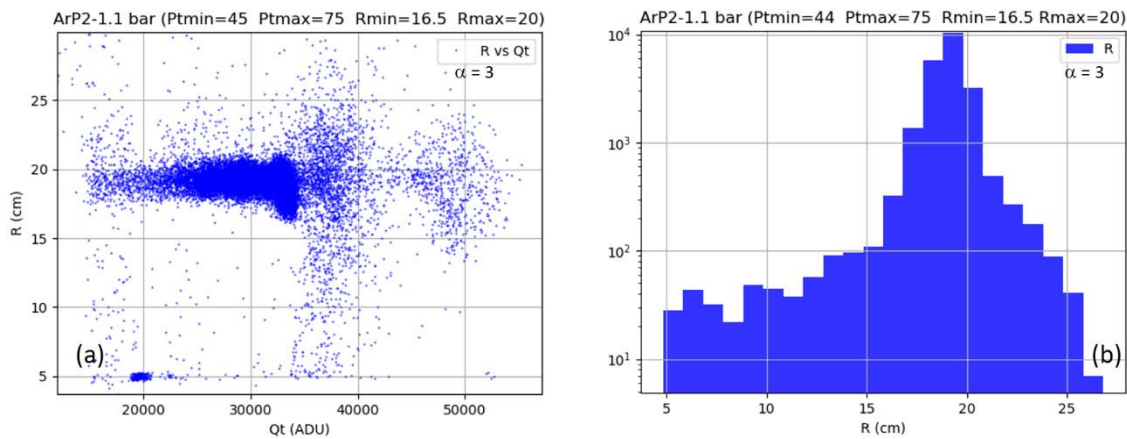


Figure 8. Resulting distribution (Q_t , R) (a) and histogram of R (b) for ArP2 gas at 1.1 bar.

7. Two-tracks recognition

Double beta decay without neutrinos produces two β -tracks of the same energy, whose sum is equal to the $Q_{\beta\beta}$ of the reaction, and of opposite direction. In a gas detector, this process can induce two distinguishable pulses. Indeed, if the radial positions of the tracks are not identical, their drift times (and therefore their P_t 's) becomes different. The maximum temporal separation between the two signals cannot exceed the maximum drift time of the primary electrons. Moreover, as figure 7 and 8 suggest, the minimum usable radial separation between the two tracks could be of the order of a centimeter. From a more general point of view, with regard to the background reduction, even with a modest separation, the possibility of discriminating the tracks, one by one, would also be a considerable asset.

To give us an idea of this, we searched for coincident alpha decays. The double event of figure 9 illustrates this situation with two alphas from ^{210}Po .

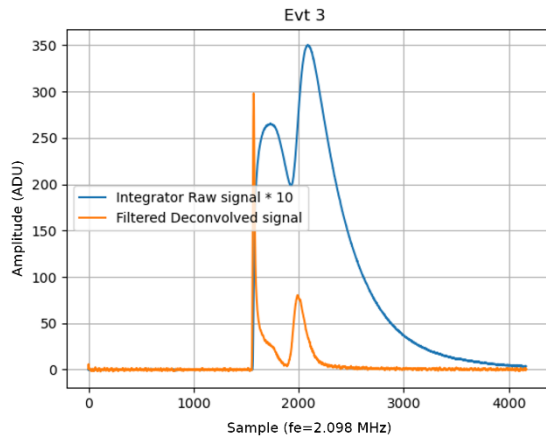


Figure 9. Waveform showing two coincident alphas. The deconvolution step improves the individual analysis of each track.

The figure suggests that such an analysis might be feasible, although in the present configuration, the directions are not opposite because they start from the same source spot on the cathode. Compared to argon, with xenon at 40 bar we expect the slower drift to be an advantage (but the length of a 1 MeV beta trace will only be a few centimeters).

8. Summary and future prospects

The first stage of the R2D2 R&D, using an ArP2 gas mixture up to 1.1 bar, has confirmed that an energy resolution of about 1% (FWHM) for alphas of 5.3 MeV was achievable. This observation looks independent on track length or direction. Use of pure Ar gas at 1.1 bar, combined with the detection of scintillation light, has allowed to extract temporal information from the SPC signal. Drift time, diffusion contribution as well as distance of the primary interaction in the detector volume were deduced gradually.

Large margins for improvement still remain, whether in terms of sensor design, gas quality, electronic noise reduction or signal analysis methods. Of course, further data are necessary in order to confirm firmly the relevance of the presented interpretation, in particular at higher pressures. This is why, as next step of this R&D, a new SPC certified for operation up to 40 bar is already commissioned. In order to reach the corresponding gas quality, a recycling system (recuperation for Xe + cleaning) is under development. As soon as we are ready, we will start studying the detector response up to 10 bar using energetic electrons from ^{207}Bi .

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