Chapter 1

The SuperNEMO Experiment~~s~~

SuperNEMO is a neutrinoless double beta decay experiment using tracker-calorimeter technology, built on the successes of the NEMO-3 experiment. It is designed to search for $0\nu2\beta$ decay and is capable of reaching a half-life sensitivity of $T_{1/2} > 10^{26}$ years, equivalent to an effective Majorana neutrino mass of $\langle m_\beta \rangle <$ 40 - 100 meV. Its unique tracker-calorimeter technology allows for the reconstruction of the 3D topology of the detected event, providing both a powerful background rejection method and evidence for the underlying decay process. The baseline design of SuperNEMO contains 20 identical planar modules, housing 100kg of source isotope in total. The first one, SuperNEMO Demonstrator, is constructed at the Modane Underground Laboratory (LSM) with the aim of reaching zero background in the region of interest for the $0\nu2\beta$ decay of ^{82}Se. This target placed challenging demands on the radiopurity of detector components, in particular, the radon (^{222}Rn) activity within the tracker. All internal detector components and construction materials are screened for radon emanation to minimise radon levels.

1.1 SuperNEMO Baseline Design

In the baseline design of the SuperNEMO experiment, all 20 modules are fully operational independent detectors. Each module is 6m long, 4m high, and 2m wide.

In the centre of the module, there are source foils containing 5-7 kg of source isotope with a density of $\sim$ 40 mg/cm^2. ~~And~~ they are made into very thin foils to avoid secondary scattering. The source foil is sandwiched by the tracker, which is a drift chamber operating in Geiger mode, capable of detecting the charged particles and recording their 3D tracks. A magnetic field is applied to the tracker to curve the charged (except alpha) particles. The tracker chamber is then enclosed by the calorimeter walls, containing 500 Optical Modules (OM) consisting of PMTs and scintillator blocks. The principle of the Demonstrator is illustrated in Figure 1.1.

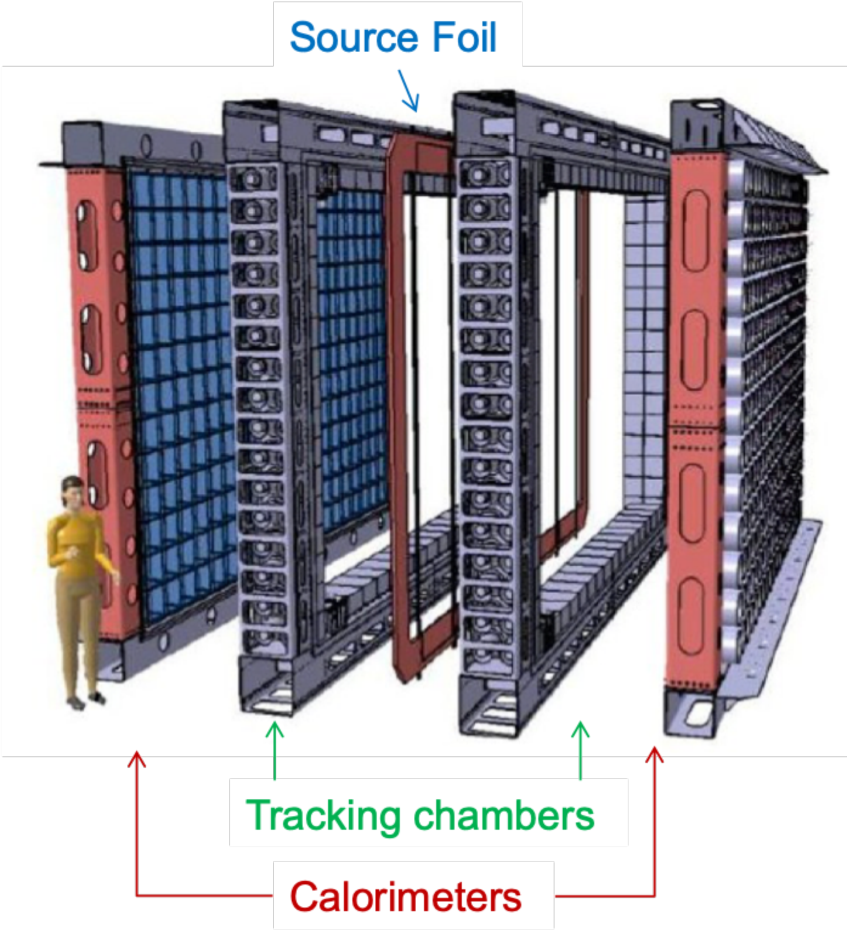

Figure 1.1: Exploded view of the SuperNEMO demonstrator module with source foil in the centre surrounded by the tracking chambers on both side, followed by the calorimeters.

1.2 Source Foil

As the design of SuperNEMO is such that the source is separate from the detector, it allows for the measurement of different isotopes as it is possible to extract and exchange the source foil for one of a different isotope. The transition energy $Q_{\beta\beta}$, NME, phase space, natural abundance, and the feasibility of purification and enrichment are the major considerations when choosing the isotope of an experiment. For SuperNEMO, ^{82}Se was primarily selected. The source isotope, ^{82}Se, was enriched using the centrifugation method in Russia and then used to produce source foils at LAPP (Annecy) and ITEP (Moscow). The radiopurity requirement of the source foil is the most strict of all components on account of its central location: A(^{214}Bi) < 10 μBq/kg, A(^{208}Tl) < 2 μBq/kg. To confirm this level of radio-purity has been achieved, a dedicated detector known as the BiPo detector

1.3 Tracker

The Demonstrator tracker is a drift chamber containing over 2000 wire drift cells operating in Geiger mode. The composition of the tracker gas mixture is ~~He~~ 95% helium, 1% argon, and 4% ethanol. The drift cells are arranged in nine layers parallel to the foil. Each cell has a 40 μm stainless steel central anode wire surrounded by twelve 50 μm field wires, with a cathode pickup ring at each end. A 25G magnetic field is used to reject positron events from the external background. Since a large number of wires are used in the chamber, the radio-purity requirement of the wires should be stringent. The wires were produced using the automatic wiring robot in Manchester, then the cassette of the wires are inserted into the tracker at UCL-MSSL (see Figure 1.2 and Figure 1.3).

1.4 Calorimeter

The critical functions of the Demonstrator calorimeter are to measure the energy and the time-of-flight (TOF) of particles, and to provide a fast trigger signal. The

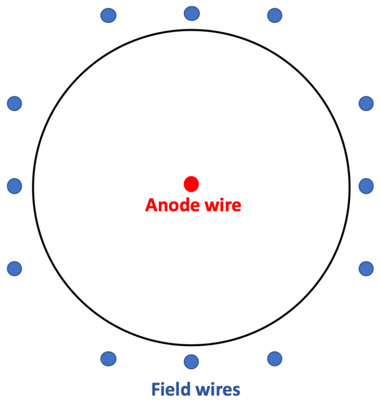

Figure 1.2: Sketch of a tracker Geiger cell from transverse view. The anode wire is drawn in the centre, and the 12 field shaping wires are all around.

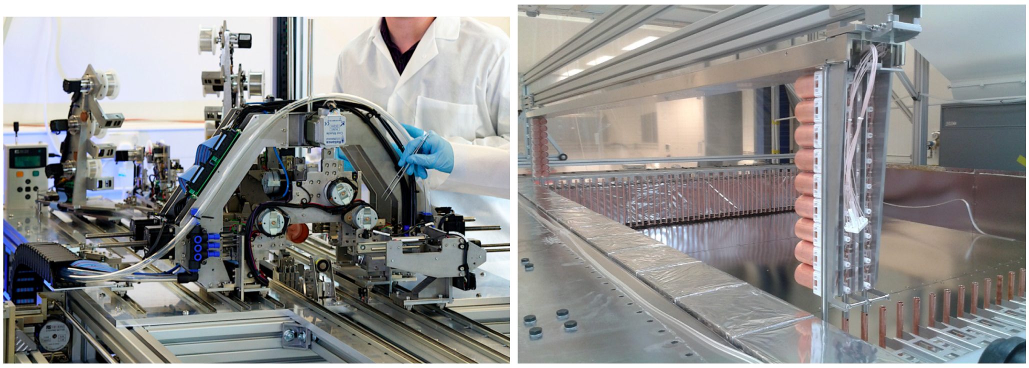

Figure 1.3: (left) Tracker cell production using the wiring robot. (right) The tracker wire cassette insertion at MSSL.

Demonstrator calorimeter contains 550 OMs on the main wall, 64 veto OMs on the top and bottom, and 128 X-wall OMs on the sides. Each main wall OM has a scintillator block with a cross-section of 26 cm$\times$ 26 cm coupled to a low radioactive 8-inch Hamamatsu R5912 PMT, as shown in Figure 1.4. The veto and X-wall OMs use 5-inch Hamamatsu R6594 PMTs recovered from NEMO-3, coupled to scintillator blocks. Dedicated studies have shown that this design can reach an energy resolutions of 4%FWHM at 3 MeV [1], which is a factor 2 improvement compared to NEMO-3. The improved energy resolution can reduce the background by decreasing the overlap of the spectra of $2\nu2\beta$ and $0\nu2\beta$ events, which can not be distinguished from each other by reconstructed event topology.

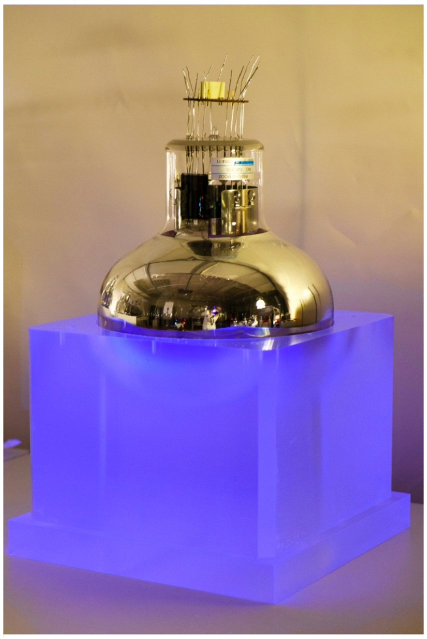

Figure 1.4: An optical module of the calorimeter consists a photomultiplier tube which is directly coupled to a scintillator block.

1.5 Readout Electronics and Data Acquisition System

The data acquisition rate for SuperNEMO is very low comparing to collider experiments, such that running the SuperNEMO readout as a triggerless system is practical, where all data will be recorded for offline analysis. The trigger and data acquisition system for the tracker and calorimeter are inter-dependent. The calorimeter front-end boards determine timing as the calorimeter is much faster than the tracker. The tracker is then synced to the calorimeter clock. This is not only for the triggering and data collection for double-runs, but also for calibration runs and background studies. A block diagram of the SuperNEMO readout electronics can be seen in Figure 1.5.

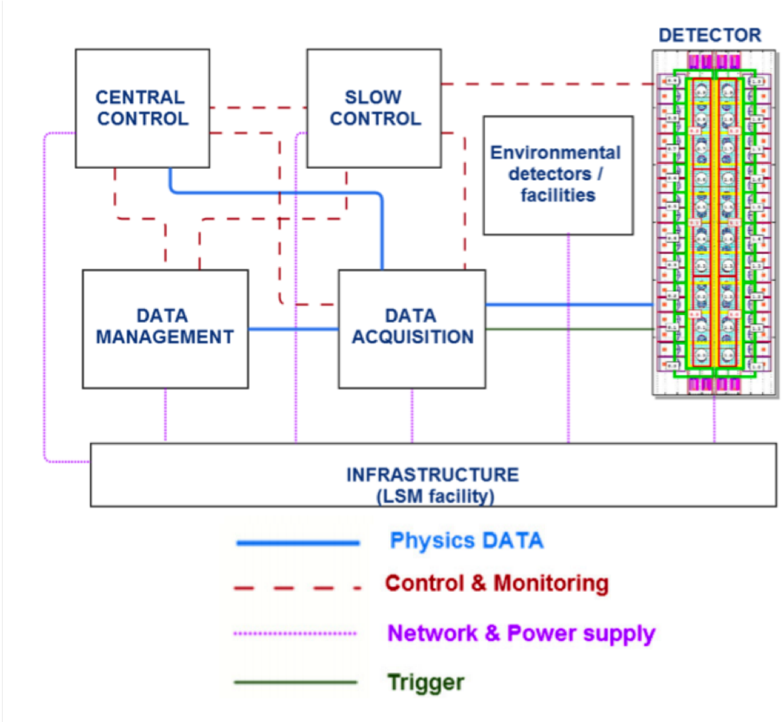

Figure 1.5: Schematic of the SuperNEMO readout electronics [2].

1.6 Shielding

1.6.1 Radon Shielding

The detector is isolated from the external environment for low background consideration. The tracker is tightly sealed together with the detector mainframe using selected materials which are good radon barriers. Thorough leak tests are then carried out, and all leaks are sealed using styrene-butadiene rubber (SBR). In front of the calorimeter wall, there is a layer of nylon film to reduce radon diffusion from the calorimeter into the tracker. The thickness of the nylon films, 25 μm, was selected in particular to prevent loss of energy resolution due to multiple scattering of electrons in the film.

1.6.2 Anti-radon Factory

The average radon level at LSM is 15 Bq/m^3, which mainly comes from the radon emanation of the surrounding the rocks. To prevent radon diffusion, the Demonstrator is housed in an anti-radon tent, which is continuously flushed with filtered air. The air is filtered through two radon trapping columns, 0.6 m and 3 m high, filled with 500 kg of activated charcoal cooled to -50°C. The anti-radon facility filters air at a rate of 150 m^3/hr, and the absorbed radon will naturally decay away inside the columns. The radon levels in the anti-radon tent are reduced by $\sim 10^3$ compared to the environmental radon level, dropping down from 15 mBq/m^3 to 18 mBq/m^3.

1.6.3 Passive Shielding

The Demonstrator is housed inside the Modane Underground Laboratory (LSM) beneath the Frejus mountain, where under 1700 meters of rock (4800 m.w.e.) the cosmic muon flux can be reduced by $\sim 10^6$, down to 4 events / $m^2 \cdot$ day. While cosmic muons themselves do not directly contribute to the background due to their distinct event signature, they can produce neutrons from spallation.

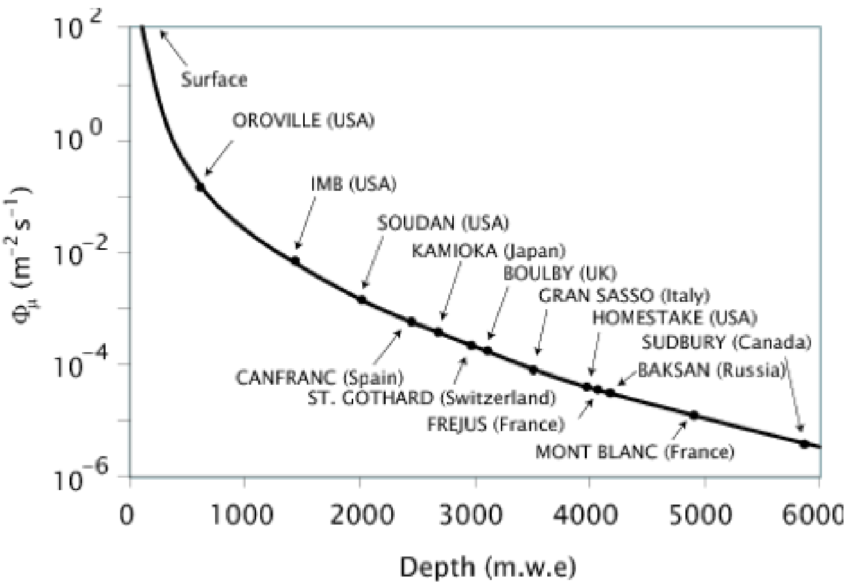

Figure 1.6: Cosmic ray flux in different underground laboratories as a function of the overburden expressed in meter water equivalent units [1].

In addition, gamma rays and neutrons are present from nuclear decay in the surrounding rocks under the mountain. The neutrons can undergo neutron capture on various parts of the detector frame, producing up to 10 MeV gammas. The gamma rays can interact with the source foil and cause the emission of two electrons (or positrons) via three processes shown in Figure 1.7.

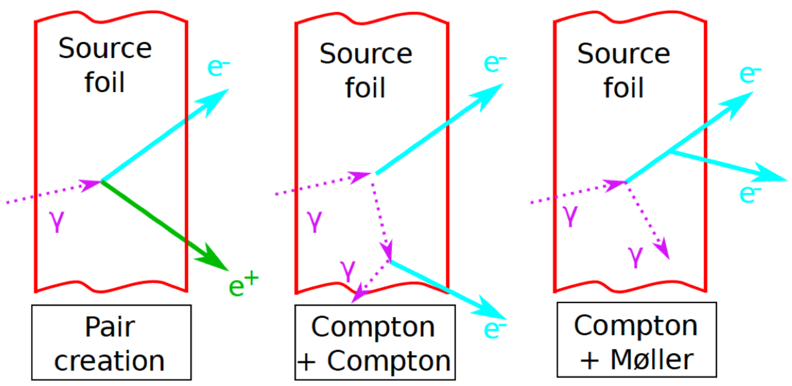

Figure 1.7: External gamma mimicking two electrons (or positrons) event topology [2].

The external shielding was constructed to prevent the background from the surrounding environment. Iron, 20 cm in thickness, will be used to stop external γs, with water shielding for neutrons outside of the iron. Some studies indicate that borated water or sheets of borated polyethene constitute better shielding against neutrons [1], but is also more expensive. A completed SuperNEMO module with external the shielding is shown in Figure 1.8.

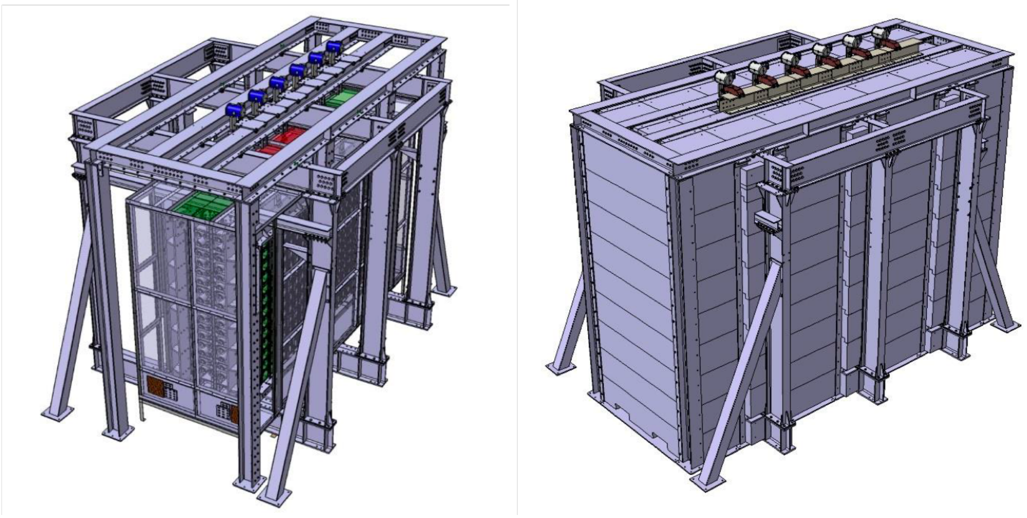

Figure 1.8: (left) Schematic of the SuperNEMO demonstrator module in the Anti - Radon tent. (right) Schematic of the SuperNEMO demonstrator module with all external shielding [3].

1.7 General Analysis Techniques

1.7.1 The SuperNEMO software

The SuperNEMO collaboration has developed a series of software packages for simulation, reconstruction, and analysis, including three major components: Cadfael[4], Bayeux[5], and Falaise[6].

- Cadfael is a software development kit which gathers the software packages needed for the development of SuperNEMO, including Boost[7], ROOT[8], Camp[9], CLHEP[10], Xerces[11], Geant4[12], Doxygen[13] and Qt5[14], which are all popular packages in nuclear and particle physics.
- Bayeux holds a C++ library for experimental nuclear and particle physics, which contains many C++ classes and function designed for event simulation, data taking, and data analysis [1]. This functionality is split into several specialised submodules including:
  - data handling: serializable data structures based on Boost (data tools), a basic data processing pipeline API (dpp), and data selection (cuts).
  - numerical tools: C++ wrapper and extensions to the GNU Scientific Library (mygsl).
  - utilities for GEANT4 simulation: definition of the primitive geometrical volumes (geomtools), database of the elements and isotopes composing the detector (materials), modelling of the electromagnetic field applied in the tracker (emfield), definition of the primitive geometrical volumes (geomtools), database of the elements and isotopes composing the detector (materials), nuclear database describing the kinematics of the radioisotopes (genbb_help, a C++ port of Genbb/DECAY0 from Vladimir Tretyak [15]), and a random generator of the vertex (genvtx).

  Cadfael and Bayeux were particularly designed for the SuperNEMO experiment by the collaboration, but now they are also used by other nuclear and particle physics experiments.

- Falaise is depended on Cadfael and Bayeux. It provides the main computational environment for the simulation, algorithms of reconstruction, processing and analysis of data for the SuperNEMO experiment. It consists of three major part: a core library called libFalaise, a main detector simulation tool called flsimulate, and the main reconstruction tool called flreconstruct.

The complete analysis procedure can be compared to a pipeline where events flow through, starting with the simulated or the real recorded data, followed by the reconstructed data, and ends with the analysed data[1].

1.7.2 Sample Simulation and Reconstruction

Falaise is capable of virtually reproducing the geometry, materials, and physical conditions of the detector, and simulating the steps and processes of an event—this process is called simulation. Event simulations are generated by GENBB, with the propagation of the particle inside the reconstructed SuperNEMO detector being carried out by GEANT4[12].

GENBB is a Monte-Carlo event generator for 2β processes and the decay of radioactive nuclei and contains information relating to decays—including the half-life, energy, decay mode, and probability—of all known isotopes. It is capable of generating nuclear decay events and providing information with regard to the decay energy, time, and direction of the emitted particles[12, 15].

The detector geometry, materials and physical conditions such as electromagnetic field, are reproduced virtually thanks to Geant4. Under this environment, it is possible to simulate~~d~~ physics process in the detector. For a typical double beta decay event from the source foil, its vertex is generated randomly within the source volume, and the kinematics is also generated randomly according to the specific probability distribution function for the process given by the existing database. The two electrons propagate in the detector volume following the Monte-Carlo procedure. Each particle is propagated step by step, and the length of each step is subject to the materials and physics conditions. The interactions which can affect the length of a step, like decays and scattering, are implemented in the software, and the step length is randomly simulated according to these interactions. Possible secondary particles generated in the interactions, for example, a Moller electron or γ from Bremsstrahlung are also simulated. The simulation will stop if a previously defined criterion is met, such as the low energy cutoff, particle entered no-defined volume, etc.

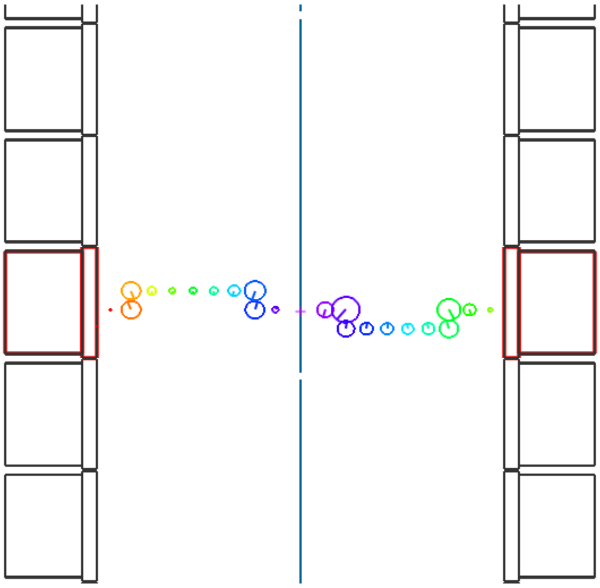

Figure 1.9: Visualisation of a simulated $2\nu2\beta$ event in the SuperNEMO demonstrator from the top view. The calorimeter PMTs, the side and top scintillator blocks and the tracker cells are not represented for the sake of readability. The source is displayed in blue, and the different source pads are distinguishable. The scintillators are displayed in gray. The colored circles represent the tracker cells where the two simulated electrons have crossed.

Figure 1.9 shows a simulated $2\nu2\beta$ event. Each circle represents a hit on the tracker cell. The centre of the circle locates on the anode wire of the cell, and the radii represent the minimum distance between the particle track and the anode wire. The colour of the circle is related to the time when the particle hits the cell. It should be noted that the simulation is based on the assumption of ideal detection efficiency and time resolution of the tracker. In reality, not all the hitted cells considered by the simulation will be triggered by the particle because the detection efficiency decrease from the central anode wire to the edge of each cell (but still remains above 99%). Also, due to the stochastic nature of the Geiger cell, the radii are only known associated with uncertainty so that it is almost possible to arrange hit cells by time. The electron goes through the tracker in several nanoseconds, but it takes microseconds for the avalanche created and the plasma propagation towards the cell. The red box on the calorimeter blocks represents the energy deposits in the scintillator. All the simulated event information are stored in the Simulated Data bank (SD bank). The simulated or real data will then go through a succession of algorithms, each striving to improve comprehension of the events and to reconstruct them accurately.

To match the real data, the running conditions should be considered in the simulation: the PMTs' gains, dead Geiger cells, dead PMTs, and ageing of the detector. Therefore pseudo-calibration are carried out at this stage, and the event information is saved in the Calibrated Data bank (CD bank)

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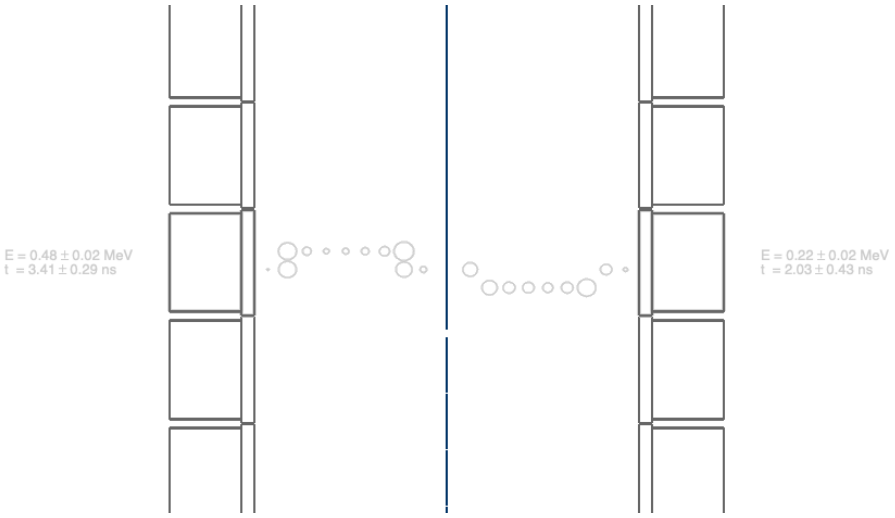

Figure 1.10: Visualisation of $2\nu2\beta$ event from the top view, with information from the Calibrated Data bank. The chronological information of the tracker hits is not avaliable.

The simulated data can then go through the reconstruction stage, which consists a serious of the module in pipeline[6].

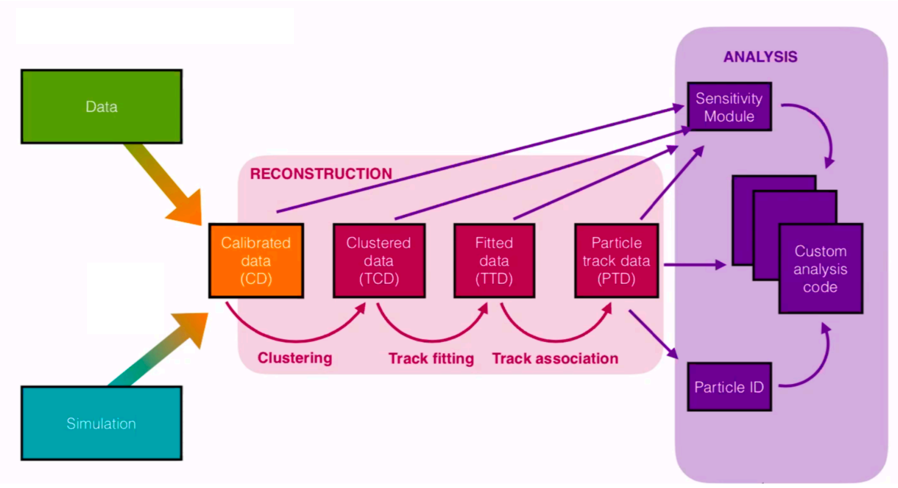

Figure 1.11: SuperNEMO software pipeline. Real data or simulated data flowthrough the reconstruction modules and then go into customised analysis mudule.

Cellular Automaton Tracker Module The first step in the reconstruction is to find out the number of charged particles in the event based on the tracker hits. This work is done by the Cellular Automaton Tracker (CAT) Module which can cluster all the neighbouring calibrated Geiger hits. It starts working from the inner layers of the tracker (close to the source), and then add neighbouring hits layer by layer towards the calorimeter wall. If there are still unclustered hits, it starts another clustering job until all the hits are clustered. Particles crossing the foil will generate two separate clusters as a CAT cannot gather a cluster across the foil by definition. If a tracker hit is 10 μs later than the prompt signal given by the calorimeter hit, it will be identified as a delayed hit. These delayed hits are ususlly from the alphas in the BiPo events(^{214}Bi $\rightarrow$ ^{214}Po $\rightarrow$ ^{210}Pb, see Figure **??**). Tracker hits occurring after this time window will be recorded by a second trigger and acquisition system. Figure 1.12 shows the clustered hits of electrons from a $2\nu2\beta$ event. Different clusters are represented by a different colour in event visualisation. This information fills up the Tracker Clustering Data bank (TCD bank).

Track Trajectory Module

The clusters found by CAT are fitted to a trajectory by the Tracker Trajectory Mod-

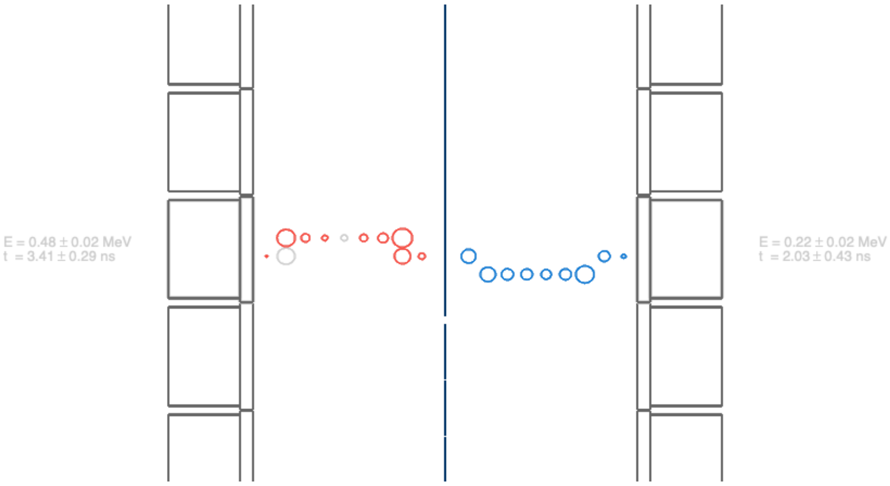

Figure 1.12: Visualisation of a $2\nu2\beta$ event from the top view, with information from the Tracker Clustering Data bank. Tracker hits clustered and represented by a specific colour if they are from the same cluster.

ule. This module only processes the clusters with 3 or more Geiger hits. During this trajectory fitting step, different patterns, both helices and straight lines, are tested because 25 Gauss magnetic field is not strong enough to bend high energy electron tracks or alpha particles. The best fit is chosen according to the lowest χ^2/ndof, shown in Figure 1.13. For delayed clusters, straight-line fitting is applied, and the radius is one-fourth of the total radius of the cell by construction. All information processed by the fitting trajectory step is stored in Tracker Trajectory Data (TTD) bank.

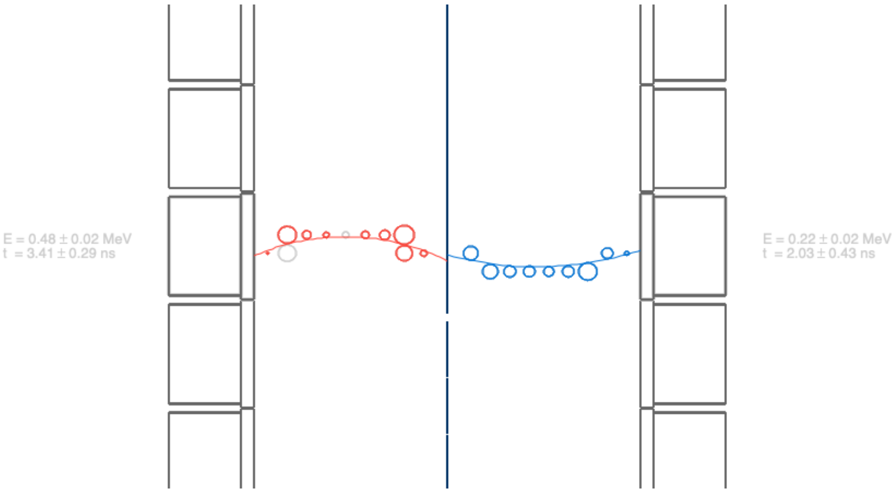

Figure 1.13: Visualisation of a $2\nu2\beta$ event from the top view, with information from the Track Trajectory Data bank. Clusters found by CAT are fitted to a trajectory.

Charged Particle Tracking Module

Charged particle tracks fitted by the tracker trajectory module are processed to the next step where the tracks will be resituated in the SuperNEMO detector. The tracks are extrapolated both to the calorimeter walls and the source in an attempt to find a possible associated calorimeter hit and to locate the vertex of the event respectively. Based on the assumption that particles travel from the source towards the calorimeter, it is able to extract the charge of the particle from the curvature of the track. Figure 1.14 shows the two negatively charged electrons in a $2\nu2\beta$ are associated with their corresponding calorimeter hits, and the vertex is found in the source.

Alpha particles coming from the BiPo events are mostly delayed with respect to a prompt electron. The clustering algorithm can not process these delays tracks. As there is no calorimeter hit which can provide a reference time, it is impossible to calculate the drift radii. The longitudinal coordinate is reconstructed according to the anode time when the initial avalanche reached the anode. Straight-line tracks are fitted to the delayed tracker cells, and the drift radius is set as one-fourth of the total radius of the cell. The information processed by the charged particle tracking module is stored in the Particle Track Data (PTD) bank.

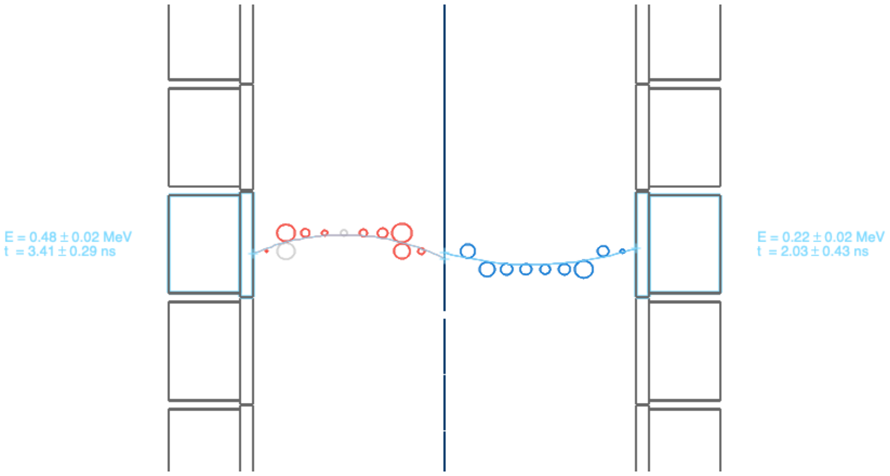

Figure 1.14: Visualisation of a $2\nu2\beta$ event from the top view, with information from the Particle Track Data bank. Tracks are extrapolated both to the calorimeter walls and the source to find a possible associated calorimeter hit and to locate the vertex.

Sensitivity Module Sensitivity Module[16], is a customised output module for the storing of simulated and reconstructed data from the SD, CD, TCD, TTD, and PTD banks in a ROOT ntuple file.

The reconstructed particles are identified according to definitions given by the user, see Figure 1.15 [1]:

- **Electron** has a negatively curved track with an associated calorimeter hit.
- **Position** has a positively curved track with an associated calorimeter hit
- **Alpha** has a short straight track (normally being delayed).
- **Gamma** has one or more unassociated calorimeter hits.

After all the particles in an event are identified, they can be associated to form a topology. Then a number of observables can be computed based on different topologies, such as:

- the angle between the particles.
- the distance between the source vertices of charged particles.
- the delayed time between the prompt electron and delayed alpha.

1.7.3 Alpha Finder

Alpha particles come to a stop at a very short distance into the tracker due to their high ionisation power, and due to their high mass, and are not significantly affected by the magnetic field. As such, the typical signal of an alpha particle is a short straight track (typically less than 40 mm) and, if it comes from the foil, has no associated calorimeter hit.

For alpha particles which hit 3 or more Geiger cells (see Figure 1.16) the tracks are treated as normal by CAT: Centres of the cells in the delayed cluster are connected

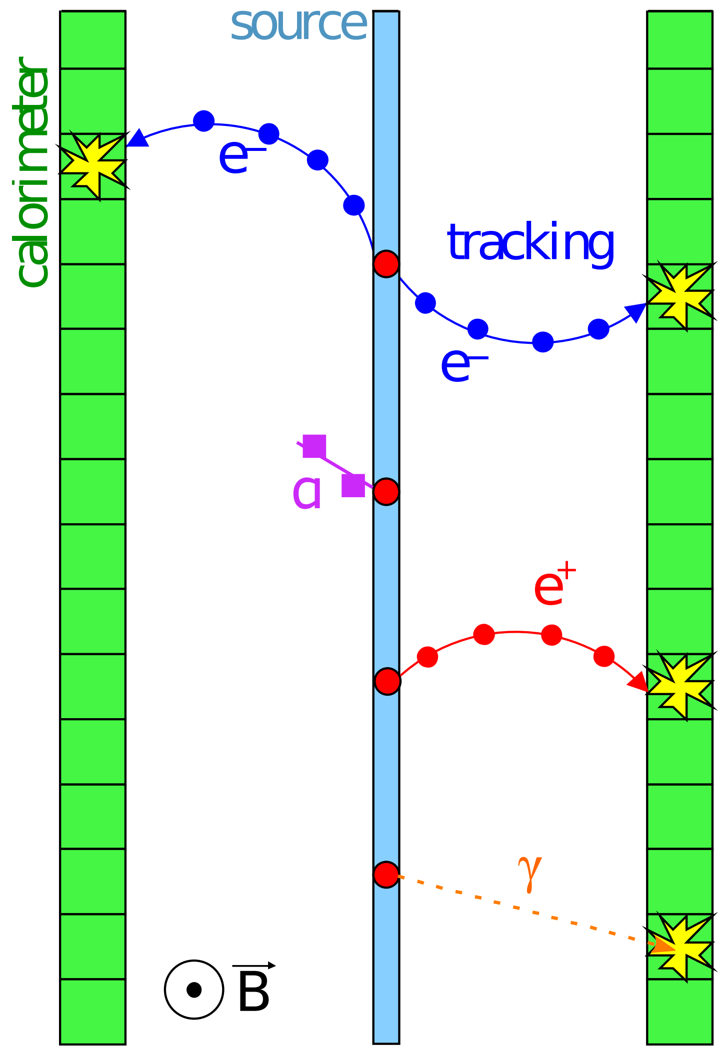

Figure 1.15: A sketch of particle topologies in the SuperNEMO detector.

with a straight line of best-fit, and in cases where projection of the line intercepts the foil, the track is extended to the foil. The track will not be connected to other particles, such as the prompt electron.

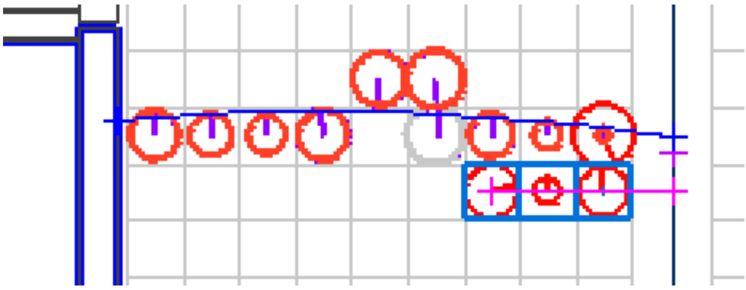

Figure 1.16: Visualisation of a 1e1α event where the α hits 3 tracker cells. The centre of the 3 hitted cells are connected and extrapolated to the foil inn attampet to locate the α
vertex.

Some alpha particles will hit only 1 or 2 Geiger cells in the tracker, and cannot be processed by the TrackFit module. Because such an alpha particle will not trigger the SuperNEMO detector itself, to identify the alpha event, a prompt electron is required for verification, as during data taking, a 1 ms window will open after a calorimeter hit is triggered by a prompt track. In the event a prompt track is present, the existence of delayed unfitted tracks (a 2-hit cluster) or a delayed unclustered Geiger hit (a single hit) can be verified. These alphas are found by the Alpha Finder algorithm.

In the event an alpha particle hits 2 Geiger cells, the centre of the furthest cell hit is connected to the vertex of the prompt electron track to construct a track (see Figure 1.17).

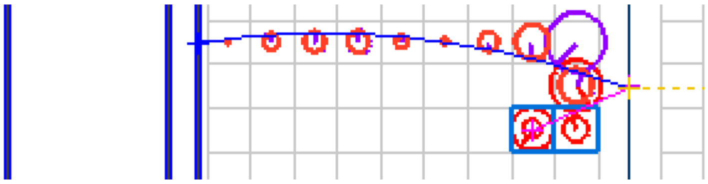

Figure 1.17: Visualisation of a 1e1α event where the α hits 2 tracker cells. The centre of the furthest α hit is connected to the vertex of the prompt electron track to construct an alpha track.

In the event the alpha particle hits only 1 Geiger cell, the centre of the cell is connected with the delayed hit to the closest end of a prompt electron track (see Figure 1.18).

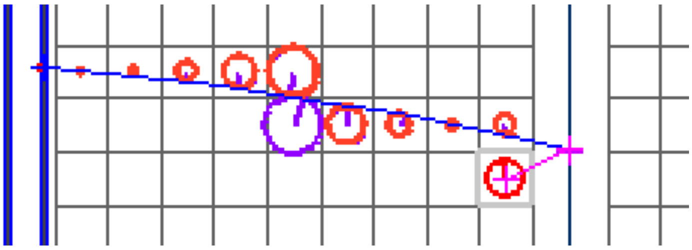

Figure 1.18: Visualisation of a 1e1α event where the α hits only one tracker cells. The centre of the cell is connected with the delayed hit to the closest end of a prompt electron track

All alphas are treated equally during the analysis, regardless of the way they were found.

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