Dilution Refrigerator — Attaining milli-Kelvin range of temperatures

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Abstract

Research at low temperatures is an extremely fruitful field because of the many phenomena that occur only there. Unusual phases of matter such as superconductors and superfluids occur at low temperatures and many subtle behaviors that are obscured by thermal motion at higher temperatures can be studied in great detail at low temperatures.
To carry out research at low temperatures it is necessary to have a refrigerator that cools down to the required temperature, is reliable, operates continuously for days or weeks as long as the experiment continues and can be automated.
On ground this need is almost universally fulfilled by the $He_3 - He_4$ dilution refrigerator(DR). It is the most common method for reaching temperatures in the order of $\sim 0.01K$. It relies on the unique properties of $He_3 - He_4$. Cooling to 0.01 K and below is produced when the He_3 atoms cross the phase boundary that exists between the liquid He_3 and liquid He_4 at low temperatures (essentially He_3 evapourates into He_4).

1 Introduction

Before we can understand the working of the DR we need a brief idea about the properties of $He_3 - He_4$ mixture. Helium is the only element in nature that remains a solid down to absolute zero. This is a consequence of the weak van der Waals interaction between the atoms and the large kinetic energy at low temperatures. The latter arises from the zero-point motion, a purely quantum mchanical effect, that is particularly large in Helium due to the small atomic mass.
There are two stable isotopes of Helium – He_4 - which follows Bose-Einstein statitics and He_3 - which follows the Fermi-Dirac statistics to two paired protons. The influence of the statistics of the Helium atoms becomes important at temperatures slightly below the boiling point ($\sim 4K$). Since the interaction between the two Helium atoms is relatively simple, liquid Helium is well suited for studying the quantum mechanical effects – both theoritically and experimentally. An example would be some of the heavy fermion materials which are superconducting only below 1K and so the experiments have to be done with the help of a dilution refrigerator.

2 Phase diagram of a liquid Helium mixture

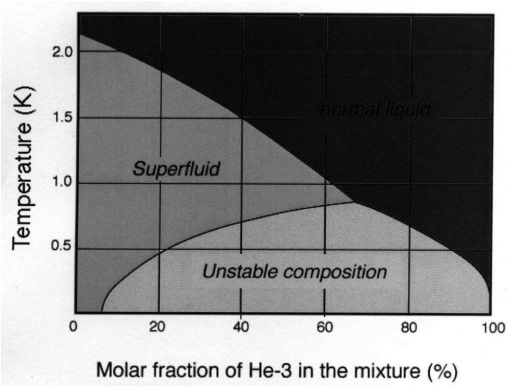

Figure 1: *Molar fraction of He_3 in the mixture (%) – fig. has been downloaded from na47sun05.cern.ch*

Fig. 1 and Fig. 2 show that dilution cooling can take place only below the highest temperature of unstable composition,the tri-critical point. The mixture can be a normal liquid, a fermi liquid, a superfluid or a stratified combination depending on the average concentration and temperature.

This character of the mixture led F. London (around 1950) to first suggest the principle of the DR - he noticed this very important fact that a liquid mixture of $He_3 - He_4$ would undergo a phase transition at temperatures below 1K.

Liquid mixtures of $He_3 - He_4$ form a single phase with any degree of concentration at temperatures down to 0.87K. Below that temperature some concentrations become unstable and separate into two distinct phases (as shown before). The concentrated He_3 rich phase floats on the denser dilute He_4 rich phase with a visible interface between them. The concentrations in the two phases are functions of temperature and pressure, and at zero

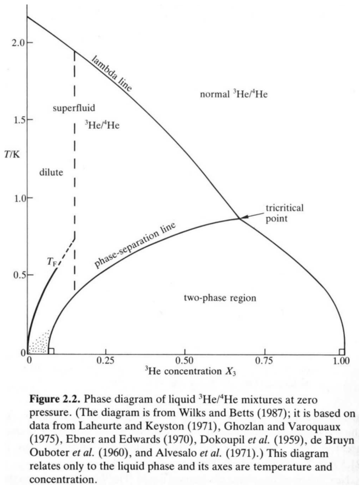

Figure 2: *The phase diagram of liquid $He_3 - He_4$ mixtures in equilibrium with their vapour [1]*

temperature and pressure the concentrated phase is pure He_3 whereas the dilute phase contains about 6% of He_3.

3 Principle / Working of a Single-Cycle Dilution Refrigerator

The lowest temperature occur in the mixing chamber where there is a phase boundary between the liquid $He_3 - He_4$. Cooling is produced when He_3 crosses this boundary into the He_4. From the mixing chamber this dilute He_3 flows through the He_4 to a higher temperature chamber where it is fractionally distilled from the He_4. The resulting He_3 gas is collected by the charcoal pump. The cooling cycle ends when all the He_3 is in the charcoal pump. Because the refrigerator uses adsorption onto charcoal for its pumping, all operations can be controlled by heaters and, as a result there are no moving parts in the refrigerator.

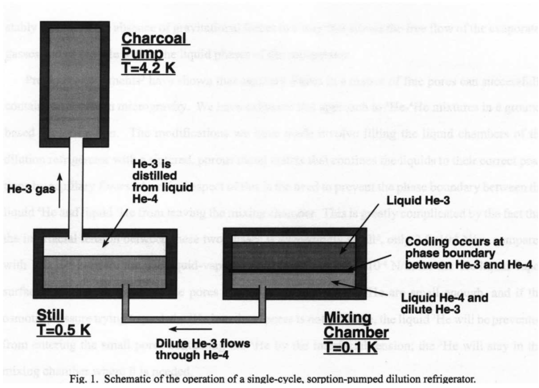

Figure 3: *Operation of a compact single cycle DR using a charcoal pump [2]*

4 Principle / Working of a Continuously-Operating DR

The working time limitation of the above DR has led to the increasing use of this slightly moified DR. It directly cools to 0.040K in a microgravity envoirnment. It can also precool an adiabatic demagnetization stage for reaching temperatures of 0.001K and below.
Fig. 5 shows the configuration.The still and the mixing chamber of this design are similar to those of the single-cycle refrigerator. The dilute He_3 flows out of the mixing chamber into the *still* as before but the He_3 gas, instead of being pumped from the *still* into a charcoal pump goes into a new chamber, the *condenser*, at 0.4K, where it condenses back to liquid and pure He_3 returns to the *mixing chamber* ie; this He_3 never leaves the low temperature region. As long as the *still* is heated to maintain its temperature at 0.6K and the *condenser* is cooled to maintain its temperature at 0.4K, He_3 will be continuously pumped from the *still* into the *condenser* and forced back into the *mixing chamber*. This continuous circulation of He_3 will produce continuous cooling in the *mixing chamber* where He_3 crosses the phase boundary from pure He_3 to He_4.
The notable feature of this design is the method by which the *condenser* is continuously cooled (while maintaining the advantages of compactness, reliability and complete absence of moving parts). The *condenser* is cooled by a pair of independent, single cycle He_3 refrigerators (see Fig. 5), each with its own charcoal pump, and each thermally linked to the *condenser* by a gas-gap heat switch. While one He_3 pot is cold and coupled to the *condenser*, the other He_3 pot is isolated from the *condenser* while it is being refilled at high temperature. Then, before the first He_3 pot runs empty, the second He_3 pot would be cooled down and coupled to the *condenser* by its heat switch. The first He_3 pot could then be decoupled and refilled and there would have been no interruption of the cooling to the *condenser*.

5 Modification for microgravity - why required ?

On the ground the operation of a DR depends on gravity to keep the liquid He_3 and He_4 in their correct chambers (the charcoal pump contains no liquid and is gravity independent). Within the DR there are two liquid-vapour interfaces and one liquid-liquid interface. All of these interfaces must be stably located in the absence of gravitational forces in a way that allows the free flow of the evaporated gases and of the He_3 within the liquid phases of the refrigerator. Since capillary forces in a matrix of fine pores can successfully contain liquid Helium in microgravity, so the liquid chambers of a DR are filled with a sintered, porous metal matrix that confines the liquids to their correct positions by capillary forces. A critical aspect of this is the need to prevent the phase boundary between the He_3 - He_4 from leaving the *mixing chamber* which is done by suitably orienting the set-up and by regulating pore size and osmotic pressure (which tries to push the He_3 into the pores).

Actual photographs of a DR (all taken from www.hmi.de) are shown below.This gives us a feel of the experimental system and setup being discussed in this paper.
Also figure 10 shows the schematic diagram of the general working of the DR for a side by side comparision and better understanding.

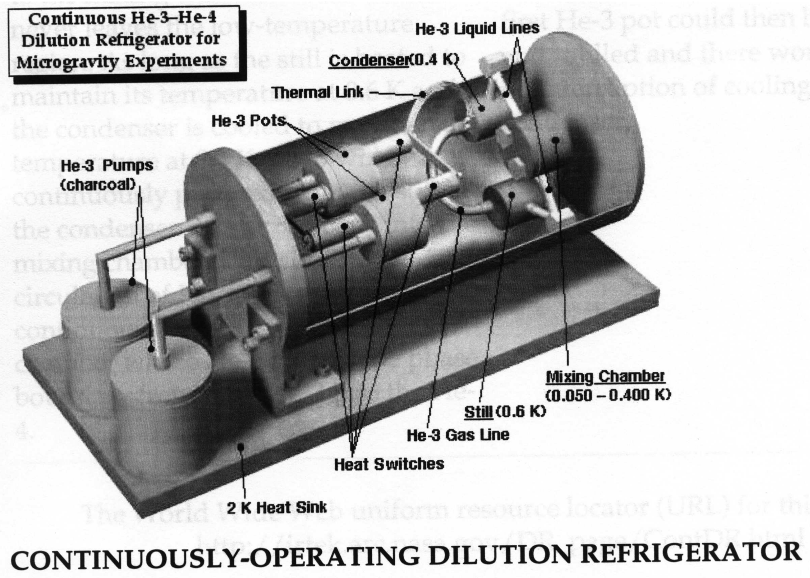

Figure 4: *Continuously-Operating DR [2]*

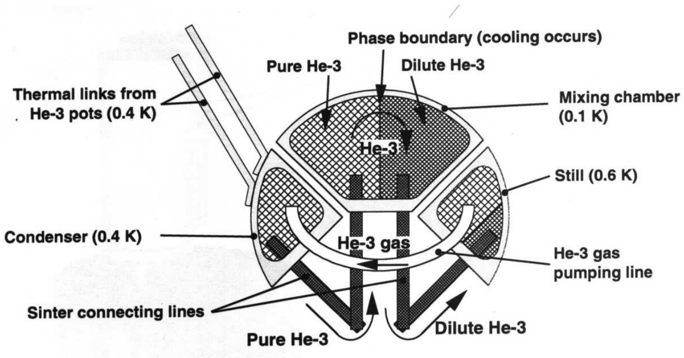

Figure 5. Details of the low-temperature chambers of the continuously-operating dilution refrigerator.

Figure 5: *Details of the low-temperature chambers of the continuously-operating DR [2]*

6 Advantages

1.It can operate continuously for days or weeks.
2.When operated with sorption pumps it is small and light.
3.It has no moving parts to wear out - its lifetime is unlimited.
4.It produces no vibrations.
5.Its operation can be completely automated by the use of computer controlled heaters.
6.Its thermal efficiency is relatively high and it does not reject large amounts of heat at higher temperatures.

7 Acknowledgements

I wish to acknowldge my gratitude to Prof. R. Newrock for suggesting me this exciting topic and for his useful suggestions and discussions and also Prof. M . Jarrell for his constant encouragement both inside and outside the class. I also researched a lot of articles

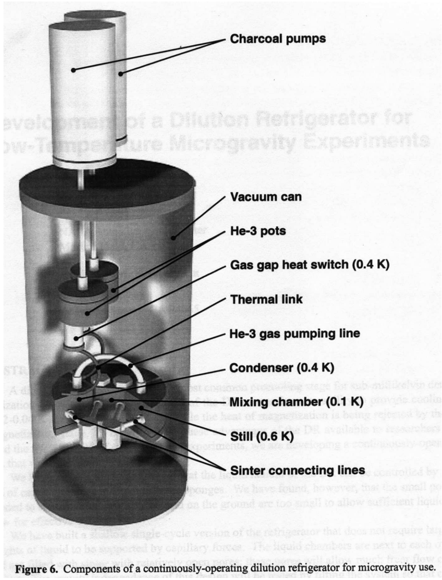

Figure 6: *Components of a continuously-operating DR [2]*

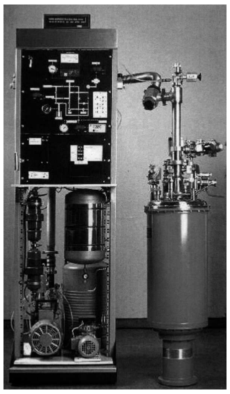

Figure 7: *Dilution Refrigerator*

on the web on this topic and would like to specially mention the Ames Research Centre (NASA)at irtec.arc.nasa.gov and also the website na47sun05.cern.ch .

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[3] P.R.Roach and P.B.M. Helvensteijn, 16th Space Cryogenics workshop held in Quebec City, Canada, July 11-12, 1999(proceedings to be published in a special issue of the

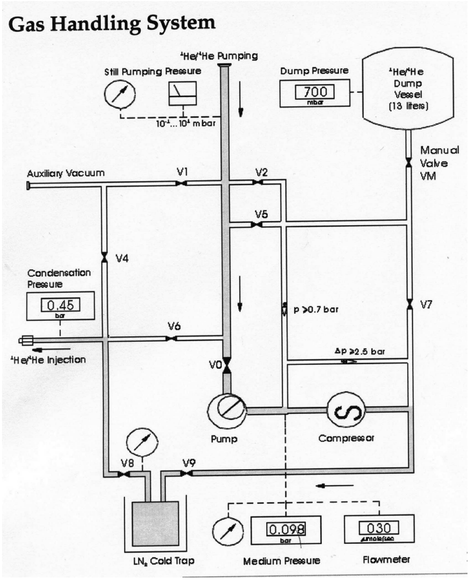

Figure 8: *Gas handling system for the DR*

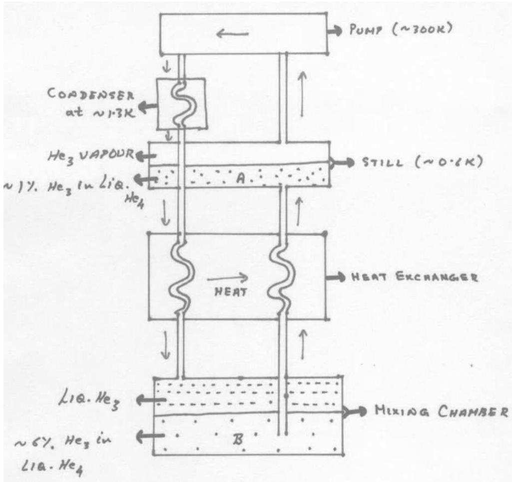

Figure 9: *Schematic diagram of the DR*

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