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Calculations and TPMC simulations of the reduction of radioactive decays of a noble gas by cryo-panels

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ABSTRACT

In the KATRIN neutrino mass experiment, radioactive decays inside the large UHV chamber of the Main Spectrometer can increase the background rate considerably and thus, diminish the sensitivity for the actual signal. In particular, the amount of the short-lived radon isotopes ^{219}Rn and ^{220}Rn has to be reduced. Three LN_2 -cooled cryogenic baffles have been installed to capture the radon atoms before they decay. However, radon does not stick to a cold surface indefinitely. It either desorbs after a limited sojourn time, or it decays into polonium.

We compare two different methods which describe the radon suppression for different baffle temperatures. The first method calculates the suppression factor analytically, using the effective pumping speed and the transmission probability of the baffles simulated with the Test Particle Monte Carlo code MolFlow+. A newly introduced *effective sticking coefficient* takes into account the radon lifetime and its mean sojourn time on the cold copper baffles. For the second method the MolFlow+ code was extended to simulate directly the radon lifetime and sojourn time. At the end experimental data are compared to the simulations and the mean sojourn time is determined as a function of the baffle temperature.

1. Introduction

The radioactive noble gas radon is a serious source of background for low-countrate particle physics experiments, such as the KATRIN[1] experiment [1], which is currently being commissioned at the Karlsruhe Institut of Technology (KIT) to measure the effective mass of electron anti-neutrinos with a sensitivity of 0.2 eV/c^2 over a period of five years. The neutrino mass will be deduced from tiny deviations of the β-electron spectrum from tritium decays, close to the endpoint at 18.6 keV. The width of the energy resolution of the vast 1240-m^3 Main Spectrometer is 1 eV. The expected signal rate in the last eV of the β-spectrum is about 10^{-2} cps.[2] Therefore, the background rate should not be much larger than this signal rate. In particular, short lived radon isotopes, such as ^{219}Rn ($T_{1/2} = 3.96$ s) and ^{220}Rn ($T_{1/2} = 55.6$ s), are likely to decay inside the UHV chamber of the Main Spectrometer, before they can be pumped out [2]. In Section 2 we describe possible sources of radon and the design of LN_2 -cooled cryogenic baffles as a countermeasure to reduce the rate of radon decays inside the vacuum chamber.

For the optimization of the baffle design and a better understanding of the reduction of the background rate the Test Particle Monte Carlo (TPMC) code MolFlow+ 2.5 was used to simulate the effective pumping speeds of the baffles and the turbo-molecular pumps (TMP) of the spectrometer. For short sojourn times of radon atoms after the adsorption on the cold baffle surface an atom can be redesorbed into the vacuum chamber, where it adds to the background rate. If the atom decays while still adsorbed on the baffle surface, it is similar to being pumped out. So, instead of the usual sticking coefficient used to describe a vacuum pump in a TPMC simulation, an *effective sticking coefficient* has been introduced to describe the effects of the finite sojourn time and lifetime of radon on the effective pumping speed of the baffles. The basic principles of the MolFlow+ simulation and the Main Spectrometer model are described in Section 3.

In Sections 4 and 5 two methods are introduced which describe the vacuum performance of the cryogenic baffles and their effect on the background rate. The first method calculates the radon suppression factor analytically from the effective pumping speed of the baffles, which has been simulated with MolFlow+ using the

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[1] **KA**rlsruhe **TRI**tium **N**eutrino experiment.

[2] counts per second.

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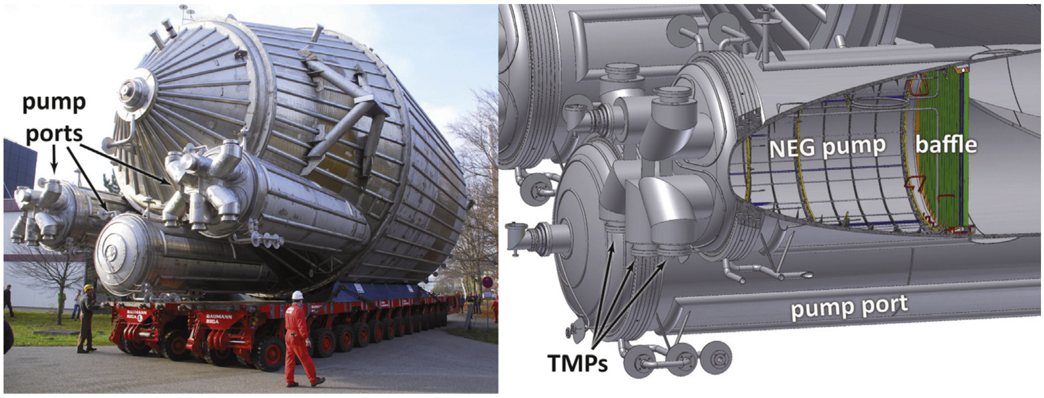

Fig. 1. Left: Picture of the KATRIN Main Spectrometer vacuum vessel. The pump ports, housing the NEG pumps and the LN_2 baffles are indicated. Right: Location of the main vacuum pumps in one of the three pump ports.

effective sticking coefficient. The second method employs a modified version of the MolFlow+ code, where a finite lifetime for each radon atom and a mean sojourn time for each surface element of the geometrical model were added. This new MolFlow+ code also stores the coordinates of decays in the volume of the vacuum chamber, allowing to produce a 3-dimensional decay map, and subsequently, determine the percentage of radon decays in the main volume of the Main Spectrometer.

In Section 6 the simulation results are compared to experimental data, and the mean sojourn time of radon on the cold copper baffles is extracted as a function of the temperature.

2. Radon in the KATRIN Main Spectrometer

The KATRIN Main Spectrometer is 23.3-m long and has a diameter of 10 m (see Fig. 1, left). The ultra-high vacuum (UHV) chamber is made of 316LN stainless steel. Both the outer vessel and the inner electrode system are on high voltage at a potential of −18.6 kV, while the vacuum beam-lines at both ends are on ground potential. The spectrometer works as a MAC-E filter[3] [3,4], an electrostatic high-pass filter, which measures the integral spectrum of electrons with energies in the range of 18.6 keV. Two superconducting solenoids at both ends with magnetic fields between 4.5 T and 6 T and a 12.6-m diameter aircoil system provide the magnetic guiding field for electrons through the vacuum chamber of the spectrometer. Electrons with energies above the electrostatic retarding potential can pass the spectrometer, to be counted at the other end by a segmented silicon detector. Electrons with lower energies are reflected back to the source.

If electrons are produced in the center of the spectrometer, the super-conducting solenoids act as magnetic mirrors, which can trap the electrons for hours inside the vacuum chamber, where they slowly lose energy by ionizing residual gas molecules. The secondary low-energy electrons produced in this process, can leave the trap to be counted by the detector as background events. Thus, a single radon decay can lead to an elevated background rate for a limited time interval, until the energy of the primary electron is spent [5]. The length of the time interval depends on the pressure and the energy of the primary electron. At an artificially increased base pressure of 10^{-8} mbar the interval can be reduced to mere seconds, leading to clearly identifiable peaks in the otherwise constant background rate. These clustered events are used to identify individual radon decays unambiguously. In Section 6 the cluster rate is used to investigate the effectiveness of the radon suppression at various baffle temperatures.

The vacuum system of the Main Spectrometer has been designed for an ultimate pressure of 10^{-11} mbar [6]. The three-stage pumping system consists 6 TMPs, 3 getter-pumps, and 3 LN_2-cooled cryogenic baffles. All vacuum pumps are located in three 1.7-m-diameter pump ports (see Fig. 1). The 6 TMPs (Leybold MAG W 2800) have an effective pumping speed of 10 m^3/s for hydrogen and are connected via three DN250 CF-flanges to each of the two outer pump ports. The three getter-pumps consist of 1000 m of SAES St707 NEG strips each [7]. The 2-m-long pumps are located at the end of the pump ports and have been designed for a combined effective pumping speed of 10^6 m^3/s for hydrogen.

As the experiment is sensitive even to a single radon decay, we cannot always select materials with low enough radioactivity. Despite the careful screening and selection of the NEG material, the emanation of tiny amounts of the short-lived radon isotope ^{219}Rn could not be avoided. The effect on the background rate was studied in prototype measurements with the much smaller Pre-Spectrometer (3.4-m long, 1.7-m diameter) of the KATRIN experiment [8]. It was found that LN_2 -cooled cryogenic baffles between the NEG pumps and the spectrometer volume can reduce the transmission of radon sufficiently to lower the background rate to the required level [9]. The price to be paid for the reduced background rate is a lower effective pumping speed for hydrogen, due to the limited conductance of the baffles. In the Main Spectrometer the effective pumping speed of the NEG pumps for H_2 is reduced to 375 m^3/s.

Another possible source of radon is the emanation from the stainless steel walls and from the welds. We expect ^{219}Rn from the thorium decay chain to be the most likely candidate. Since most of the inner surface (1222 m^2) is in the main volume, the cold baffles have to pump out the radon quickly before it decays. This is much less effective than the reduction of the transmission of radon from the NEG-pumps, as will be shown in Sections 4 and 5.

The schematic design of the Main Spectrometer baffles is shown in Fig. 2. Their circular shape with a diameter of 1.7 m fills out the cross section of the pump ports. The basic framework is made of vertical stainless steel tubes with V-shaped copper panels attached to each tube. The panels allow no direct line of sight through the baffles. A continuous flow of liquid nitrogen through the interconnected tubes cools down the copper panels to a temperature of approximately 88 K. The low temperature is limited by the surrounding vacuum chamber, which is at room temperature.

A radon atom adsorbed on the cold copper surface does not stay adsorbed indefinitely. The mean sojourn time τ_{des}, after which it

[3] Magnetic Adiabatic Collimation combined with an Electrostatic filter.

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