Material Screening Needs for a Next Generation Double Beta Experiment

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The materials assay campaign, performed in preparation of the EXO-200 experiment, is used as an example for what a next generation neutrinoless double-beta decay experiment might require.

1) **Surface contamination:**
   a. EXO: Surface contaminations of concern for EXO are mainly from ^{232}Th, ^{238}U, and ^{40}K (their energetic gamma radiation). Unlike germanium-based experiment in which alphas can be a concern, EXO can use fiducial volume data cuts and the particle type-dependent ratio of ionization and scintillation to identify and remove alpha-induced events. Thus, ^{210}Pb and its daughter are not a major concern. Depending on the used construction materials this may need to be watched. ^{210}Po induced $^{13}C(\alpha,n)^{16}O$ (neutrons and gammas) might become a concern in case large amounts of plastics are used. The required surface activity screening sensitivity, in terms of Th and U, is 10 pg/cm^2 (achieved in EXO-200) or better. Perhaps a factor 10 to 100 improvement would be desirable.
   b. Germanium-based: The alphas from ^{210}Pb can be a concern. The screening is required to be sensitive to less than 0.5 μBq/cm^2 for ^{210}Pb.
2) **Bulk contamination**
   All parts and components used in the construction of a double beta decay experiment must be screen for radioactivity, natural, cosmogenic, and anthropogenic. Based on the EXO-200 experience small parts and components constituted about one third of the screening load.
   a. Small parts
      All small parts, which are used to build the experiment, must be screened (at least by production lot). The sensitivities vary depending on where in the geometry of the experiment the small parts will be used. In general, ^{232}Th, ^{238}U, and ^{40}K are the main concerns. However, cosmogenic and man-made activities are a concern too. The former problem can be address by careful exposure management and is therefore not necessarily a screening issue.
   b. Large parts
      Large parts form the balance of the screening load. In EXO-200 the screening load was more or less evenly spread over all major components. Sampling of only small subsets of the material and assurance of material identity are an issue here.
3) **Next generation screening facilities and techniques**

Neutrinoless double-beta decay experiments require screening to be sensitive to 0.01 ppt for ^{238}U and ^{232}Th. A numerical example is in order here. A concentration of 10^{-14} g/g of ^{238}U corresponds to one decay per day per 100 kg of sample! Testing such low concentration by counting seems extremely difficult as there are simply not enough decays. Activity screeners typically test for order MeV gamma radiation; 100 kg samples are already impractically large because of severe self-absorption. Smaller samples resulting in even smaller rates are thus needed. When screening with low background Ge detectors typical gamma ray counting efficiencies are of order 10% further reducing an already infinitesimal rate. This argumentation doesn't even take into account background which will further reduce the utility of this tool. Thus, the screening needs mostly to be done through atom counting: ICPMS (Inductively Coupled Plasma Mass Spectroscopy), GDMS (Glow Discharge Mass Spectroscopy), or NAA (Neutron Activation Analysis). While these techniques do offer ppt or better detection limits for Th and U incur a risk: they count the number of atoms of the long lived head of the decay chains while background is created by energetic decays in the lower part of the chains. The measured number of Th and U atoms can only be translated into a low-chain decay rate by making assumptions about chain equilibrium. Equilibrium does not necessarily need to be established. Due to the lack of alternatives EXO-200 was prepared under this assumption for all materials requiring ppt or better screening. The measured background rate of the EXO-200 detector is close to that estimated using radio assay data *and* the equilibrium assumption. This ultimately justified the chosen approach.
During the EXO-200 preparation: 50% of sample measurements were done by ICP-MS, 20% by NAA, 20% by Ge screeners (above and below ground depending on the component), 10% by other methods.

4) **Disequilibrium in the decay chains**

The main concern of the counting is the detection of the breakage of equilibrium in the decay chains. In general, the Ge counters, which measure all gamma rays from the lower decay chain, could address the disequilibrium issue. However, direct screeners that could test the ppt and sub-ppt domains do not seem to exist. The other methods, NAA and Mass Spectrometers, are not sensitive to this feature of the series. To resolve this issue, it may be beneficial to explore alternative techniques such as probing the outgassing of ^{222}Rn from samples of interest. ^{214}Bi-^{214}Po delayed β-α-coincidences could be utilized for highly efficient and almost background free counting. It will have to be understood, however, what fraction of the radon escapes the sample and is ultimately transferred into the counter.

5**) Screening samples and time scales**

It took about 7 years to do all screening for EXO-200. About 420 sample measurements were performed during that time. In addition about 80 lead samples were alpha screened for their ^{210}Pb content and 30 high sensitivity (could test 5 atoms/day production yield) ^{222}Rn-outgassing measurements were performed. The sample load was not uniform in time and somewhat phase shifted when comparing the demands on the different methods. In

EXO-200 ICPMS delivered a maximal sample load of about 90 samples per year at peak demand during detector assembly. The NAA throughput was about 20 samples per year, mostly before start of detector assembly. The demand for Ge counting was approximately uniform in time. To shorten the screening time to increase the counting capability is to couple it with a good coordination. It should be noted that, for the case of EXO-200 as an example, the rate of project progress was not significantly slowed down by the screening task.

It is hard to extrapolate the EXO-200 experience to a much larger next generation double beta decay experiment. Should a detector be built similar to EXO-200 then the screening demand will probably be comparable. A completely new approach might have an even higher demand. The EXO-200 TPC is a technically complex device, requiring many components. Its main strength is in its active background rejection capability directly derived from this complexity. One could envision that a technically simpler approach, for example relying entirely on high-resolution calorimetry, might create less screening demand. This projected sample load, therefore, needs to be interpreted carefully as there is no generic double beta decay experiment.

6) Conclusions

a. Though Ge gamma spectroscopy is essential to screen materials for rare event experiments, the EXO-200 experience suggests that ICPMS is more important in the ultra sensitive screening for double-beta decay experiments. NAA and radon emanation as well as outgassing are equally important to the Ge screeners. More studies on properties and behavior of ^{222}Rn, ^{210}Pb and ^{210}Po are required.

b. Surface contamination needs attention and the appropriate techniques for its early detection must be in place.

c. ^{210}Po plate out studies and Ra supported Rn emanation studies should be undertaken.

d. It is beneficial to design low background experiments with safety margins, since there can be surprises and contributions from unexpected sources. However, when taking into account that the screening is already pushed to its limits by meeting the minimal requirements this is not always possible within finite time scales. In case this desire for safety becomes the dominant factor in the project schedule, taking of risks (e.g. making the chain equilibrium assumption) may be advantageous to assure adequate progress. Stalled project may ultimately go nowhere when seen in the international competitive environment.

e. Underground storage and production will become necessary.

f. It is beneficial to verify Monte Carlo simulations against data. However, previous experience has shown that Monte Carlo based background estimates, when coupled with a vigorous materials screening program, do yield reliable background predictions.