Status of the R2D2 project: A future neutrinoless double beta decay experiment

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Abstract. The nature of the neutrino is a central question in physics. The search for neutrinoless double beta decay is the most sensitive experimental approach to demonstrate that the neutrino is a Majorana particle. Observation of such a rare process demands a detector with an excellent energy resolution, extremely low background, and a large mass of a double beta decaying isotope. R2D2 aims to develop a novel spherical high-pressure TPC that meets all the above requirements. As a first step, the energy resolution of the R2D2 prototype was measured. A 1.1% (FWHM) energy resolution was achieved for 5.3 MeV α-particles in Ar:CH₄ at pressure up to 1.1 bar. This is a major milestone for R2D2 and paves the way for further studies with Xe gas and the possible use of this technology for neutrinoless double beta decay searches.

1. Introduction
The most sensitive experimental approach to demonstrate the Majorana nature of the neutrino is to observe the so-called neutrinoless double beta decay (0νββ). In the case of a regular double beta decay reaction (2νββ), two neutrinos and two electrons are emitted. The kinetic energy of the emitted electrons has a continuous spectrum with an upper limit of the Qᵦᵦ value of the reaction. In 0νββ, the absence of neutrinos results in the electrons being emitted practically back-to-back, sharing the Qᵦᵦ value energy. The measurement of the 0νββ two-electron energy results in a peak at the Qᵦᵦ value, as shown in Fig. 1. The measurement of the Q-value is a robust experimental signature that can be used to observe the 0νββ reaction. Experiments so far have reached the inverted mass hierarchy region but in order to cover it, a tonne scale experiment will be required, as shown in Fig. 2, which has to fulfil certain requirements. The three main ones are:

- **Excellent energy resolution.** This is a critical parameter as a narrow peak from 0νββ electrons will minimise backgrounds from the 2νββ continuous spectrum. In addition, it allows reducing the width of the region of interest (ROI), minimising external backgrounds as well.
- **Very low background.** Low background is achieved through a radiopure construction, shielding from external radioactivity, and event discrimination.
- **Large isotope masses.** For an experiment to reach the mass required for high sensitivity, an element with a high natural abundance in a double beta decaying isotope or one that can be easily enriched is needed.
Figure 1: The shape of the spectrum of the kinetic energy of the two emitted electrons (divided by the transition energy $Q_{\beta\beta}$) for the two channels of double beta decay. The continuous distribution up to $Q_{\beta\beta}$, belongs to the electrons from $2\nu\beta\beta$ and the peak at the $Q_{\beta\beta}$ corresponds to the $0\nu\beta\beta$ electrons. The energy resolution of the detection system determine the width of the $0\nu\beta\beta$ peak.

Table 1: A summary of the state-of-the-art detector technologies and their performance.

| Detector Type | Energy Resolution | Low Background | Large Isotope Mass |
|---------------|-------------------|----------------|-------------------|
| Solid state   | Excellent         | Extremely low (zero BG) | Large number of crystals and electronics makes it difficult to scale up |
|               | 0.1% @ $Q_{\beta\beta}$ |                 |                   |
| LXe           | Not Good          | Non zero       | Tonne scale achievable |
|               | $\sim 4\% @ Q_{\beta\beta}$ |         |                   |
| GXe           | Good              | Non zero       | Complex detectors |
|               | $\sim 1\% @ Q_{\beta\beta}$ |         | Tonne scale is a question |

The state-of-the-art of detector technologies used in $0\nu\beta\beta$ searches are presented in Table 1. Up to now no detector meets all requirements. R2D2 (Rare Decays with Radial Detector) is an ambitious R&D program aiming to develop a new detector, based on the spherical proportional counter, to search for $0\nu\beta\beta$, that achieves all requirements.

2. The R2D2 experiment

R2D2 is a collaboration established to explore the possibility of a tonne-scale background free detector to search for the $0\nu\beta\beta$. The idea is to use a high-pressure Xe spherical Time Projection Chamber (TPC). Gaseous Xe TPCs have several advantages that make them excellent candidates for $0\nu\beta\beta$ searches. Natural Xe has a relatively high abundance of about 8% in $^{136}\text{Xe}$, a double beta decaying isotope. $^{136}\text{Xe}$ is easy to enrich in very high concentrations close to 100%.
Figure 2: Mass regions probed in the $0\nu\beta\beta$ decay process. The green band represents the inverted hierarchy allowed region, whereas the red band represents the normal hierarchy [2].

Furthermore, working in the gaseous phase rather than the liquid phase provides better energy resolution, as energy resolution in Xe densities greater than 0.55 g/cm$^3$ rapidly deteriorates, as demonstrated by previous measurements over a wide range of densities [3].

2.1. The spherical proportional counter

![Spherical proportional counter diagram](image)

Figure 3: Spherical proportional counter design and principle of operation.

The detector used in R2D2 is the spherical proportional counter (SPC), an innovative gaseous
detector. The design of the detector and its principle of operation is shown in Fig. It consists of a grounded spherical shell which acts as the cathode and a small spherical anode, the sensor, supported at the centre by a grounded metallic rod, to which the high voltage is applied and from which the signal is read-out. In the ideal case the electric field has an $1/r^2$ dependence on the radial distance from the detector centre. This dependence naturally divides the detector into the drift region, where under the influence of the electric field the electrons drift towards the anode, and the amplification region, where charge multiplication occurs.

The spherical geometry provides several advantages for building large volume detectors [4]. The sphere has the lowest surface-to-volume ratio and is well suited for high pressure operation. Overall, the spherical proportional counter exhibits the following key features:

- very low energy thresholds, down to single electron detection, thanks to small sensor capacitance and high gain operation;
- small number of read-out channels
- background rejection and fiducialisation handles through pulse shape analysis
- simple and robust construction with radiopure materials
- variety of light target gases, allowing optimisation of momentum transfer for light particles
- possibility to vary the operational pressure and high voltage, providing additional handles to disentangle potential signals from unknown backgrounds

The SPC is a versatile detector, used in several applications. The most notable of them is in the NEWS -G [5] experiment, searching for dark matter particles, using a large volume ($\sim 1$ m$^3$), radiopure SPC. Moreover, the possibility to reach high gain with moderate voltages applied on $O(mm)$ diameter anodes, along with the large volume to contain energetic (MeV) particles allows the SPC to be used for neutron detection. The SPC is filled with N$_2$ to exploit the $^{14}$N(n,p)$^{14}$C and $^{14}$N(n, α$^{11}$B reactions [6, 7, 8].

2.2. The R2D2 roadmap

The primary aim of the R2D2 R&D program is to validate the desired detector features towards a future tonne scale detector. The roadmap is summarized as follows:

- **Prototype 1.** A 40 cm in diameter SPC is constructed without radiopurity precautions. The detector will be able to contain Xe mass up to 7.9 kg (at 40 bars). The goal is to demonstrate the desired energy resolution of 1%. This is the current stage.

- **Prototype 2.** Following the demonstration of the energy resolution goals, a low background detector will be built, containing 50 kg of $^{136}$Xe. The shielding design presented in Fig. includes a liquid scintillator veto. This detector will be used for the first $0\nu\beta\beta$ search and demonstrate the possibility for zero background operation. In addition, prototype 2 will be used to study detector behaviour using other gases and the possibility to perform particle tracking.

- **Experiment.** The construction of the full-scale detector is subject to funding and results from the first two prototypes. The tonne scale detector will cover the inverted mass hierarchy region.

2.3. Sensitivity projections

Several shielding designs, detector sizes and pressure of operation were simulated to estimate an optimised sensitivity for prototype 2 and optimise the background rate that can be achieved. The final geometry and components for the setup is presented in Fig. The assumptions on the detector characteristics and performance taken into account are listed below:

- Energy resolution of 1% FWHM at the $Q_{\beta\beta}$ of 2.458 MeV.
Figure 4: Schematic of the simulated setup.

- Optimized ROI of $Q_{\beta\beta} \pm 0.6\%$.
- Possibility to reconstruct the radial distance of the energy deposition.
- Threshold of 200 keV for the liquid scintillator veto.
- Copper radioactivity of 10 $\mu$Bq/kg per background source i.e. each element of the $^{232}$Th and $^{238}$U decay chain.

A detector with these features can set a limit on the $0\nu\beta\beta$ half-life of $2.5 \times 10^{25}$ years, with one year of operation, i.e. an effective mass $m_{\beta\beta}$ smaller than 160 - 330 meV depending on the matrix element values. The expected background from the simulation study is 2 events per year for the 50 kg $^{136}$Xe mass, and a signal efficiency of 64%. More details on the sensitivity projection studies can be found in [9].

3. Energy resolution measurement

As discussed earlier, the first goal of R2D2 is to validate the energy resolution assumption for the detector. The energy resolution measurements took place at CENBG (Centre d’Études Nucléaires de Bordeaux Gradignan). A 40 cm diameter SPC was used, equipped with a single anode sensor with a resistive glass correction electrode [11]. The detector setup and the sensor are shown in Fig. 5 and 6 respectively. The detector vessel was pumped down to at the level of $10^{-6}$ mbar before being filled with an Ar:CH$_4$ 98%:2% gas mixture. Ar was used for these first tests as the Xe recuperation system was still under preparation. A $^{210}$Po source was placed on the bottom part of the detector (Fig. 5). The source emitted $\alpha$-particles of 5.3 MeV with an activity of 4 Bq. The detector was placed in an environment with minimised temperature variations and human activity to reduce acoustic and electronic noise. Furthermore, purpose-made preamplifiers were used to read out the sensor signal. The preamplifiers were developed by the OWEN project [12] which aspires, among other things, to develop low noise readout electronics to minimise electronic noise.

The digitised waveforms of the detector signal were analysed to produce observables that could be used in pulse shape analysis and to estimate the energy resolution of the system. The
waveforms were processed to treat the ballistic deficit and parasitic electronic noise that degrade energy resolution by deconvolving the preamplifier response and filtering. More details on the waveform processing can be found at Ref. [10].

The experimental setup was simulated using the simulation framework presented in Ref. [13]. The framework is based on Geant4 [14], which is used to simulate the particle interactions with matter. Garfield++ [15] is integrated into Geant4 to simulate gaseous particle detector operation. These detailed simulations were used to investigate event properties and complement the studies performed on the data.

An example is presented in Fig. 7 for a pressure of 200 mbar of Ar:CH₄ 98%:2%. The
observables $Dt$ and $Qt$ that correspond to the signal duration and the total reconstructed charge are plotted against each other. The simulation results indicate that pulses in the "tails" left of what is seen as a vertical accumulation at $Qt$ of approximately 15500 ADU belong to partial energy deposition events due to $\alpha$-particles hitting the wall (wall effect). Furthermore, it is shown that full tracks at $\cos\theta = -1$ (towards the anode) have smaller $Dt$ from $\cos\theta = -0.6$ (towards the wall) due to diffusion effects. Such comparison can be exploited to classify events inside the detector, event reconstruction, and probe various event configurations and topologies. Further studies are planned to demonstrate and quantify the potential for event discrimination and background suppression.

Finally, the energy resolution of the setup was measured for gas pressures of 200 mbar and 1.1 bar. Using two different pressures helps to estimate the contribution of the track length in the resolution, as $\alpha$ tracks have an approximate range of 20 cm at 200 mbar and a five-fold decreased range at 1.1 bar. The results of the energy resolution for the measurement of the 5.3 MeV $\alpha$-line at the two pressures are are presented in Fig. 8. The energy resolution of approximately 1.1% FWHM obtained in both conditions demonstrates that the result does not depend on the track length of the $\alpha$-particles. Furthermore, after subtracting statistically the contributions of the read-out electronics an energy resolution resolution of 0.97% is obtained.

![Energy Resolution](image)

Figure 8: The energy resolution of the 5.3 MeV $\alpha$-line signal at (a) 200 mbar and (b) 1.1 bar. From Ref. [10].

Assuming Poisson statistics the 1.1% at 5.3 MeV corresponds to an energy resolution of 1.6% at 2.458 MeV which is the Q-value of the double beta decay reaction of $^{136}$Xe. This is an overall positive result and a milestone for R2D2 since the energy resolution is expected to improve in Xe, which has a W-value lower than Ar and a lower or similar Fano factor for electrons.

4. Summary and future prospects

A detector used to investigate $0\nu\beta\beta$ has to fulfil three critical requirements in order to achieve this task: a) excellent energy resolution, b) extremely low radioactivity, and c) large mass of the double beta decaying isotope. Many techniques have been pursued up to now, but none of them meets all requirements. R2D2’s objective is to develop a new spherical high-pressure Xe TPC that satisfies requirements and serves as an excellent detector for the $0\nu\beta\beta$ decay search. A critical parameter in this effort is the 1% FWHM energy resolution at 2.458 MeV, the $^{136}$Xe double beta decay Q-value.

The first tests with the R2D2 prototype show a resolution of 1.1% for $\alpha$-particles at 5.3 MeV, corresponding to 1.6% at 2.458 MeV. R2D2 aims to improve this result by optimising the sensor design (the multi-anode sensor ACHINOS is considered [16]) and minimising gas impurities and
electronic noise. A new SPC certified for operation up to 40 bar is commissioned at CENBG, and the Xe recuperation system is installed. The detector will operate in high pressure (up to 10 bar) to study the detector response to energetic electrons from sources such as $^{207}$Bi.

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References
[1] Giomataris I et al. 2008 JINST 3 P09007 (Preprint 0807.2802)
[2] Pocar A 2012 Physics Procedia 37 6–15 ISSN 1875-3892 proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (TIPP 2011) URL https://www.sciencedirect.com/science/article/pii/S1875389212016550
[3] Bolotnikov A and Ramsey B 1997 Nucl. Instrum. Meth. A 396 360–370
[4] Katsioulas I (NEWS-G) 2018 NEWS-G, Light dark matter search with a Spherical Proportional Counter, First results and Future prospects 53rd Rencontres de Moriond on Electroweak Interactions and Unified Theories (Preprint 1809.02485)
[5] Arnaud Q et al. (NEWS-G) 2018 Astropart. Phys. 97 54–62 (Preprint 1706.04934)
[6] Bougamont E et al. 2017 Nucl. Instrum. Meth. A 847 10–14 (Preprint 1512.04346)
[7] Katsioulas I, Giomataris I, Knights P, Neep T, Nikolopoulos K, Papaevangelou T and Ward R 2019 Fast Neutron Spectroscopy with a Nitrogen-Based Gaseous Detector 2019 IEEE Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC)
[8] Giomataris I et al. 2021 Neutron spectroscopy with N$_2$-filled high-pressure large-volume spherical proportional counters International Conference on Technology and Instrumentation in Particle Physics (Preprint 2107.02682)
[9] Mereagli A et al. 2018 JINST 13 P01009 (Preprint 1710.04536)
[10] Bouet R et al. 2021 JINST 16 P03012 (Preprint 2007.02570)
[11] Katsioulas I, Giomataris I, Knights P, Gros M, Navick X F, Nikolopoulos K and Savvidis I 2018 JINST 13 P11006 (Preprint 1809.03270)
[12] https://r2d2.in2p3.fr/owen.html
[13] Katsioulas I, Knights P, Matthews J, Neep T, Nikolopoulos K, Owen R and Ward R 2019 (Preprint 2002.02718)
[14] Allison J et al. 2016 Nucl. Instrum. Meth. A 835 186–225
[15] Schindler H 2019 Garfield++ user guide
[16] Giomataris I et al. 2020 JINST 15 11 (Preprint 2003.01068)