Chapter 1

Radon and SuperNEMO Sensitivity

In the SuperNEMO experiment, a double beta decay signal is characterised by the observed two electrons from the same location in the source foil. In addition, the $0\nu\beta\beta$ requires the total energy of the two electrons meet $Q_{\beta\beta}$ of the isotopes (2.99 MeV for ^{82}Se). Therefore, any process that can mimic this signal will contribute to the background of the experiment. The sensitivity of SuperNEMO is directly related to the background level (as discussed in Chapter **??**), thus it is essential to reduce the background and to measure the background accurately. One unavoidable background is from the $2\nu\beta\beta$ process when considering $o\nu\beta\beta$ as the signal only. The $2\nu\beta\beta$ process is observed across the entire energy spectrum, and its high energy tail becomes a background to the $0\nu\beta\beta$ observation. The only practical way to suppress this background is to improve the energy resolution.

1.1 The SuperNEMO Backgrounds

The main source of background for SuperNEMO is the trace amounts of radioactive isotopes in all materials. β-decay isotopes inside the source foils are generally the most problematic, whereas γ-emitting isotopes mostly contribute to the external background. Almost all radioactive isotopes are background to $2\nu\beta\beta$ searching, but only isotopes with high Q_β values contribute to the background of $o\nu\beta\beta$ searching. The two most problemic isotopes are the β-decaying isotopes ^{214}Bi (Q_β =

3.27MeV) and ^{208}Tl (Q_{β} = 4.99MeV) from the ^{238}U and ^{232}Th decay chains respectively which are shown in Figure **??**).

The SuperNEMO backgrounds can be classified into three types: internal backgrounds, external backgrounds, and radon background.

1.1.1 Internal Background

Internal backgrounds are original from inside the source foils, and thus they are dominated by the radioactive contaminants in the foils. The β-decay isotopes are most harmful because they can mimic two electron events via the processes of β-decay with Møller scattering, β decay followed by internal conversion or β-decay to an excited state with Compton scattering of the de-excitation photon, as shown in Figure 1.2.

To monitor the internal backgrounds, all the source foils are measured by the HPGe detectors prior to installation into the SuperNEMO detector [**?**]. The in-situ activity measurements made by the SuperNEMO will be directly compared with these HPGe measurement results. From these HPGe measurements and by considering commonly-found naturally occurring isotopes, the list of expected contaminants is comprised of 214Bi, 214Pb, 208Tl, 212Bi, 228Ac,234mPa and 40k [1]. Most of these isotopes are from the 238U and 232Th decay chains except 40k.

1.1.2 External Background

External backgrounds refer to those from anywhere in the detector other than the source foils and that are not radon-induced. In order to mimic two electron events, external backgrounds usually involve a photon that interacts with the source foil, as shown in Figure 1.2. In the case of pair production, the outgoing positron must also be misidentified as an electron, which is unlikely given the magnetic field. Electrons that do not interact in the foil, but cross the detector, can also be mistaken for two electron events. However, these crossing electrons are heavily suppressed by removing events based on their timing information. External background is pre-

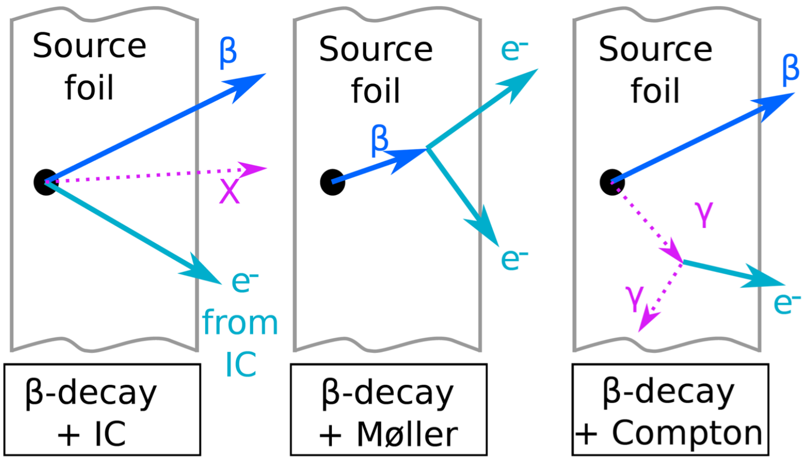

Figure 1.1: Three dominant processes via the β-decay isotope contamination in the source foil, leading to the emission of two electrons, which contributing to internal background [2].

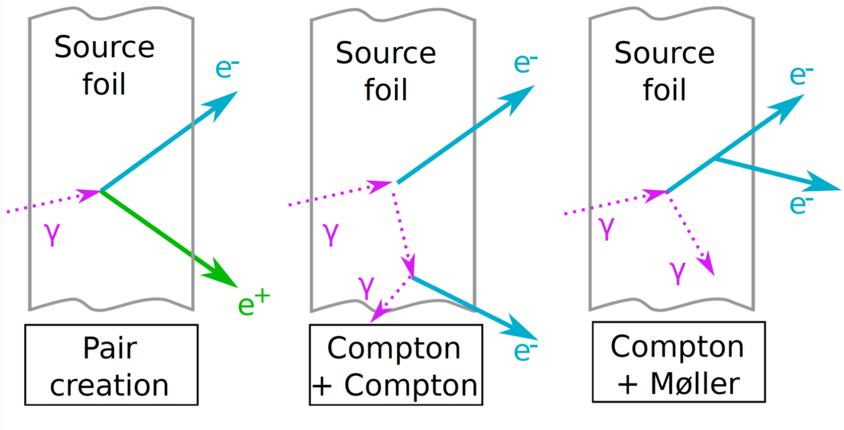

Figure 1.2: Process of three dominant processes of production of two electrons from an external particle interactinng with the source foil [2].

dominantly from the radioactive decay within the rock surrounding the laboratory, neutron capture and decay within the detector components themselves.

1.1.3 Radon Background

The third type of background is radon-induced backgrounds. The radon background is originally from radon in the tracker gas. Radon progenies can be deposited on the source foil surface, thus effectively becoming internal backgrounds. The radon level inside the detector can be measured in situ by studying BiPo events as described in

Chapter **??**

1.2 The Property of Radon

Radon is a colourless and odourless noble gas with the symbol Rn and atomic number 86. It is the only gas that consists entirely of radioisotopes under normal conditions.

Friedrich Ernst Dawn first reported the discovery in 1900 in a series of experiments where radium compounds emitted a radioactive gas[3]. Later in 1904 and 1910, William Ramsay isolated the gas and studied its properties at University College London [4, 5], discovering that the spectrum of this gas and its low-level chemical interaction were similar to those of argon, krypton, and xenon. Eventually, after a series of suggestions, this new element was named as radon in 1923.

All 36 radon isotopes that have been characterised are radioactive, with only four of them being found in nature. The most stable radon isotope, ^{222}Rn with a half-life of 3.8235 days, is from the ^{238}U decay series (see Figure **??**). In addition, there is another important radon isotope — ^{220}Rn from the ^{232}Th decay series. For $0\nu\beta\beta$ decay experiments, ^{222}Rn and ^{220}Rn are of interest as they provide ^{214}Bi and ^{208}Tl dut to their high Q_β values. The decay schemes are shown in Figure 1.3 and Figure 1.4.

Radon, as a noble gas, has a full valence shell and is thus inert to most chemical reactions, making it difficult to remove chemically. Its long diffusion length in solids has posed a significant challenge to seal on a large scale. The diffusion length L is defined as:

$$L = \sqrt{\frac{D}{\lambda}} \tag{1.1}$$

where λ is the decay constant and D is the diffusion coefficient of the material. Metals usually have minimal diffusion coefficient.

Some typical values of radon level are 1-100Bq/m^3 in the open air, and 30-50 Bq/m^3

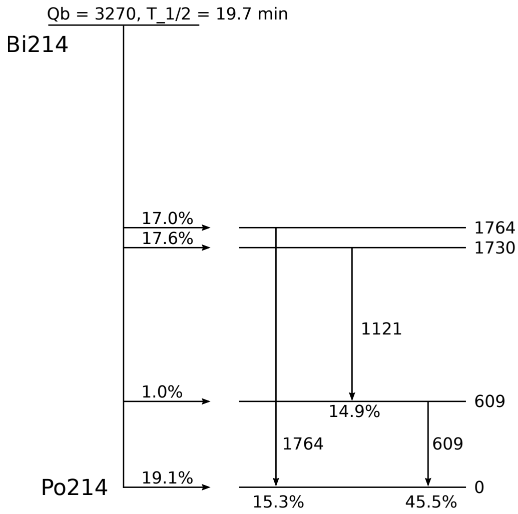

Figure 1.3: Decay scheme for the decay of ^{214}Bi.

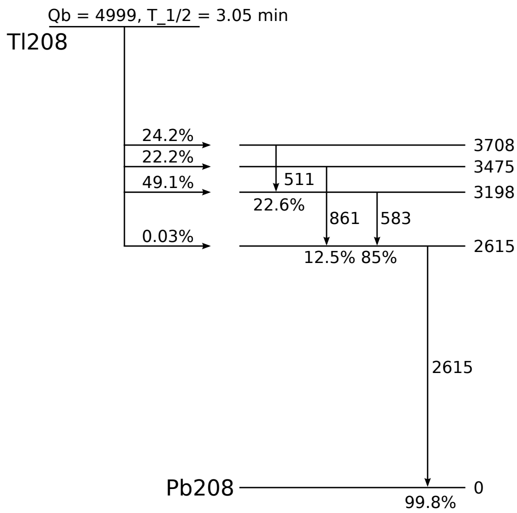

Figure 1.4: Decay scheme for the decay of ^{208}Tl.

indoor radon. These values are heavily dependent on the location, ventilation, and the surrounding materials and thus can vary dramatically. In a cleanroom, with the barrier from brickwork and active ventilation, the level can be reduced to <5 Bq/m^3. Radon levels in underground laboratories also varies depending on the surrounding rock, which can range from ~ 2 Bq/m^3 in a salt mine to several kBq/m^3 in a uranium mine.

Beyond experimental high energy physics, the study on radon has also become a general interest in public health. It is regarded as the second highest cause of lung cancer after smoking. Aside from radon itself, which is easily inhaled as a gas, the radioactive decay products are solid and can stick to the surface of dust in the air, which can in turn be breathed in. While there are extensive commercial radon detection devices sensitive to an activity range of 0.1 Bq/m^3 - 1 Bq/m^3, such sensitivity is far below the requirement for low background experiments. As such, a custom-made detector is required for the SuperNEMO experiment.

1.3 Radon in SuperNEMO

From the NEMO-3 experience, as the decay daughters of ^{222}Rn and ^{220}Rn, ^{214}Bi and ^{208}Tl contribute a large part to the background due to their high β decay Q_β values of 3.27 MeV and 4.99 MeV respectively. All materials are naturally contaminated with trace from the ^{232}Th and ^{238}U. Radon can enter the SuperNEMO detector generally via the following ways: emanation from the detector construction material and diffusion from the environment. The study on the effect of different radon concentrations on the sensitivity of SuperNEMO is shown in Figure 1.5. In the study, radon from the source foil and from the tracker are treated separately, and as such the radon budget of 280 μBq/m^3 for the sensitivity of 10^{26}yr is calculated with the assumption that the contribution from the source foil is 0. This being the case, the target of radon level should be divided between internal contamination and the tracker, resulting in a target for the tracker activity of $<150\mu$Bq/m^3. To achieve this target, various methods have been used to mitigate radon which effect as a major background: screening of the construction materials and components, purification of the tracker gas and in-situ monitoring of radon background levels.

1.4 Gas Flow Suppression of Radon in Tracker

Besides monitoring the radon contamination of material used in SuperNEMO, a sufficient improvement on the radon level in the tracker can be gained by replacing the contaminated tracker gas with clean gas. The diffused and emanated radon can be flushed away, creating a suppression that is, unsurprisingly, a function of flow

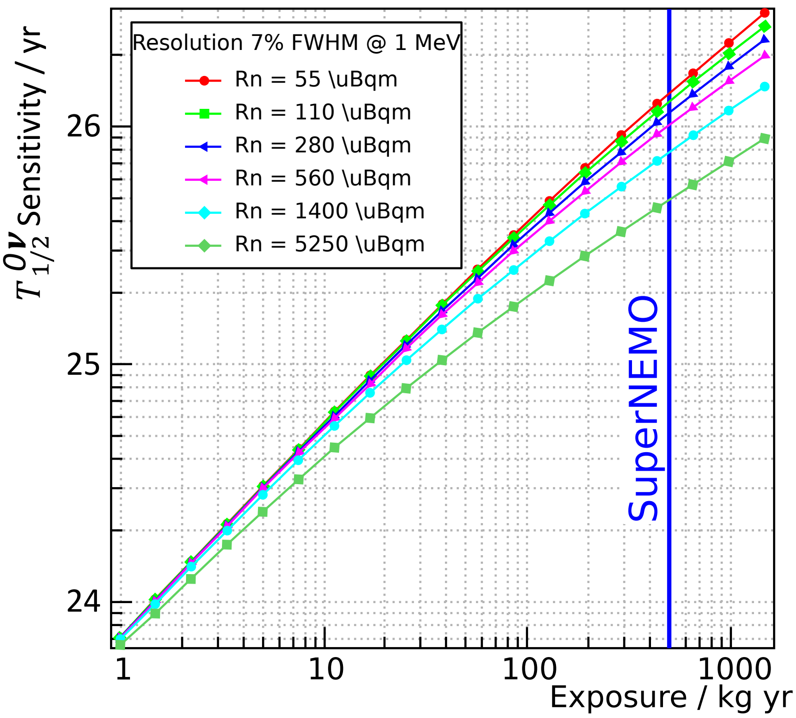

Figure 1.5: SuperNEMO sensitivity as a function of exposure for different radon activities inside the tracker. Internal contamination of ^{214}Bi is neglected [6].

rate and the activity of the supply gas. Naively, one may expect the flow rate to be as high as possible to reduce the radon activity, however, in reality this flow rate is limited. The tracker performance will decrease if the volume exchange too fast. Accuracy of the gas mixing system which is introducing the required 4% ethanol into the tracker gas can also be affected by high flow rate. Studies showed a satisfactory performance of the tracker up to a maximum flow rate of 2m^3/hr, which provide a radon suppression factor of 18.4. The flow rate is also limited by the ability of the gas purification system used to trap radon in the supply gas before being flushed into the tracker. To achieve effective suppression, an active gas purification system was developed, similar to the anti-radon factory, to purify the gas mixture of helium and argon prior to the gas mixing system delivering the correct concentration of tracker gas. The gas purification system is described in Section **??**. The major part of the gas purification system is a trap which use activated charcoal to trap radon at

-80 ^{o}C, and, as it is known that ethanol can quickly saturate the trap and stop radon trapping, this gas purification system must not be installed post gas mixing system. As radon emanated from the gas mixing system will be delivered to the tracker, the radiopurity of the gas mixing system should be minimised.

When radon level inside the sealed tracker reaches equilibrium, A_T, the number of radon atoms, N, is:

$$N_T^0 = A_T/\lambda \tag{1.2}$$

where λ is the decay constant. The suppression factor can be extracted by taking a ratio of the number of radon atoms inside the tracker with a certain gas flowrate and without flushing:

$$F_S = \frac{N_T}{N_T^0} = \frac{\lambda_T'}{A_T + A_G}\frac{A_T}{\lambda} = \frac{1 + f/V_T\lambda}{1 + A_G/A_T} \tag{1.3}$$

where N_T is the number of radon atoms inside the tracker while flushing, A_T is the activity of the tracker, A_G is the activity of the flushing gas, f is the flowrate, and V_T is the volume of the tracker. Here λ_T' is the effective decay constant: λ_T':

$$\lambda_T' = \lambda + \frac{f}{V_T} \tag{1.4}$$

The radon suppression factor as a function of gas flow rate is shown in Figure 1.6 [1], in which three different radiopurities of gas are considered. When the radon level of the replacing gas is negligible, a suppression factor of 18.4 can be achieved by flushing at 2 m^3/hour.

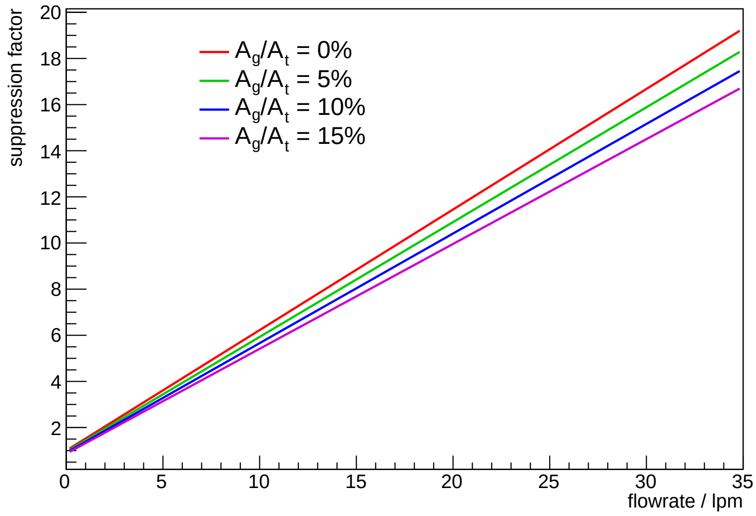

Figure 1.6: The radon suppression factor as a function of gas flow rate. Four different levels of radiopourity of the replacing gas are shown at 0%, 5%, 10%, and 15%[1].

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