Simulating the Expected Background in the PICO-500 Dark Matter Detector

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INTRODUCTION

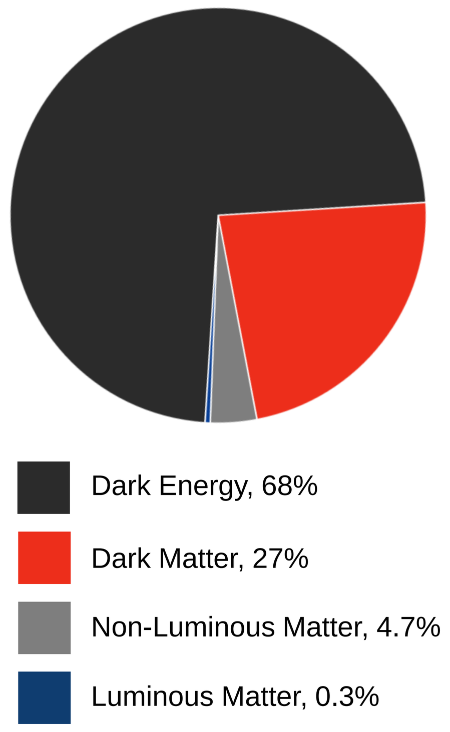


Figure 1: The estimated amounts of the types of matter in the universe.

Dark Matter

- Supported by decades of astronomical evidence, it is believed only 0.3% of the universe is made up of luminous matter, as shown in Figure 1 [1].
- 27% is made up of a yet-to-be-found type of matter known as dark matter.
- Weakly-Interacting Massive Particles (WIMPs) are the most popular candidate for this new type of matter.
- WIMPs would be non-baryonic, long-lived, electrically neutral, and non-relativistic particles.

Low-Background Experiments

- Because WIMP interactions will be rare, dark matter detectors must have very low background.
- The expected background must be very well known in order to design a detector that is sufficient enough to search for dark matter.
- In order to achieve the lowest background possible, PICO is located 2 km underground at SNOLAB, in Sudbury, ON, which helps shield from cosmic rays.

SIMULATIONS

Geant4

- Due to the complexity and number of possible processes, calculating the expected background rates cannot be done analytically.
- Therefore, Geant4 was used for all simulations. Geant4 is a Monte Carlo toolkit, written in C++ and developed at CERN, for simulating the passage of particles through matter [2]. Images from Geant4 are shown in Figure 5.

Internal Neutron Background Simulations

- PICO-500 is currently designed to have a pressure vessel of radius 122 cm. The effect of changing the radius by up to ±30 cm on the internal neutron background coming from natural contaminants in the detector materials was explored.
- NeuCBOT was used to generate neutron spectra from (α, n) reactions, which were then used to generate 10^8 neutrons in Geant4 [3].

Alpha Background Simulations

- Alpha events can come from decays of ^{222}Rn in the active liquid, or from decays of natural contaminants in the inner wall of the quartz jar. The latter are referred to as wall events.
- The surface area of PICO-500 will be much larger than previous PICO detectors, so low alpha background must be ensured.
- Geant4 was used to confine 10^7 α particles to the inner 200 μm of the quartz jar wall and simulate their interactions.

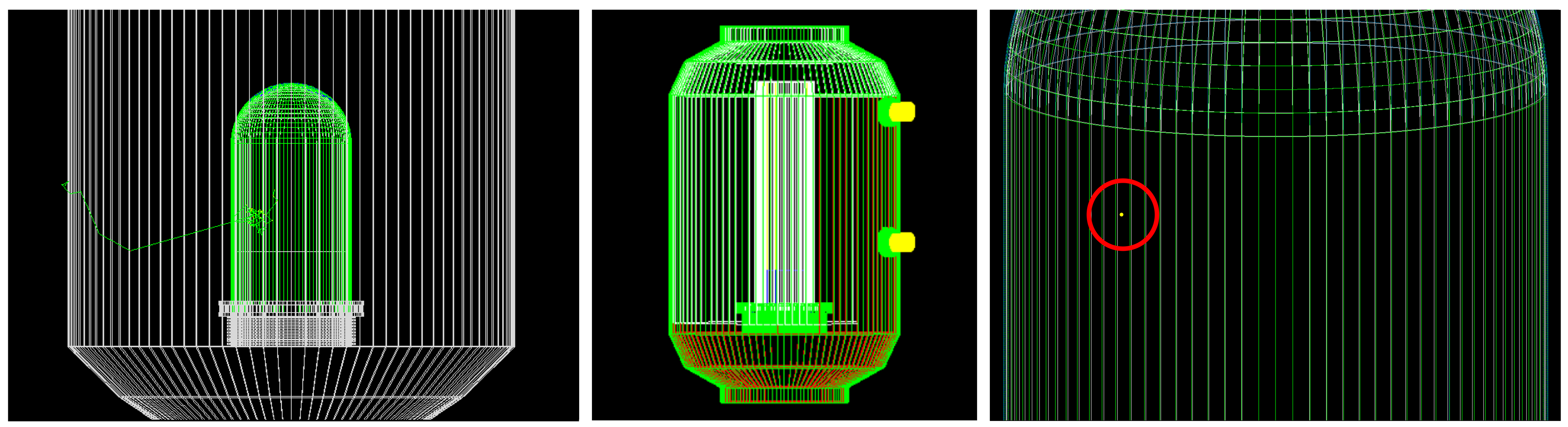


Figure 5: The geometry of PICO-500 as displayed in Geant4 (centre), showing an example of a neutron entering the C_3F_8 from the pressure vessel (left) and an alpha event from the wall of the quartz jar (right). Because the range of α particles is so short, they show up in Geant4 as points, rather than visible tracks.

PICO-500

Current Design

- PICO-500 will be the next generation of PICO detector, with the current design shown in Figure 4. It will be similar to PICO-40L, which is currently being assembled at SNOLAB.
- It will consist of a quartz jar (radius 23 cm and height 200 cm) filled with approximately 260 L of active C_3F_8.

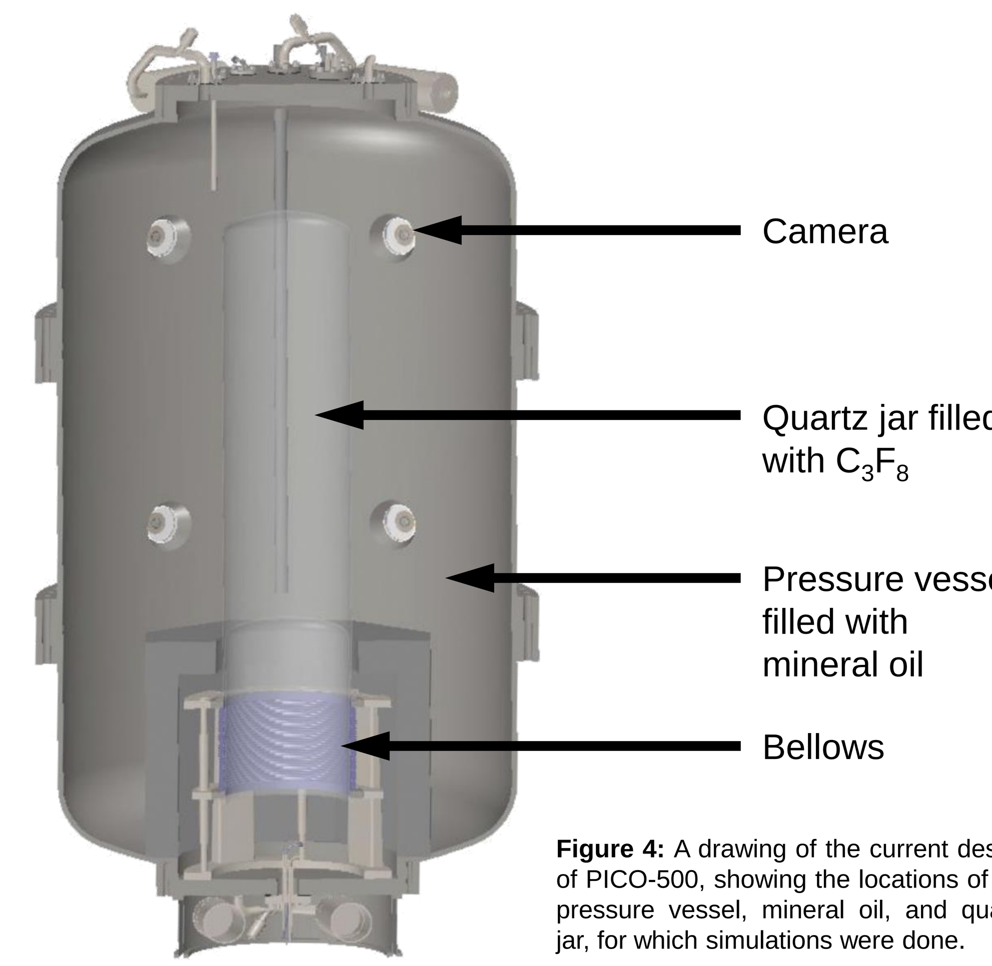


Figure 4: A drawing of the current design of PICO-500, showing the locations of the pressure vessel, mineral oil, and quartz jar, for which simulations were done.

PICO DETECTORS

Detection Principle

- The PICO Collaboration searches for WIMPs directly using bubble chamber technology.
- Liquid C_3F_8 is put in a superheated state by slowly decreasing its pressure below its vapour pressure. As a dark matter particle passes through the detector and hits a C_3F_8 nucleus, the charged recoiling nucleus loses energy as it moves away. The ionisation then boils the C_3F_8, causing bubbles to form.

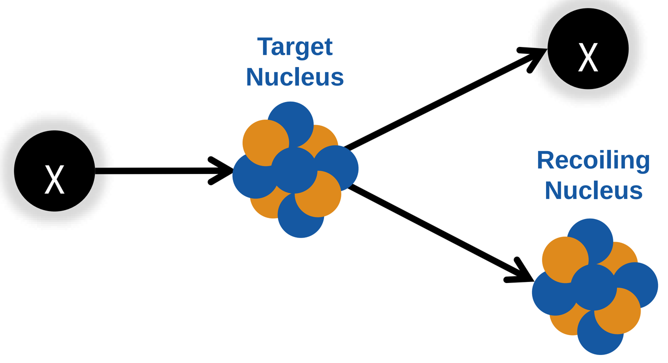


Figure 2: The expected interaction between a dark matter particle (χ) and a nucleus of C_3F_8.

Backgrounds

- Fast neutrons from cosmic rays (external) or components of the detector (internal) can cause nuclear recoil events, as shown in Figure 3.
- α particles from the decays of natural contaminants, such as ^{238}U, ^{235}U, and ^{232}Th, can also cause nucleation.

Figure 3: An image of the PICO-2L detector, showing multiple bubbles in the C_3F_8, caused by neutrons used for calibration.

RESULTS

Internal Neutron Background Results

- As the pressure vessel radius decreases, the background rate increases. This is because the wall of the pressure vessel will be closer to the active volume, meaning neutrons have a higher chance of entering the C_3F_8.
- Figure 6 shows the results for each simulated radius and the contribution to the number of single bubble events from each decay chain in the pressure vessel (PV) and retroreflector. These numbers, however, do not take into account the activity of the pressure vessel or retroreflector.
- There is a range of radii for which the expected neutron background is low enough to search for dark matter.
- Similar simulations were also done for the mineral oil inside the pressure vessel, and future simulations will be done for the cameras and piezoelectric sensors.

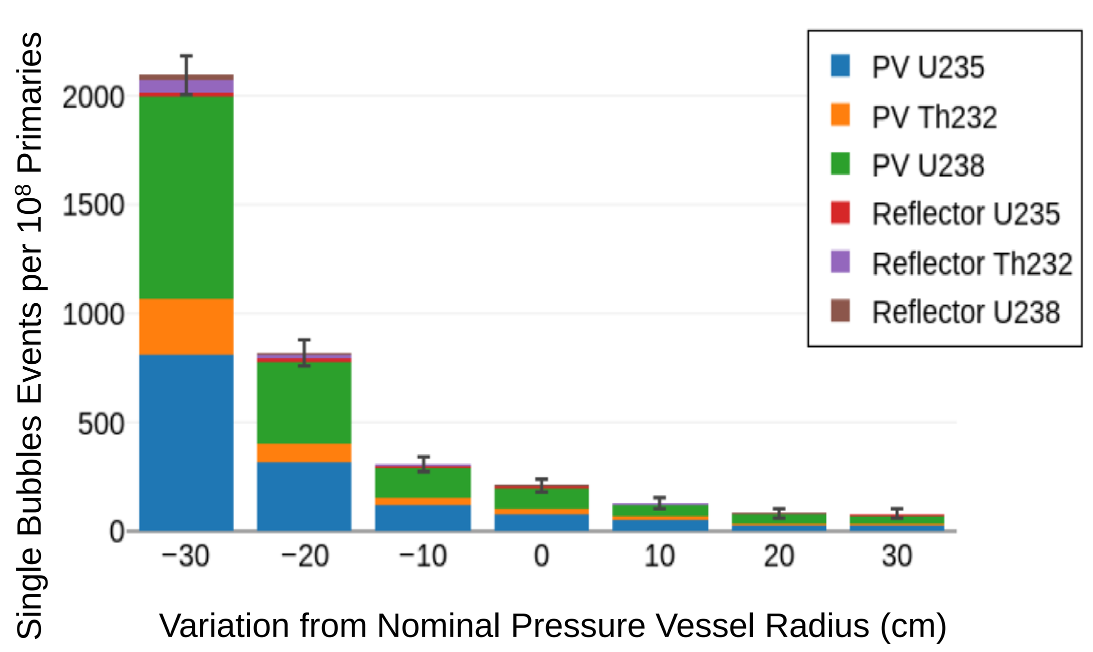


Figure 6: A plot of expected single-bubble events per 10^8 thrown neutrons from various contaminants in the pressure vessel (PV) and the retroreflector against variation from the nominal pressure vessel radius of 122 cm.

Alpha Background Results

- 3% of ^{222}Rn alpha particles made it into the C_3F_8.
- 4% of ^{218}Po alpha particles made it into the C_3F_8.
- 6% of ^{214}Po alpha particles made it into the C_3F_8.
- Using these results, and taking the activity of the quartz jar (measured with ICPMS) to be ~10^{-7} Bqkg^{-1}, wall alpha events are expected to be seen at a rate of ~10^{-2} events per m^2 per year, as shown in Table 1. This corresponds to seeing events from a given ^{238}U daughter every 3–6 years.

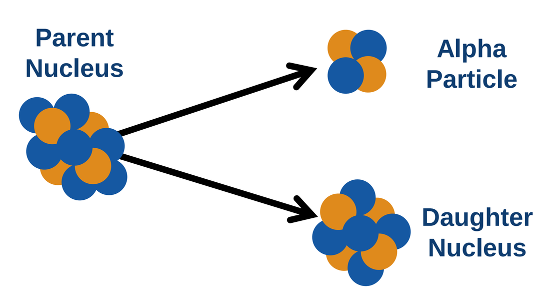


Figure 7: An alpha decay process. After an event, the detector has an intrinsic dead time, during which it compressed to collapse bubbles, then expands in order to put the C_3F_8 back into a superheated state. If the alpha background is too high, this will create bubbles too often, and the detector will have to spend too much time in an inactive state, preventing actual data collection.

- As in Figure 7, the main concern is the frequency at which the chamber will have to be compressed due to wall alpha events, but these results show that this should not be a problem.
- However, this is currently only a lower limit on alpha activity, based on the intrinsic bulk activity. Surface depositions of contaminants that occur during the assembly process have not yet been simulated.

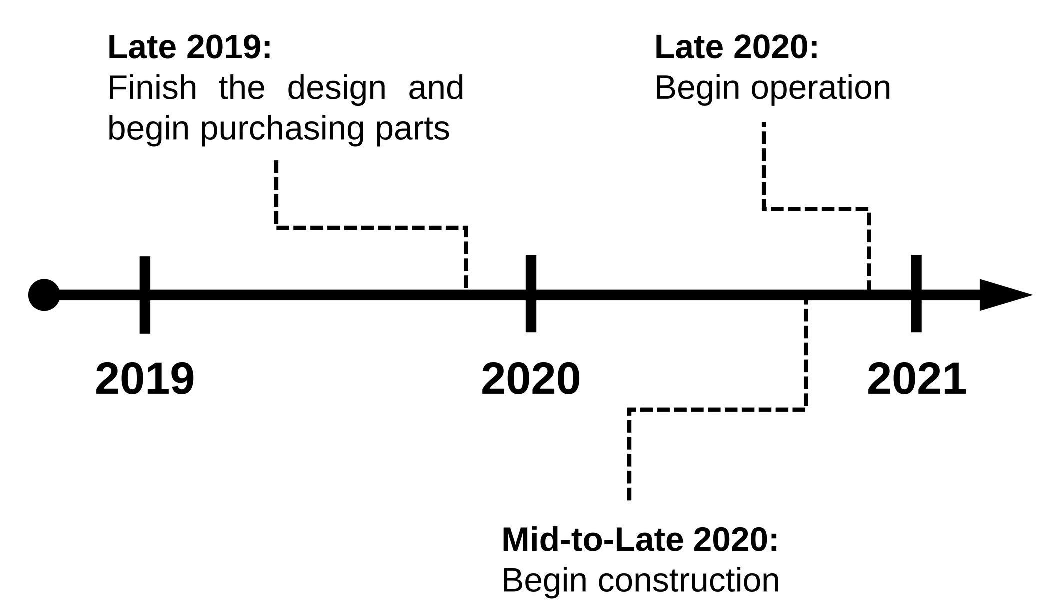
Table 1: The expected surface activity of the inner wall of the quartz jar per meter squared per year from the three main ^{238}U decay chain products. From these results, the total number of events per year is expected to be 1.05.

Parent	Energy (MeV)	Surface α Activity (×10^{-2} events m^{-2}yr^{-1})
^{222}Rn	5.590	5.24
^{218}Po	6.115	6.06
^{214}Po	7.833	9.13

FUTURE STEPS

Projected Timeline

- This is the projected timeline for the completion of PICO-500:



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[1] N. Aghanim *et al*. (Planck Collaboration). arXiv:1807.06209 [astro-ph.CO] (2018).

[2] S. Agostinelli *et al*. GEANT4: A Simulation toolkit. *Nucl. Instrum. Meth.*, A506:250–303, 2003.

[3] S. Westerdale and P. D. Meyers. Radiogenic Neutron Yield Calculations for Low-Background Experiments. *Nucl. Instrum. Meth.*, A875:57–64, 2017.