Final report

The “Gen 2” Axion Dark Matter Experiment (ADMX)

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Abstract

The Generation-2 ADMX project is an upgrade of the existing Axion Dark Matter eXperiment to add a high-performance dilution refrigerator to the cavity axion detector. The refrigerator reduces the operating temperature of the experiment from 3–4 K to of order 0.12 K (120 mK). There is a corresponding 20-fold reduction in the background noise of the experiment. The refrigerator has been installed and commissioned. The reduced background has allowed a search for the very weakly-coupled but highly compelling DFSZ-model axions. This search, at this sensitivity, is a definitive experiment, able to detect axions or to reject the axion dark matter hypothesis with high confidence.

Introduction

This document is the final report for the University of Florida (UF) project "Construction and operation of the Generation-2 ADMX detector," grant DE-SC0009723TDD, covering activities from March 2013 through March 2018.

Florida is a member of the Axion Dark-Matter eXperiment (ADMX), an experiment operated by a collaboration that includes the University of Washington, the University of California Berkeley, Lawrence Livermore National Laboratory, Pacific Northwest National Laboratory, Los Alamos National Laboratory, Fermi National Laboratory, Washington University St Louis, and the University of Florida. The scientific goal of the project is to either detect the dark-matter axion or exclude it over a broad range of plausible masses and couplings. ADMX is conducting a search for axions as a component of the dark-matter halo of our Galaxy and is sensitive to axions with masses of 2–40 μeV. The axion affects two key issues in physics, one in particle physics and the second in astrophysics: (1) the origin of CP symmetry in the strong interactions and (2) the composition of the dark-matter of the universe.

The science case for axions and for the Generation-2 upgrade of the ADMX detector remains strong. Results from Planck observations of the cosmic microwave background give a dark matter density in the Universe at about 27% of the closure density. Moreover, our own Galaxy has a substantial dark-matter halo. Axions are a plausible candidate for this dark matter, with their case made stronger recently on account of the absence of results from the LHC for supersymmetry and from LUX and other experiments for weakly interacting massive particles. Axions constituting the Galactic halo may be stimulated to convert into a narrow-band microwave photon signal in a microwave-cavity resonator permeated by a strong static magnetic field.

Beginning in the mid-1990s, the Axion Dark Matter eXperiment (ADMX) collaboration successfully developed a sensitive cavity detector for halo axions. The Generation-2 ADMX detector reported reaching design sensitivity in early 2018. It is first axion experiment to have sensitivity to DFSZ axion dark matter in the μeV mass range. The DFSZ model gives the weakest coupling strength of axions to photons. Limits resulting from the first two searches are shown in Fig. 1. Halo axions with couplings at the DFSZ value or stronger are ruled out over most of the 2.67–3.32 μeV mass range. Earlier, the first generation ADMX detector reached enough sensitivity to rule out the more strongly coupled axion benchmark models (KSVZ) for axion masses in the range 1.9–3.5 μeV. Experiments are continuing and the collaboration expects to search up to 9 μeV during the next two years.

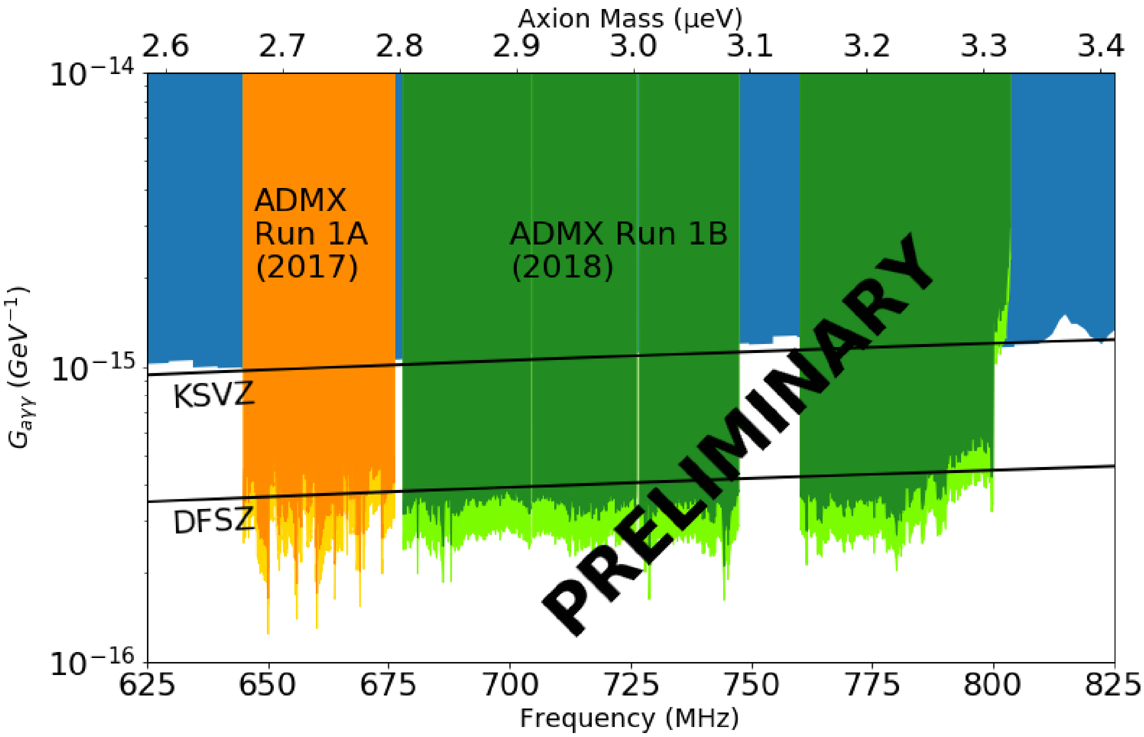


Fig 1. The 90% confidence excluded region of axion mass (upper axis) and coupling by the Generation-2 ADMX detector. The KSVZ and DFSZ coupling-mass lines are also shown as well as the limits from the first generation detector.

The background limiting the sensitivity of RF cavity axion searches decreases as the detector temperature is cooled to ultralow temperatures. Indeed, the system noise temperature (the sum of cavity physical temperature and amplifier electronic noise) is proportional to the physical temperature. The broadband, high-gain, ultra-low noise Superconducting QUantum Interference Device (SQUID) microwave amplifiers, developed specifically for ADMX, have signal-to-noise ratios that decrease linearly with temperature all the way to base temperatures of 50–100 mK.

Therefore, the key improvement by the Generation-2 ADMX project was to install a powerful dilution refrigerator, associated cryogenics, and gas-handling system. The refrigerator has cooled the cavity and these SQUID amplifiers to about 100 mK. This provided a gain in sensitivity of 20x over the 3–4 K system temperatures of the first generation detectors. The increased sensitivity allowed a search for the more weakly-coupled but very compelling “DFSZ” axions. This search, at this sensitivity, is a “definitive experiment,” able to detect axions or to reject the axion dark matter hypothesis with high confidence.

As part of the Generation-2 ADMX project, the University of Florida led the acquisition and testing of the dilution refrigerator. We also participated in the installation of the refrigeration in the ADMX insert, designed, built, and installed two “1 K” pots for the insert, built and delivered a pumping station suitable for storage of the helium-three/helium-four mixture in the dilution refrigerator, developed for use at Florida, a helium-three refrigerator capable of reaching 400 mK with high cooling power, and designed the four-cavity array which will be used to extend the search to 9 μeV.

Dilution refrigerator

The overall layout of the ADMX experiment is shown in Fig. 2. The cavity is located in the 50-cm diameter bore of the 8 T magnet and the SQUID amplifier sits inside a field compensation coil and 4 K reservoir above the cavity. The dilution refrigerator is located in the ultra-high vacuum space between the bottom of the 4 K reservoir and the top of the cavity, providing cooling of both the cavity and the SQUID amplifier.

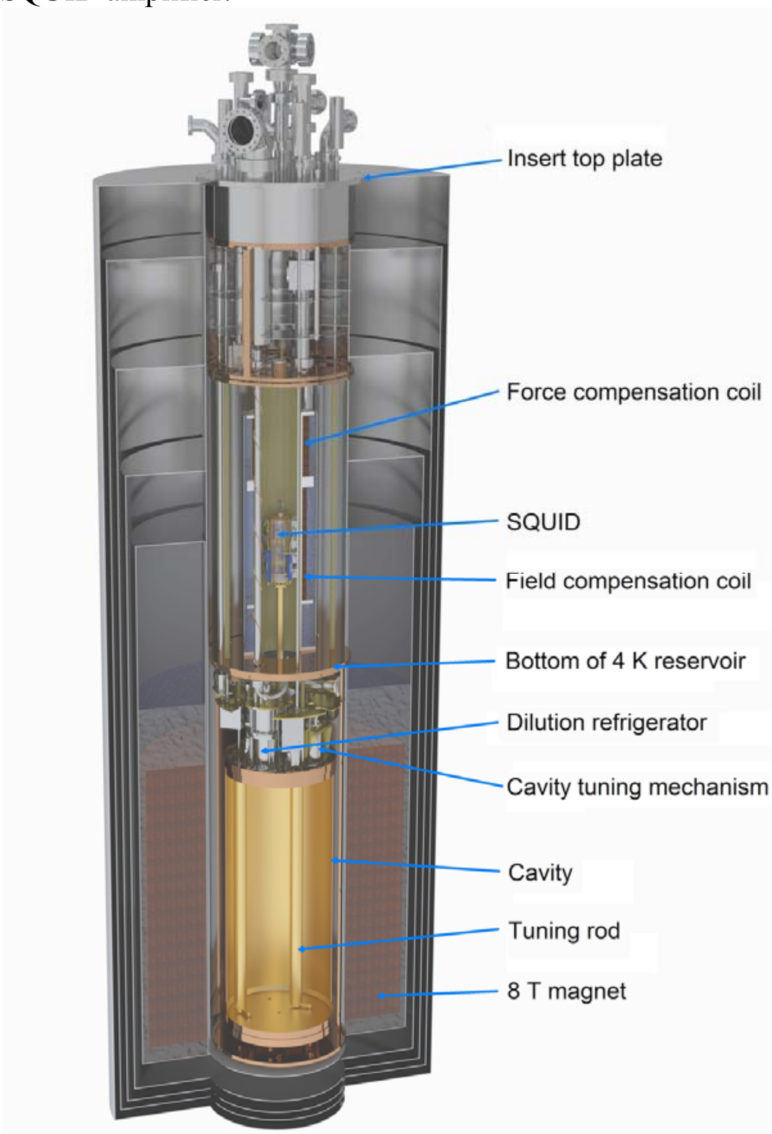


Fig. 2. Drawing of the ADMX apparatus. One or more microwave cavities is in the 50 cm diameter × 100 cm long bore of the 8 T magnet. The dilution refrigerator is located between the 4 K reservoir and the cavity and the SQUID amplifiers are within a field compensation coil just above that.

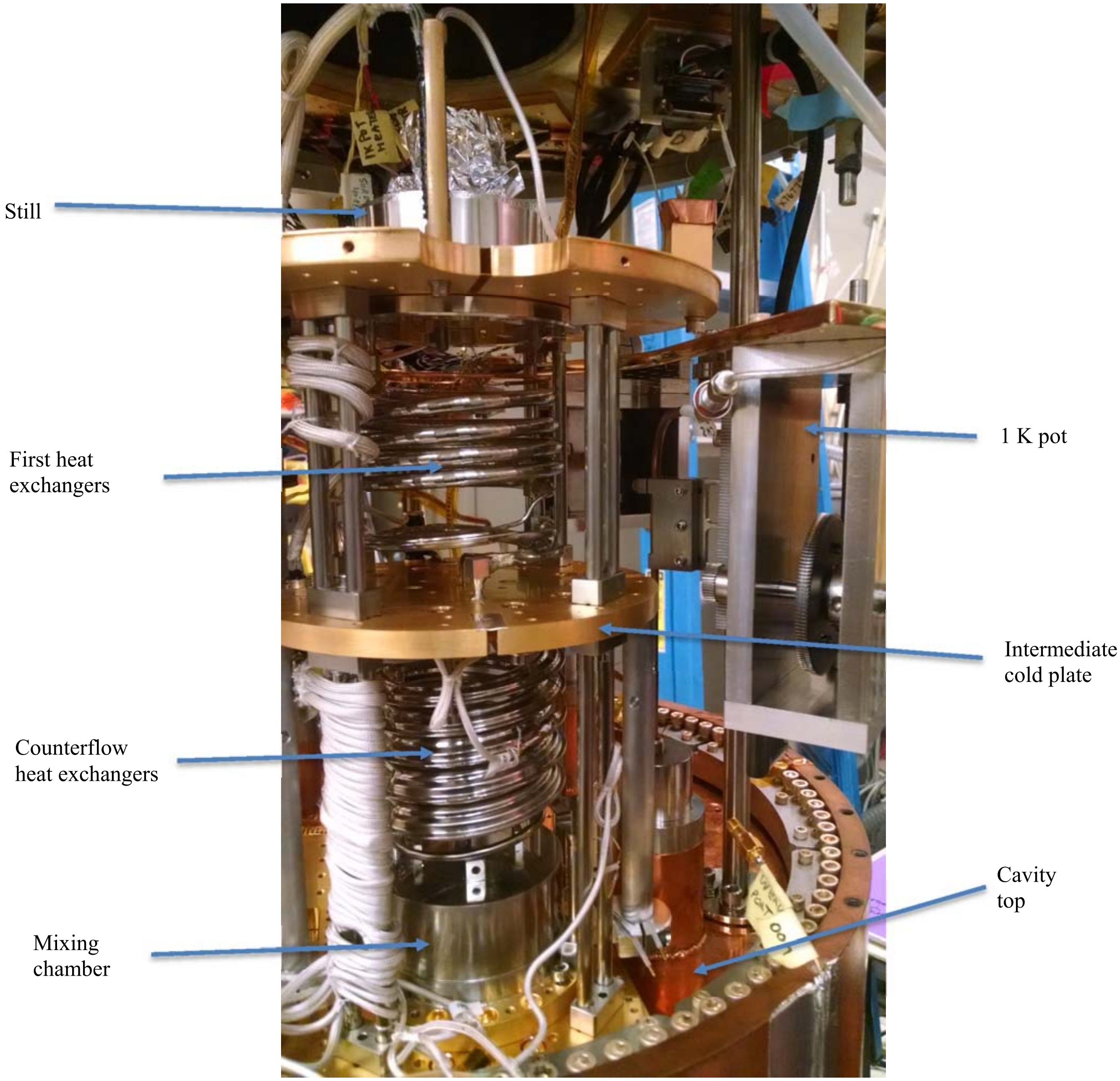
The motivation for lowering the system temperature (T_s) is straightforward. The rate at which the cavity output can be searched for axions (at a given halo density and a given axion-to-photon coupling) improves as $1/T_s^2$. Moreover, for a given scan rate, the sensitivity of the detector scales as T_s. In ADMX the system noise temperature is $T_s = T + T_N$, the sum of the physical temperature T of the cavity and the excess noise temperature T_N of the amplifier. The low temperature provided by the dilution refrigerator is crucial to achieving the ultimate sensitivity goal of ADMX. The refrigerator components have been customized for ADMX's unique requirements. The principal requirement is a very high cooling power: 800 µW at a temperature of 100 mK. The cooling power is 20% higher than previously available refrigerators.

The dilution refrigerator was built by Janis, Inc. under a contract monitored by the University of Florida. The system consists of the cold stage (mixing chamber and still) that are installed in the ADMX insert, an automated and computer controlled gas handling system, sealed pumping system, two 1 K pots, and pumping lines. The dilution refrigerator system was tested several times at the Janis plant in Woburn, MA. Janis did make some modifications to the original design after which testing confirmed that the design specifications had been met, with 800 µW cooling power at a temperature of 100 mK. A base temperature (at minimal heat load) of 6.5 mK was also demonstrated.

The refrigerator was delivered to the ADMX site, installed, and commissioned in 2015-16. Also installed were two Florida-built 1 K pots. These use pumped helium delivered through a capillary from the 4 K reservoir; one intercept heat from the 4 K space (including radiation) and the other is used to condense the Helium-3/Helium-4 mixture. Figure 3 shows the mixing chamber, counterflow heat exchangers, dilution refrigerator still, and one of the 1 K pots. The mixing chamber bottom is gold-plated and this is bolted to a gold-plated area on the top of the ADMX cavity.

The dilution refrigerator has met its requirements during the data runs 1A and 1B. The mixing chamber has operated at temperatures as low as 85 mK. The cavity and squid regions are warmer, typically 120 mK and 320 mK respectively. These temperatures are indicative of a significant thermal impedance to the mixing chamber. The cause of this is under active investigation, with some redesign of the SQUID housing and some changes to assembly procedures.

Both 1 K pots maintain temperatures below 1.2 K. They will continue to operate as they did in earlier runs.



<u>Figure 3</u>. Photo of the ADMX Gen 2 dilution refrigerator (mixing chamber and still) installed in the ADMX Gen 2 experiment insert. The bottom of the mixing chamber is bolted to the top of the ADMX resonant cavity.

Mixture pump out station

The gas handling system for the dilution refrigerator has a gas "dump" where the mixture may be stored at a fraction of an atmosphere pressure, with manual valves to seal it off from the rest of the system. With the dump sealed, the rest of the gas handling system may be vented, leak checked, disassembled, or serviced in one way or another. Still, there are situations where it might be desirable to remove the mixture entirely. There could be a pump failure, a leak, an ice block in the cold space, problems with the automatic valves or controller, or other issues. The risk of these problems happening is deemed to be low; nevertheless, we have built a pumping system to enable the mixture to be removed totally from the dilution refrigerator system and stored safely. The system is shown in Figure 4 of the attachment. There is a sealed mechanical pump on the bottom shelf. The four storage reservoirs are large enough that the entire helium-three/helium-four mixture may be stored at a fraction of atmospheric pressure. (This is desired so that any leak causes air to leak in rather than mixture to leak out.) The pump-out station is at the ADMX site.

Figure 4. Photo of the ADMX mixture pump out station. The sealed pump may be seen under the panel on the right. There are four storage tanks and manual valves to configure the pumping system.

Helium-three system

We have built at the University of Florida a helium-three refrigerator, including the helium-three reservoir, a 1-K helium-four pot for condensing the helium-three, gas handling system, and sealed pump. Figure 5 of the attachment shows a picture of the refrigerator with the inner vacuum can removed. The 1-K pot in the upper right is identical to the two 1-K pots we prepared for the ADMX insert. (One is used to condense the incoming helium-three/helium-four mixture and one to cool the 1-K plate and radiation shields, intercepting heat from the 4.2 K space coming to the milliKelvin space.) The reservoir at the bottom is the helium-three pot. We have run this system many times. It reaches a base temperature of 330 mK and extracts 400 mW at 700 mK. It is used for testing components for the ADMX insert.

Figure 5. Photo of the cold stage of the helium-three refrigerator. The upper reservoir is the continuous-flow 1 K pot, with a capillary to the left bringing liquid in from the outer bath. The second capillary supplies the returning helium-three gas, to be condensed and delivered to the helium-three pot at the bottom. Both pots are pumped through the stainless-steel tubes to which they are attached.

Design of a four-cavity array

The cylindrical cavity used by ADMX operates in the TM_{010} resonant mode. This is a mode where the RF electric field is along the cylinder axis and hence parallel to the static magnetic field of the 8-T solenoid. It is the mode with by far the highest form factor for conversion of axions to photons. The resonant frequency of the cavity depends inversely on its diameter *d*, according to $f_0 = c/1.3d$, with c the speed of light. The cavity frequency is tuned upward by moving a metal rod from wall to center. A cavity that tunes from 1.5–2.2 GHz, enabling a search over the 6–9 μeV mass range, would be 16 cm in diameter, considerably smaller than the 42 cm diameter of the cold space in the bore of the magnet. Because the signal is proportional to cavity volume, the smaller diameter reduces the signal by a factor of 7.

We can recover much of this reduction by building 4 cavities and combining their outputs. We have designed such an array. Figure 5 of the attachment shows a solid model of the array. The coarse tuning of the cavities is accomplished by rotating metal or dielectric rods from wall to center. The rods are mounted on a common wheel mechanism (above and below the cavities). Fine tuning (not shown) is accomplished by inserting small dielectric rods to perturb the cavity resonance.

Prototype testing and four-cavity array construction is underway at Florida, supported by a contract from Fermilab, the location of the ADMX project office. Scheduled delivery is in about a year.

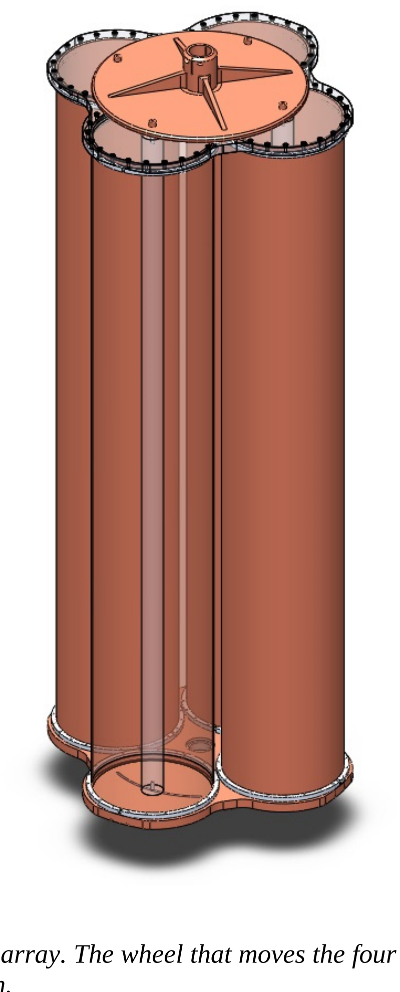


Figure 6. Model of the four cavity array. The wheel that moves the four tuning rods is shown. Fine tuning and antennas are not shown.

Products.

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"ADMX: Recent results at the DFSZ frontier and future prospects for axion haloscopes," D.B. Tanner, *Sensitivity Frontier Workshop* (Santa Barbara, 22 May 2018) (Invited)

"ADMX: Recent results at the DFSZ frontier," *Patras 2018* (Hamburg, 18 June 2018). (Invited)

5. People working on this research activity

Engineer Joe Gleason joined the project in summer 2014 and has worked on cryogenic engineering, the mixture pump-out system, gas handling, tests and evaluation of the 1 K pots, evaluation of the performance of the dilution refrigerator, the ^{3}He system, and the design of the four-cavity array.

Nicole Crisosto, a Florida graduate student, was stationed at the ADMX site at the University of Washington for almost a year. She has contributed to commissioning, leak checking, and dilution refrigerator operations. She wrote a script to capture the status of the gas handling system, displaying on the WWW the temperatures, pressures, gas flow, valve status, and pump status of the system. She has graduated and is now a postdoc with ADMX.

Faculty participating in this research were Neil Sullivan and David Tanner. Both participated in the specifications, bidding process, and vendor selection for the dilution refrigerator. Tanner was responsible for following the construction and acceptance tests of the dilution refrigerator and has been the main point of contact between Janis and ADMX. Both and spent time at Janis' headquarters for acceptance testing. Sullivan designed, monitored fabrication, and tested the helium three system. Sullivan also participated in the design and testing of the mixture pump-out system. Tanner worked on the design of the four cavity array.