50 Shades of Cooling

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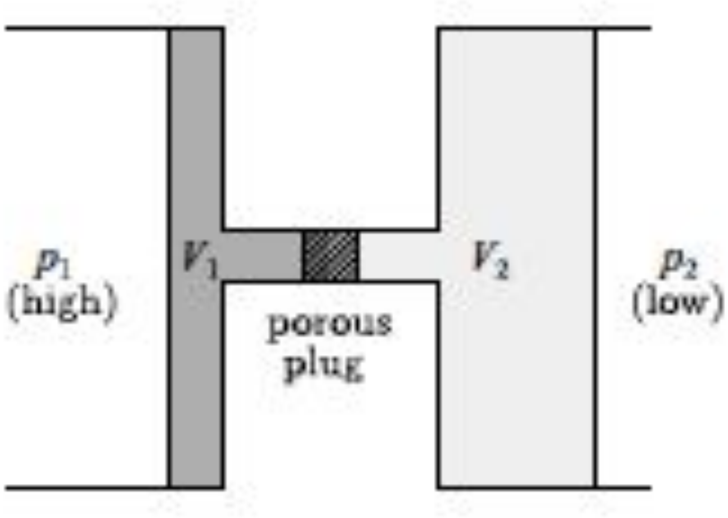
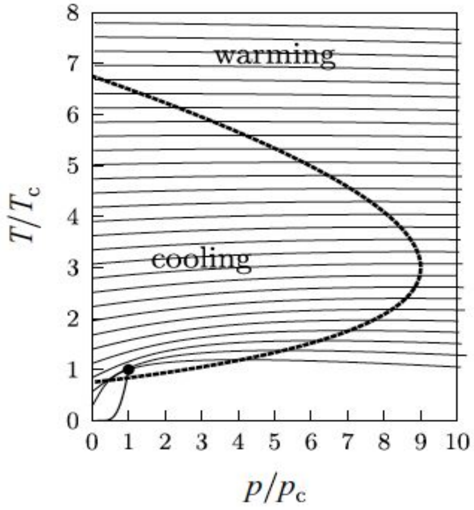
What do we know about cooling already?

Joule-Kelvin Expansion

****Gas slightly cools when it expands into a 2nd evacuated vessel**



$$\Delta T = \int_{p_1}^{p_2} \frac{1}{C_p}\left[T\left(\frac{\partial V}{\partial T}\right)_p - V\right] dp.$$

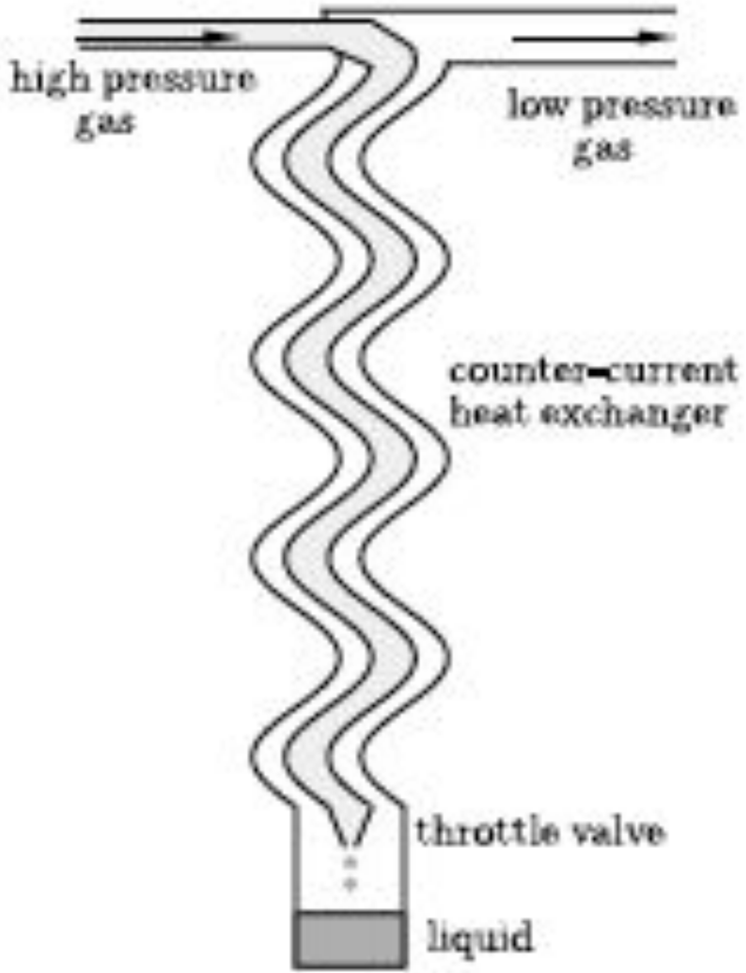


Joule-Kelvin Expansion Applied

^4He	H_2	N_2	Ar	CO_2
43	204	607	794	1275

Gas Liquefier

But we are not satisfied...



Way to 0.1 K: Evaporative Cooling

** Liquid turning gas demands energy

** Pressure ↓, boiling point ↓

He4 ~1K

He3 ~0.3K

Ex. Liquid Helium

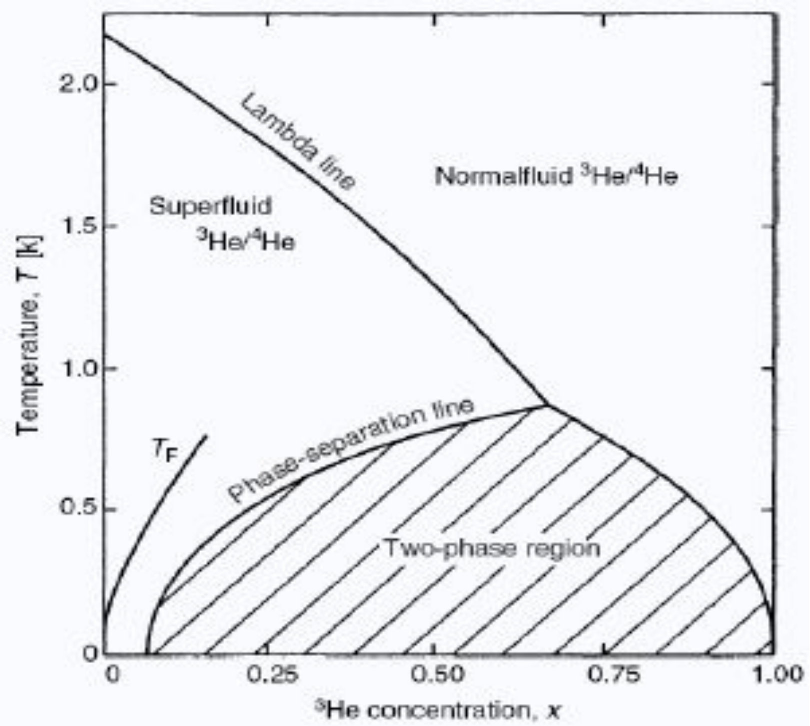
Pump away the vapor to reduce pressure ↠ cool liquid helium through evaporation

But we are not satisfied...

WHY? Fascinatinating phenomenon @ mK, ɰK

March to mK: Helium Dilution Refrigerator

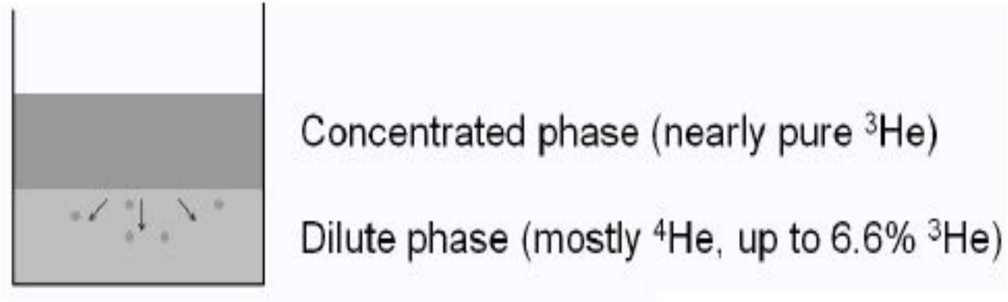
** "Evaporate" pure liquid He3 into He3+4 mixture



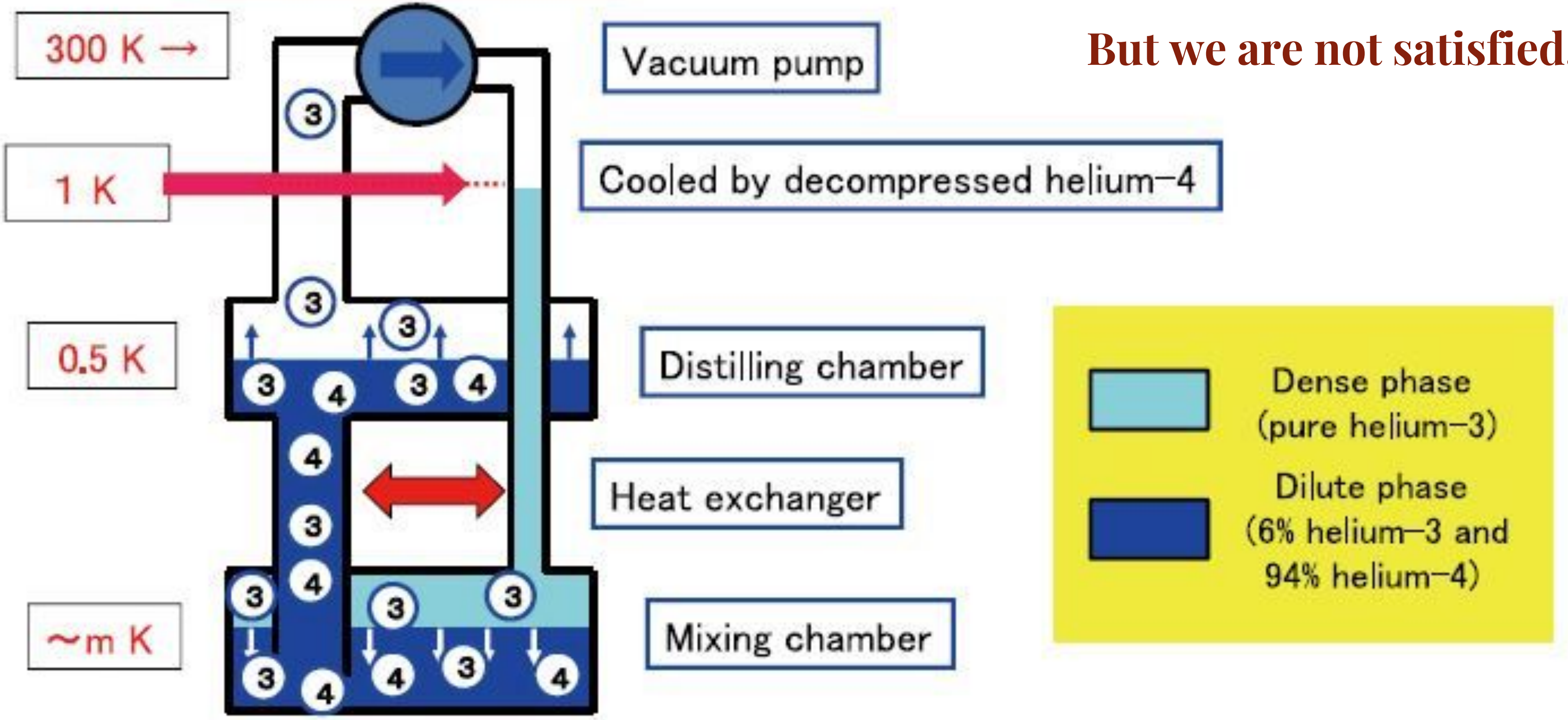
Note that in the dilute phase,

the solubility of 3He = 6.6% even T~ 0 K.

=> Property that allows us to COOL



March to mK: Helium Dilution Refrigerator



But we are not satisfied...

Crawl to ɰK: Magnetic Cooling

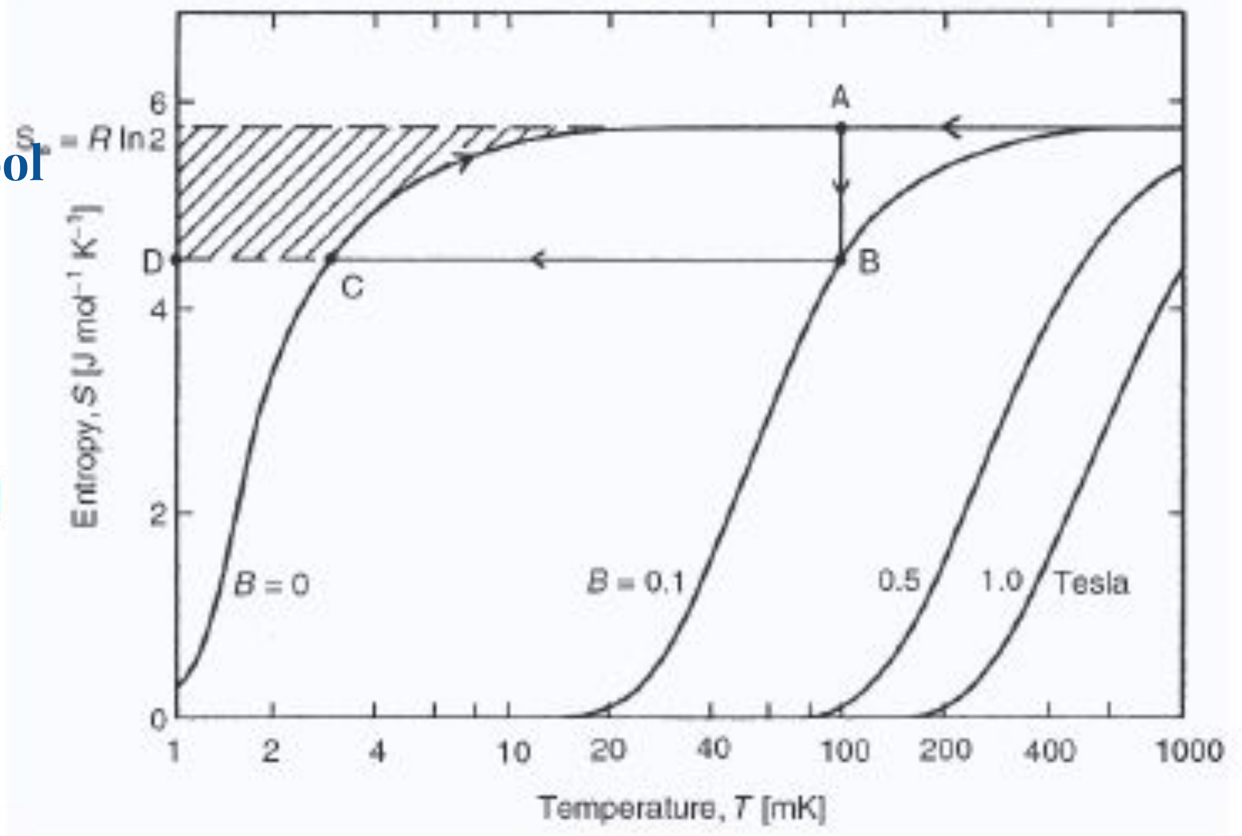
**** Utilize properties of paramagnetic salts to cool**

Concept simplified:

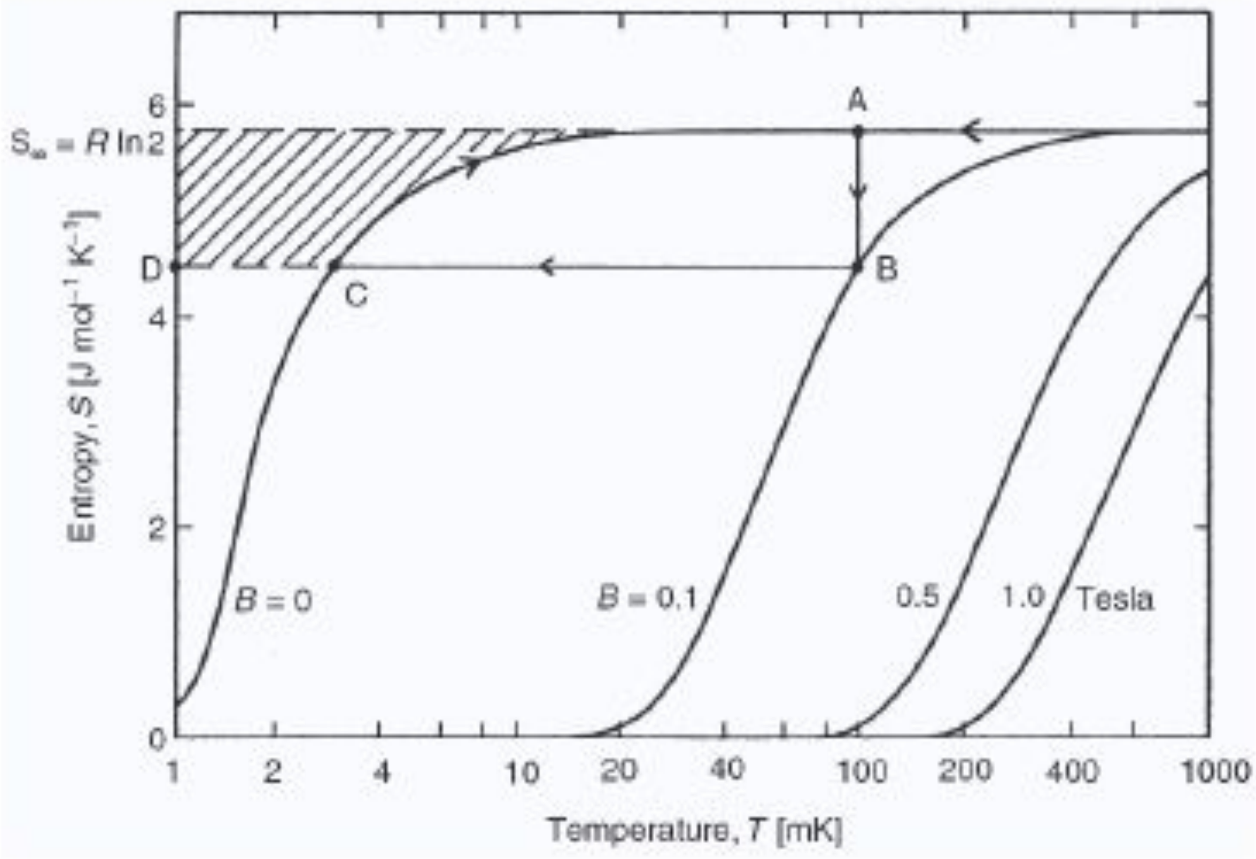
1D Ising Chain

$$S = Nk\left[\ln(e^{2\beta J}+1) - \frac{2\beta J}{1+e^{-2\beta J}}\right]$$

M = Nɰ tanh (ɰB / kT)

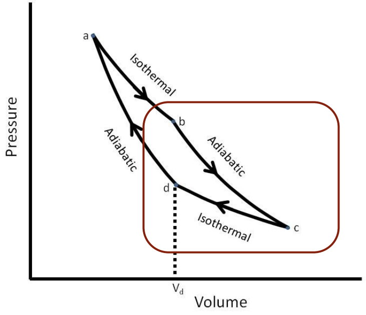


Crawl to ɰK: Magnetic Cooling

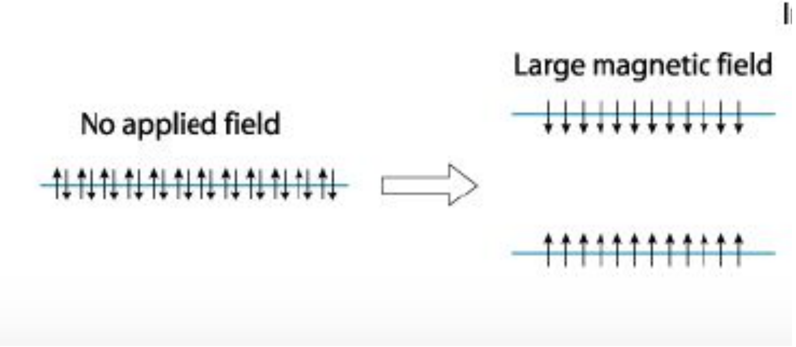


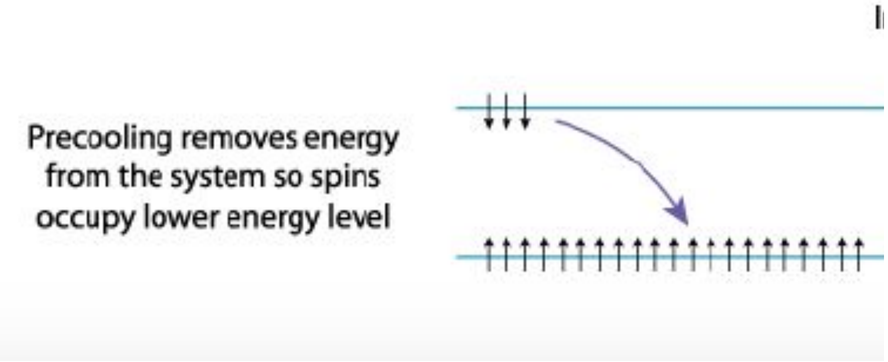
Cooling steps:

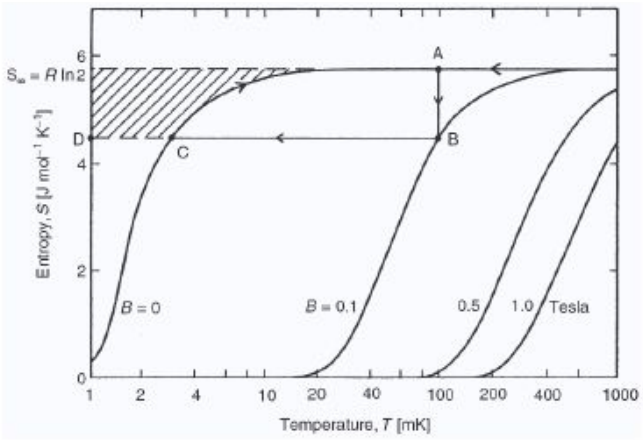
1. Recooling (A)
2. Turn on B-field (A-B)
3. Adiabatic demagnetization (B-C)



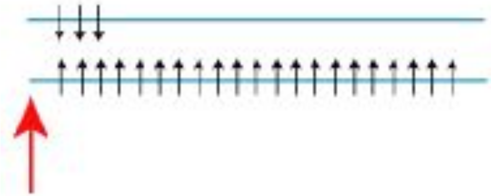
Crawl to μK: Magnetic Cooling (Physical view)







Remove from heat bath



Crawl to ɰK: Magnetic Cooling Improvement

M = Nɰ tanh (ɰB / kT)

Why don’t we turn off B to obtain absolute zero?

Weak dipole interactions stil self-produce a B
Improvement: Nuclear paramagnet

Electronic paramagnet ~1mK

Nuclear paramagnet ~2.8 *10^-7 K (pico)

The Cooling Hierarchy

1. Joule-Kelvin Expansion ~K
2. Evaporation Cooling ~ 0.1K
3. Dilution Cooling (Helium Refrigerator) ~ mK
4. Magnetic Cooling ~ μK ~pK
5. Laser Cooling ~ nK