Control of Contamination of Radon-Daughters in the DEAP-3600 Acrylic Vessel

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Abstract.

DEAP-3600 is a 3600kg single-phase liquid-argon dark matter detector under construction at SNOLAB with a sensitivity of 10^{-46}cm^2 for a 100 GeV WIMP. The argon is held an an acrylic vessel coated with wavelength-shifting 1,1,4,4-tetraphenyl-1,3-butadiene (TPB). Acrylic was chosen because it is optically transparent at the shifted wavelength of 420 nm; an effective neutron shield; and physically strong.

With perfect cleaning of the acrylic surface before data taking the irreducible background is that from bulk ^{210}Pb activity that is near the surface. To achieve a background rate of 0.01 events in the 1000-kg fiducial volume per year of exposure, the allowed limit of Pb-210 in the bulk acrylic is 31 mBq/tonne ($= 1.2 \times 10^{-20}$g/g). We discuss how pure acrylic was procured and manufactured into a complete vessel paying particular attention to exposure to radon during all processes. In particular field work at the acrylic panel manufacturer, RPT Asia, and acrylic monomer supplier, Thai MMA Co. Ltd, in Thailand is described. The increased diffusion of radon during annealing the acrylic at 90C as well as techniques to mitigate against this are described.

Keywords: Dark matter, astro-particle physics, radon, radon progeny, acrylic
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1. INTRODUCTION

DEAP-3600 is a single-phase liquid-argon direct-search dark-matter detector under construction at SNOLAB in Greater Sudbury, Ontario, Canada. The liquid argon will be held in an acrylic vessel (AV) coated on the inside surface with TPB. Acrylic light guides direct light from the TPB surface to the 255 photomultiplier tubes (PMTs) that surround the vessel. Neutron shielding is placed between the light guides. The entire apparatus is placed in a stainless steel shell. The shell is in a large water tank instrumented with PMTs to detect the rare cosmic rays at SNOLAB. The detector and the three main pieces of the AV before bonding are shown in figure 1.

Acrylic is a physically-strong, transparent, and radiologically clean thermoplastic suitable for use in low-background detector construction. Acrylic, poly methyl methacrylate (PMMA), is a polymer of methyl methacrylate (MMA) which is produced in large petrochemical plants. Architectural acrylic is used, for example, in zoo-sized aquaria, strong windows, and detectors for astrophysics.[1].

2. SURFACE BACKGROUNDS IN DEAP-3600

Alpha decays in the acrylic near the surface can deposit a fraction of its energy into the liquid argon and mimic a dark matter signal. Thus the acrylic surface will be machined under radon free air just before fill with argon leaving a surface ideally as clean as the bulk acrylic.

Thus the acrylic was manufactured with controls on ^{222}Rn exposure to reduce the contamination from the progeny, ^{210}Pb. Monte Carlo calculations of alpha transport through acrylic demonstrate that a contamination of ^{210}Pb at 31 mBq/kg in the bulk of the acrylic will result in 0.01 surface events in three tonne years. This value takes credit for fiducialization but not pulse-shape discrimination for alphas.

3. PANEL MANUFACTURE

The AV was made from 128-inch by 96-inch by 4.5-inch thick flat panels made at RPT Asia Ltd (Eastern Seaboard Industrial Estate, Rayong, Thailand) from "pure monomer", which is MMA and $\simeq 2\%$ proprietary additives. The MMA

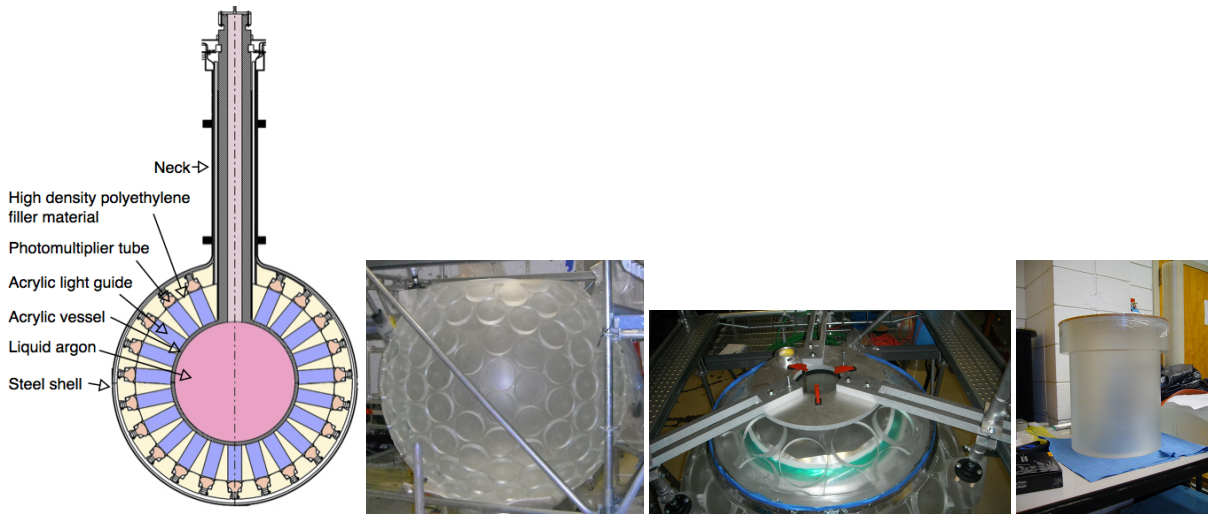

FIGURE 1. From left to right: (1) the DEAP detector showing the argon region, TPB, acrylic vessel, light guides, filler blocks and steel shell; (2) the sphere of the AV; (3) the collar mounted on top of the sphere ready for bonding; and (4) the neck of the AV.

used to make the DEAP acrylic vessel came from the Thai MMA Co. Ltd's plant, located in the Eastern Seaboard of Thailand. Both RPT Asia and Thai MMA were visited by DEAP collaborators prior to manufacture and the processes were described in detail by company staff. During all steps of manufacture except the final curing in a hydroclave, a DEAP collaborator was present.

The final stage of MMA production at Thai MMA was fractional distillation in the presence of air. The air is introduced at a rate of 1.25m^3 per tonne of MMA. The MMA was taken from continuous-flow production and pumped into a stainless-steel lined truck. This was important as storage at Thai MMA (under a pillow of air) has an unknown and potentially large radon exposure. The radon activity in the air was measured with a Durridge Rad-7 radon detector. The truck had a sealed container. All transfers were by two hoses: one for liquid and one to allow displaces air to flow back into the original container.

The MMA was unloaded at RPT Asia within three hours. The sealed storage tank at RPT Asia continuously stirred the MMA to keep it cool - ensuring any contamination is equally distributed in the MMA. The MMA was pumped to a reactor where it was mixed with approximately 2% proprietary additives and was then transferred into a storage vessel and to the moulds. Moulds were formed from glass sheets separated by a fixed distance and nylon dams that allowed for expansion and contraction during polymerization. Mould preparation was done in a HEPA-filtered clean room. The panels were placed in a hydroclave to polymerize.

4. RADON LOADING DURING PREPARATION OF PANELS

In order to assess radon loads, a unit of contamination was constructed. The density of MMA is approximately 1 tonne per cubic meter. If MMA enters a closed region, the radon or daughters in the region can enter the MMA. (This effect is mitigated somewhat as filling of volumes is done in closed loop and thus the air in the volumes can be old. Nonetheless, this is a useful, conservative approximation.) Using the relative half lives of ^{222}Rn and ^{210}Pb the activity of the ^{210}Pb in the acrylic is

$$A^{\text{acrylic}}(^{210}\text{Pb})[\text{mBq/tonne}] = 0.46 \times A^{\text{air}}(^{222}\text{Rn})[\text{mBq/m}^3] \quad (1)$$

This is *one unit* of contamination when transferring MMA.

At each stage of production the radon levels in the air were measured with a Durridge Rad-7 monitor. Based on these levels and the production process it is possible to estimate the loading of ^{210}Pb in the bulk acrylic. The results are summarized in table 1.

Once the panels were made, the ^{218}Po could settle onto the plastic and the ^{218}Po and ^{214}Po alpha decays could drive the daughter nuclei into the material a short distance. Light sanding of the surface removes this material. More

seriously, radon can diffuse into the acrylic and decay farther inside. The diffusion issue is discussed below.

TABLE 1. The exposure to radon and radon daughters at the steps of production of acrylic panels are listed. Radon was measured in a series of one-hour samples at each location. The average and standard deviation are shown. The contamination is in units as described in the text.

Process	**Contamination** units	**A(Rn)** Bq/m^3	**A(Pb)** mBq/tonne
Distillation	1.25	3.5 ± 2.0	1.9
Truck to RPT Asia	1	$\simeq 5$	2.3
Storage at RPT Asia	1	6.3 ± 3.5	2.90
Mixing Additives in Reactor	1	8.9 ± 5.7	4.1
Storage of Mixed MMA	1	10.8 ± 7.1	4.7
Pouring into Mould	1	10.8 ± 7.1	4.7
		Total	**20.6**

5. MANUFACTURE OF THE AV FROM PANELS

The flat panels were shipped from RPT Asia Ltd. to Reynolds Polymer Technology in Grand Junction, Colorado, USA. For the sphere, five panels were thermoformed into shape: they were heated above the glass-transition temperature and pressed onto a mould. The five gores (or orange sections) were bonded into the main sphere. A south pole section was then bonded in place. A collar (the top of the sphere and start of the neck) was also made as was the neck. The sphere, collar and neck were shipped to the University of Alberta where they were machined on a five and a half axis mill. See figure 1.

6. ASSEMBLY AT SNOLAB

The sphere, the collar and the neck were shipped underground to SNOLAB. (The sphere was designed to be as large as possible and still fit in the mine shaft.) Before bonding it was necessary to remove post-machining stresses by annealing. The acrylic was warmed slowly to 90C and then held for 12 hours. The air in the oven was cooled at $\simeq$ 0.5C/hour until close to room temperature.

Then the collar was bonded to the sphere. This bond is visible to the PMTs. The bond is formed by holding the parent material a certain distance apart and filling the space between with *bonding syrup*, a mixture of MMA, PMMA grains, and proprietary initiators. The $\simeq$ 1mm PMMA grains are $\simeq$ 30% of bonding syrup and a source of ^{210}Pb. Assuming that the PMMA used in all the bonds to make the sphere and bond the collar are exposed to radon (but otherwise kept clean) then the ^{210}Pb load can be calculated.

The total amount of PMMA in syrup is $\simeq$ 0.4% of the sphere's mass. Assuming the PMMA used in the syrup is fully saturated with radon in equilibrium with air at 5 Bq/m^3, and the solubility of radon in acrylic is 8.3[1][2], the PMMA grains could be 1000 days old and still contribute less than 10% of the allowed limit of ^{210}Pb. While the precise radon history of the grains is unknown, Reynolds Polymer used recently purchased material.

After this bond a second anneal was performed. Then the neck was bonded onto the collar. Then there was a third anneal. After the third anneal, the machining of the AV was completed. In this machining the light-guide stubs at the sphere-collar bond were completed and the neck was honed.

During annealing cycles the inside of the AV was covered and purged with radon-reduced air at 5 standard cubic feet per minute. There was an open vent as well as a sample line for the Rad-7 monitor. This purge reduced the radon load in the air from approximately 120 Bq/m^3 to less than 5 Bq/m^3. This is important as diffusion of radon increases at higher temperatures as described in the next section.

[1] The solubility, S, is a dimensionless number and is the ratio of concentration of radon in the acrylic to radon in the air. Concentration is expressed in units of amount of radon per unit volume.

7. RADON DIFFUSION INTO ACRYLIC

Diffusion of radon into acrylic is governed by the diffusion equation with decay: $\frac{dC}{dt} = D\frac{d^2C}{dx^2} - \lambda C$ where $C = C(x,t)$ is the local concentration, x is the distance into the slab, $\lambda = 2.1 \times 10^{-6}\,\mathrm{s}^{-1}$ is the decay constant of ^{222}Rn and D is the diffusion constant. The diffusion length is $\sqrt{(D/\lambda)}$. The concentration of radon in the acrylic at the air-acrylic interface is given by the solubility, S, times the volumetric concentration in the air.

Using data from Wojcik [2] and calculations[2] by CheFEM software [3] we use as a function of temperature: $D = D_0\, e^{-\Delta E_d/RT}$ [cm^2/s] and $S = S_0\, e^{-\Delta H_S/RT} \times 76T/273$ [g cm^{-3}/g cm^{-3}] with $R = 1.986 \times 10^{-3}$ [kcal/mol], $D_0 = 481.5$, $\Delta E_d = 16.14$, $S_0 = 3.55 \times 10^{-4}$, and $\Delta H_s = -3.32$. (Note that a somewhat larger value of D at room temperature was reported by Mamedov in a poster at this conference.) D increases by two orders of magnitude between 20 and 80C. The solubility decreases by a factor of $\simeq 2$.

The radon levels inside the acrylic vessel were measured during annealing with a Rad-7 monitor as was the temperature of the air inside the AV. These are also shown in figure 2.

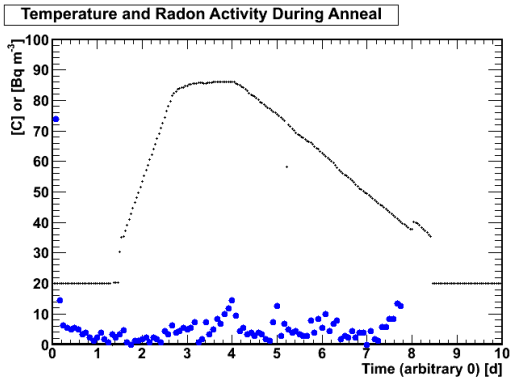

FIGURE 2. The air temperature profile (small black dots) and radon activity (large blue dots) inside the acrylic vessel during one anneal cycle.

The entire temperature and radon exposure history of the AV is known after the vessel arrived in the high-radon environment at SNOLAB. Using that and the diffusion equation we arrive at the (preliminary) result for the ^{210}Pb contamination as a function of depth into the acrylic. This contamination is after the first three anneals. Two further anneals are anticipated but the AV will be purged with pure nitrogen and sealed before annealing so further contamination is not expected. We expect < 0.02 events in three tonne years from radoon diffusion.

From the contamination of the parent material we expect approximately 0.006 surface background events in DEAP-3600. From diffusion of radon into the acrylic, especially during annealing, we expect < 0.02 events, after resurfacing.

ACKNOWLEDGMENTS

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[2] The Sanchez-Lacombe equation of state is used over the complete temperature range; diffusion is based on the Free Volume theory for diffusion; and the mass transfer is based on Maxwell-Stefan equation for diffusion.