ANR NEWS and R&D R2D2

Conseil scientifique du 25 et 26 octobre 2018

"Physique des événements rares : matière noire et décroissance double beta sans neutrino"

1 Context

Dark matter (DM) is now clearly an essential ingredient of our understanding of the Universe [1, 2]. Massive neutral particles, non relativistic at decoupling time, are a generic class of well motivated candidates [3]. Lack of evidence of SUSY at LHC, and failure from direct detection experiments to find any candidate at masses above 10 GeV/c^2, suggest that a wider parameter space should be explored. Several new approaches (e.g. dark sector, asymmetric dark matter, U-boson or generalized effective theory) open the way to candidates with lower mass and/or more complex couplings that the traditional ones [4, 5, 6, 7], but expected signals are often close to the detection thresholds of current experiments [8]. In such a situation, new detection concepts, in particular oriented towards low-mass candidates, become attractive (see for example DAMIC for an initiative contiguous to ours).

Another critical piece of information missing in our understanding of the universe, is the determination of the nature of the neutrino mass i.e. if neutrino is a Dirac or Majorana particle. Observation of the double beta decay without emission of neutrinos (the so called $\beta\beta0\nu$) remains today the most sensitive way to asses the Majorana nature of neutrino. Search is strongly pursued worldwide, exploiting basically two techniques : one based on pure calorimetry and the other one combining calorimetry and tracking [9, 10]. While experiments are trying to fully rule out the region of the inverted mass hierarchy and the challenge comes from the huge masses of isotopes needed, the possibility to reach a zero background measurement with a new technique, not fully based on the increase of the detector size, becomes exciting (see for example NEXT and EXO for an initiative contiguous to ours).

In this context, two approaches are currently being developed : R2D2 for the neutrinoless double-beta search (program started in 2017 and involving 5 French laboratory) and NEWS for DM search of very low mass (0.1–1 GeV) (international collaboration started in 2015 and regrouping 13 laboratories). The development of these two experiments leans on a common base : the sphere SEDINE installed in the LSM. As far as NEWS is concerned, the final detector (1.4 m diameter) optimized for the detection of DM is currently under construction and will be operated at SNO laboratory around 2020. Concerning R2D2, the first prototype (0.4 m diameter) capable to support high pressures with purified Xe is currently under construction at CENBG. For very much aspects, both programs have common synergies and developments (FEE, DAQ, anode design, sphere cleaning, signal processing) in which the french teams are strongly involved and motivated to continue their investment.

2 Proportional Spherical Counters

The Proportional Spherical Counter (SPC) proposed by I. Giomataris [11] presents most of the desired characteristics needed for the DM search in the low mass region as well the background rejection and signal selection in the search of the $\beta\beta0\nu$ decay [12, 13, 14, 15, 16, 17, 18] :

- Its mechanical structure naturally induces a low material budget and thus ensures the lowest possible internal radioactivity.
- It can provide an excellent energy resolution (potentially better than 1 %) and it can reach a threshold low enough to observe single electrons.
- The ability to vary the nature of the active medium i.e. the use of different gases to cover a wide range of WIMP mass (He, Ne, Xe and possibly H) or to have different $\beta\beta$ isotopes (^{136}Xe and possibly MoF_6), and to vary the pressure (from 0.1 to 40 bar), can provide very valuable redundancies to check any possible evidence of signals.

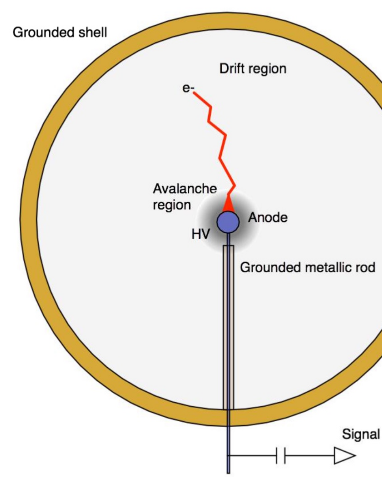

FIGURE 1 – *Working principle of the sphere TPC.*

The detector is a hollow sphere connected to the ground and filled with gas. At the center a small conducting ball hold by a metal support works as anode. Given the geometrical configuration (see Fig. 1) a radial electric field can be obtained with a $1/r^2$ dependence where r is the distance from te central anode. All the inner volume represent a drift volume whereas the amplification volume corresponds to a few mm^3 around the central anode. Primary electrons, created in the drift volume, drift towards the anode with a time which depends on the gas and its pressure going from one μs up to one ms. At a few mm from the anode, the electric field is high enough to start the avalanche. The working principle is the same as the one used by Time Projection Chambers (TPC) detectors, but with only one readout channel connected to the anode. The signal shape depends on the primary charge distribution, on the amount of the energy deposited and on the distance of the primary charge creation from the anode, allowing to locate the interactions inside the volume. Due to the small capacity of the spherical geometry (even for large size detectors), the detector presents intrinsically a low electronic noise. The limiting factor on the detection threshold is given by the mean ionization energy of the gas used. Based on a very simple mechanical design, a large volume can be built. This makes it suitable for analysis of point energy deposits and long tracks. The detection range goes from few eV up to few MeV, allowing to detect gammas, electrons, alphas, neutrons and nuclear

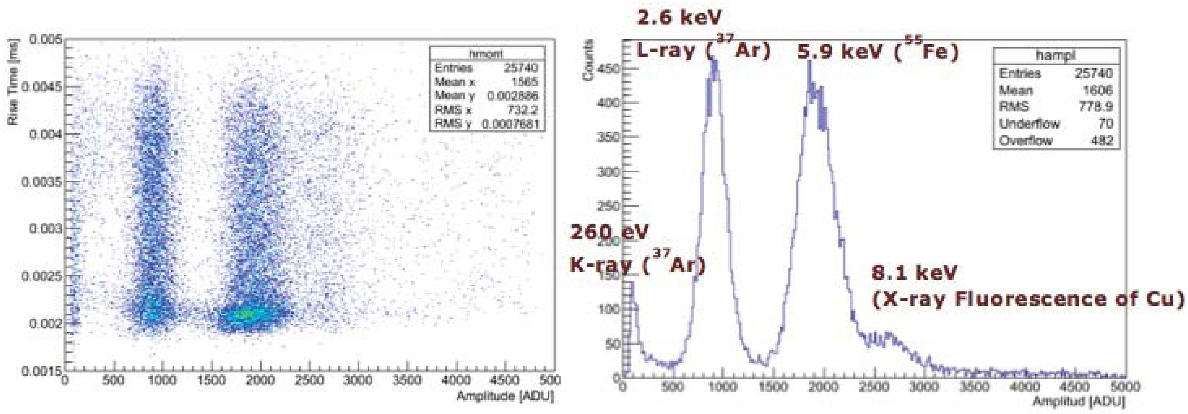

FIGURE 2 – *Low energy calibration results at 50 mbar Ar/CH4 (2%) : (left) rise time versus amplitude matrix ; (right) associated energy spectrum.*

recoils. In addition, based on the principle of proportional sensing, mastered for decades, this cheap single-channel detector is perfectly suited for precise adjustment of its operating parameters and well suited for sophisticated signal processing to extract the desired signal.

3 ANR NEWS(New Experiments With Spheres)

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+ Department of Physics, Engineering, Physics-Astronomy, Queen's University, Kingston, Ontario, Canada (13 Members)
** Spokesperson*

NEWS-G collaboration (New Experiments With Spheres-Gas) : *+ Pacific Northwest National Laboratory, Richland, Washington, USA, (2 Members) + Chemistry-Chemical Engineering Department, Royal Military College of Canada, Kingston, Ontario, Canada, (2 Members) + Physik Department E12, Technische University Munchen, Garching, Germany, (1 Member) + SNOLAB, Lively, Ontario, Canada, (1 Member) + Aristotle University of Thessaloniki, Thessaloniki, Greece, (1 Member) + University of Birmingham, Birmingham, UK, (1 Member) + University of Alberta, Alberta, USA, (1 Member) + TRIUMF laboratory, Vancouver, Canada, (1 Member) + SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France, (1 Member)*
(Spokesperson : G. Gerbier, co-spokesperson : I. Giomataris)

NEWS-G, set-up at the Laboratoire Souterrain de Modane (LSM), is a direct DM detection experiment using a Spherical Proportional Counters (SPC). This program has been initiated 4 years ago under the impulse of a team of physicists of CEA and the team of LSM [19]. For the french part, it has benefited from an ANR (ANR NEWS) support of 530 kE granted for the period October 2015 - October 2019, with the aim is to solve the most critical parts required to reach the expected performance for NEWS-G : low-radioactivity sensor, FEE, DAQ and calibration system. Today, the NEWG-G collaboration counts 13 laboratories, 35 collaborators, including 4 French laboratories (3 of IN2P3) with 14 members (7 of IN2P3).

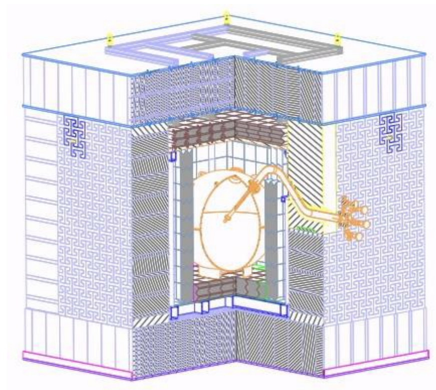

FIGURE 3 – *Cartoon of the SEDINE setup.*

3.1 Present activities

The currently operated detector is the prototype SEDINE (SphErical DetectIon of NEutrons) which was initially designed for low flux neutron measurements at LSM. It is a 60 cm diameter SPC made of ultra-pure (NOSV) copper. In order to further protect from external radiation, it is enclosed in a compact shielding made of 30 cm of polyethylene, 15 cm of lead and 8 cm of copper (see Fig. 3).

The contribution of the French groups IN2P3 is important part of the joint effort to develop the detector and its analysis. It covers the following aspects :

- LSM is in charge of handling of the shielding, gas transportation, installation, insure a high vacuum, gas injection by taking care of purity running, and maintenance of every operational detail.
- All calibration sources such as neutron and gamma are installed and run at LSM. The LSM team has been in charge of the neutron source calibration installed at different parts of the shielding. Also, for gamma source, the 37Ar and X ray generator have been used for very low energy calibration.
- The LSM team is in charge of the fast analysis of the calibration runs before a deeper offline analysis.
- The LSM team ensured the installation of a new acquisition chain. For the analog part, a dedicated box was built to accommodate HT filters and both FEE amplifiers. All electrical connections were also made by the team.
- The LSM team is in charge of the selection of low radioactivity materials (archaeological lead, shielding, copper sphere).

— The LPSC team is in charge of the quenching factor measurements for different gaz mixtures used for Light WIMP search (indeed, a high pressure SPC is used on MIMAC facility for calibration below 30 keV).

In 2016, SEDINE has been operated with a Ne/CH4 (99.3%/0.7%) mixture at 3.1 bars in sealed mode during 42.7 days for a total exposure corrected for dead times of 9.6 kg.days. A 6.3 mm in diameter silicon sensor was used and set at 2520 V. The resulting gain allowed to set the trigger threshold at 35 eVee, providing a 100% trigger efficiency above the analysis threshold of 150 eVee. Analysis of the physics-run has been performed using a Boosted Decision Tree (BDT) algorithm. An upper limit at 90% C.L on the SI WIMP-nucleon scattering cross section was then deduced. This result established new leading constraints for WIMP masses lower than 0.6 GeV, and making NEWS-G one of few experiments in the world capable of detecting sub-GeV WIMPs [20].
Since 2017, the exploitation of SEDINE with He gas has begun. This should allow to improve low-mass particle detection in the GeV/c^2 mass range, and to increase the sensitivity to sub-GeV/c^2 WIMPs.

3.2 Prospects

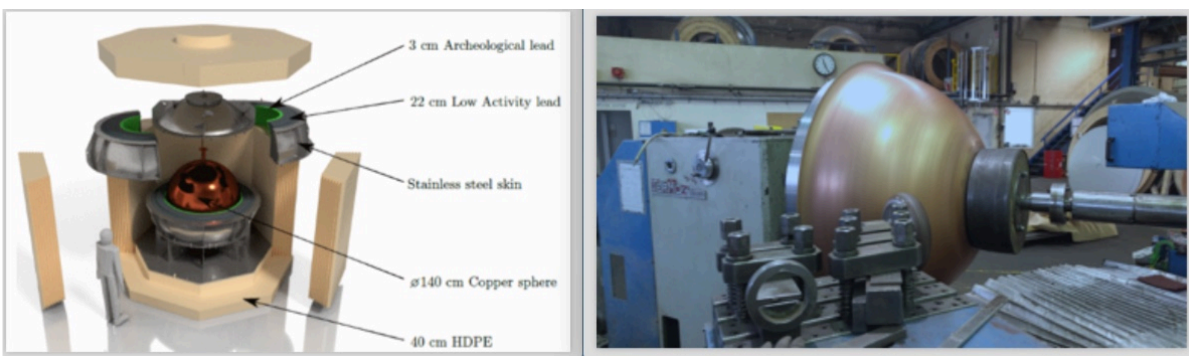

FIGURE 4 – *Exploded view of the detector to be installed at SNOLAB (left) and picture of the detector construction (right).*

The next phase of the experiment will build upon the knowledge acquired from the operation of SEDINE. It will be based a new 140 cm diameter sphere (today under construction) capable of holding gas up to a pressure of 10 bars, installed at SNOLAB. The goal is to focus on very light nuclei targets like He and H to reach WIMP mass sensitivity down to 0.1 GeV. The sphere will be shielded by a shell of 25 cm of both archaeological and low activity lead, itself inside a 40 cm thick polyethylene shield. Selection of extremely low activity copper (in the range of a few Bq/kg of U and Th impurities) and dedicated handling to avoid radon entering the detector at any time will ensure significant reduction of the backgrounds levels and allow sensitivity down to cross sections of $\mathcal{O}(10^{-41}$ cm$^2)$. Space in SNOLAB has been assigned, the design of the whole project is completed and technical design review is ongoing. A picture of the detector under construction is shown in Fig. 4. The sensitivity reached with NEWS-G at LSM in 2016 and the expected sensitivity of NEWS-G at SNOLAB are presented in Figure. 5.

For this step, similar investments are planned by the french teams (as part of the ANR program),

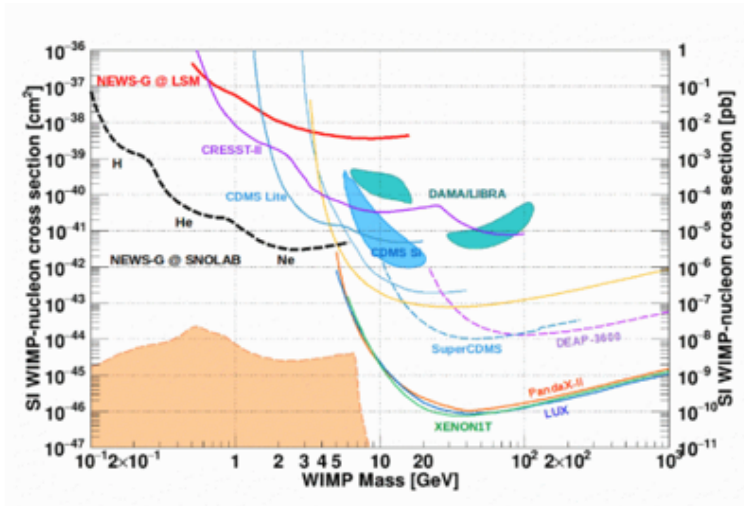

FIGURE 5 – *Measured (at LSM) and expected sensitivity (at SNOLAB) of NEWS-G. Projections for SNOLAB account for the anticipated background from materials, assuming a threshold of 1 electron (i.e. 20 to 40 eVee), and quenching factors extrapolated down to 100-200 eV_{NR}.*

but the following points can be underlined :

— LSM team drives the design and fabrication of the spherical detector : a fresh copper, grade 4N (99,99% Cu+Ag), has been used for building this pressure vessel. The different operations for the fabrication have been determined in order to get a very low background TPC.

— Lead and HDPE shieldings have been designed as compact as possible to make easier the radon sealness (LSM team) ; each piece of theses shielding in sized in order to be handled in the lift of Sudbury mine.

— To reduce the background from surface - radon daughters - and bulk - U/Th -, the electrolysis cleaning has been done on two 140cm hemisphere at LSM. After surface treatment, the electropolish was performed to remove 10μm of copper surface then 500μm very pure copper was plated on.

— Given the diameter of the new sphere, one of the main challenge will be to preserve, far from the anode, a sufficiently strong field to effectively migrate the primary charges. This point is the subject of a joint effort concerning the development of the multi-anode sensor Achinos [21].

— In june 2018, one researcher from SUBATECH officially has joined the collaboration. The purpose of this contribution is to share the signal processing tools developed for R2D2 with NEWS. Indeed, the method of treatment (filtering-deconvolution) of very low energy events (which are precisely those sought for the search for low mass WIMPS) should be similar for $\beta\beta$ decays (at least for decays with strongly asymmetric energies).

3.3 IN2P3 resources

The contribution of the IN2P3 French groups to NEWS-G is made in the frame of the ANR NEWS with the goal to develop the detector and its analysis (electronics, radioactive shielding, detector cleaning, analysis tools, electronics treatment).

Group	Local responsible	Number of participants	Group ETP	Tasks
LPSC	D. Santos	3	0.3	Quenching factor measurements
LSM	A. Dastgheibi-Fard	3	0.5	Detector construction Sensor development Background optimization
....	....	....	......	....
SUBATECH (since June 2018)	P. Lautridou	1	0.4	Signal processing and analysis

TABLE 1 – Summary table of the different IN2P3 groups, manpower and specific tasks in NEWS-G.

Today, within NEWS-G, the IN2P3 contribution amounts to 20% in human terms. The biggest part of the NEWS-G budget (2 M$) is assured by Queen's University (thanks to a grant of excellence) and is dedicated to the vessel and the infrastructure. At the French level, the IRFU institution brings 7 members with activities focused on the gas and anode optimization, FEE electronics, mechanical design, and DAQ and it filed two CEA patents (BD14437SG and BD16064SG).

4 R&D R2D2 (Rare Decays with Radial Detector)

J. Busto [1], C. Cerna [2], F .Druillole [2], A. Dastgheibi-Fard [3], C. Jollet [2], I. Katsioulas [4], I. Giomataris [4], M. Gros [4], P. Lautridou [5], A. Meregaglia [2,], X. F. Navick [4], F. Perrot [2], F. Piquemal [2,3], A. Rebii [2], M. Roche [2], B. Thomas, [2], M. Zampaolo [3]*

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[3] *LSM, CNRS/IN2P3, Université Grenoble-Alpes, Modane, France*
[4] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[5] *SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France*
* *Coordinator : A. Meregaglia*

For the search of $\beta\beta0\nu$ decay, very low radioactive contamination and excellent energy resolution of the detector are key points. Thus, favoring the best volume/surface ratio, the possible use of SPC has been investigated since a couple of years and a proto-collaboration began in October 2017 under the name R2D2. Today, the collaboration counts 5 French laboratories (4 of IN2P3) with 17 members (13 of IN2P3).

The most natural choice for the SPC gas, which needs to be at the same time a $\beta\beta0\nu$ emitter isotope, is ^{136}Xe. Regarding energy resolution with present experiments based on (liquid) Xenon $\beta\beta$

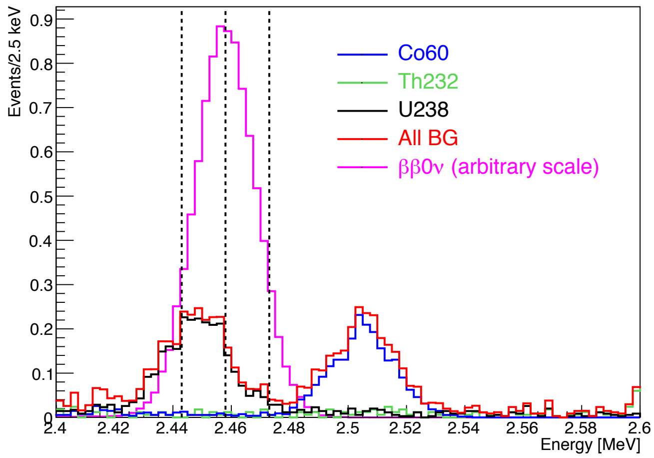

FIGURE 6 – *Figure taken from Ref. [25]. Background events after the selection cuts in the 50 kg setup considering 1 year of data taking. The vertical lines represent the ROI at 0.6% of the* $Q_{\beta\beta}$.

emitter, KamLAND-Zen has an energy resolution at the Q value of 2.458 MeV of 8% FWHM [22] when EXO-200 exhibits a resolution of 3-4% FWHM [23]. Furthermore, experimental tests on a Xenon gas detector working in proportional mode showed already a resolution of 0.4% FWHM at 662 keV [24]. We could in principle achieve with the proposed high pressure Xenon detector such a resolution in energy. To estimated the performances of our detector in terms of signal efficiency and background contamination, a detailed simulation was developed. We assumed in a conservative way an energy resolution of 1% FWHM whereas, re-scaling the preliminary results just mentioned, we expect to achieve a resolution better than a factor of 5. Our calculations [25] showed that a sphere of 50 kg of Xenon at a pressure of 40 bar could reduce significantly the number of background events per year in the region of interest (more than an order of magnitude) with respect to running experiments such as EXO-200. In Fig.6 (see details in Ref. [25]) the different backgrounds remaining after the selection cuts are shown.

The main goal of the proposed R2D2 R&D is to build a small demonstrator to validate the energy resolution. Once this major showstopper has been overcome we will move on towards a low background detector with the first physics program.

4.1 Present activities

Thanks to the IN2P3 funding at the level of 35 k€ we concentrated ourselves on the demonstrator conception and construction. For the first R&D phase background is not our concerns and we decided to build a detector which is much cheaper with respect to a low background one using Aluminum and profiting from the CENBG mechanical workshop (see Fig. 7), focusing on the following aspects :

- A Sphere with a radius of 20 cm has been built with the constrain of being resistant up to 40 bars to test the energy resolution at different pressures. The detector has not been certified yet but it can be used up to 4 bars while waiting for that.
- To calibrate the detector as a function of the source radial position a system has been

implemented with a ^{207}Bi source moving radially inside the sphere. The source of 200 Bq was especially ordered to have monoenergetic electrons at a rate not too high to have overlap considering the drift time of charges inside the sphere.
- A critical point to operate such a detector is the possibility to achieve a vacuum at the level of 10^{-5} mbar with a leakage at the level of 10^{-7} mbar/s. To achieve that we had to set up a pumping system including zeolites filter to trap possible radioactive source leakages and heating strips to increase out-gassing of the different materials.
- Although the Xenon recuperation system conceived and built at CPPM is ready we plan to test the resolution with ultra pure ArP2 (i.e. 98% Ar and 2% CH_4) since operating the detector with Xenon is more complicated (additional purification is needed as well as higher HV for the same gas pressure) and highly more expensive.
- The optimization of the sensor (part of the LSM tasks), namely size, geometry and HV of the central anode, is therefore another important point which is already addressed at this stage (multi-ball anode could also be considered to segment the volume and reduce the applied high voltage [21]).
- The development of signal processing tools, essential from the test phase, has been started at SUBATECH in 2017 with two essential objectives : to reinforce the intrinsic performances that are already anticipated for the energy resolution by improving the signal to noise ratio, and to have a capability to recognize long tracks (through deconvolution of the integrator transfer function).
- The DAQ consists in the CCALI card developed at CEA for the Edelweiss experiment and a high performance Mac, although discussion about possible alternatives are ongoing in particular related to the work carried out at SUBATECH on the signal analysis to distinguish between one and two traces in the same pulse.

The remaining funding, after deducing consumables and missions, will be used to order some Xenon considering that the volume to work at 1 bar costs about 3 k€. The setup is now ready and we are performing the firsts tests on vacuum and measurement at low pressure. Most of the funding requested for next year will be used to pay for the certification to work at high pressure, to buy the needed Xenon and to have a more powerful HV supply which is needed when operating with Xenon at high pressure.

4.2 Prospects

As mentioned before the main goal of the R2D2 R&D is to demonstrate that an excellent energy resolution i.e. below 1% FWHM at the Xenon $Q_{\beta\beta}$ of 2.458 MeV, can be achieved operating in TPC mode with Xenon at pressures as high as 40 bars. To do this, we plan to invest the following tasks as a priority :
- A step-by-step migration of ArgonP2 at low pressure to Xe-high pressure (via ArgonP2 at high pressure and Xe-low pressure) will be performed in order to establish the precise working parameters of the SPC (HV, gain, resolution, etc.).
- The contamination of the Xe gas by Rn will be checked. An additional purification step based on a distillation method may be considered if necessary.
- The capability to recognize two-tracks events will be studied via the signal processing. Full digitalisation of the multi-anodes signals (Achinos) will also be considered.

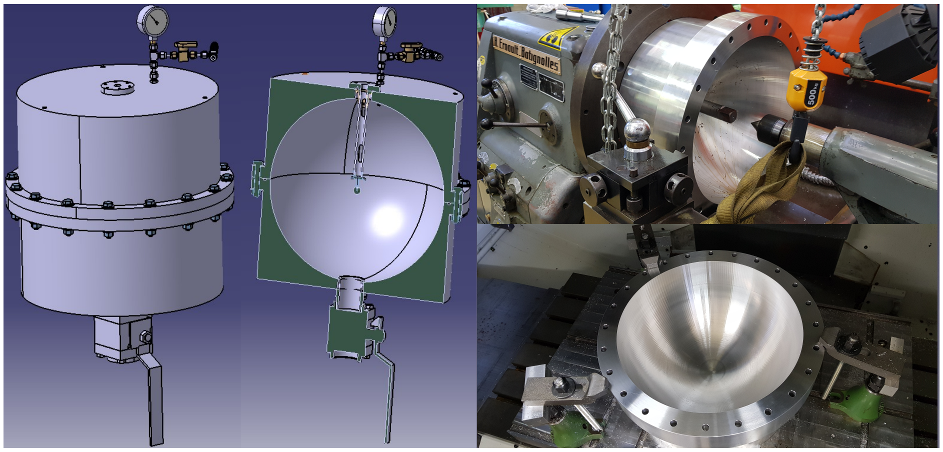

FIGURE 7 – *On the left the mechanical design of the prototype is shown. On the right some pictures of the Aluminium hemispheres being prepared at the machining shop of the CENBG are shown.*

This program is expected to be carried out in 2018/2019 and depending on the obtained results an appropriate strategy will be conceived for the follow up of the R&D. If the desired energy resolution is achieved, the major project showstopper, the idea is to move on to a larger scale project to build a low background demonstrator. The new demonstrator will have already a physics goal in terms of the achievable limit which could be set on $T_{1/2}^{\beta\beta0\nu}$ (i.e. about 10^{25} years with an exposure of 27 kg $\times$ year) and will be used to benchmark the background models, study the detector calibration, and to optimize the sensor (i.e. geometry and electronics of the central anode). All these steps, if successful, could lead to a zero background detector at the ton scale.
An additional and important asset of the R2D2 project is the possibility operate the TPC with different gasses (e.g. MoF6) having a $\beta\beta$ emitter isotope with a larger $Q_{\beta\beta}$ allowing for a smaller background issued by the natural radioactive chains. The use of different gases with exactly the same detector will allow for an additional control on the background which will be gas independent. While the current R&D is fully funded by IN2P3, the plan is to look for funding answering ANR and ERC calls if the energy resolution is proved to meet the requirements.
To summarize we do not plan to build "yet another Xenon experiment" but to design and demonstrate the feasibility of a brand new technique which will allow to reach competitive physics results with a relative small and low cost detector, thanks to the energy resolution and the extremely low background, and not based on large masses of radioactive isotopes.

Group	Local responsible	Number of participants	Group ETP	Tasks	Funding 2018 (k€)	Request 2019 (k€)
CENBG	A. Meregaglia	9	1.6	Detector development	25	25
LSM	A. Dastgheibi-Fard	2	0.3	Sensor development	5	5
CPPM	J. Busto	1	0.2	Xenon recuperation system	3.5	6
SUBATECH	P. Lautridou	1	0.6	DAQ and signal analysis	1.5	1.5
CEA	I. Giomataris	4	0.2	Sensor development	-	-
Total	-	17	2.9	-	35	37.5

TABLE 2 – Summary table of the different groups specific tasks, manpower, funding in 2018 and request for 2019.

4.3 IN2P3 resources

A summary table showing the involved IN2P3 manpower, the tasks distributions as well as the IN2P3 funding received in 2018 is given above.

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