A new neutrinoless double beta decay experiment: R2D2

Cécile Jollet
CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France
E-mail: cecile.jollet@cenbg.in2p3.fr

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 preliminary results are presented as well as the project roadmap.

1. Introduction
The nature of the neutrino mass (i.e. Dirac or Majorana) is a crucial question in the neutrino physics scenario and most sensitive experimental way to address it is an observation of the so called neutrinoless double beta decay ($0\nu\beta\beta$). 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.

Ongoing experiments are just hitting the inverted mass hierarchy region whereas to fully cover it and reach a limit on the effective mass probed $m_{ee}$ of few meV, a ton scale experiment is needed as shown in Fig. 1.

The best way to search for such a rare decay is to have and excellent energy resolution which 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. The use of an extremely low background detector is also critical and the most natural way to meet such a requirement is to have a low material budget detector. Finally to cover a region at low values of $m_{ee}$ large isotope masses are required.

Presently used technologies do not meet at the same time all the requirements. 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.
Experiments so far are just hitting the inverted mass hierarchy region and to fully cover it we need a ton scale experiment. 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.

Figure 1. 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. An excellent energy resolution (goal of 1% FWHM at 136Xe $Q_{\beta\beta}$ of 2.458 MeV) is expected as well as 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. The R2D2 project is today funded as IN2P3 R&D and the roadmap to go from the currently ongoing R&D to the final ton scale detector consists of three phases.

- **Phase 1** A first prototype consisting of an aluminum (no low radioactivity) sphere able to host a Xenon mass of 7.9 kg has been build to demonstrate that the desired energy resolution can be achieved. The detector was conceived and built at CENBG and it is today under commissioning.
- **Phase 2** If the energy resolution requirements are met with the first prototype, the next step would be the construction of a low background detector of 50 kg of enriched Xenon. It could provide competitive results with respect to present results on $^{136}$Xe lifetime and it will be used to demonstrate the possibility to reach zero background.
- **Phase 3** Based on the success of the previous phases, a ton scale detector could be built to cover the inverted mass hierarchy region. In addition the previously built detectors will be exploited to study the possible use of 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] and optimized given the different energy regime for neutrinoless double beta decay search. The working principle is shown in Fig. 2: 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 a 50 kg low background detector.
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 $m_{ee}$ 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 depend on the assumption made, the most stringent one being an energy resolution of 1% FWHM at the $Q_{\beta\beta}$ of 2.458 MeV. The goal of the R2D2 R&D is indeed to demonstrate that the assumptions are correct to validate the computed detector sensitivity.

4. Preliminary results
A first test was carried out testing the detector with an $\alpha$ source. First we used a $^{239}$Pu emitting an $\alpha$ particle at 5.15 MeV which immediately demonstrated that the detector was working correctly as shown in Fig. 3. Unfortunately such a source can not be used for an estimate of the energy resolution due to the low energy tail mostly due to the source holder and the finite thickness of the source itself.

To overcome this issue we used 2% thoriated tungsten welding rods positioned at the level of the hole at the bottom of the sphere in a dedicated holder especially conceived to avoid as much as possible $\beta$ emissions in the detector. The $^{220}$Rn gas emitted by the rods enters the sphere and its decay chains consists of several $\alpha$’s particle between 6.3 and 8.8 MeV. We clearly see the alpha particles in particular at 6.29 MeV ($^{220}$Rn decay) and 6.78 MeV ($^{216}$Po decay) as can be seen in Fig. 4. A preliminary value for the energy resolution of 1.6% $\sigma/E$ for the 6.78 MeV peak was observed, which is quite promising for a first test. Unfortunately the source activity is very small at the level of 30 mBq and we need to take long runs to have a reasonable statistics.

At the same time we noticed that the stability of the gain is not yet achieved and we noticed a strong dependence on temperature changes both via impact on the electronics and on the gain change due to the pressure change. This point will be addressed soon with the highest priority.

5. Conclusions
To optimally search for neutrinoless double beta decay the detector has to meet three critical requirements: an excellent energy resolution, an extremely low radioactivity and a large mass of emitter isotope. Amongst the different techniques pursued today, one which is able to meet all
Figure 3. Amplitude in arbitrary units versus signal risetime for the first run using $^{239}$Pu source.

Figure 4. Preliminary energy resolution for $\alpha$'s at 6.29 MeV ($^{220}$Rn decay) and 6.78 MeV ($^{216}$Po decay) in 3 hours run.

the requirements at the same time does not exist. The goal of R2D2 is to prove that a spherical high pressure TPC could indeed meet all the requirements at the same time and provide an ideal detector for the $0\nu\beta\beta$ decay search. Sensitivity 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, a setup has been built at CENBG and preliminary results showed a good energy resolution. Efforts are ongoing to improve it to the desired level of 1% FWHM at 2.458 MeV, furthermore current experimental efforts aim at a stabilisation of the gain which is strongly affected by environmental conditions (i.e. temperature variation or electronic and acoustic noise).

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).