Cooling Below 4.2 K
1. Evaporative Cooling
2. Dilution Refrigeration
3. Heat exchangers
4. Pomeranchuk Cooling
5. Adiabatic Demagnetization Refrigeration
6. Acoustic/Pulse Tube Refrigeration
7. Laser Cooling

Evaporative Cooling
Latent heat (also known as enthalpy change of vaporization)
Change in energy as system particle goes from liquid state to vapor state
\[ p^* \text{ is the vapor pressure} \]
\[ \Delta H \text{ is the heat of vaporization (kJ/mole)} \]
\[ R \text{ is the gas constant} \]
\[ T \text{ is the temperature (Kelvin)} \]
\[ B \text{ depends on the substance} \]
- Responsible for cooling by sweating
- Building AC
- Power Plant Cooling

Energy Distribution of Atoms in Equilibrium at Two Temperatures

Phase Diagram of H₂O

Vapor Pressure of Water

Refrigeration Methods for Very Low Temperatures

Latent heat (also known as enthalpy change of vaporization)
Change in energy as system particle goes from liquid state to vapor state
\[ p^* \text{ is the vapor pressure} \]
\[ \Delta H = \frac{\Delta H}{RT} + B \]
\[ \text{Sprinklers} \]

Fig. 2. Evaporative cooling. The graph shows the distributions of the kinetic energies of atoms at an initial temperature \( T_0 \) and at a lower temperature \( T_1 \). After the removal of the distribution at \( T_0 \), collisions among the atoms cause the gas to rethermalize to the lower temperature \( T_1 \).
Evaporation Cryostats

Principle of Operation
Technical Realization
Cooling Power

Evaporation Cryostats

Principle of Operation

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Continuous Filling pot

Evaporation Cryostat–Principle of Operation

4He

Evaporation Cryostats

Continuous

Single-Shot

4He pump

4He at 4.2 K

Impedance

4He bath at ~1.3 K

Thermal anchor

Return capillary

3He bath at ~0.3 K

Space for experiments

Evaporation Cryostats

4He

Single-Shot

Continuous

Pumping on Bulk Liquid

Capable of reaching temperatures of
about 300 mK in 3He and approx 1 K in 4He
Main disadvantage is that the amount of liquid 4He is reduced by close to 50% to reach 1 Kelvin
Used in cascade to reach lower temperatures

Evaporation Cryostats–Cooling Power

Clausius-Clapeyron Equation

\[ \frac{dp}{dT} = \frac{L}{\Delta VT} \]

\[ Q = n_L \times p \times e^{-L/RT} \]

\[ \ln p = -\frac{\Delta H}{RT} + B \]

\[ p_v = p_0 e^{-\frac{\Delta H_v}{RT}} \]

Minus sign in exponential implies lowering p leads to lowering T—many ways to accomplish this

- Bulk liquid: Pumping the vapor away from above the liquid, induces more liquid to vaporize, thus cooling the liquid
- Mechanical - Adsorption - Turbo molecular - Diffusion pumps

BECs: Remove atoms from magnetic trap using rf field
Dilution Refrigeration—What an Idea!
Proposed by Heinz London in 1951 (Later at Duke University).

Enthalpy (pure $^3\text{He}$) $<$ Enthalpy (dilute phase)
Like “expanding” $^3\text{He}$ into the dilute phase—
a mechanical vacuum

Where is the Cooling Power?
Define:

- Enthalpy (pure $^3\text{He}$) = $H_3$
- Enthalpy (dilute phase) = $H_D$

Circulation rate of $^3\text{He}$ = $n$

What is the cooling power of an ideal dilution refrigerator?

- A. $n$
- B. $n H_3$
- C. $n H_D$
- D. $n (H_3 - H_D)$
- E. $n H_D - H_3$

$Q = 82 n T^2$ watts

Dilution Refrigeration Development
1965—Das, DeBruyn, & Taconis (Leiden)
T = 220 mK
--Hall et al (England) T $\approx$ 50
1966--Neganov (Russia) T $\approx$ 50 mK
1998—Lowest recorded temperature by dilution refrigeration is 1.7 mK (Cousins et al–Lancaster).
Can have enormous cooling power: 1 µW at 10 mK
Can cool tons of matter—CERN
Can cool quickly-- few hours from room temperature

Remember the Phase Diagram
- $^3\text{He} / ^4\text{He}$ mixture at low temperature
- Phase separation for more than 6.5% $^3\text{He}$ in $^4\text{He}$
- Phase separation for more than 6.5% $^3\text{He}$ in $^4\text{He}$
- Light phase: 100% $^3\text{He}$
- Higher entropy in heavy phase
- $\Rightarrow$ Transfer of $^3\text{He}$ from light to heavy phase similar to evaporation

Image from: www.cresst.de
How many places in a standard dilution refrigerator use evaporative cooling?
A. One  
B. Two  
C. Three  
D. Four  
E. Five
**Metal/He Thermal Boundary Resistance**

- Acoustic Impedance: \( Z = \rho v \)
  - \( \rho \) density, \( v \) acoustic velocity
- \( Z_{Cu} > Z_{He} \)
- Transmission coefficient for phonons with perpendicular incidence:
  \[ t = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2} \]
- For Cu/He: \( t = 10^{-3} \)
  - High thermal boundary resistance
- Kapitza Resistance \( R_K \approx T^{-3} \)

**Heat Exchangers are the Key**

**Dilution Refrigerator Heat Exchangers**

- Continuous Heat Exchanger
- Step Heat Exchanger

**What does the impedance do below the pot on the condensing line?**

A. Slow down the helium atoms
B. Cause the required pressure drop
C. Allow the required temperature drop for condensation
D. All of the above
E. None of the above

**Counterflow Heat Exchanger**

**Other Parts**
Where is the Cooling Power?
Define:
Enthalpy (pure $^3$He) = $H_3$ < Enthalpy (dilute phase) = $H_D$

Circulation rate of $^3$He = $n$
What is the cooling power of an ideal dilution refrigerator?

A. $n$  
B. $nH_3$  
C. $nH_D$
D. $n(H_3 - H_D)$  
E. $n(H_D - H_3)$

$Q = 82nT_n^3$ watts

Evaporation Vs. Dilution Power
Curves are for the same $^3$He Circulation rate
QUIZ: What is the approximate proportion between $H_3$ and $H_D$ at 0.35 K?

A. $H_3 = H_D$  
B. $H_3 = 0.5 H_D$  
C. $H_3 = 2H_D$

Pomeranchuk Cooling
- Principle of Operation
- Technical Realization
- Cooling Power

Pomeranchuk Cooling--Principle of Operation
\[ \frac{dp}{dT} < 0 \text{ for } T < 0.3K \]
- Entropy of solid $^3$He is higher than that of liquid $^3$He
- Heat of solidification is negative
- Solidifying by applying pressure adiabatically leads to reduced temperature

Pomeranchuk Cooling--Apparatus

Pomeranchuk Cooling--Power
1971 – Superfluidity discovered in 3He (US)

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