Latest results of the R2D2 project

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on behalf of
the R2D2 collaboration

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Introduction

• To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called $0\nu\beta\beta$ decay.

• The three **main requirements** to search for such a rare phenomenon are:
  - Excellent energy resolution
  - Low background
  - Large masses of isotopes

  **Can we meet all the requirements at the same time?**

  **goal of R2D2 (Rare Decays with Radial Detector)**

• R2D2 is an **R&D program** aiming at the development of a **zero background ton scale detector** to search for the neutrinoless double beta decay.

  **How?**

  **Using a spherical high pressure xenon TPC**
The detector

- The detector is a spherical Xenon gas TPC as proposed by Giomataris et al. and used today in the NEWS-G collaboration for the search of dark matter.

- The design has to be optimised for the background reduction in the $\beta\beta 0\nu$ search with $^{136}\text{Xe}$ ($Q_{\beta\beta}$ of 2.458 MeV).

**Detector features**

- High energy resolution (goal of 1% FWHM at $^{136}\text{Xe} Q_{\beta\beta}$)

- Extremely low (zero?) background due to the very low material budget.

- Scalability to large isotope masses (1 ton = 1 m radius at 40 bars)

- Low detection threshold at the level of 30 eV i.e. single electron signal.

- High detection efficiency ($\sim 65\%$ after selection cuts).

- Simplicity of the detector readout with only one (or few in the upgraded version) readout channels.
A proto-collaboration has been formed.

R2D2 is today approved as IN2P3 R&D to assess in particular the possibility to reach the desired energy resolution which is the major showstopper.
The R2D2 Roadmap

**Prototype 1**
Up to 10 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution.

**Prototype 2**
Sensitivity studies carried out
50 kg Xenon detector (low radioactivity) with LS veto for first physics results to demonstrate the almost zero background.

**Running - Funded by IN2P3 R&D**
If prototype 1 successful and prototype 2 funded

**Experiment**
Going towards a 1 ton background free detector

$m_{\beta\beta} < 10 \text{ meV (I.H. covered)}$

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Experimental setup

- In 2018 the R2D2 was funded as R&D by the IN2P3: the main goal is the demonstration that the desired energy resolution is achievable.

- A 20 cm radius sphere made of Aluminium (i.e. not low background but much cheaper) was built at CENBG.

- Efforts were made to reduce the noise as much as possible:
  - Isolated and temperature controlled environment.
  - Vibrational insulation of the supporting structure and of the central anode.
  - Custom made low noise electronics (OWEN project).

- The setup was commissioned and is currently being operated with Ar (98%) + CH₄ (2%) at CENBG at pressures up to 1.1 bar.

Certified sphere to go up to 40 bars and Xenon recuperation system under commissioning
Detector operation

- To assess the energy resolution a 4Bq $^{210}$Po alpha source of 5.3 MeV was used.
- The source deposited on a silver film is located on a support and inserted from the bottom of the detector.
- Runs were taken at different pressures.
- A pulse generator was used as input in the electronic chain to monitor and correct for possible electronics response variations.
- Runs were typically short (30 minutes) to avoid to apply corrections due to gas degradation and new gas was used each time after pumping the detector at a vacuum of $10^{-6}$ mbar.
- A dedicated simulation (JINST 15 (2020) C06013) based on Geant4 and Garfield++ was used to cross check the obtained results and confirm our understanding of the detector response.
Detector stability

- Short runs over a period of 14 days without changing the gas were taken to assess detector stability.
- Electronegative impurities concentration, due to material outgassing and leakages, increases in time resulting into a smaller number of electrons reaching the anode.
- The mean value of the reconstructed energy for alphas and for the generator was used to estimate the signal loss variation in time.
- A loss of 0.05% per hour was measured.
- Such a loss can be corrected offline, and reduced in future upgrades of the detector reducing the leakage (today at $5 \times 10^{-9}$ mbar/s).
Results

- In ArP2 at 200 mbar alpha tracks have a length of about 15 to 20 cm.
- Several variables were computed on the waveform to study the signals, two of which are the total reconstructed charge ($Q_t$) and the signal length ($D_t$).
- The agreement between data and simulation is very good and the detector behaviour is well understood.

![2D representation of events](image)

Tracks hitting the cathode (large angle, $\cos\theta < -0.4$) have a decreasing $Q_t$ and the decrease in $D_t$ is driven by threshold effect (smaller signals go under threshold in a smaller time).

Tracks not hitting the cathode at large angle ($\cos\theta = -0.6$) should have a smaller $D_t$ with respect to tracks going towards the anode ($\cos\theta = -1$) since electron drift is similar. It is not the case since diffusion effects dominate as demonstrated by the simulation.

Figure 11. Example of 2D representation of events for different observables for data at 200 mbar and 720 V ($D_t$ vs $Q_t$ (a), $P_t$ vs $Q_t$ (c), $D_t$ vs $Q_t$ (e)) and corresponding simulation ($D_t$ vs $Q_t$ (b), $P_t$ vs $Q_t$ (d), $D_t$ vs $Q_t$ (f)). For the data the colour stands for the number of event in the bin whereas for the simulation the color indicates the original direction: $\cos\theta = 1$ for tracks going towards the central anode and $\cos\theta = 0$ for tracks emitted orthogonally to the radial direction. The figures were made with about 2000 events corresponding to about half an hour of data taking.
Resolution

- The resolution was computed at 200 mbar and 1.1 bar.
- We obtained a similar resolution showing **no impact due to the length of the tracks** (from 3-4 cm at 1.1 bar to 15-20 cm at 200 mbar).
- We estimate to 0.6% the contribution of the source itself and of the electronics giving an intrinsic resolution due to the detector at 0.97%.

![Graphs showing energy resolution comparison between 1.1 bar - 2000 V and 200 mbar - 720 V](image)

**Figure 17.** Integral of the 5.3 MeV signal at 1.1 bar and 2000 V (a) and at 200 mbar and 720 V (b). The Gaussian fit in red shows an energy resolution of 1.2% FWHM and 1.1% FWHM respectively.
Scintillation light detection

• We run the detector in pure argon to observe the scintillation light and use it as trigger for the first time in a SPC detector.

• We used a 6x6 mm² SiPM from Hamamatsu with a 15% QE at 128 nm.

• We observed two signals on the SiPM: a trigger given by the scintillation light and a second signal on time with the SPC signal due to the light emitted in the avalanche.

• The time between the trigger and the SPC signal gives the electrons drift time and can be used to validate the Garfield++ simulation. An excellent agreement is found for alphas emitted at about 19 cm from the anode as expected.

Figure 2: SiPM setup.

Figure 7: Waveforms of SiPM (red) and anodic signal (green) for one event taken at 1.1 bar and 2200 V. The Δt of about 300 μs is shown in orange.

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++ simulation for as a function of the anode HV for different starting radial distances spanning between 17 and 20 cm (colored solid lines). The experimental data is also shown and the bar width corresponds to the RMS of the drift time distributions of Fig. 8.

Figure 10: Radial deposition of α’s energy depositions simulated by Geant4 at 1.1 bar in argon.
Avalanche light analysis

- We studied the light emitted in the avalanche to see if we could extract some information on the event topology.

- **Work is in progress** but the SiPM signal width is proportional to the SPC signal rise-time typically used for radial position reconstruction.

- A delayed signal is also observed on the anode corresponding to electrons ripped off the cathode by the avalanche photons (confirmed by the time difference which corresponds to a 20 cm drift).

- **Preliminary studies** showed that the energy resolution **is not degraded** when such a component is present in the waveform, which indicates that it could be possible to operate the detector without a quencher.
Next steps

- The results should be confirmed in different conditions:
  - Higher pressure
    - New detector certified at 40 bars under commissioning
  - With electrons
    - $^{207}$Bi source available but more than 10 bars needed to contain electron tracks
  - In xenon
    - Recuperation and recirculation systems ready in summer
  - With a diffuse source
    - Clean radon source yet to be found (problem with electronegative impurities)

- Fundings requested for low background prototype

- Possibility to use multi-sensor anode (ACHINOS).
Conclusions

• The R2D2 collaboration has been formed and the R&D has been approved by IN2P3.
• Preliminary sensitivity studies showed that we could have competitive sensitivity with small masses and **potentially zero background detectors with large masses**.
• A good detector understanding demonstrated and a resolution at the level of 1.1% was **achieved** with alphas at 5.3 MeV.
• We also demonstrated that the energy resolution is not degraded going from point-like energy deposits to long particle tracks.
• Results to be confirmed in xenon at higher pressure.
• **Scintillation light in argon** used as trigger for the first time.
• Results in xenon and at higher pressure expected by the end of the year.