A new neutrinoless double beta decay experiment: R2D2

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Abstract. The search for neutrinoless double beta decay could cast light on one critical piece missing in our knowledge i.e. the nature of the neutrino mass. Its observation is indeed the most sensitive experimental way to prove that neutrino is a Majorana particle. The observation of such a potentially rare process demands a detector with an excellent energy resolution, an extremely low radioactivity and a large mass of emitter isotope. Nowadays many techniques are pursued but none of them meets all the requirements at the same time. The goal of R2D2 is to prove that a spherical high pressure TPC could meet all the requirements and provide an ideal detector for the $0\nu\beta\beta$ decay search. In the presented talk the R2D2 goal and roadmap are discussed as well as the ongoing R&D and the future developments.

1. Introduction

To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so called neutrinoless double beta decay ($0\nu\beta\beta$). In case of a double beta decay with neutrinos the kinetic energy of the two emitted electrons has a continuous spectrum reaching the $Q_{\beta\beta}$ of the reaction. The measurement of the $0\nu\beta\beta$ relies on the observation of a peak in the distribution of the energy of the two electrons corresponding to the $Q_{\beta\beta}$ of the reaction as shown in Fig. 1.

Experiments so far are just hitting the inverted mass hierarchy region and to fully cover it we need a ton scale experiment as shown in Fig. 2.

The three main requirements for a $0\nu\beta\beta$ decay search experiments are:

- **Excellent energy resolution** This is critical in order to have a narrow peak of the $0\nu\beta\beta$ signal and minimize the background coming from the $2\nu\beta\beta$ continuous spectrum. In addition it would allow to reduce the width of the region of interest (ROI) reducing therefore the external background.

- **Low background** The most natural way to achieve low background is to have a low material budget detector.

- **Large isotope masses** Gaseous isotopes have the advantage of reaching large masses easily and at relatively low cost, with an extremely low radioactive contamination with respect to solid isotopes.

Presently used technologies do not meet at the same time all the requirements as shown in Tab. 1. 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 with the ambitious goal of showing that all the requirements can be meet in the same detector.
• To demonstrate the Majorana nature of neutrino the most sensitive experimental way is an observation of the so-called $0\nu\beta\beta$ decay.

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**Neutrinoless Double Beta Decay ($0\nu\beta\beta$)**

If the neutrinos are Majorana particles the Lepton Number Violating ($L=2$) decay could occur:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-_{\beta\beta}$$

The corresponding Feynman diagram is:

$$\nu_L \rightarrow e_L$$

The expression for the rate $T_{0\nu\beta\beta}$ is:

$$T_{0\nu\beta\beta} = \frac{G_0\nu_{1/2}|M_{0\nu\beta\beta}|^2}{m_{\nu_2}^2} > 10^{24} \text{y}$$

**Figure 1.** Kinetic energy of the two electrons for $0\nu\beta\beta$ (red) and $2\nu\beta\beta$ (orange) decays. We used an arbitrary normalisation of the two spectra.

**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 one.

2. **The R2D2 project and its roadmap**

R2D2 stands for Rare Decays with Radial Detector. The idea is to use a high pressure Xenon gas TPC spherical detector to search for the $0\nu\beta\beta$ decay, profiting from several detector key features. Indeed we expect an excellent energy resolution (goal of 1% FWHM at 136Xe $Q_{\beta\beta}$ of 2.458 MeV) and a detection threshold at the level of 30 eV i.e. single electron signal. In addition the detector is simple with only one or few readout channels which is an incredible advantage in the scale up to one ton isotope mass. Thanks to the very low material budget we expect an extremely low background, possibly at the level of zero events per year per ton.

The goal of the R2D2 R&D program is indeed the validation of the mentioned detector features paving the way for a future ton scale detector. A collaboration has been formed and the project is today funded at the level of IN2P3 R&D. The roadmap to go from the currently ongoing R&D to the final ton scale detector can be summarized as follows:
Table 1. Status of currently used techniques. The met requirements are highlighted in bold.

| Type of detector       | Energy resolution | Low background       | Large isotope mass                                                                 |
|------------------------|-------------------|----------------------|-----------------------------------------------------------------------------------|
| Solid state detectors  | Extremely good    | Extremely low        | Large number of crystals and electronics channels. Difficult scalability to large masses |
|                        | (0.1% at Q value) | (zero background)    |                                                                                   |
| Liquid Xenon experiments| Order of 4% at Q value | Far from zero background | Ton scale easily achievable                                                        |
| Gaseous Xenon experiments| Order of 1% at Q value | Far from zero background | Complex detector. Feasible at ton scale?                                            |

- **Prototype 1** It consists of a small detector with a mass up to 7.9 kg (at 40 bars) of Xenon made of aluminum (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution. It is under commissioning and it has been funded by the IN2P3 R&D.

- **Prototype 2** Depending on the results of prototype 1 we aim at building a low background detector of 50 kg of enriched Xenon with liquid scintillator veto for first physics results and to demonstrate the possibility to have zero background.

- **Experiment** Depending on the results of prototype 2 and on available fundings we aim at the construction of one ton detector to cover the inverted mass hierarchy region. In addition we aim at using prototype 2 to study the detector behaviour using other gases as well as the possibility to perform tracking.

3. The R2D2 detector
The R2D2 detector is a spherical high pressure Xenon TPC based on the developments carried out for the search of dark matter within the NEWS-G collaboration [1]. The detector has to be optimized for the background reduction given the different energy regime i.e. keV for dark matter and MeV for neutrinoless double beta decay. The working principle is shown in Fig. 3: a central anode at high Voltage collects and amplifies the electrons produced by the ionisation of the passage of particles in the Xenon gas.
A Monte Carlo simulation was used to study the sensitivity of prototype 2 and in particular the background rate that can be achieved. Assuming the expected detector response we obtained in one year a limit on the $0\nu\beta\beta$ half life of $2.5 \times 10^{25}$ years i.e. an effective mass $m_{\beta\beta}$ smaller than 160 - 330 meV depending on the matrix element values. The background is at the level of 2 events per year in 50 kg for a signal efficiency of 64% as reported in Ref. [2]. The published results were obtained assuming some detector feature listed here below: the goal of the R2D2 R&D is indeed to demonstrate that the assumptions are correct. The assumed detector characteristics are:

- Energy resolution of 1% FWHM at the $Q_{\beta\beta}$ of 2.458 MeV.
- Optimized ROI of $Q_{\beta\beta} \pm 0.6\%$.
- Possibility of performing a radial energy deposition reconstruction.
- Threshold as low as 200 keV for the liquid scintillator.
- Copper activity of 10 $\mu$Bq/kg.
4. Ongoing R&D
In 2018 the R2D2 was funded as R&D by the IN2P3. As mentioned before the main goal of the R&D is the demonstration that the desired energy resolution can be achieved, and to do that the idea is to use a smaller detector (20 cm radius) made of Aluminium i.e. no low background but much cheaper. The setup is under commissioning at CENBG and will be used with atmospheric Xenon to validate the energy resolution at different pressures, and to understand any possible radial position dependence. The energy resolution is indeed the most critical point to be validated. Despite the fact that a resolution of 0.6% FWHM at 662 keV in proportional counter has already been demonstrated [3] (this could be rescaled to 0.3% at the Xenon Q value of 2.458 MeV) this has to be demonstrated in the spherical TPC where the ultimate showstopper could be given by inhomogeneities of the central sensor.
A picture of the setup at CENBG as well as a mechanical drawing of the detector can be seen in Fig. 4.

5. Foreseen developments R&D
Several further developments are under study and could be tested on the prototype 2 to enhance the signal over background ratio.

5.1. Electronics
The signal waveform analysis is a critical ingredient for a particle identification and therefore for background reduction. We need an electronics that allows for a signal waveform reconstructions without affecting the energy resolution. To reach the desired goal, custom made electronics are under developments at CENBG/CEA.
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5.2. Materials
Needless to say the activity of materials used has a critical impact on the background. This is indeed the reason to have a detector with the lowest material budget as possible. In our sensitivity studies we assumed a copper activity of 10 µBq/kg which is conservative considering that on the market copper with an activity of 1 µBq/kg can be found [5]. In addition developments are ongoing at Pacific Northwest National Laboratory in US to have electrodeposited Copper with a much smaller activity. So far an activity at the level of 0.1 µBq/kg has been obtained.

5.3. Light readout
The radial position reconstruction is today based on a waveform analysis looking at the width of the signal normalised by its amplitude. The knowledge of the starting time of the event given by the Xenon scintillation would be an important additional piece of information to have a more precise position reconstruction relying on the knowledge of the drift velocity. In addition it would make the coincidence with the external liquid scintillator veto signal much shorter and easier, minimising the risk of accidental coincidences. Given the impossibility to have PMTs directly in the liquid scintillator sphere since they are not radiopure enough, and the difficulty to extract the light with fibers, an option of deposing small regions of photocathode inside the sphere is under study. At the same time the instrumentation of the anode supporting rod is also under study.

5.4. Gases
The use of different gases in the same TPC (i.e. same background sources) could be an advantage to understand and benchmark the background. In addition gases with ββ emitters at higher $Q_{\beta\beta}$ would result in a smaller background. Possible gas such as MoF$_6$ or SeF$_6$ could be used but they are far too dangerous therefore different possibilities have to be studied in the R&D.
5.5. Central sensor

High pressure and large spheres require a high voltage (HV) on the central anode, however experimentally it seems that a reasonable limit before reaching technical difficulties is about 10 kV. A solution might come from a multi-ball readout ACHINOS [4] developed at Saclay: with a smaller HV on each anode we could have the same field far from the anodes and a higher amplification with respect to a single central ball. Furthermore the anodes could be read independently giving a coarse detector segmentation (i.e. coarse tracking) which could result into an additional handle for background rejection.

6. Conclusions

To search for neutrinoless double beta decay three critical requirements should be met by the detector: an excellent energy resolution, an extremely low radioactivity and a large mass of emitter isotope. Nowadays many techniques are pursued but none of them meets them all. The goal of R2D2 is to prove that a spherical high pressure TPC could meet all the requirements and provide an ideal detector for the $0\nu\beta\beta$ decay search.

Preliminary studies showed that we could have competitive sensitivity with small masses and potentially zero background detectors with large masses.

The R2D2 proto-collaboration has been formed and the R&D has been approved by IN2P3 with the principal goal of demonstrating that the energy resolution at the level of 1% FWHM at the Xenon Q value can be reached. A setup is under commissioning at CENBG and results are expected soon.

References

[1] Q. Arnaud et al. [NEWS-G Collaboration], Astropart. Phys. 97, 54 (2018).
[2] A. Meregaglia et al., JINST 13, no. 01, P01009 (2018).
[3] A. Bolotnikov and B. Ramsey, Nucl. Instrum. Meth. A 396, 360 (1997).
[4] A. Giganon et al., JINST 12, no. 12, P12031 (2017).
[5] https://www.aurubis.com