Latest results of the R2D2 project

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

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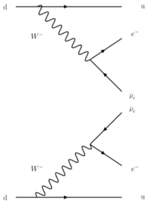
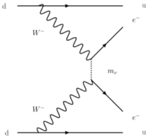
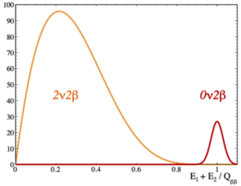
Overview

$\beta\beta0\nu$ decay

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







- $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2(\frac{m_{\beta\beta}}{m_e})^2$: $\beta\beta0\nu$ 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.

Motivations

- NEWS-G (dark matter experiment) show promising results in low energy measurements with an SPC[1], like a **single electron detection** abilities and **two tracks discrimination**.
- A full simulation (*JINST 13 (2018) no.01, P01009*) shows that an extremely low background SPC could reach a competitive sensitivity for $\beta\beta0\nu$ decay searches.
- **R2D2** - *Rare Decays with Radial Detector* : R&D project to evaluate the feasibility of a ton scale detector with **ultimate low background**.

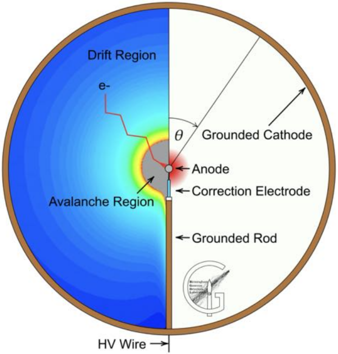
[1]Spherical Proportional Counter, *i.e.* a spherical high-pressure gaseous TPC

Detector's principles

Main advantages

- Simplicity of readout: one channel + light readout.
- Simplicity of structure ⇒ Low material budget ⇒ Low background.
- Scalable to large isotope masses (1 ton = 1m radius at 40bars).
- Low detection threshold (single electron).
- Two tracks recognition.
- High energy resolution (1% FWHM expected at ^{136}Xe $Q_{\beta\beta} = 2.45 MeV$).

The Spherical Proportional Counter



$\beta\beta$ emitter gas (Xenon) served as detector medium.

R2D2 Roadmap

Prototype 1 Demonstrate the detector capabilities (focus on **energy resolution**, no radio-purity) $\rightarrow$ Xenon prototype up to 10 kg (40 bars). First phase with Argon.

- Electronic design
- Light readout
- Sensor improvements

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

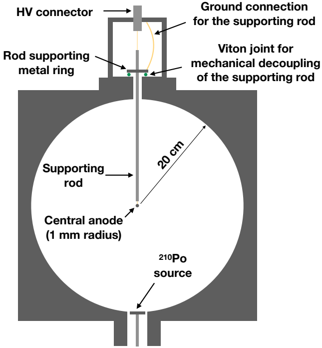
Experiment **Cover the Inverse Hierarchy** $m_{\beta\beta} < 10$ meV (1 ton Xenon, in a background free experiment)

Detector Design

- It aims to **demonstrate that the desired energy resolution is achievable**.
- Prototype built in aluminum (no radio-purity required at this stage).
- Noise improvement:
  - Vibration reduction
  - Controlled room temperature
  - Low noise electronics (OWEN project[2])
  - Electronic and cable shielding
  - Ground uniformization
- New : High pressure certification

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

Detector Operation



- ^{210}Po source of 5.3 MeV α: study gas behaviours, signal shape.
- **Argon P2** (98% Ar, 2%CH_4) used in the early stage ; **Argon alone** used for drift-time measurements.
- **Different pressures tested** (various track length) from 200 to 1100 mbars.
- In sealed mode: **short runs** to avoid contamination effects.
  Purification technology mature[3,4] for longer runs.

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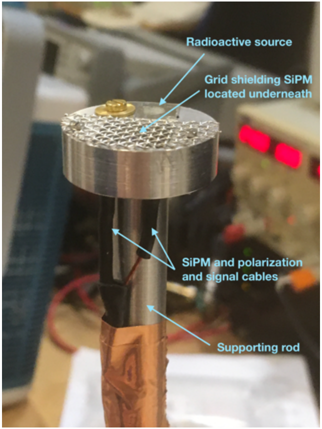
[3] *V Álvarez et al, JINST 7 (2012) T06001*

[4] *Chen et al, Science China Physics, Mechanics & Astronomy 60 (2017) no.6, P061011*

Light readout challenges

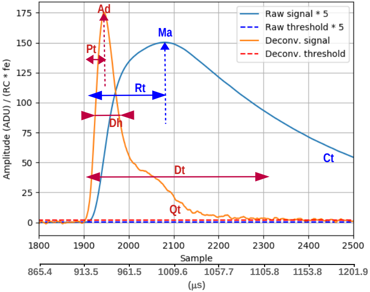
Use 6×6 mm^2 SiPM with a photon detection efficiency (PDE) of 14% at 128 nm

- ⇒ Operation at room temperature require temperature correction of the SiPM response
- → Distant readout electronic result in noisy signal: coaxial for both signal and bias voltage + low-pass filter
- → SiPM electric field disturb the SPC one: need to be shielded



SPC waveform analyses

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

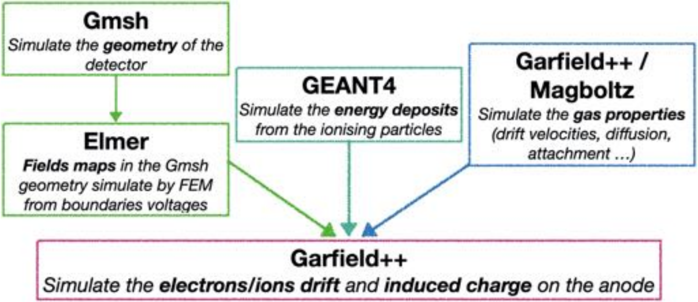


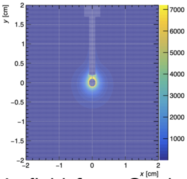
The **shape of the deconvoluted signal contain the event history**.

- 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 $\rightarrow$ α angular direction
- Pt: direction of the track (toward anode $\Rightarrow$ small Pt)

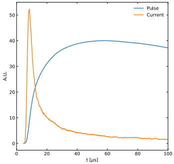
Simulation Framework

It aims to improve our variables understanding from waveform analysis.





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

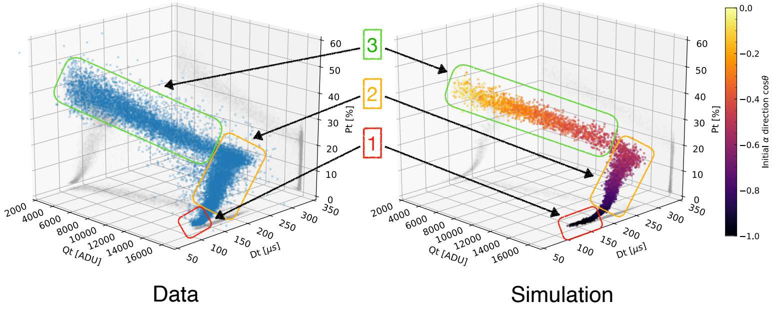


Signal produce by α track (orange) and its integration (blue, rescaled).

Simulation outcomes

The observables combination are closely linked to the **event topology, resulting in specific patterns**, *e.g.* 3 regions in the following plots:

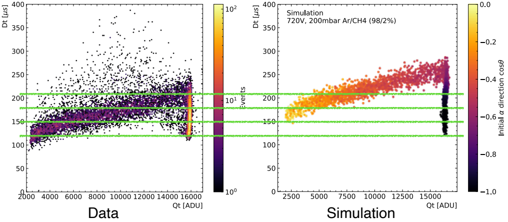
1. Tracks toward the anode.
2. Tracks at larger angles but contained in gas.
3. Tracks hitting the cathode (loosing energy in it).



→ Allow a better understanding of the data (*e.g.* the α track direction).

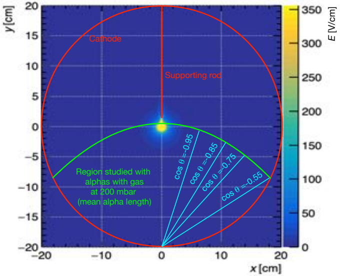
1st Resolution main result - Direction effects

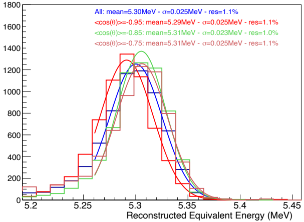
Cuts for angle selection from simulation.



Dt cuts corresponding to angular direction selection.

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

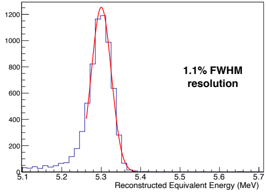




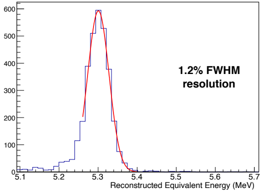
200mbar - 720V data.

2nd Resolution main result - Track length effects

Runs at **200mbar (720V) and 1100mbar (2000V)** to change α **track length** ($\sim$20cm vs $\sim$4cm respectively)



200mbar



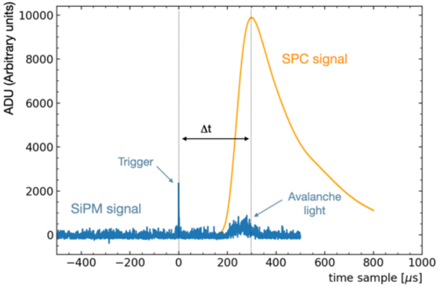
1100mbar

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

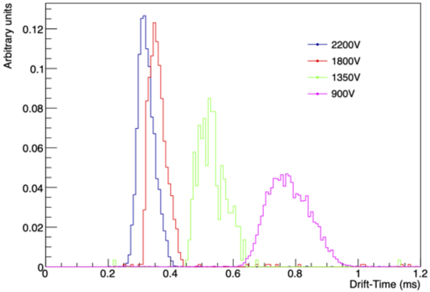
$\Rightarrow$ **Track length and pressure do not (strongly) affect the energy resolution**

Preliminary results on light readout

SiPM use for light collection, giving the t_0 of the event (detector operate with Argon at 1100 mbar).



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



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:

$\rightarrow$ Sensor updates could improve performances.

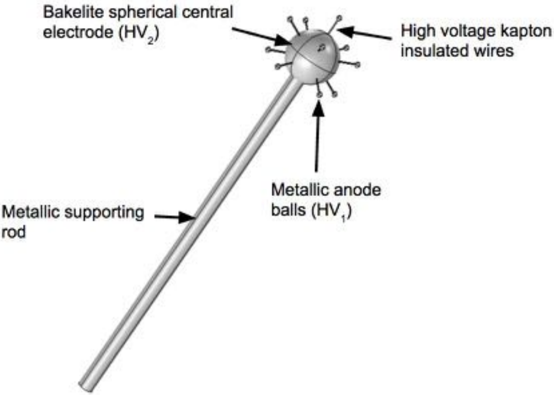
$\rightarrow$ Correlation of the light readout information to the SPC observables could improve event reconstruction.

$\rightarrow$ Results have to be confirmed in Xenon.

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

BACKUP

ACHINOS



Multi-anode sensor "ACHINOS" design

Xenon advantages

- $\rightarrow$ A large **natural abundance** (8.9%)
- $\rightarrow$ It is a **neutral gas**, meaning easy manipulation and few molecular reaction
- $\rightarrow$ It has a **high** $Q_{\beta\beta}$, lowering the background in the ROI
- $\rightarrow$ **Enrichment methods** are already known
- $\rightarrow$ It has a good **intrinsic energy resolution**, *i.e.* Fano's theory:

$$\frac{\delta E}{E} = 2.355 \frac{\sigma}{N_i} = 2.355 \frac{\sqrt{F \times W}}{\sqrt{E}} \sim \mathcal{O}(10^{-3})$$

- $\rightarrow$ The long $T_{1/2}^{2\nu}$ with respect to $T_{1/2}^{0\nu}$ allow a **large SNR for this background**:

$$\frac{S}{B} = \left(\frac{Q_{\beta\beta}}{\Delta E}\right)^6 \frac{(T_{1/2}^{2\nu})}{(T_{1/2}^{0\nu})}$$

Sensitivity I

Why background rejection is so important in $0\nu\beta\beta$ searches ?

If $0\nu\beta\beta$ is mediated by light Majorana ν exchange, rate is given by

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M^{0\nu}|^2(\frac{m_{\beta\beta}}{m_e})^2$$

The number of signal event is related to the half-life through the following (background-free) formula

$$T_{1/2}^{0\nu} = \epsilon log2\frac{\eta N_A}{A}\frac{M.t}{N}$$

By combining equations, the sensitivity to the effective neutrino mass is:

$$S(m_{\beta\beta}) = \sqrt{\frac{m_e^2 A}{\eta N_A log2\ G^{0\nu}|M^{0\nu}|^2}}\sqrt{\frac{N}{\epsilon M.t}}$$

Sensitivity II

In presence of background $N \rightarrow \overline{N}$ the number of signal like events (signal + background).
For large background, $\overline{N} \approx \sqrt{b}$ (b the number of background events).
And in an energy windows ΔE, $b \propto$ rate (r_b) and exposure M.t
$\Rightarrow b = r_b.M.t.\Delta E$.

Replacing N by $\overline{N}$, we get a sensitivity S of

$$S(m_{\beta\beta}) = \sqrt{\frac{m_e^2 A}{\eta N_A log2 \; G^{0\nu}|M^{0\nu}|^2}} \left(\frac{r_b \Delta E}{\epsilon^2 M.t}\right)^{1/4}$$

Since we need $S(m_{\beta\beta})$ sensible to small masses, it require large exposure.
Background reduce heavily the effect of large exposure, we need to suppress it.