The R2D2 project

An SPC R&D for the neutrinoless double beta decay search

V. Cecchini

Université de Bordeaux, CENBG, CNRS/IN2P3

Subatech, IMT-Atlantique, Université de Nantes.

GdR DUPhy / IRN ν - 1/12/2021

Overview

Motivations

- NEWS-G (dark matter experiment with SPC[1]) show promising results in low energy measurements like a **single electron detection** ability.
- A preliminary simulation[2] shows that an extremely low background SPC could reach a competitive sensitivity for $\beta\beta0\nu$ decay searches, with following requirements:
  1. Excellent energy resolution;
  2. Extremely low radioactive background;
  3. High masses of $\beta\beta$ emitter medium.

  2-tracks recognition $\Rightarrow$ important asset.
- **R2D2** - Rare Decays with Radial Detector: R&D project to evaluate the feasibility of a ton scale detector with **ultimate low background**.

[1] Spherical Proportional Counter, *i.e.* spherical high-pressure gaseous TPC
[2] *JINST 13 (2018) no.01, P01009*

R2D2 Roadmap

***Prototype* 1** Goal: Demonstrate the **energy resolution** capabilities: expect 1% FWHM at 2.46 MeV, the ^{136}Xe $Q_{\beta\beta}$. $\rightarrow$ **No radio-purity**, first phase with **Argon**, target of 10 kg Xenon (40 bars).

* Electronic design
* Light readout
* Sensor improvements

***Prototype* 2** **Demonstrate the almost zero background** $\rightarrow$ 50kg Xe; Radio-pure SPC; First measurements (limits $m_{\beta\beta}$ <160-330 meV)

Experiment **Cover the Inverse Hierarchy** ($m_{\beta\beta} < 10$ meV) with 1 m radius SPC: 1 ton Xenon, in a background free experiment.

R2D2 Roadmap

***Prototype* 1** Goal: Demonstrate the **energy resolution** capabilities: expect 1% FWHM at 2.46 MeV, the ^{136}Xe $Q_{\beta\beta}$. $\rightarrow$ **No radio-purity**, first phase with **Argon**, target of 10 kg Xenon (40 bars).

- Electronic design
- Light readout
- Sensor improvements

***Prototype* 2** **Demonstrate the almost zero background** $\rightarrow$ 50kg Xe; Radio-pure SPC; First measurements (limits $m_{\beta\beta}$ <160-330 meV)

Experiment **Cover the Inverse Hierarchy** ($m_{\beta\beta} < 10$ meV) with 1 m radius SPC: 1 ton Xenon, in a background free experiment.

R2D2 Roadmap

***Prototype* 1** Goal: Demonstrate the **energy resolution** capabilities: expect 1% FWHM at 2.46 MeV, the ^{136}Xe $Q_{\beta\beta}$. → **No radio-purity**, first phase with **Argon**, target of 10 kg Xenon (40 bars).

* Electronic design
* Light readout
* Sensor improvements

***Prototype* 2** **Demonstrate the almost zero background** → 50kg Xe; Radio-pure SPC; First measurements (limits $m_{\beta\beta}$ <160-330 meV)

Experiment **Cover the Inverse Hierarchy** ($m_{\beta\beta} < 10$ meV) with 1 m radius SPC: 1 ton Xenon, in a background free experiment.

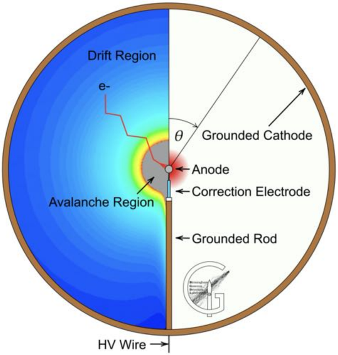
Detector's principles

Main advantages

- Simplicity of readout: one channel + light readout.
- Simplicity of structure
  $\Rightarrow$ Low material budget
  $\Rightarrow$ Low background.
- Low detection threshold (single electron).
- Two tracks recognition (gas properties).

Design

Spherical Proportional Counter



$\rightarrow$ $\beta\beta$ *emitter gas (Xenon) used as detector medium.*

Detector Features

- Prototype built in aluminum (no radio-purity required at this stage).
- Stringent requirements on sealing (avoid external contamination).
- Noise improvement:
  - Vibration reduction
  - Controlled room temperature
  - Low noise electronics (OWEN project[3])
  - Grounding and shielding improvements
- Additional **light readout**.
- New: High pressure certification.

[3] https://r2d2.in2p3.fr/owen.html

Detector Features

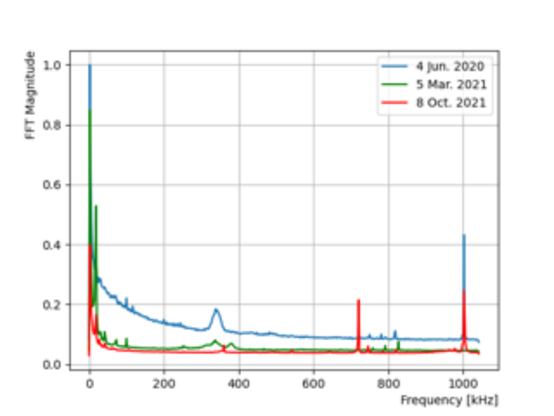
e).

g (avoid

project[3])

vements

Evolution of the noise frequency response.



Improvements by factor 3 over the last 16 moths. Linear scale.

[3] https://r2d2.in2p3.fr/owen.html

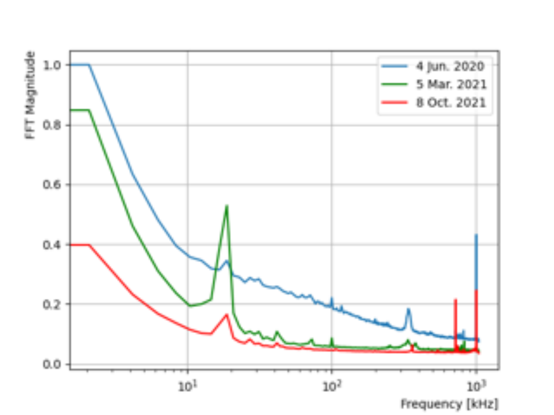
Detector Features

e).

g (avoid

project[3])
vements

Evolution of the noise frequency response.



Semi-logarithmic scale, highlighting the improvement at low frequencies.

[3] https://r2d2.in2p3.fr/owen.html

Detector Features

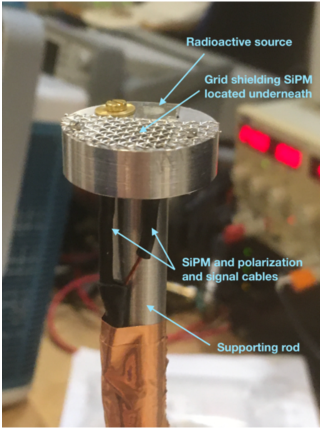
- Prototype built in aluminum (no radio-purity required at this stage).
- Stringent requirements on sealing (avoid external contamination).
- Noise improvement:
  - Vibration reduction
  - Controlled room temperature
  - Low noise electronics (OWEN project[3])
  - Grounding and shielding improvements
- Additional **light readout**.
- New: High pressure certification.

[3] https://r2d2.in2p3.fr/owen.html

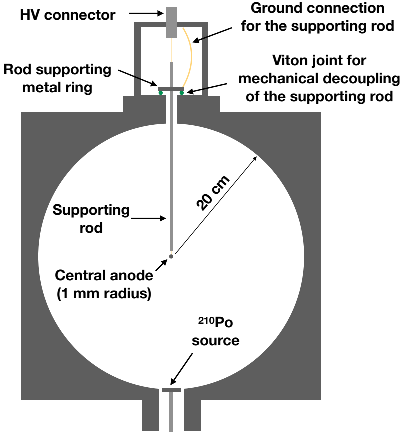
Light readout challenges

Use 6×6 mm^2 SiPM with a photon detection efficiency (PDE) of 14% at 128 nm

- ⇒ Operation at room temperature require **temperature correction** of the SiPM response
- → Distant readout electronic result in noisy signal: coaxial carry both signal and bias voltage + low-pass filter
- → Shielding the SiPM electric field is needed to not disturb the SPC one.



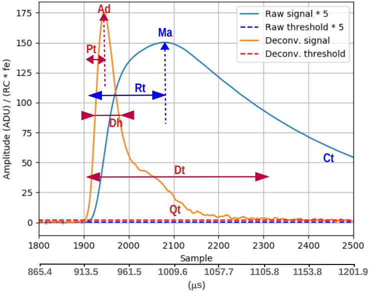
Detector Operation Condition



- **Argon P2** (98% Ar, 2%CH_4) used in the early stage ;
  Pure argon used for drift-time measurements.
- ^{210}Po source of 5.3 MeV α: study gas behaviours, signal shape.
- **Different pressures tested** (various track length) from 200 to 1100 mbars.

SPC waveform analyses

For very high precision measurements, we compute **variables from integrator and deconvoluted** signals.

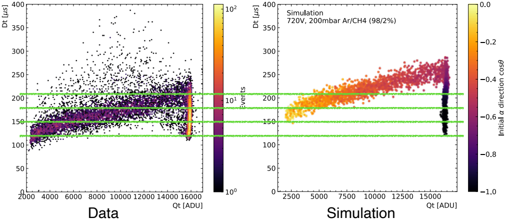


The **shape of the deconvoluted signal contain the event history**.

- Charge observables (linked to energy): Qt compares to Ct $\rightarrow$ accuracy of deconvolution
- Temporal observables linked to anode distance and track length: Dt (signal width neglecting ion tail) and Dh $\rightarrow \alpha$ angular direction
- Pt: direction of the track (toward anode $\Rightarrow$ small Pt)

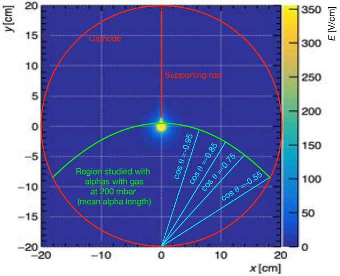
1st Resolution main result - Direction effects

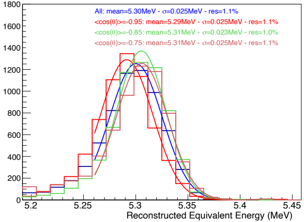
Cuts for angle selection from simulation.



Dt cuts corresponding to angular direction selection.

⇒ **Track direction doesn't affect energy resolution.**

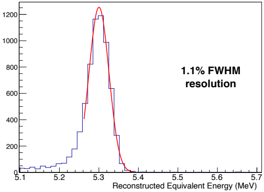




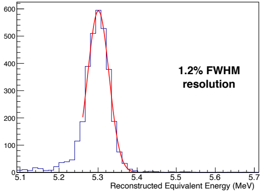
200mbar - 720V data.

2nd Resolution main result - Track length effects

To **vary the track length**, runs was taken at 200 mbar (720V) and 1100 mbar (2000V), *i.e.* 15 to 20 cm and $\sim$4 cm respectively.



200mbar



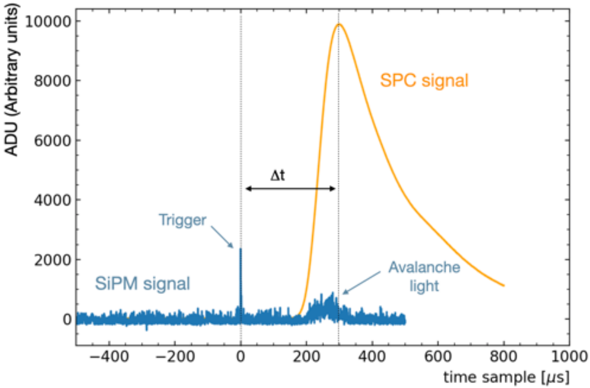
1100mbar

Histograms of Ct variable (charge) convert in recovered energy.

$\Rightarrow$ Track **length and pressure do not affect** (strongly) **the energy resolution**

Preliminary results on light readout

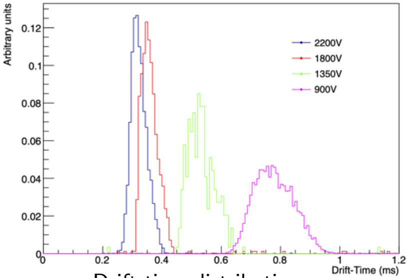
- SiPM use for light collection, giving the t_0 of the event.
- Suitable operation conditions are achieved with **Argon at 1100 mbar** (primary ionisation is contained near the SiPM).



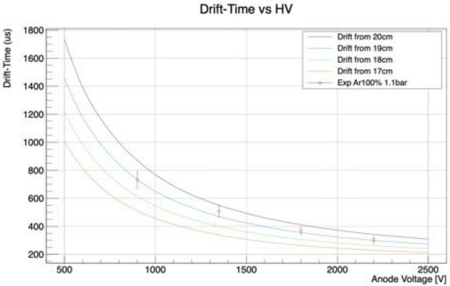
2200V event: SiPM signal in blue, SPC (ball sensor) in orange

Drift-time measurements

Measure the drift-time at various anode voltages and compare it to simulation:



Drift-time distributions.

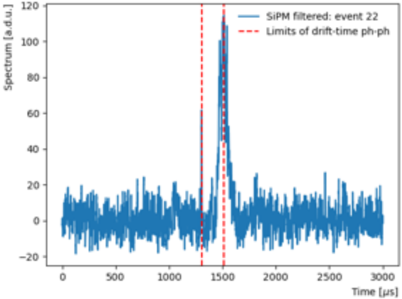


Data (points) and simulated drift-time (for different energy deposit position) as function of anode voltage.

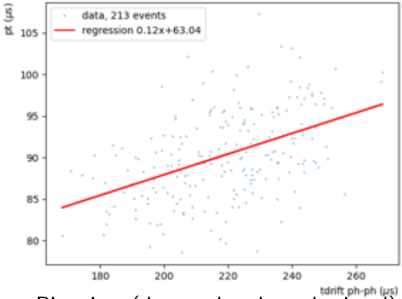
→ **Good agreement** between data and simulation.

Offline light signal analysis

Attempt to correlate anode signal observable to the drift-time



Drift-time ph-ph = interval between the maximums of primary scintillation and avalanche scintillation.

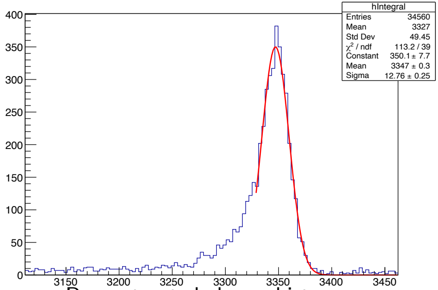


Rise-time (deconvoluted anode signal) compared to drift-time compute on light signal only.

Require further studies but already **encouraging knowing tracks are short** (3 cm @ 1.1 bar).

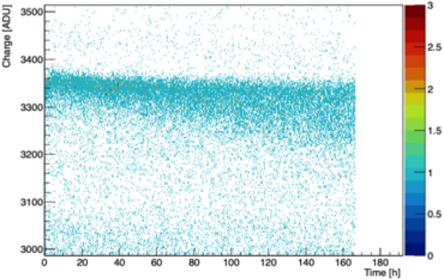
Latest results

ArgonP2 at 200mbar, 800V in cleaner noise conditions:



Reconstructed charge histogram

0.9% FWHM was reached at the beginning of the run.



Nevertheless, the resolution deteriorates through time → **expect improvements with recirculating system** (where a cold getter will take place).

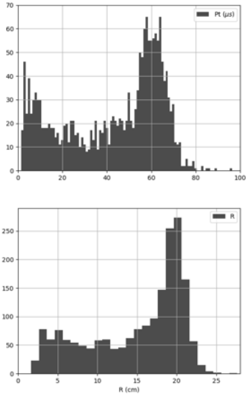
Position reconstruction

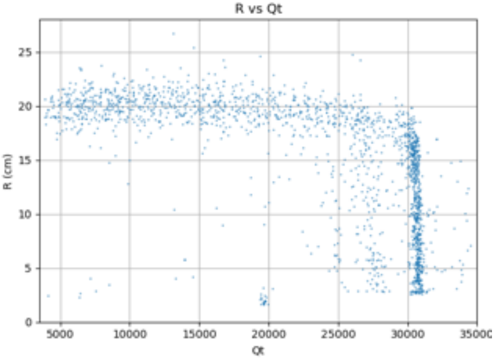
To **reconstruct radial position**, NEWS-G obtained an empirical dependence: $Pt = Pt_{max} \times (R/R_C)^{\alpha}$:

α an empirical fit factor

R the radius, R_C the Cathode radius (=20 cm)

Pt the rise-time of deconvolved signal (Pt_{max} = 62 μs).





$$R = 20 \times e^{(log(Pt) - log(62))/1.5}$$

Conclusions

- A good understanding of the detector response was achieved.
- **1.1% energy resolution** have been reached in Argon with 5.3MeV α.
- **Neither track length nor direction affect the energy resolution**.
- Deal with light readout: successful **drift-time measurements**.

Plenty of work:

$\rightarrow$ Correlation of the light readout information to the SPC observables could improve event reconstruction.

$\rightarrow$ Results have to be **confirmed in Xenon** and at **higher pressure**.

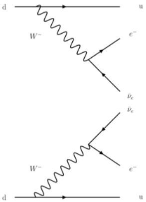
$\Rightarrow$ Expect to build prototype with features adapted to physics measurements (depending on results).

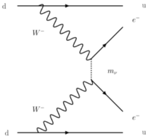

The End

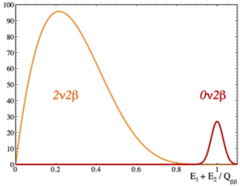
BACKUP

$\beta\beta 0\nu$ decay

- BSM process with lepton number violation (LNV): forbidden in SM
- Sensitive way to determine if the neutrino is Majorana particle.





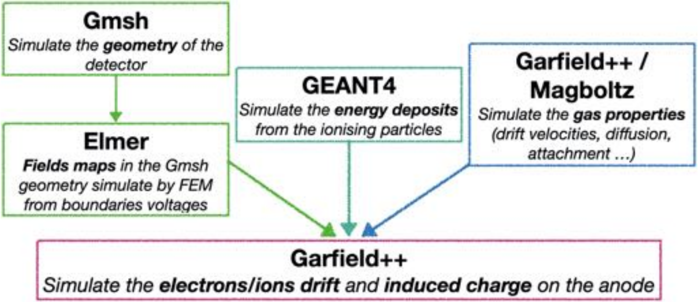


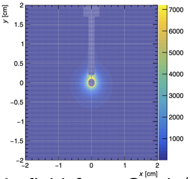
- $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2(\frac{m_{\beta\beta}}{m_e})^2$: $\beta\beta 0\nu$ evidences requires, at least
  1. Excellent energy resolution;
  2. Extremely low radioactive background;
  3. High masses of $\beta\beta$ emitter medium.

2-tracks recognition = important asset.

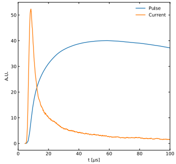
Simulation Framework

It aims to improve our variables understanding from waveform analysis.





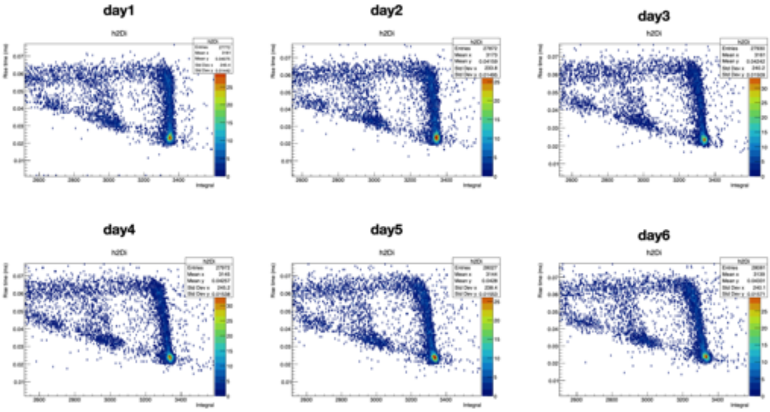
Electric field from Gmsh/Elmer (V=720V, $2 \times 2cm^2$ around anode).



Signal produce by α track (orange) and its integration (blue, rescaled).

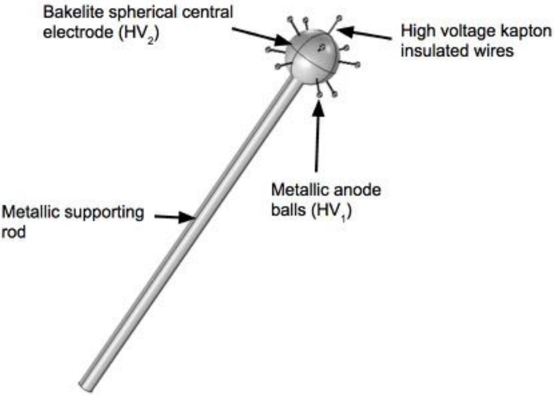
Gas evolution

Due to attachment, we expect a more inclined shape of Rt vs Qt.



Outgassing may increase attachment, and indeed we observe a steeper slope.

ACHINOS



Multi-anode sensor "ACHINOS" design