IL NUOVO CIMENTO **45 C** (2022) 5
DOI 10.1393/ncc/i2022-22005-0

Colloquia: SoUP 2021

Rare decays with radial detector: A Spherical Proportional Counter (SPC) R&D for the neutrinoless double beta decay search

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received 4 November 2021

Summary. — This proceedings is intended to briefly expose the progress of the R2D2 R&D toward a potential ton-scale experiment for the neutrinoless double beta decay searches. We focus our studies on the energy resolution measurements and on the integration of a light sensor for drift-time measurements.

1. – Introduction

The search for the neutrinoless double beta decay ($\beta\beta0\nu$) is one of the hottest topics in particle physics, as it is a probe for physics beyond the standard model (SM). Indeed, the observation of a $\beta\beta0\nu$ decay would prove the Majorana nature of the neutrino [1].

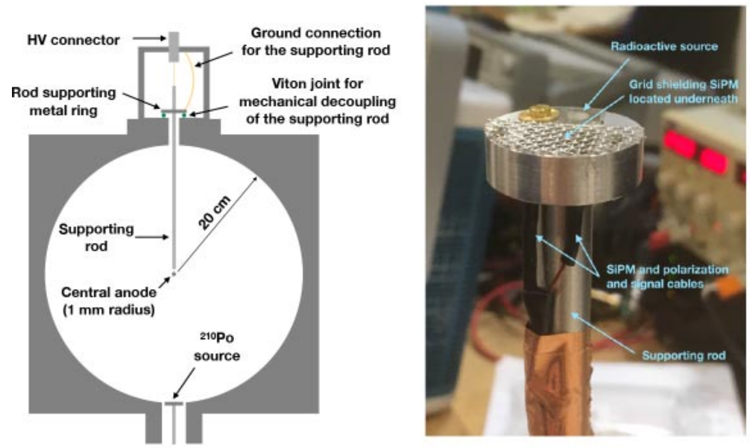
The half-life of this process ($T^{0\nu}_{1/2}$) being extremely long, we need to maximise the discovery sensitivity of our detectors, by maximising the mass of the beta beta emitter isotope, by lowering the background to almost zero and by maximizing the operation time. In the mean time, an excellent energy resolution is mandatory to discriminate between the tail of $\beta\beta2\nu$ (a double beta decay with emission of two neutrino) continuous spectrum and the $\beta\beta0\nu$ emission line. On the top of that, track recognition is an important asset to prove that the two electrons come indeed from the same vertex.

To address the problem of extremely-low-background detectors, we study the possibility to use a Spherical Proportional Counter. The SPC is a spherical high pressure gas time projection chamber (TPC). Such a detector has multiple assets, like the simplicity of the readout and of the mechanical structure or a two tracks recognition ability. However, the scalability to large isotope masses (1 ton of Xenon at 40bars fit in a 1m radius detector) has to be proved.

In the R2D2 (Rare Decays with Radial Detector) R&D, we evaluate the performances of the SPC design, with a focus on the energy resolution. We aim to achieve 1% FWHM at the $Q_{\beta\beta}$ value of ^{136}Xe, *i.e.* 2.46 MeV, the total amount of energy released by the decay.

2. – SPC Principles

The principle of the detector shown in fig. 1(a) is to use the (gaseous) $\beta\beta$ emitter as target medium for calorimetric detection. An incident charged particle will ionize the gas



(a) (b)

Fig. 1. – R2D2 overview with (a) the general design and (b) a focus on the source and SiPM (embedded in a shielded hole) support.

and the electrons will drift toward a central anode where a high-voltage is applied. This resulting electric field is quadraticaly dependent to the inverse of the radial distance:

$$E(r) = \frac{V_0}{r^2} \frac{1}{\frac{1}{r_a} - \frac{1}{r_c}} \tag{1}$$

where V_0 is the applied voltage, r the radial distance with respect to the anode, r_a the anode radius and r_c the cathode radius.

In the anode nearby region, where the voltage is sufficiently high, an avalanche occurs, creating pairs of electrons and ions. The collection of the electrons and most importantly the backward drift of the ions induce a charge current on the anode. The electronic chain will first decouple the HV from this additional charge, then a charge preamplifier will integrate and amplify the signal. Signal is then digitize with a 16 bits ADC and recorded on a disk.

Afterwards, an offline signal processing is performed. After a deconvolution, several observables are computed and are related to the energy and topology of the tracks. More information can be found in [2].

In addition to the SPC charge readout, we add a Silicon Photomultiplier (SiPM, shown in fig. 1(b)) to record the scintillation light emitted by the gas de-excitation. The light readout provide the starting time of our events to compute the drift-time and then deduce the radial position of the energy deposit. This proceedings provides a preliminary picture of those results, while a peer-reviewed paper is being prepared.

3. – R&D Status

Our first studies focus on the resolution measurements, making radiopurity unnecessary. Consequently, we built a prototype in commercials materials. A ^{210}Po α source (fig. 1(b)) of 5.3 MeV is used for calibration. It is placed in the bottom part of our detector, 20cm away and opposite the rod supporting the anode as shown in fig. 1(a). The anode is a stainless steel, 2mm diameter, ball.

The measurements were taken at pressure from 200 mbar to 1100 mbar, the α track having a range between 20 cm to 3 cm, respectively. In this range, it is contained inside the detector volume.

3˙1. *Detector important aspects.* – The energy-resolution and track-topology characterisation are highly constrained by the quality of the charge measurement. Indeed, the energy is reconstructed by integrating the charge signal after having subtracted the baseline. For such a configuration, low frequency noise constitutes the limiting factor of the analysis.

The charge measurement could also be affected by the presence of residual gases like oxygen or H_2O by changing the electrons propagation properties.

To avoid this, we pump the detector to a level of 10^{-6} mbar before each filling. In addition, we have imposed stringent requirements on the air-tightness of the detector and on its outgassing rate.

The second point of attention is the noise control in both its acoustic components (decouple at the maximum the detector potential sources of vibrations) and in its electronic part. Attention was paid on the grounding impact of each element from the acquisition chain to the room temperature control. To get a low noise electronic readout, a custom preamplifier has been funded by the OWEN Grant from Bordeaux University.

3˙2. *Resolution measurements.* – As gas medium for our measurements we use argon P2 (*i.e.* a mixture of 98%Ar +2%CH_4) which is a well known gas as it is widely use in gaseous TPC. This choice was driven by three parameters: a gas exhibiting similar properties as xenon, a gas having to be cost affordable and easily available in our suppliers stocks and a well known gas that gives references to compare our detector performances to other data.

Several runs were taken at different pressures to observe the effect of the track length on the resolution. Tracks of about 15cm are given by 200 mbar of pressure and 1100 mbar results in tracks of few centimeters.

The signal processing described in Sec. 4 of [2] was applied on the registered data and a Gaussian fit excluding the low energy shoulder (*i.e. tracks hitting the source support*) was performed. This results in similar resolutions for both track lengths, namely 1.1% FWHM at 200 mbar and 1.2% FWHM at 1.1 bar (fig. 2).

3˙3. *Light measurements.* – The SiPM we use is Hamamatsu VUV4 family S13370. It has a size of 6×6 mm^2 and a quantum efficiency (QE) of 14% at 128nm (wavelength of argon scintillation light). A shielding grid (1 mm holes, 65% of optical transparency) was installed over the SiPM (fig. 1(b)), acting as a Faraday cage to preserve the SPC electric field homogeneity. We filter the high frequency noise of SiPM with a 10 MHz low-pass filter (CLPFL-0010-BNC) from CRYSTEK.

To compensate the SiPM low geometrical acceptance due to its size, we operate the detector only at 1.1 bar, containing the α tracks in their nearby region.

For light measurements, we have to avoid an admixture of quenchers in the gas. This is why we use argon with a manufacturer purity level of 99.9999%. One of the drawbacks usually mentioned as an argument to not use a pure gas, comes from the electrons stripped off the sphere shell by the VUV photons produced during avalanche. Those electrons could combine with the primary signal. To quantify this effect, we also measure the energy resolution with the SPC readout.

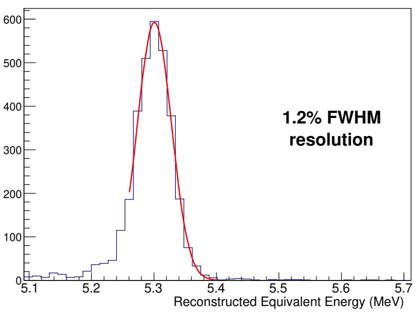
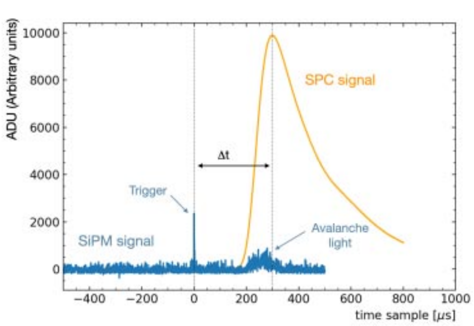


Fig. 2. – Energy spectrum of a 5.3 MeV ^{210}Po α source in an ArP2 mixture at 1100 mbar, 2000V. The fit excludes the low energy shoulder, formed by the tracks losing energy in the nearby material.

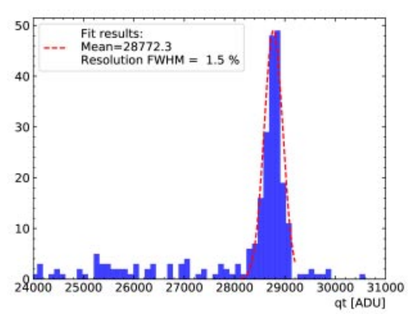
A second channel of our acquisition chain is dedicated to measure the SiPM output signal. Figure 3(a) show the readout output for run at 1.1 bar and 2200V applied on SPC anode. The acquisition chain was set to trigger over a threshold of about 13 photoelectrons of light signal (blue line). This threshold was crossed by the primary signal (energy deposit by α particle). After few μs we observe the avalanche, both on the SPC readout (yellow line) and on the light readout. We define the drift-time Δt as the time interval between the maximums of the light readout and the SPC readout signals.

From this run, we found 1.5%FWHM of energy resolution on the SPC signal, highlighted in fig. 3(b). This result is really promising as it shows we could reach a competitive energy resolution without using quenchers (in a reasonable regime of gain).

We repeat the measure at different voltages (900V, 1350V, 1800V and 2200V), their drift-time distribution is shown in fig. 4(a), and the fig. 4(b) compares the obtained values to simulation results. A Geant4 simulation shows a mean deposit energy position at 19.15 cm for 1.1 bar pure argon, in good agreement with our data.

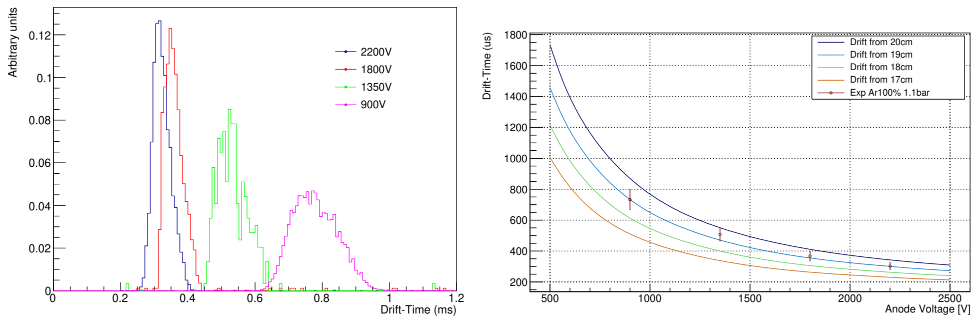


(a)



(b)

Fig. 3. – (a) Data acquisition output, with in blue the SiPM waveform (primary and secondary scintillation are visible) and in yellow the SPC waveform (only the secondary ionization is measured). (b) Energy spectrum of a 5.3 MeV ^{210}Po α source in pure argon at 1100 mbar.



(a) (b)

Fig. 4. – Spectrum of drift-time at various voltages in (a) and comparison with Magboltz simulation for several initial radial distances in (b).

4. – Conclusion

R2D2 is an R&D prototype to assess the feasibility of a neutrinoless double beta decay experiment based on the Spherical Proportional Counter principle. We focus our studies on the energy resolution measurements and on the scintillation light readout integration.

An energy resolution of 1.1% FWHM has been reached on a ^{210}Po α source of 5.3 MeV in a gas mixture of 98% Argon + 2% CH_4 at 200 mbar. The track length does not affect this energy resolution since similar results have been found at 1100 mbar.

The light sensor integration has been successful and we demonstrate the ability of such set-up to measure the drift-time, with data and simulation showing a good agreement. Those measurements have been conducted in pure argon, giving the opportunity to evaluate the energy resolution in a gas free of quencher. The 1.5% FWHM obtained shows that the resolution could be conserved without quencher, in a suitable regime of gain, which is a really encouraging result.

Future prospects are to test the detector response at higher pressure (with a β source) and with Xenon as target medium (its recycling system is under construction).

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