EUROPEAN SPALLATION SOURCE

Cooling Below 1 K

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Goals

- Describe 3 methods for cooling below 1 K
  - Subatmospheric ^3He
  - Dilution Refrigerators
  - Adiabatic Demagnetization Refrigerators
- Provide some examples of these techniques in use

Introduction

- Why go below 1 K ?
- There are basic scientific questions that require operating at these temperatures:
  - Sensors for X-Ray and IR Astronomy
  - Dark Matter Searches
  - Fundamental condensed matter studies (superfluid ^3He, solid He etc)
- The cryogenic techniques for operating at these temperatures are essentially the same that we have seen already only more so:
  - Greater attention to minimizing heat leaks
  - Specialized sensors
- What is very different is how we get to these temperatures.
  - The various refrigeration cycles and methods we've discussed so far won't get us there

Limits to Pumping on ^4He

- We can reduce the temperature of liquid helium by reducing its saturation pressure – but there is a limit.
- The vapor pressure of the most abundant He isotope (^4He) becomes very small below ~ 1.2 K so cooling below this temperature using this technique isn't feasible
- The solution is ^3He !

^3He

- This is the other stable isotope of helium
- Very rare < 0.1 ppm of He in nature
  - However can be produced via radioactive decay of Tritium (^3H)
- ^3He is still very expensive and shortages have occurred driven by Homeland Security applications
- Pumped ^3He systems can provide cooling down to 200 – 300 mK
  - Such systems always recycle the ^3He and frequently use soption pumps employing activated charcoal
  - Typical performance is up to 400 μW @ 300 mK for 6 hours
- ^3He does become a superfluid below 2.65 mK but the explanation of the superfluid properties are very different than that of ^4He superfluid (He II)
  - In ^3He the superfluid mechanism is similar to BCS theory in superconductors
    - (Fermions vs. Bosons)

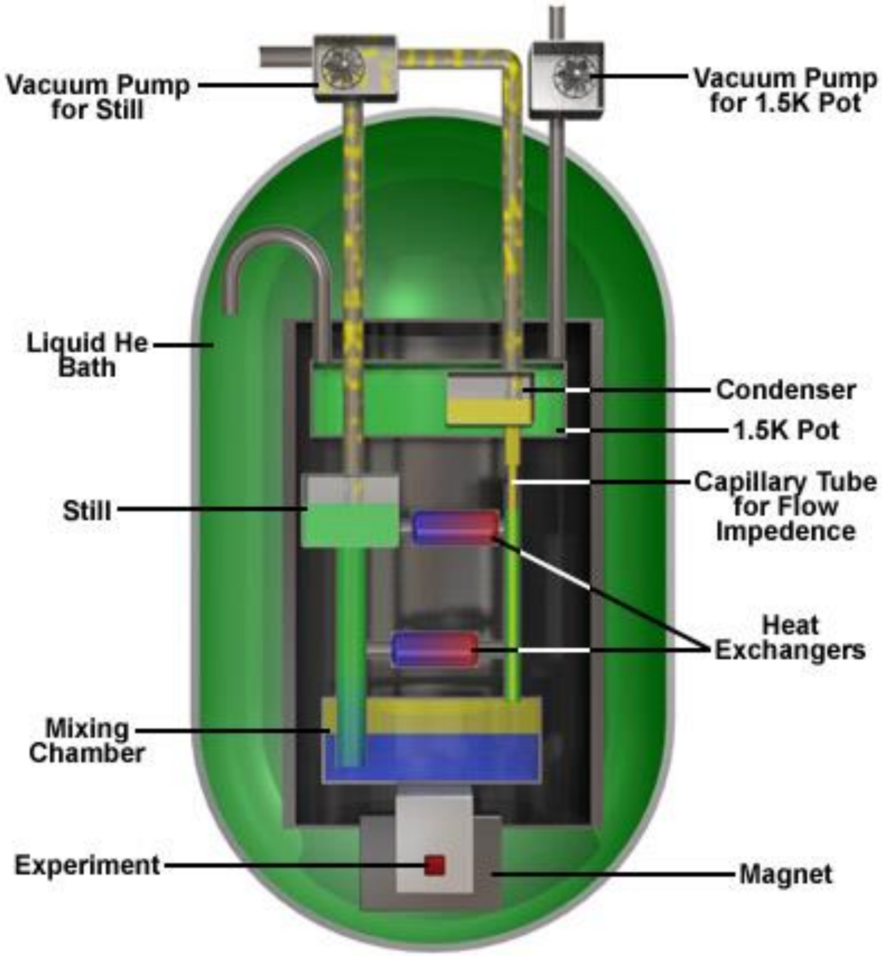
Dilution Refrigerators

- These use a mixture of $^3He/^4He$ and take advantage of 3 physical effects:

1. Below 0.8 K a $^3He/^4He$ mixture will spontaneously separate into a ^3He rich zone atop a heavier ^4He rich zone
2. It requires energy to move a ^3He atom from the ^3He rich zone to the ^4He rich zone. This energy reduces the temperature of the $^3He/^4He$ mixture
3. Below 1 K the vapor pressure of ^3He is much higher than that of ^4He Thus, pumping on the ^4He rich side will preferentially remove ^3He atoms.

- Pumping on the ^4He rich side of the mix causing ^3He atoms to leave. In order to maintain equilibrium ^3He atoms will move from the ^3He rich zone to the ^4He rich zone. This results in net cooling of the mixture and of whatever it is tied to.

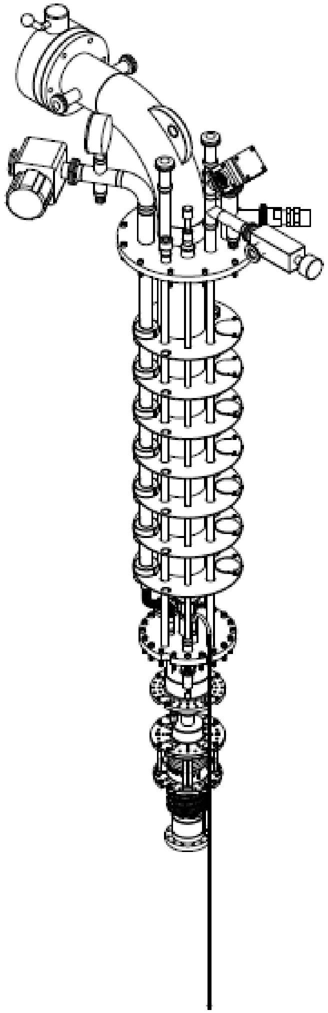
Schematic of Typical Dilution Refrigerator



From NHMFL/ FSU Website
Note Magnet is not part of DR

Dilution Refrigerators are Commercial Devices

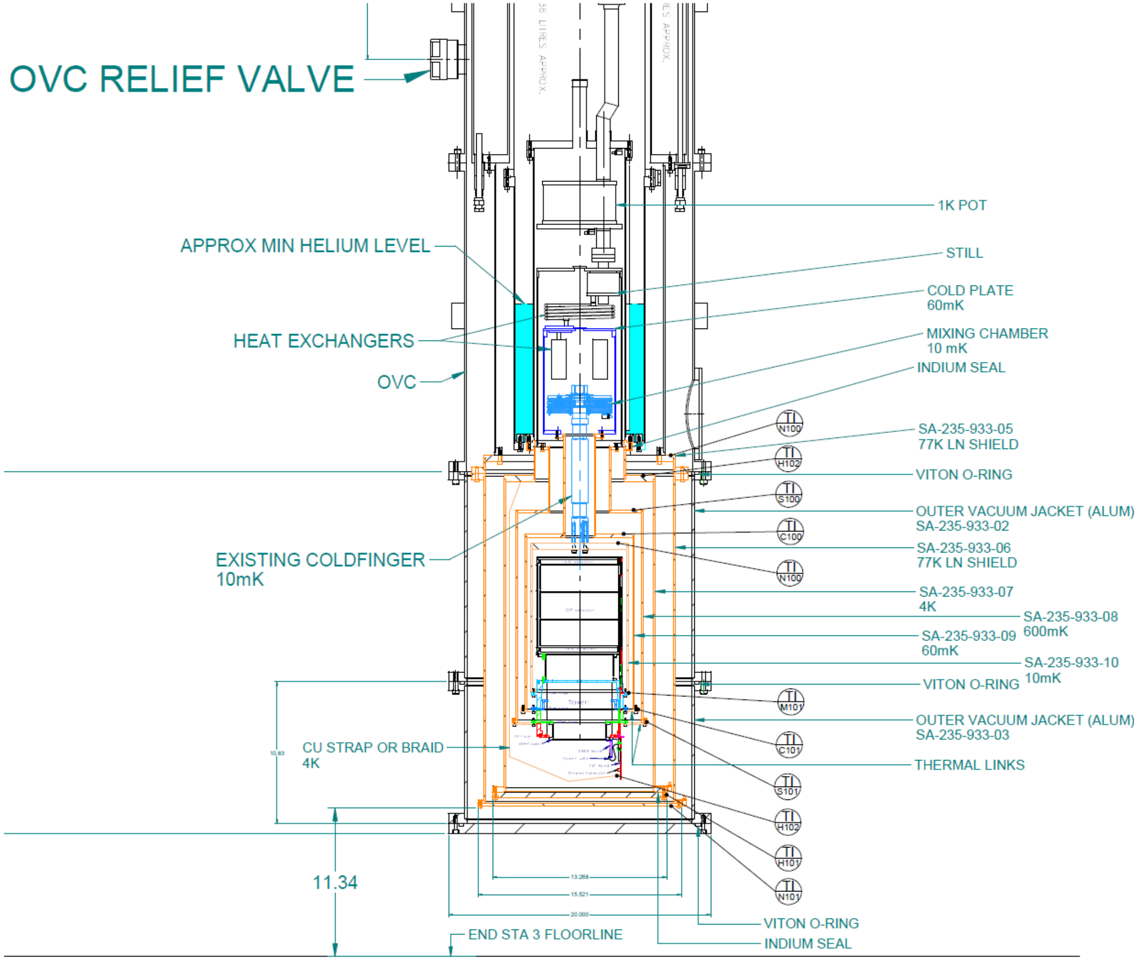
Oxford Instruments
Base temperature
(no load) 7 mK
> 400 μW @ 100 mK



Janis Research
Base temperature
(no load) 12 mK
200 μW @ 100 mK

Note:
1) Small thermal capacities
2) Multiple radiation shields & thin wall tubes for low heat leak

Cryogenic Dark Matter Search Test System



Note Multiple Temperature Stations
& Nested Shields

Based on Existing Oxford DR

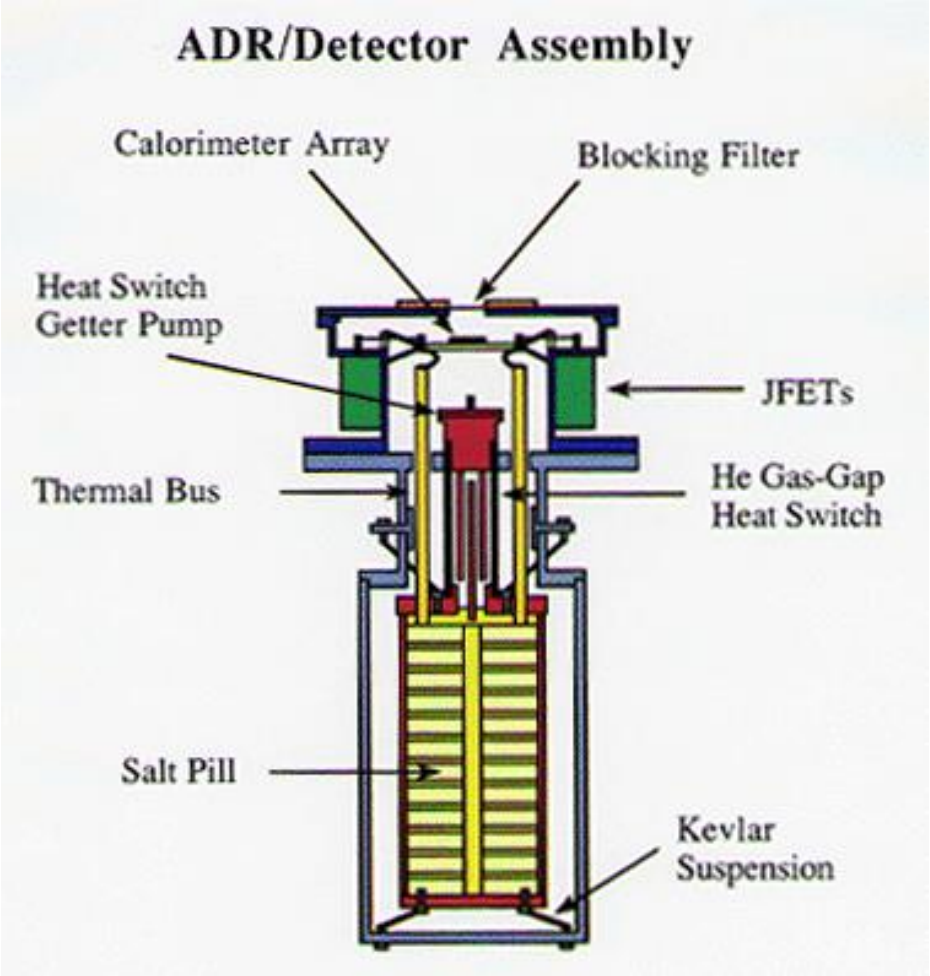
Adiabatic Demagnetization Refrigerator

- This technique makes use of two physical effects
  - In a reversible system with no heat transfer the total entropy remains constant
    - Q = TdS (second law)
  - When exposed to a magnetic field, the magnetic regions of a paramagnetic material become more ordered and thus lower in entropy
- In effect, the ADR transfers entropy between the random thermal vibrations of the paramagnetic material and the alignment of the magnetic regions.
- Note that in order for this to work, the entropy in the magnetic ordering and that of thermal vibrations must be about the same. Thus this only works below ~ 2 - 4 K
- An ADR typically consists of a paramagnetic solid or “salt pill”, magnet, heat sink (typically a <2 K), a thermal switch and item to be cooled

ADR Process

- The ADR process is cyclic
  - Step 1: The thermal switch is off and the magnet is turned on. As the field is increased, the magnetic regions in the solid start to align and the entropy of these regions decreases. In order to keep the overall entropy constant, the entropy in the thermal vibrations increases (and thus the temperature increases)
  - Step 2: Next the thermal switch is connected and heat is transferred from the solid to the heat sink while the magnetic field is held constant. This reduces the temperature of the solid back to near its starting point.
  - Step 3: The thermal switch is now closed isolating the solid and the magnetic field is now reduced. This is the adiabatic demagnetization portion of the cycle. As the magnetic field is reduced the paramagnetic regions become more disordered and absorb entropy from the thermal vibrations resulting in a cooling of the paramagnetic material and of the object being cooled.

Example of an ADR System



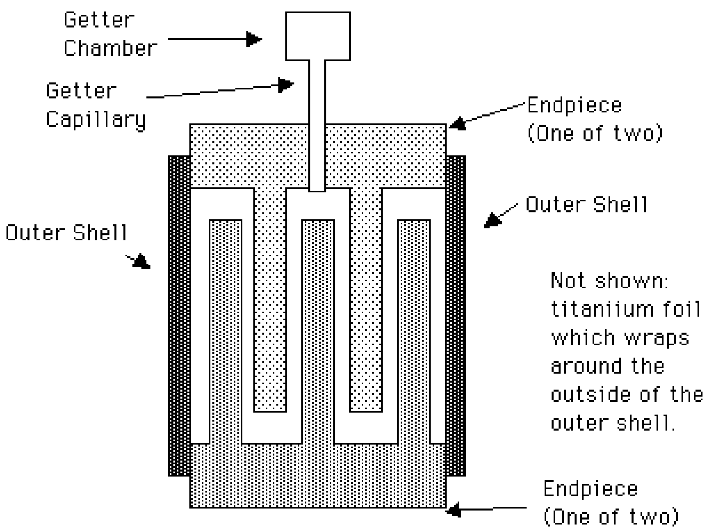
From NASA Goddard
Used in XRS Satellite
60 mK for 30 hours (5 μW)
Thermal Sink is 1.3 K He Bath

Note that ADRs are very popular in space systems as Dilution Refrigerators are difficult to use in Zero g

ADR Components

- Paramagnetic Salt Pill materials
  - Gadolinium Gallium Garnet (GGG)
  - Ferric Ammonium Alum (FAA)
- Heat Switches
  - Gas gap – the He gas provides the thermal contact. The switch is opened by absorbing the gas into a getter material This is done by allowing the getter to cool down. Heating the getter back up releases the gas and "closes the switch"
- Magnets
  - The ADR magnets are small superconducting solenoids at roughly 1 – 5 T

Heat Switch Cross Section Schematic



Courtesy NASA Goddard

Continuous Cooling

- Both ADRs and ^{3}He sorption coolers are batch cooled systems.
- Continuous cooling may be achieved by putting such systems in parallel

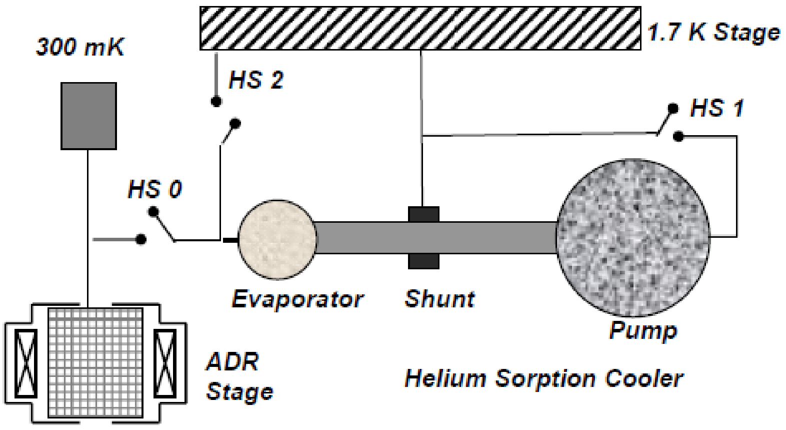


FIGURE 2. Schematic of the 300 mK continuous cooling prototype

From " 300 mK Continuous Cooling, Sorption ADR System"
Duval et al. Adv. Cryo Engr. Vol. 55 (2010)

Can We Go Even Colder?

- Nuclear Demagnetization Refrigeration
  - Essentially the same as ADR but aligns magnetic dipoles in the nucleus
  - This can get us down into the μK to 100s of pK region but require higher magnetic fields and a starting point (heat sink) in the mK range.