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Measurement of radon diffusion through shielding foils for the SuperNEMO experiment

F. Mamedov,[1] P. Čermák, K. Smolek and I. Štekl[2]

Institute of experimental and applied physics, CTU in Prague,
Horská 3a/22, 128 00 Prague 2, Czech Republic

E-mail: fadahat.mamedov@utef.cvut.cz

ABSTRACT: An apparatus developed for the measurement of radon diffusion through thin foils for the SuperNEMO project is presented. The goal of the SuperNEMO collaboration is to construct a new generation detector for the search for neutrinoless double-beta decay $(0\nu\beta\beta)$ with 100 kg of enriched isotope as the source. At present, the collaboration is carrying out R&D in order to suppress significantly intrinsic background including that caused by radon. The description of the apparatus, data analysis method, as well as the results obtained in the measurement of radon diffusion through several types of thin foils, glue and sealant suitable for shielding in the SuperNEMO detector are discussed.

KEYWORDS: Detector design and construction technologies and materials; Dosimetry concepts and apparatus; Radiation monitoring

[1]Corresponding author.
[2]On behalf of SuperNEMO collaboration.

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Contents

1 Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$) is a process beyond the Standard Model (SM) which, if observed, will imply that lepton number is not conserved. The competing process of two-neutrino double-beta decay ($2\nu\beta\beta$) is allowed by the SM. Both processes are distinguished by the distribution of the energy-sum of two electrons emitted during $\beta\beta$ decay (see e.g. [1]).

SuperNEMO is a next-generation $0\nu\beta\beta$ experiment and successor of the NEMO-3 [2] detector, which is running since 2003 in the Laboratoire Souterrain de Modane (LSM, France). The SuperNEMO detector will consist of 20 identical modules, each housing $\sim$ 5–7 kg of source isotope, surrounded by a tracking chamber enclosed in a calorimeter. The detector will employ about 100 kg of enriched isotope in order to reach a sensitivity to a half-life of about 10^{26} years, which corresponds to Majorana neutrino masses of about 53–145 meV [3].

$\beta\beta$ decay is a very rare process and, therefore, special attention is devoted to background suppression, and radon ^{222}Rn is one of the most dangerous contributors. The isotope ^{222}Rn of the ^{238}U chain has a half-life of 3.82 days and then proceeds through two alpha decays and a beta decay to ^{214}Bi. The beta decay of ^{214}Bi is energetic enough to mimic a $0\nu\beta\beta$ decay with the $Q_{\beta\beta} \sim 3$ MeV of ^{82}Se (being considered as the possible source).

2 Measurement of radon diffusion through shielding foils

The SuperNEMO detector will be shielded against the penetration of radon with a system of two foils — the first will cover the tracking detector, while the second will cover the whole module. The shielding foil of the tracker has to be very thin, so as not to significantly absorb the energy of the emitted electrons from a $0\nu\beta\beta$ decay thus decreasing the resolution of the calorimeter energy measurement.

An apparatus for the measurement of radon diffusion [4] has been built at the IEAP CTU in Prague and is shown in figure 1. It consists of two identical vessels made of stainless steel with a volume $V = 2.8$ l and a Si PIN diode (sensitive area 20×20 mm^2, thickness 300 μm, FWHM 23 keV for 5.5 MeV α particles) using 2.5 kV HV for collection of the radon progenies. The two vessels are separated by the sample foil tightened by an indium wire to avoid leakage from and to the testing volumes. The left vessel is connected with the radon emanation source made of ^{226}Ra (107.5 kBq) to get a high and constant concentration of radon. The circulation of air with high content of radon

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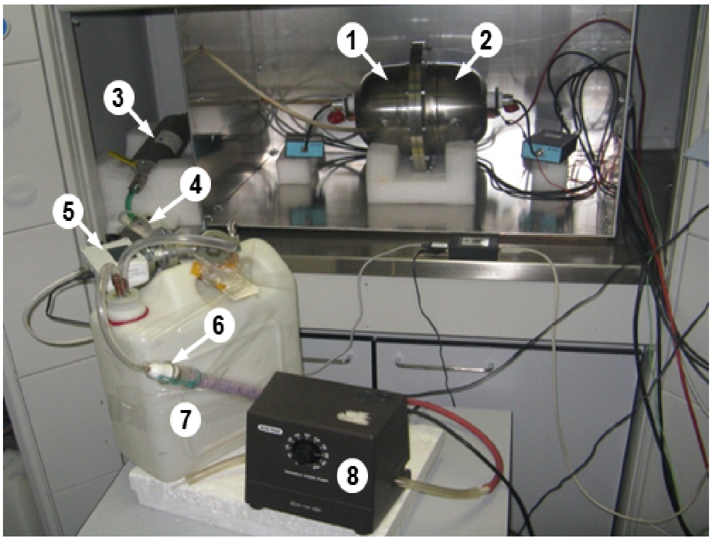

1/2 – Left/right vessel
3 – Radon source
4 – Flow-meter
5 – Sensors of temperature, humidity, and pressure
6 – Air dryer
7 – Air buffer
8 – Air pump, 0.5 l/min

Figure 1. Experimental apparatus used for testing radon penetration through shielding foils.

is performed by the air pump with tunable air flow (0.1–5 l/min). The volume activity of radon depends on the air flow (e.g. 0.5 l/min. corresponds to 27 kBq/m^3). In both vessels a Si PIN detector is installed to monitor the radon concentration in the corresponding volume. The monitoring itself is based on the electrostatic collection of radon progenies ^{218}Po and ^{214}Po on the detector and subsequent measurement of α particles spectra. Radon ^{222}Rn decays with $T_{1/2} = 3.82$ days and $E_\alpha = 5.49$ MeV to isotopes of ^{218}Po ($T_{1/2} = 3.05$ min., $E_\alpha = 6.00$ MeV), ^{214}Pb ($T_{1/2} = 26.8$ min., β emitter), ^{214}Bi ($T_{1/2} = 19.7$ min., β emitter) and ^{214}Po ($T_{1/2} = 0.164$ ms, $E_\alpha = 7.69$ MeV). As was said above, the left hemisphere contains high radon activity ($C_1 \sim 27$ kBq/m^3), while the radon activity in the right hemisphere (C_2) is caused by a radon penetration through the tested foil. The radon activities are measured in both vessels to estimate the ability of the foil to suppress radon diffusion. During measurements the relative humidity, temperature and pressure (only in left hemisphere) were recorded. The temperature was around 23° C and the relative humidity in the range 10–20% (removed by air dryer). The relative humidity has influence on the efficiency of radon progenies collection and could influence the diffusion of radon through foil [5, 6]. Therefore the measurements were performed under stable conditions similar to LSM conditions, where temperature is between 22–25° C and relative humidity is also low (in the range of 20–30%).

There are several theoretical approaches for describing the diffusion of radon through a foil. Our approach is based on those described in ref. [5, 7]. The diffusion of radon in the foil is always described with the stationary differential Fick's equation and by boundary conditions valid on the foil surfaces

$$D\frac{d^2C}{dz^2} - \lambda C(z) = 0, \qquad C(0) = \beta C_1, \qquad C(d) = \beta C_2,$$

where D is the diffusion coefficient for radon in the membrane material (m^{2}s^{-1}); λ is the decay constant of radon; $C(z)$ is the concentration of radon at a distance z from the left boundary of the membrane with the thickness of d; and β is the coefficient of adsorption (solubility) of radon in the material of the foil (see figure 2a). The concentrations $C(0)$ and C(d) of radon at the boundaries

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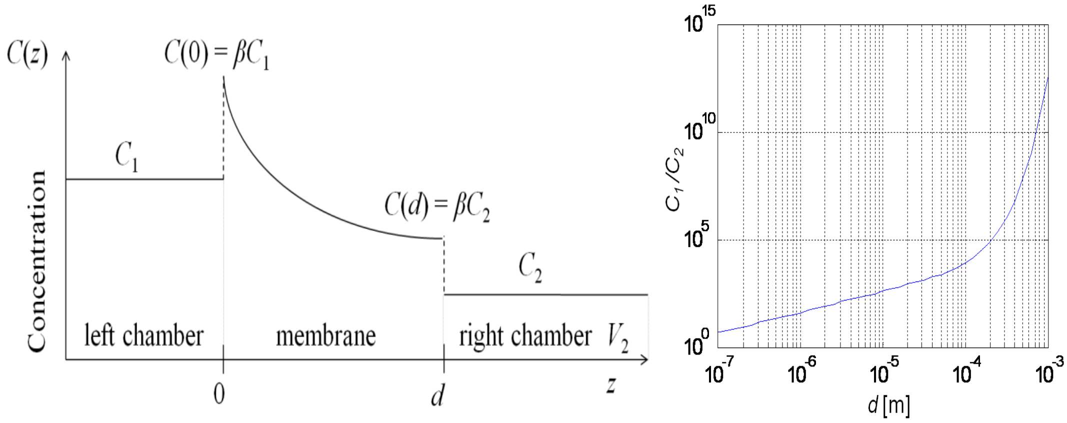

(a) **(b)**

Figure 2. Concentration of radon in the setup (a) and the radon suppression factor C_1/C_2 as a function of the membrane thickness d for a material with the diffusion coefficient $D = 4.3 \cdot 10^{-15}\ \mathrm{m^2 s^{-1}}$ (b).

of the foil are β-times higher than the concentrations C_1 and C_2 in the left (with Rn source) and right chambers. The equilibrium between the radon flux through the foil and its decay in the right chamber leads to the equation

$$-DS\frac{\mathrm{d}C}{\mathrm{d}z}(d) - \frac{\lambda V_2}{\beta}C(d) = 0,$$

where V_2 is the volume of the right chamber and S is the surface area of the measured foil.

Our model has two free parameters — the adsorption coefficient (solubility) β and the diffusion coefficient D. Solving the differential equation with the given boundary conditions, we get an expression for β, which can be solved numerically:

$$\beta = \frac{V_2 \sinh \frac{d}{L}}{SL\left(\frac{C_1}{C_2} - \cosh \frac{d}{L}\right)},$$

where $L = \sqrt{D/\lambda}$ is the diffusion length of radon in the membrane. In our experimental setup, we have used a relatively strong source of radon. The concentration C_1 in the left chamber is constant in time; the decrease caused by the diffusion through the foil is negligible. In our measurement we record the steady-state concentrations C_1 and C_2 in both chambers, but it is not enough information to estimate the coefficient of adsorption β as well as the diffusion coefficient D. The diffusion coefficient D is a decreasing function of the coefficient of adsorption β. Therefore using $\beta = 1$ in our analysis gives us a conservative estimate of D. The radon suppression factor C_1/C_2 is also an increasing function of the membrane thickness d. This fact is demonstrated in figure 2b.

Several foils which are suitable candidates for shielding of the tracking volume have been already tested:

i) high density polyethylene (HDPE);

ii) EVOH foil (ethylene vinyl alcohol copolymer, produced by Kuraray company as EVAL™) — measurements were carried out with single layer of EVOH foil (thickness 15 μm) and with two layers (thickness 2×15 μm);

Material	Thickness d [μm]	C_1/C_2	C_1/C_2 normalized to 15 μm	Diff. coefficient D [10^{-12} m^2s^{-1}]	Diff. length L [μm]
HDPE (2 layers)	2×144	3.5	1.1	19	3000
EVOH*	15	4.7	4.7	0.68	570
TROPAC III	102	>8300	>600	<0.0043	<46
Mylar (2 layers)	2×20	>9100	>2300	<0.0012	<24
EVOH (2 layers)	2×15	>31000	>8900	<0.00035	<13
Glue RTV 615	1000	1.2	1.003	800	19000
Silicon	2788	2.5	1.008	320	12000
Mylar junction	20	110	85	0.030	120
TROPAC junction	102	>6300	>500	<0.0051	<50

*The result was influenced by cracks in the foil (see explanation in the text).

Table 1. Summary of measured diffusion coefficients for different foils, glue, sealant and joined foils. The limits are given for the foils with no penetration of radon observed after three weeks of exposure.

iii) Mylar foil;

iv) aluminium barrier foil TROPAC® III (produced by TROPACK Packmittel GmbH company) — it consists of three layers, 15 μm of PET, 12 μm of Al and 75 μm of LDPE/HDPE.

The foils are produced in rolls usually 1 or 1.5 m wide. The proposed SuperNEMO tracking detector is much bigger than this and therefore it is necessary to join together several sheets of the shielding foil. This is the reason why we tested shielding foils that had been joined together. We also studied radon diffusion through different glues or sealant such as RTV 615 or silicone, which were used in NEMO 3 detector. Thin foils made of these materials were measured in the same manner as the other foil samples. The results are presented in table 1. The best radon suppression factor was measured for two layers of EVOH (2×15 μm), the TROPAC III foil, and the Mylar foil. However, the EVOH foil is brittle and the result for single layer of EVOH foil was influenced by the cracks in the foil (measurement was repeated two times with similar result). We also studied the possibility of joining together two sheets of Mylar or TROPAC III foils (the foil sample was produced from two halves joined by heating, joint width was 1 cm). The results are very promising (see table 1, last two lines). On the other hand, RTV 615 glue or silicone used as sealants are not so effective in the suppression of radon. The measurement of EVOH or TROPAC III foils gave only limits after 20 days of run time. No increase of the radon activity in the right hemisphere due to radon penetration was detected. On the contrary, for foils with low ability to suppress radon the penetration is visible within several hours, while radon activity saturation is reached in 1 day.

High attention to radon suppression has been paid in experiment Borexino (solar neutrinos detection) [6]. The detector is shielded from radon by thin nylon film. The collaboration tested radon penetration through nylon-6 and C38F nylon films for various thicknesses and relative humidity (see [6]). The tests of C38F nylon with thickness of 18 μm (RH 12%) gave diffusion coefficient $D = (2.2\pm0.3)\times10^{-12}$ cm^2/s and diffusion length $L = 10\,\mu$m. The results of our measurements give comparable results, e.g. for EVOH foil with thickness of 30 μm (RH below 10%) the diffusion coefficient D is below 3.5×10^{-12} cm^2/s and diffusion length L below 13 μm. Borexino collaboration produced also big nylon vessel made of nylon panels. Bonds between adjacent nylon panels were made using a solvent bonding recipe and clamped under pressure in order to produce a good seal and strengthen the bonds (pressure above 3×10^5 Pa, clamp time greater than 4 h) [6].

3 Conclusions and future plans

An apparatus for the measurement of radon diffusion through shielding foils has been constructed. The apparatus is used for routine evaluation of radon shielding capabilities of thin shielding foils or various glues or sealants. The aim is to select an appropriate shielding wrapping to fulfil the needs of the experiment SuperNEMO from the point of view of radon penetration into the tracking detector or into the whole SuperNEMO module. The present results show that we are able to shield the tracking volume of the SuperNEMO detector by EVOH foil (though it will be necessary to solve the problem of how to join together several sheets) or by the layered TROPAC III foil (with a lower thickness of the LDPE/HDPE layer, which has small effect on radon suppression). The whole SuperNEMO detector can be wrapped in TROPAC III foil which can be produced in large sheets (joined together simply by heat). The future activities will be devoted to the tests of various combination of foils (e.g. PET+EVOH), and various glues (e.g. Araldite 2020, Stycast 1264, RTV 70).

Acknowledgments

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