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R2D2: Rare Decays with Radial Detector

Principal Author:
Name: Cécile Jollet
Institution: CENBG
Email: cecile.jollet@cern.ch
Phone:0557120852

Co-authors:
José Busto CPPM
Cédric Cerna CENBG
Ali Dastgheibi-Fard LSM
Frederic Druillole CENBG
Pascal Lautridou SUBATECH
Anselmo Meregaglia CENBG
Fabrice Piquemal CENBG

Abstract:
R2D2 is a project aiming at a breakthrough in **neutrino physics: the determination of the neutrino nature and its mass, which are amongst the most important open questions nowadays in particle physics with huge impact also in cosmology**. The objective is to look for the neutrinoless double beta decay consisting of the simultaneous emission of only 2 electrons. Its existence would imply lepton number violation which is a necessary ingredient to **explain the creation of matter in our Universe**.
The proposed project aims at using a **new technology** made of a single/few channels **high pressure spherical Xenon Time Projection Chamber** to observe the signal issued by 50 kg of Xenon-136 in a **background free environment to pave the way for a ton scale background free detector to reach an unprecedented sensitivity covering the inverse neutrino mass hierarchy region.** The prototype will be a **major breakthrough** in neutrinoless double beta decay search meeting **for the first time all the requirements needed for the rare signal observation in the same detector**.
The proposed detector is a sphere with a central anode to collect and amplify charges created by the ionisation of the two emitted electrons interacting in the gas. It relies on a **design which minimises the mass of very low radioactive materials and with an excellent energy resolution** which are critical ingredients in order to reduce the background issued by the residual natural radioactivity of the materials. An active veto, made of very pure liquid scintillator surrounding the sphere, will be used in addition to passive shielding against surrounding radioactivity. The energy resolution, comparable to what is achieved today in semiconductor detectors, will be a **major improvement compared to other Xenon based experiments**. The well established technology used for the spherical central anode will be further developed in order to have few readout channels and allow for a **coarse tracking reconstruction**.

Physics case

The search of **neutrinoless double beta decay** (ββ0ν) is a **high priority in contemporary neutrino physics**. The observation of such a process would imply the lepton number violation and would have an **essential impact on particle physics and cosmology**: it is a necessary ingredient to validate the leptogenesis model used to **explain the creation of matter in our Universe**. Observing neutrinoless double beta decay would demonstrate that neutrinos are Majorana particles. Indeed this process requires that the neutrino is its own anti-particle, unveiling the nature of the neutrino mass. Depending on the mechanism governing the ββ0ν decay, its observation provides the most sensitive laboratory technique for measuring its value. Experimentally the ββ0ν decay consists in the emission of only two electrons, and the sum of the energy of these electrons must be equal to the transition energy (Q value of the reaction). This signal (i.e. a narrow peak at the Q value) has to be extracted from the possible background. In particular there is another process, already measured for several nuclei, which is the two-neutrino double beta decay (ββ2ν). Such a process, which is the second order process of beta decay and does not require any lepton number violation, leads to the emission of two electrons and two neutrinos. The sum of the energy of the two electrons is in this case a continuous spectrum with the Q value as endpoint. Fig.1 illustrates a background-free energy spectrum for both ββ2ν and ββ0ν double beta decay processes. It is clear that to observe the ββ0ν peak **an excellent energy resolution is needed to discriminate between the ββ0ν decay and the ββ2ν decay.**

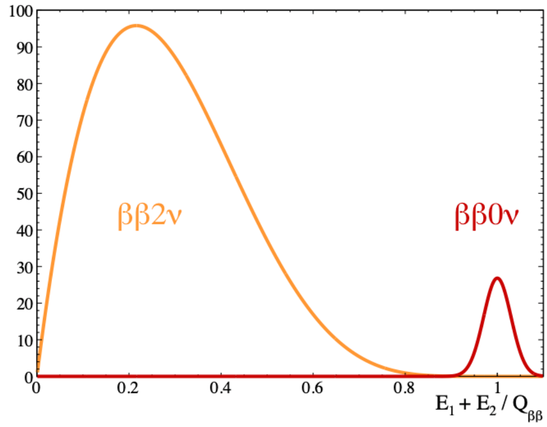

Figure 1: Kinetic energy of the two electrons for ββ0ν (red) and ββ2ν (orange) decays. We used an arbitrary normalisation of the two spectra.

Another critical problem to experimentally observe the ββ0ν peak is the background present in the so called "region of interest" (ROI) around the Q value (energy region in which the signal is searched for). Considering that typical transition energies are around 2-3 MeV depending on the nuclei, the main source of background comes from the natural radioactivity related to the decay chains of U and Th as well as cosmic rays. An **excellent energy resolution**, which is mandatory to reduce the background coming from the tail of the ββ2ν continuous distribution, **is also needed to minimise the width of the ROI**. A narrower ROI would evidently result in a smaller background and therefore in a better signal to noise ratio. A detector searching for the ββ0ν decay should be **located in an underground laboratory** to reduce the background due to cosmic-rays and to avoid cosmogenic activation of the materials, whereas gamma-rays from natural radioactivity of surrounding rocks can be reduced using active and passive vetoes. The most challenging part is to reduce the **intrinsic natural radioactivity of the materials of the detector, which represents the ultimate irreducible source of background.** Typically, the natural radioactivity is few tens of Becquerels per kg of material (Bq/kg), whereas for experiments searching for ββ0ν decays, a level of few μBq/kg must be reached (i.e. a reduction of the order of 10^6). This explains the difficulty to build low background experiments, especially when a large mass, a large number of readout channels and various types of materials are used. The materials used for the detector construction undergo a strict process of screening and selection in terms of radiopurity, nonetheless the most straightforward and natural way to have a low background experiment is to **reduce to a minimum the detector material** i.e. to use a so called **"low material budget" detector**, and to **reduce the number of readout channels**.

State of the art

Thanks to the observation of neutrino oscillation (Nobel prize in 2015 to T. Kajita and A. McDonald), we know today that neutrinos are massive particles and that we have three neutrino families, however the mass ordering between these three neutrinos is still unknown. Observing neutrino oscillation we can measure the difference between the mass states but not the absolute mass values and we do not know which neutrino is the lightest one. This is the so called "mass hierarchy problem", graphically shown in Fig.2. Two scenarios are possible: normal hierarchy (NH) where the lightest neutrino is ν_1, and inverted hierarchy (IH) where the lightest neutrino is ν_3. This has a direct impact on the ββ0ν search: in case the ββ0ν process happens through the exchange of a light neutrino, the half-live of the process depends on effective neutrino mass $m_{\beta\beta}$, which in turn depends on the ordering.

We are hitting today the inverted hierarchy region, its full coverage is the goal of next generation experiments, whereas the normal mass hierarchy region is today out of reach with presently used techniques

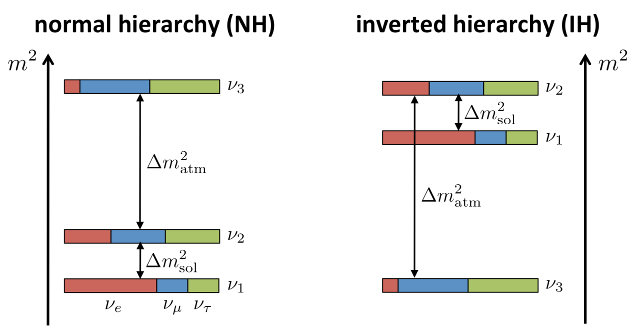

Figure 2: Illustration of the two possible mass hierarchy orderings between the three neutrinos. In the NH case ν_1 is the lightest neutrino whereas in the IH case the lightest neutrino is ν_3.

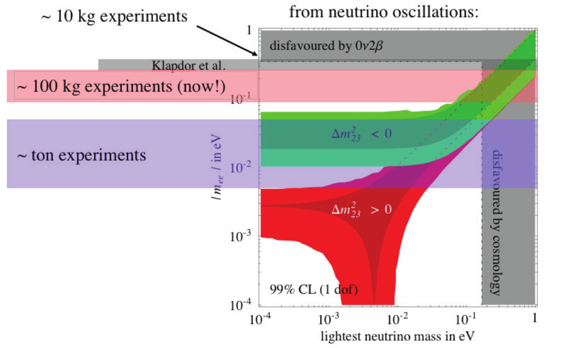

Figure 3: Mass regions probed in the ββ0ν decay process. The green band represents the inverted hierarchy allowed region whereas the red band represents the normal hierarchy one.

(see Fig.3). It is clear that to probe regions at low values of $m_{\beta\beta}$ (called m_{ee} in Fig.3), **large masses of isotopes are needed**: to fully cover the inverted hierarchy region, ton scale experiments are mandatory.
The search of neutrinoless double beta decay is a global competition and many experiments are trying to observe this possibly very rare phenomena: so far only limits on its lifetime are set at the level of 10^{25} years (depending on the isotope under study). This corresponds to limits on the neutrino mass at the level of 200 meV. The challenge for the next generation of experiments will be to reach the level of 10 meV to fully cover the inverted mass hierarchy region: this requires very large masses of enriched isotopes, of the order of one or few tons. **The limitations of present experiments** depend on the techniques and on the isotopes under study: they are typically the **small mass and/or the poor energy resolution and/or the high background in the RO**I. Experiments based on solid state detectors such as GERDA [1] or CUORE [2] have the advantage of an excellent energy resolution (at the level of 0.1% at the Q value) at the price of a large number of crystals and therefore electronics channels, and a difficult scalability to large masses: growing crystals to reach masses of the order of the ton is expensive and complicated. Other experiments such as EXO [3] or KamLAND-Zen [4] use enriched Xenon-136 as target, which makes it possible to reach easily large masses: EXO-200 has a target mass of 200 kg whereas KamLAND-Zen uses 400 kg of Xenon (800 kg in the future). The major problem of these experiments is the poor energy resolution at the level of 4% and 9% FWHM respectively at the Q value. This results in a large ROI and therefore in a large background. The NEXT [5] collaboration has worked in order to improve the energy resolution combining charge and light readout reaching a resolution of 1% at the Q value in a Xenon gaseous TPC. The drawback of the complex setup is the use of large amounts of materials which are not highly radiopure and which result in a large background compromising the scalability to higher masses.

Up to now an experiment which combines a high energy resolution and low background at the ton scale is still missing in the neutrinoless double beta decay panorama.

R2D2 goals

R2D2 aims at demonstrating that a detector based on the proposed new technique meets all the needed requirements for the neutrinoless double beta decay search.

The use of a **single/few channels high pressure spherical Xenon gas TPC** could be a **breakthrough** in ββ0ν decay search. The proposed detector **minimises the used material**, is **scalable**, and potentially has a **resolution as high as 0.3%** FWHM at the Xenon Q value of 2.458 MeV. **In addition such a detector could be operated with other gases**.

In details the possible roadmap consists of three step:

1) A small prototype using natural Xenon under pressure to demonstrate that we can reach the desired energy resolution (non-low background). Such a prototype exists and is actually under commissioning at CENBG funded by IN2P3 R&D.

2) A detector, with an active mass of 50 kg of enriched ^{136}Xe, to benchmark the estimated background, its rejection and the particle identification. If successful we will demonstrate that we can easily scale it in

order to have a ton detector running in a background free mode. Such a detector will be able to set a competitive limit on the lifetime of the ββ0ν decay at the level of 10^{26} years (i.e. a limit on the mass of $m_{\beta\beta}$ < (70 - 150) meV depending on the matrix element value) in only three years of data taking.

3) A final ton scale detector to cover the inverted mass hierarchy region.

Note that the scaling can be done increasing the sphere radius or using multiple spheres which is straight forward and does not require any additional R&D.
The reduction of the background has a critical impact on the sensitivity: as an example 400 kg of Xenon with a background of about 200 events in the ROI (as for KamLAND-Zen) correspond to 40 kg of Xenon in a background free mode.

We are now concentrating on the first phase of the project, however we are caring out in parallel several developments which will be crucial for the following steps, in particular :

- **Develop and test the multi-channel central anode** to have an additional background rejection exploiting the coarse tracking.
- **Develop a custom made electronics** to exploit the signal shape for particle identification and background suppression.

If the project is successful it would be an extremely important breakthrough in ββ0ν decay search: the newly developed technology could be used to cover the inverted mass hierarchy in three years of data taking with a ton detector to possibly assess the Majorana nature of neutrinos.

R2D2 methods

The spherical single channel TPC detector, conceived by I.Giomataris (involved in the proposed project) [6], is a running detector and it is today used by the NEWS-G [7] collaboration for the direct search of dark matter. The working principle is the following: particles crossing the Xenon volume will ionise the gas, and the charges produced will drift towards the central anode where they are amplified by an avalanche phenomenon in its near vicinity as shown in Fig.4.
Several years of R&D resulted in a detector with excellent radiopurity and a very low energy threshold at the level of 30 eV i.e. capable of detecting a single drifted electron. Nonetheless **several aspects need further studies and developments to meet the physics requirement for the double beta decay observation**. Radiopurity is a common issue in dark matter and ββ0ν decay searches, however the different energy ranges (keV against MeV) and signal topology (nuclear recoil against two electron tracks) demand a dedicated detector development.

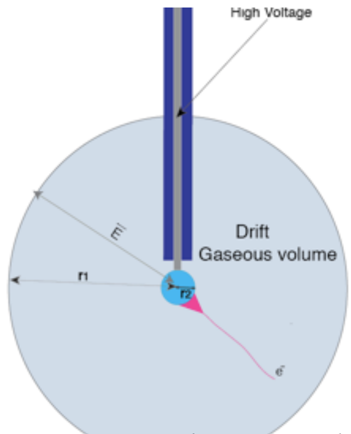

Figure 4: Working principle of the spherical TPC.

The prototype to demonstrate the energy resolution is running at CENBG and was built at the CENBG mechanical workshop (Fig 5). It is made of Aluminium since we have no special requirement on material backgrounds and it is presently used with ArgonP2 (98% Ar + 2% CH_4). We are working to achieve a good detector stability and we will soon move to Xenon to assess the energy resolution.

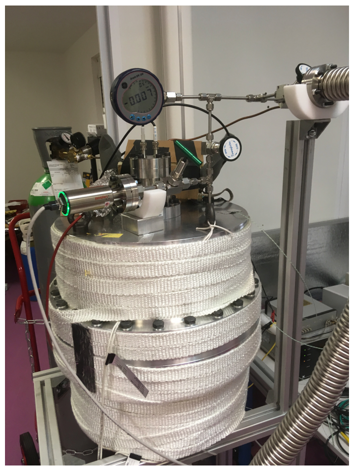

Figure 5: Setup at CENBG.

For the next phase the idea is to use a spherical **TPC made of ultra pure Copper with a specially design central anode** at high voltage, to have a high and homogeneous electric field, operated with **enriched Xenon-136**. The sphere will have a radius of 37 cm and will be operated at 40 bars holding therefore a Xenon mass of 50 kg. Most of the remaining **internal background will be rejected using a radial position reconstruction** which will allow to discriminate between multi-energy depositions given by gammas, and the expected signal given by the electrons short tracks. To achieve this, a preliminary discrimination will be based on the study of the signal rise time, nonetheless to achieve a position precision at the level of less than 1 cm the starting time of the drift is needed and this will be achieved exploiting the **Xenon scintillation light**. An active **veto made of liquid scintillator and passive layers** of shielding will also be installed to **reject external background**. Here below I list the different key features of the detector highlighting the needed developments, the related possible risks, and the envisaged solutions in case of a negative outcome of the development.

Materials and radiopurity

Status and needed developments: I showed in a dedicated sensitivity study that the use of standard Copper with a radiopurity at the level of 10 µBq/ kg resulted in a background at the level of 2 events per year in the ROI for a 50 kg detector [8]. A reduction of the Copper activity is needed, however the purest Copper on the market, produced by AURUBIS [9], has a radioactivity in terms of U and Th decay chains of about 1 µBq/kg which would reduce the background by one order of magnitude. In addition I will consider the possibility to use ultra-pure Copper produced at PNNL (US) by electrodeposition with a confirmed limit of 0.1 µBq/ kg.

Risk study: The risk could come from accidental surface contamination or cosmogenic activation of the materials. This could be limited using cleaning techniques developed for the NEWS-G detector and limiting the time for which the Copper is not underground.

Central sensor

Status and needed developments: For small detectors operating at moderate gas pressures the central sensor is a silicon ball with a diameter of several millimetres. The possible development is represented by a **multi-ball sensor called ACHINOS** [10], which has the advantage of an increased electric field for a given applied voltage, and the possibility to read each ball of ACHINOS individually allowing for a three-dimensional particle tracking.

Risk study: The major risk could be the degradation of the energy resolution. If ACHINOS will be proved to be unsuitable for the detector we will use a standard single channel anode and we will rely on a waveform analysis for the search of the two electron tracks. This would required a specific electronics.

Light readout

Status and needed developments: The event starting time is a very valuable information for background rejection and Xenon scintillation could provide it. **The introduction of the light readout system has never been done before in such a detector** and special care is needed to avoid degradation of the radiopurity.

Risk study: The risk of such a development could be the impossibility to operate such a system without degrading the detector radiopurity. In this case the radial reconstruction will be based on the signal rise time as done today in the NEWS-G collaboration with a position resolution at the level of 1-2 cm. The background reduction would still be enough according to the results of the performed sensitivity studies [8].

Active veto and passive shielding

Status and needed developments: The active veto will be instrumented to read the scintillation light to reject external background and to confirm the robustness of the estimated background rejection factor. The passive shielding will protect the detector from external gamma-rays and neutrons.

Risk study: No specific risk is identified as long as the radiopurity is carefully checked.

Readout electronics

Status and needed developments: Charge preamplifiers are commonly used to have good energy resolution, however for a signal analysis we would need a current preamplifier which has the drawback of a large noise and therefore a poor energy resolution. The solution could come from a **custom made electronics**.

Risk study: Preliminary investigations have shown that this single-readout detector is perfectly adapted to signal processing, however in case such electronics can not be developed we can rely on the multi channel sensor for the two electron tracks selection. In case of a simultaneous failure of the electronics and sensor development we could still discriminate between signal and background looking at the radial energy depositions without reconstruction of the electron tracks at the price of a lower signal/background ratio.

Xenon purification

Status and needed developments: In order to achieve the desired results we need to work in an extremely pure environment: **Xenon has to be enriched and purified** by all electronegative impurities at a level of better than 1ppb. This can be done using commercial getters and excellent results have been achieved by running experiments.

Risk study: The risk is represented by the Radon contamination and not by enrichment or electronegative impurities. **The strategy of the project to reduce the amount of materials is the best approach to reduce the Radon background**. However, Radon tents will be used, which will help to reduce also the Radon background coming from all materials constituting the detector.

Energy resolution

Status and needed developments: It has already been shown in the past that Xenon based small proportional counters can achieve a resolution of 0.4% FWHM at 662 keV up to 60 bars [11]. More recently the NEXT

experiment reached 1% FWHM at the Xenon Q value combining charge and light readout [12]. The possibility to reach a resolution better than 1% in the proposed TPC has to be demonstrated and a dedicated setup built at CENBG is currently investigating which limit can be achieved, however **within the NEWS R&D some preliminary measurements showed a resolution of 18% at 5.9 keV which corresponds to a resolution of 0.9% at the Xenon Q value** assuming a rescaling as the square root of the energy.
Risk study: The surface inhomogeneities of the central anode might be the ultimate limit in terms of resolution. This represents the most dangerous risk for the project and if the goal is not reached a possible solution would be to run the detector in proportional mode reducing the gain but assuring the energy resolution as demonstrated in the past [11].

Although the R2D2 project has to cope with some risks, they are limited and under control, and alternative possibilities exist in case of failure of the foreseen developments. We believe that the extremely valuable impact of the project on neutrinoless double beta decay search, in case of success, largely overcomes the possibility of failure.

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