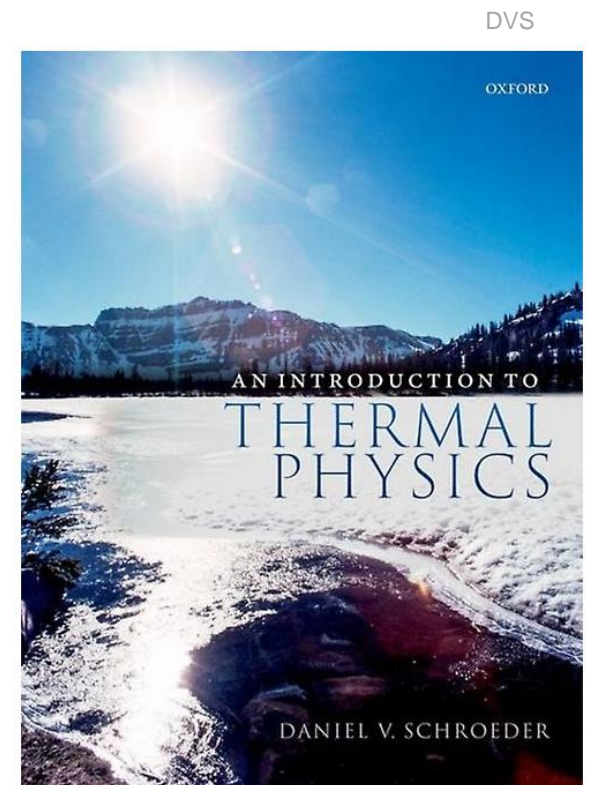


UiO • University of Oslo

Phase transitions of mixtures



Tuesdays: Store fysiske auditorium

Wednesdays: Store fysiske lesesal

- Tuesday September 26
- Wednesday October 4
- Tuesday October 31
- Tuesday November 7
- Wednesday November 8

Tuesdays: 10:15 -12:00

Wednesdays: 12:15 -14:00

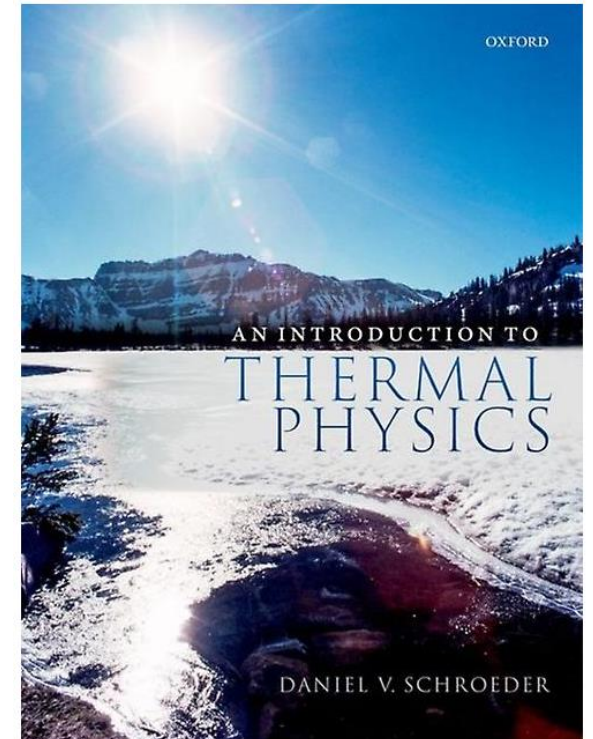
Free energies

Phase transitions of mixtures

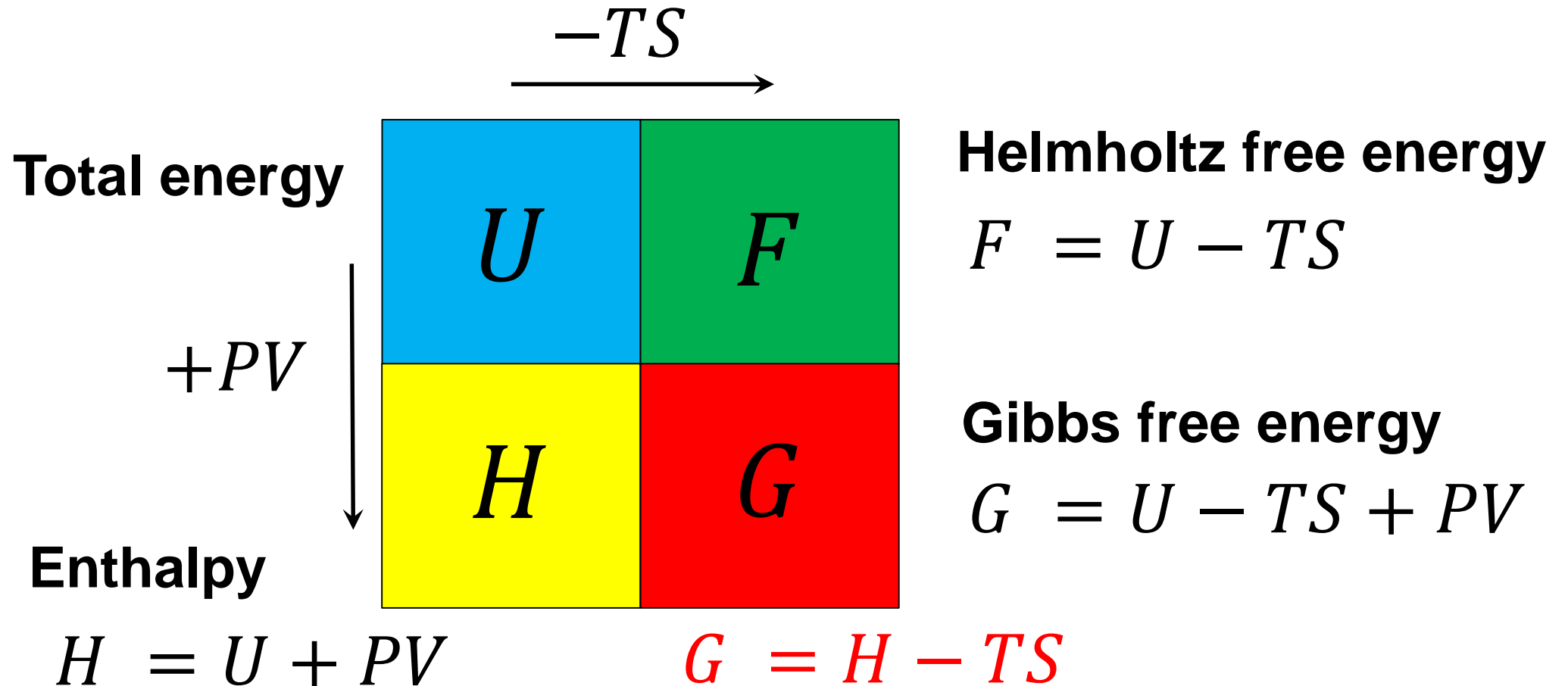
Electron gas

Black body radiation

Specific heat

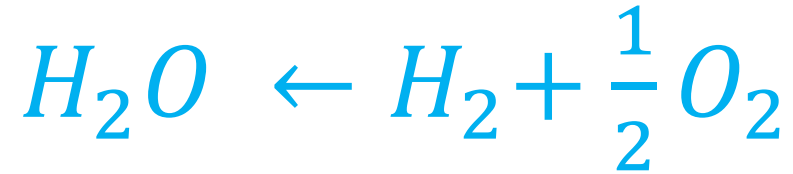


Thermodynamic potentials



By subtracting μN from $U, H, F,$ or $G,$ one can obtain four new thermodynamic potentials. Of the four, the most useful is the grand free energy (or grand potential), $\Phi = U - TS - \mu N.$

Fuel Cell



To heat 1 mole of water to 100 °C one needs 40.7 kJ.

4 kJ

$$G = U - TS + PV = H - TS$$

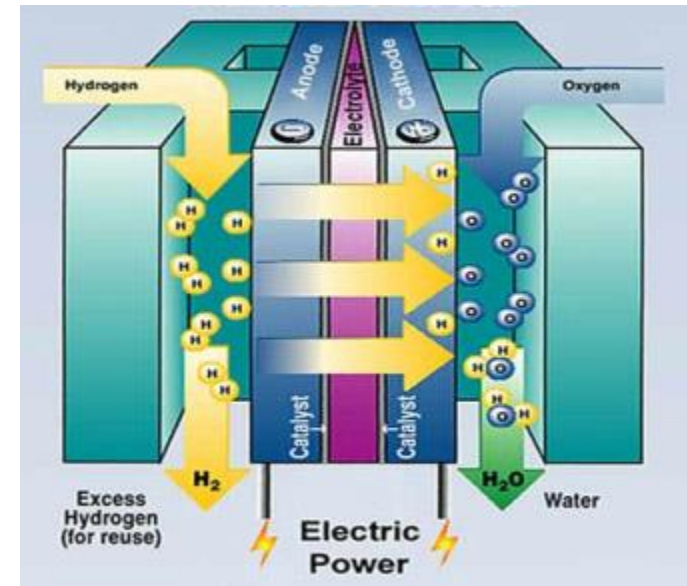
$$\Delta G = \Delta U - T\Delta S + P\Delta V$$

$$\Delta G = \Delta H - T\Delta S$$

$$237 \text{ kJ} = 286 \text{ kJ} - (298 \text{ K})(163 \text{ J/K}).$$

$$S_{H_2O} = 70 \text{ J/K}; S_{H_2} = 131 \text{ J/K}; S_{O_2} = 205 \text{ J/K}.$$

Ideal hydrogen fuel cell has an “efficiency” of 83%, much better than any practical heat engine.



Evaporation of liquid nitrogen

$$\Delta G = \Delta H - T\Delta S$$

Element	Nitrogen
Molar Heat Capacity	20.8 J K ⁻¹ mol ⁻¹
ΔS Standard Molar Entropy	153.3 J K ⁻¹ mol ⁻¹
Enthalpy of Fusion	0.72 kJ mol ⁻¹
ΔH Enthalpy of Vapourization	5.577 kJ mol ⁻¹

$$\Delta G = \Delta H - T\Delta S \quad 5.577 - 0.1533 \cdot 298 = -40,1064 \text{ (kJ mol}^{-1}\text{)}. \text{ Yes}$$

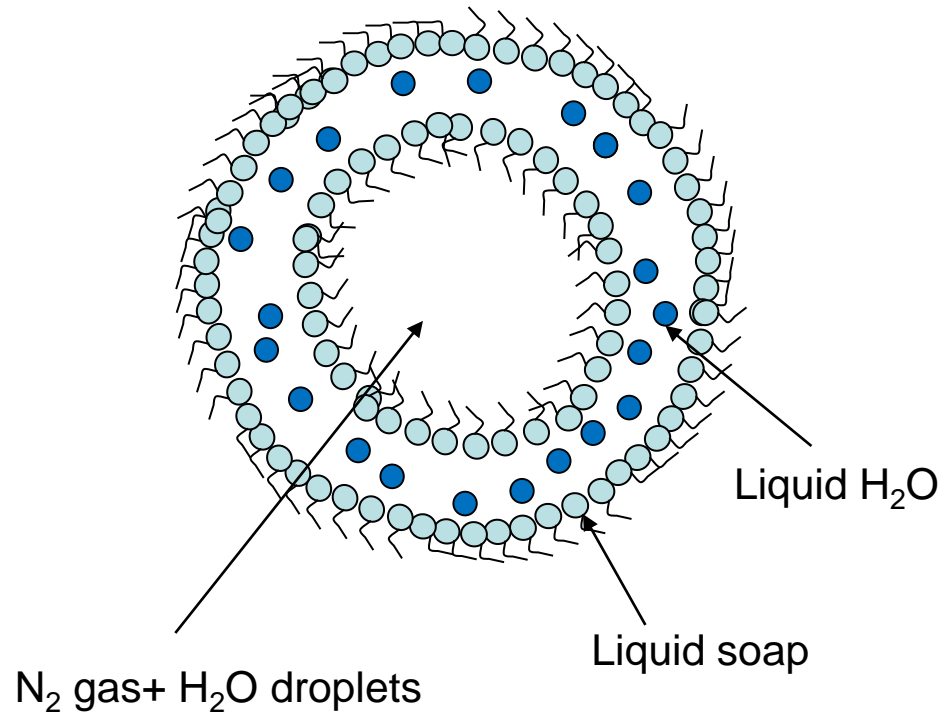
$$T = \Delta H / \Delta S \quad 5.577 / 0.1533 = 36,4 \text{ (K)}$$

$$T = 2 * \Delta H / \Delta S \quad 2 * (5.577) / (0.1533) = 72,8 \text{ (K)}$$

To heat 1 mole of water to 100 °C one needs 40.7 kJ.

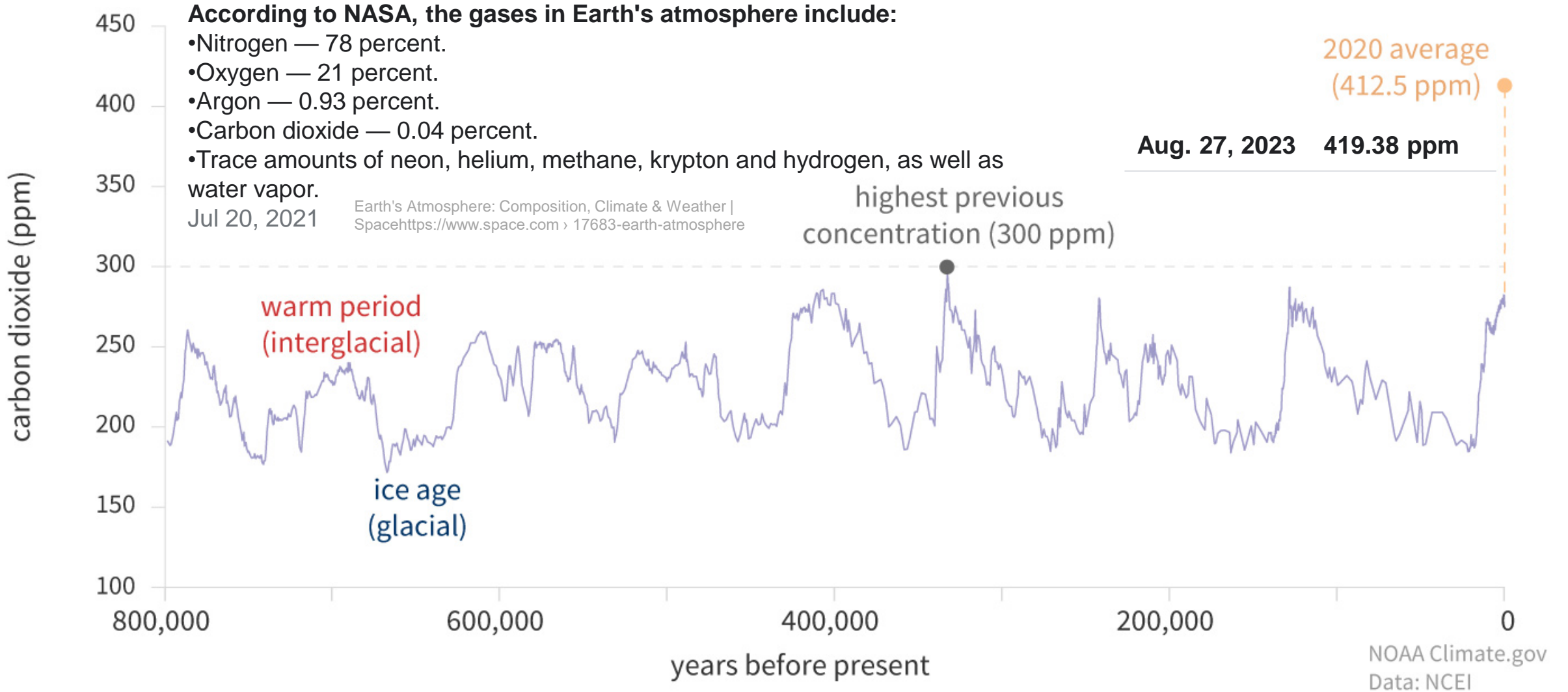
$$\Delta G = 2 * \Delta H - T\Delta S \quad (2 * 5.577) - 298 * 0.1533 = -34,5294 \text{ (kJ mol}^{-1}\text{)} \text{ Yes}$$

Soap-water mixture



Frozen soap bubble on snow at $-7^{\circ} C$ ($19^{\circ} F$)

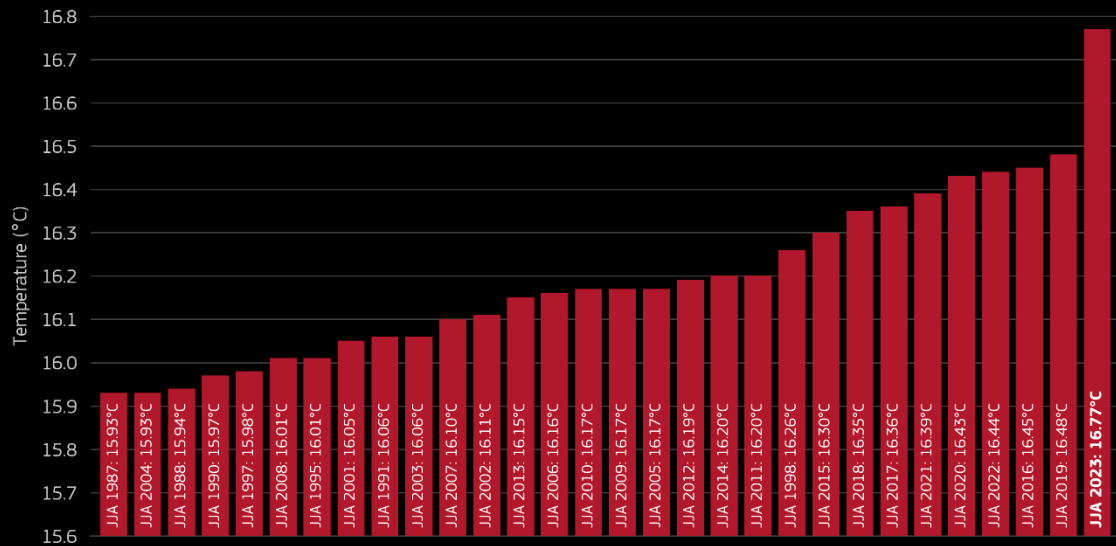
CARBON DIOXIDE OVER 800,000 YEARS



Global warming

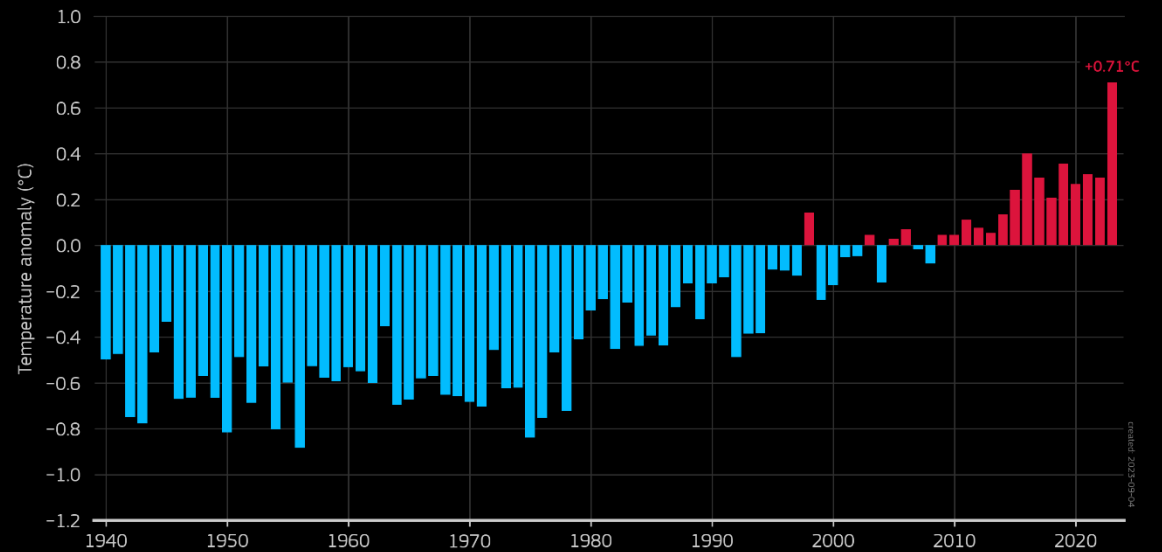
THE 30 WARMEST BOREAL SUMMERS (JJA) GLOBALLY

Data: Global-mean surface air temperatures from ERA5 • Credit: C3S/ECMWF



GLOBAL SURFACE AIR TEMPERATURE ANOMALIES • AUGUST

Data: ERA5 • Reference period: 1991-2020 • Credit: C3S/ECMWF



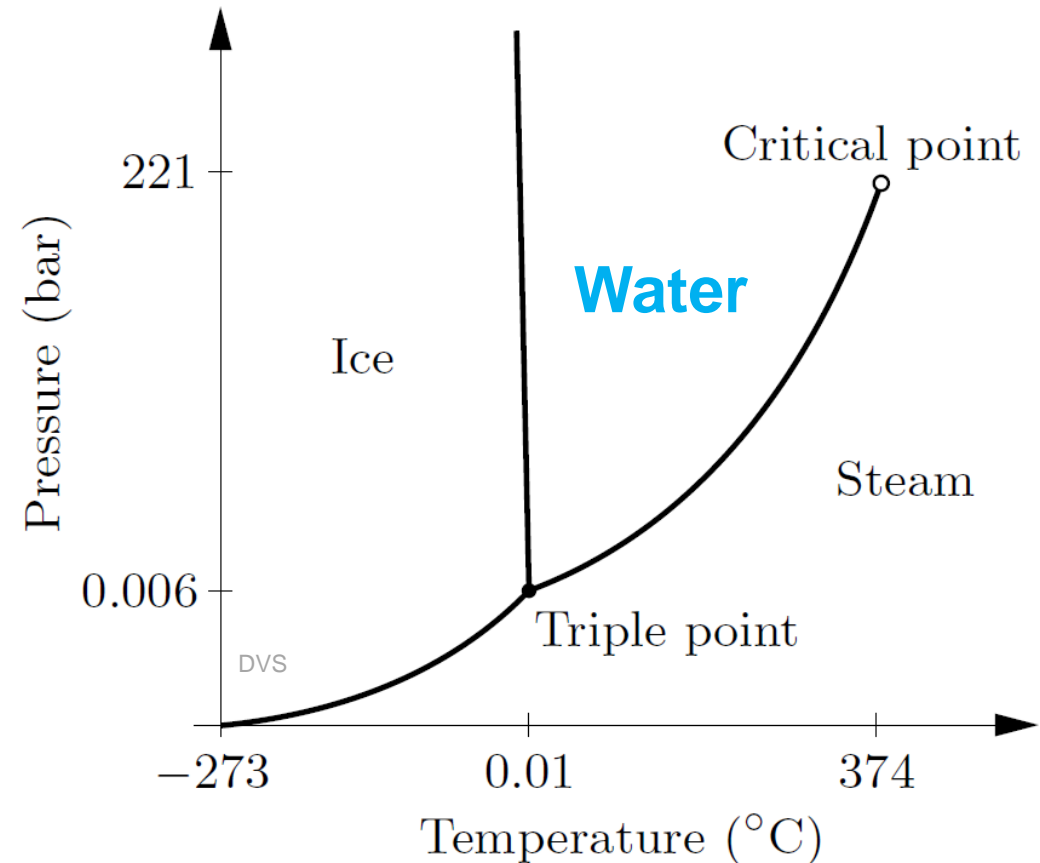
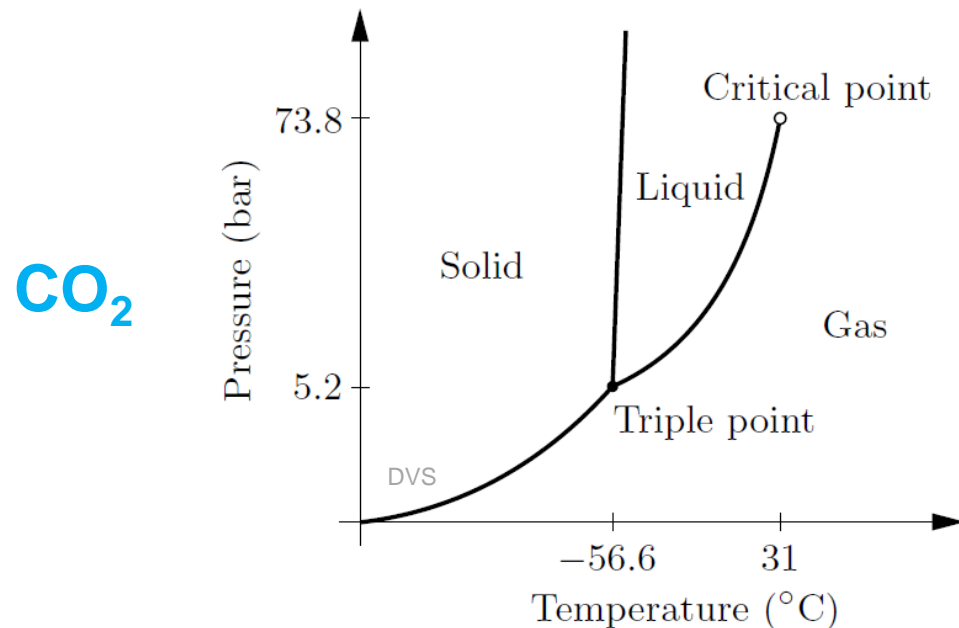
Mixture of gases: physiological effects of CO₂ at various concentrations by volume

0.03%	Nothing happens, it is the normal carbon dioxide concentration in air.
0.5%	Lung ventilation increases by 5 percent, maximum safe working level.
1.0%	Feeling hot and clammy, lack of attention to details, fatigue, anxiety, clumsiness and loss of energy, 'jelly' legs.
2.0%	Lung ventilation increases by 50 percent, headache, loss of energy, feeling run-down. It may take up to several days for the body to return to normal.
3.0%	Lung ventilation increases by 100 percent, panting, headache, dizziness and possible vision disturbance such as speckled stars.
5 - 10%	Violent panting, fatigue to the point of exhaustion, severe headache, irreversible effects to health. Possible unconsciousness and death.
10 - 15%	Intolerable panting, severe headaches and rapid exhaustion. Unconsciousness and suffocation without warning. A burning paraffin candle is extinguished.
25% to 30%	Coma and convulsions within one minute of exposure. Certain death.

Phase Diagrams of Pure Substances

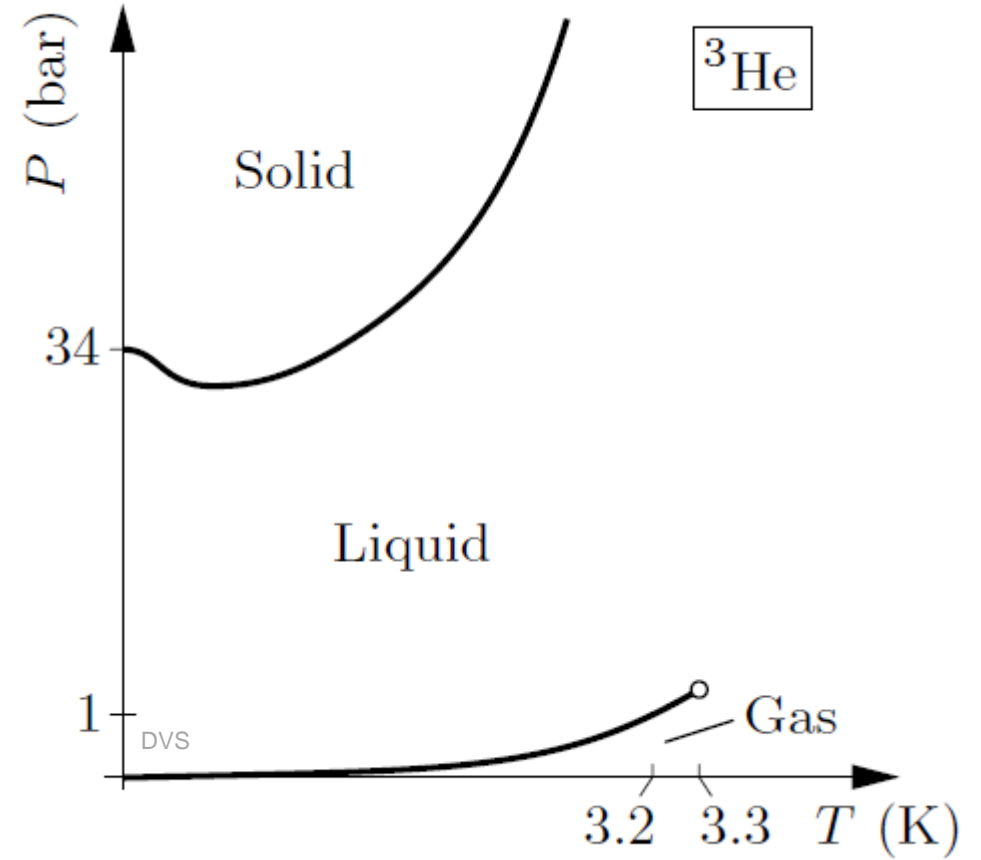
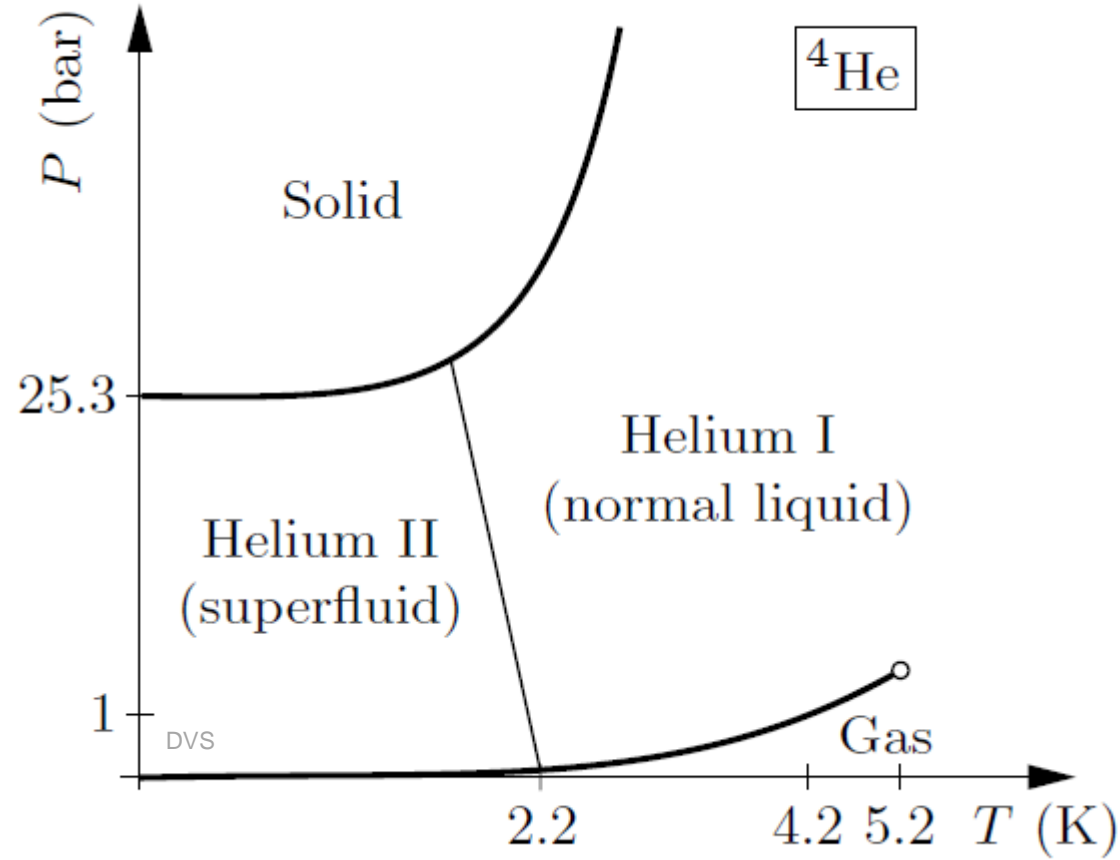
A graph showing the equilibrium phases as a function of temperature and pressure together with the lines of **phase transformations** is called a **phase diagram**.

A phase transformation is a **discontinuous change in the properties of a substance**, as its environment is changed infinitesimally.

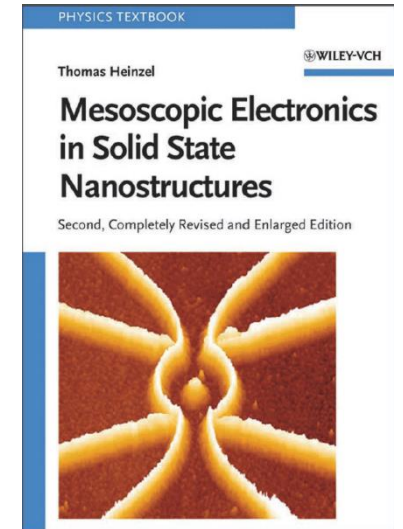
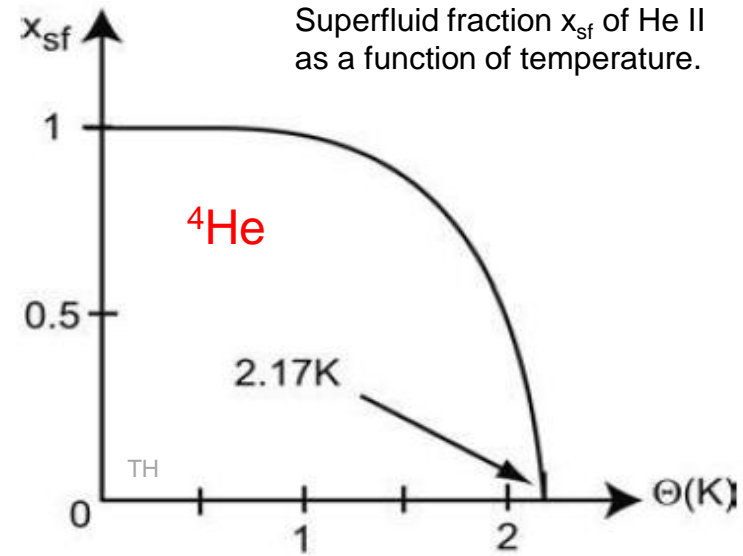
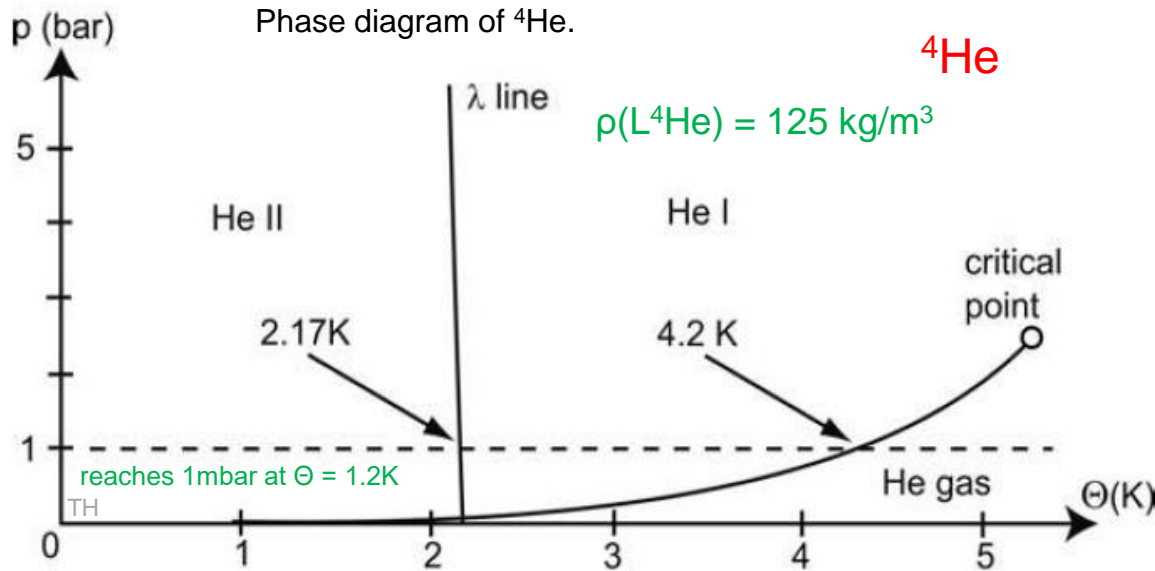


The liquid-gas phase boundary always has a positive slope.

Phase diagrams of helium



Properties of liquid helium



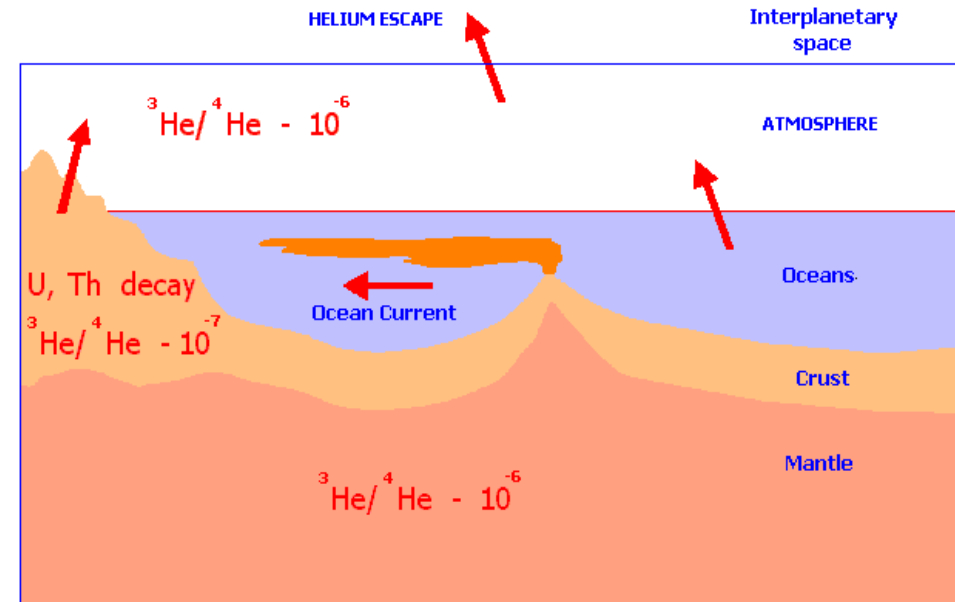
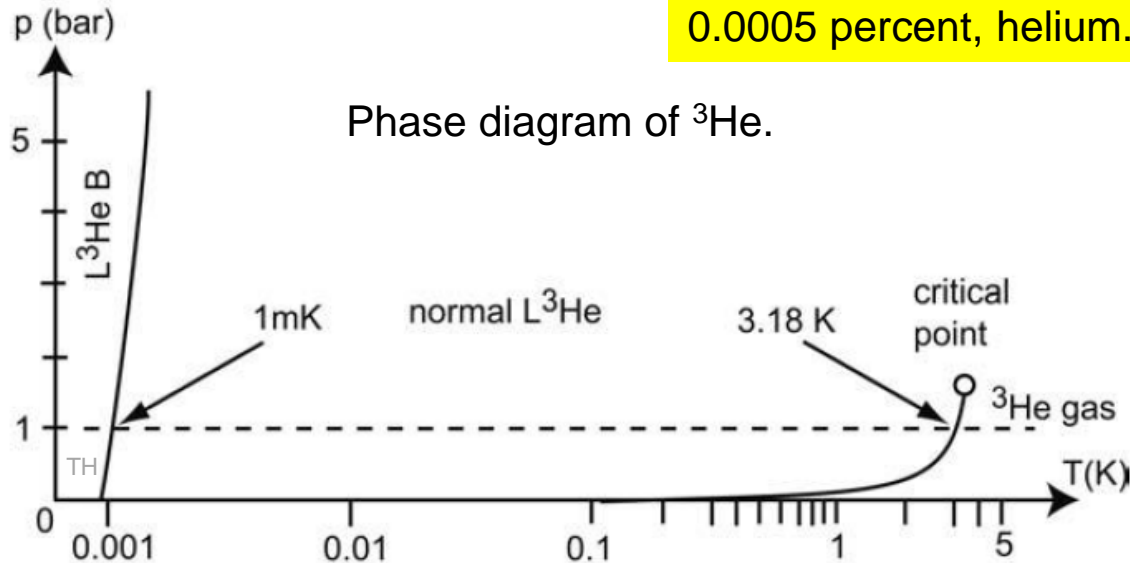
TH

- Helium is **the only element that remains liquid when cooled to the temperatures well below 1 mK**. The latent heat that has to be absorbed when liquid helium is evaporated generates the cooling power.
- Helium comes in two isotopes, the boson ^4He and the fermion ^3He .
- Helium is **the only element for which the van der Waals energy is smaller than the kinetic energy of the atoms due to zero-point fluctuations**.

Properties of pure ^3He

- The density of L^3He is $\rho(^3\text{He}) = 59 \text{ kg/m}^3$. Under atmospheric pressure, it liquefies at $\Theta = 3.19 \text{ K}$. It is **near-to-completely absent on Earth**.
- The vapour pressure is higher (at identical temperatures) than in L^4He . **Pressure drops to 10^{-3} mbar at about $\Theta = 270 \text{ mK}$** .
- ^3He atoms are **fermions**, and the **liquid** can be approximated by a **Fermi gas**.
- For $\Theta < 2 \text{ mK}$, the ^3He atoms form Cooper pairs and undergo a Bose–Einstein condensation into **superfluid ^3He** .

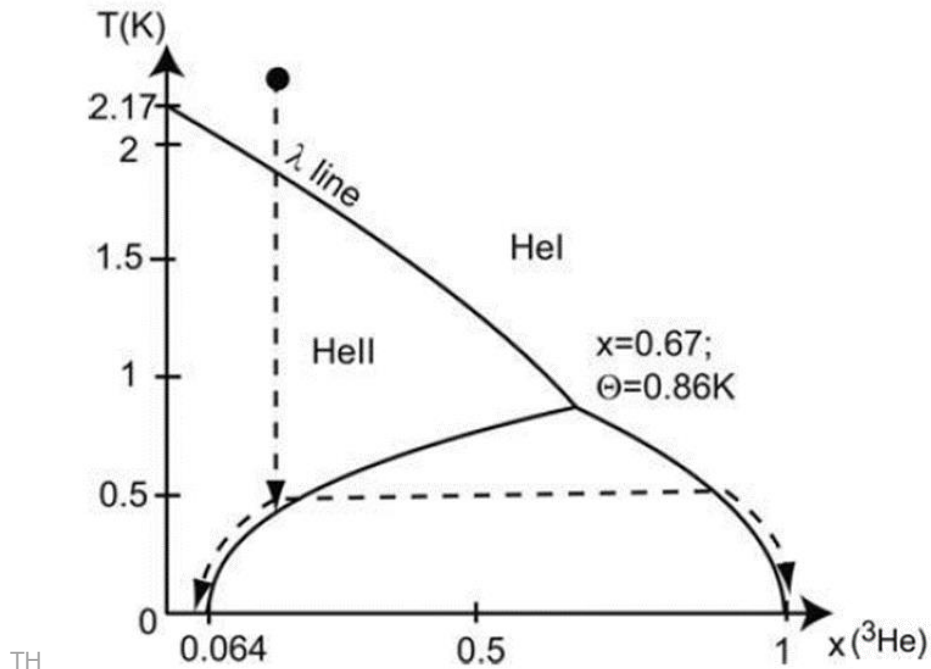
Earth's atmosphere is only about 5 parts per million, or 0.0005 percent, helium.



Seamounts release plumes of ^3He -rich water into the ocean. These helium plumes can be traced for thousands of kilometres

The $^3\text{He}/^4\text{He}$ mixture

- For temperatures below 860 mK, an important **phase separation** into a **dilute ^3He -poor phase (D)** and a **^3He -rich phase (C)** takes place.
- The ^3He dissolved in ^4He is a dilute Fermi gas with an effective mass $\approx 2.4m(^3\text{He})$. **^3He atoms move in ^4He without friction.**
- The chemical potential of the C-phase is somewhat higher than that, of a single ^3He atom in ^4He . Hence, **^3He atoms will go into ^4He until the chemical potentials have aligned.**

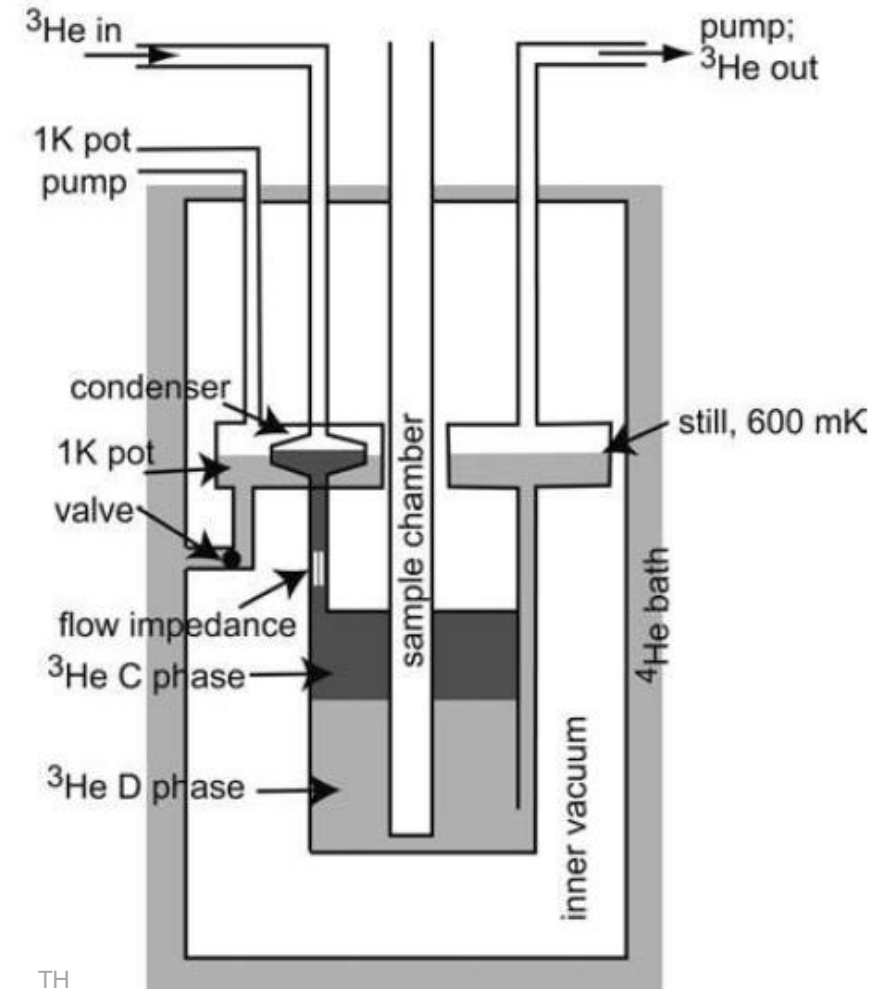


Phase separation is important for operation of dilution refrigerators.

Phase diagram of the $^3\text{He}/^4\text{He}$ mixture vs. ^3He concentration

$^3\text{He}/^4\text{He}$ dilution refrigerator

- Since the dilute ^3He phase (D) can be thought of as the ^3He vapour of the ^3He -rich phase (C) with a significant vapour pressure even at T close to 0, pumping the ^3He atoms out of the D is able to reduce T down to 1 mK.
- C phase has a smaller density than D and the “liquid” is floating on top of the “gas”.
- Pumping the ^3He atoms out of the D phase pulls the corresponding effective latent heat out of the mixture.
- The D phase is connected through a tube with the still heated to about 600 mK. At this temperature, the vapour pressure of ^3He is significant, while that of ^4He is negligible. The still therefore effectively distils ^3He from the D phase.
- ^3He is re-condensed in the “1K pot”.



Essential components of a $^3\text{He}/^4\text{He}$ dilution refrigerator.

Description of gas mixtures: basic mathematics

$$G = U + PV - TS$$

$$S = k \ln \Omega$$

$$S_{\text{total}} = k \ln \Omega_{\text{total}} = k \ln(\Omega_A \Omega_B) = k \ln \Omega_A + k \ln \Omega_B = S_A + S_B.$$

Stirling's approximation

$$N! \approx N^N e^{-N} \sqrt{2\pi N}$$

Multiplicity and entropy of a **monatomic ideal gas**:

$$\Omega_N = \frac{1}{N!} \frac{V^N}{h^{3N}} \frac{2\pi^{3N/2}}{\left(\frac{3N}{2} - 1\right)!} (\sqrt{2mU})^{3N-1}$$

Sackur-Tetrode equation:

$$S = Nk \left[\ln \left(\frac{V}{N} \left(\frac{4\pi mU}{3Nh^2} \right)^{3/2} \right) + \frac{5}{2} \right]$$

Entropy of Mixing

Sackur-Tetrode equation:

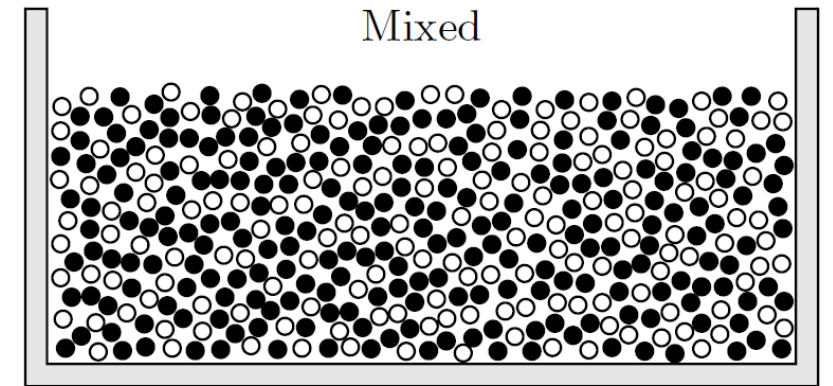
$$S = Nk \left[\ln \left(\frac{V}{N} \left(\frac{4\pi mU}{3Nh^2} \right)^{3/2} \right) + \frac{5}{2} \right]$$

$$N_A = xN \quad N_B = (1 - x)N$$

$$S_{mix} = S_A + S_B$$

$$\Delta S_{mixing} = S_{mix} - S$$

$$\Delta S_{mixing} = -Nk [x \ln x + (1 - x) \ln(1 - x)]$$

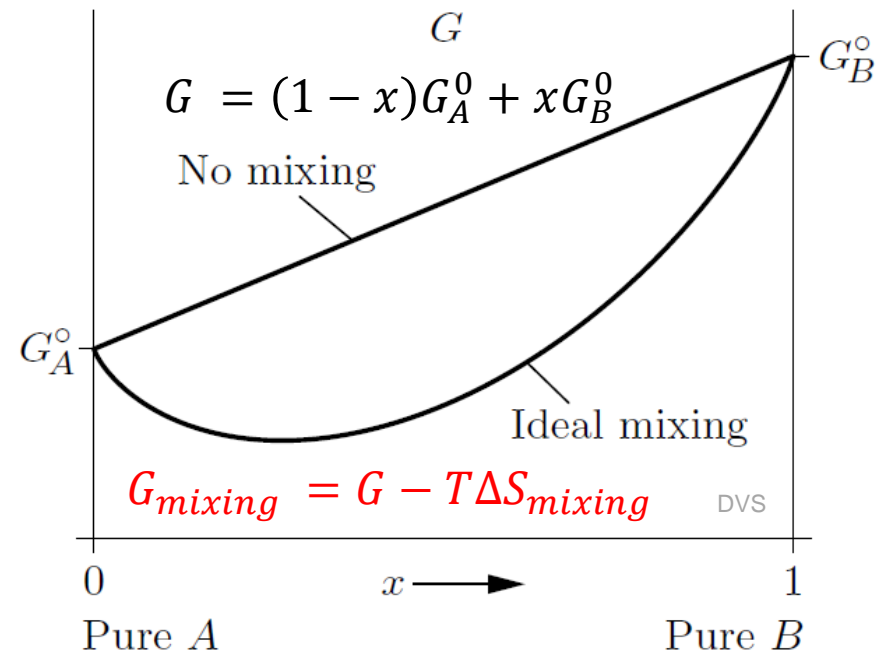
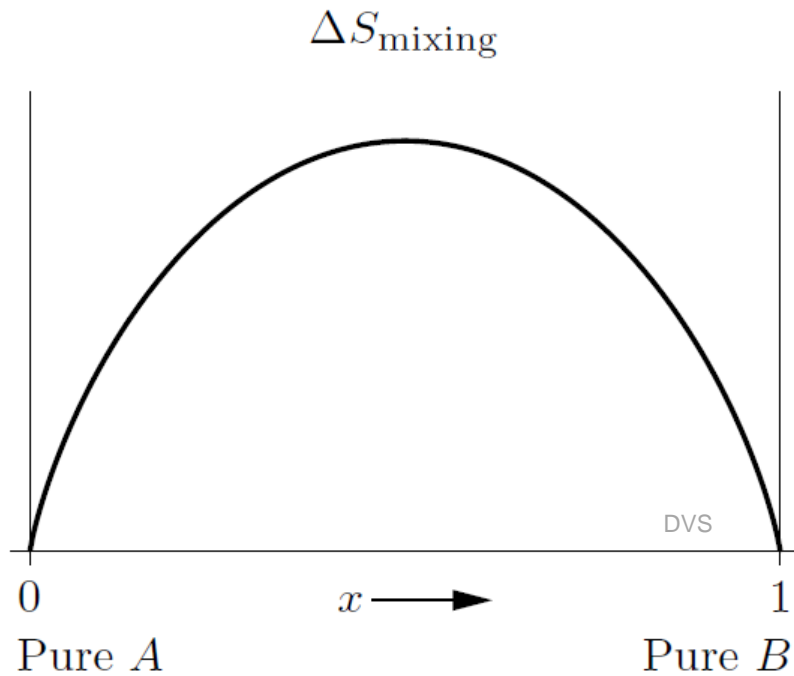


DVS

Ideal mixing

$$G = U - TS + PV$$

$$\Delta S_{mixing} = -Nk[x \ln x + (1 - x)\ln(1 - x)]$$



Entropy of mixing

$$\Delta S_{\text{mixing}} = -Nk[x \ln x + (1-x)\ln(1-x)]$$

Per one mole: $\Delta S_{\text{mixing}} = -R[x \ln x + (1-x)\ln(1-x)]$ DVS

$$Nk = nR$$

Boltzmann constant

$$k = 1.380649 \times 10^{-23} \text{ J/K}$$

Gas constant

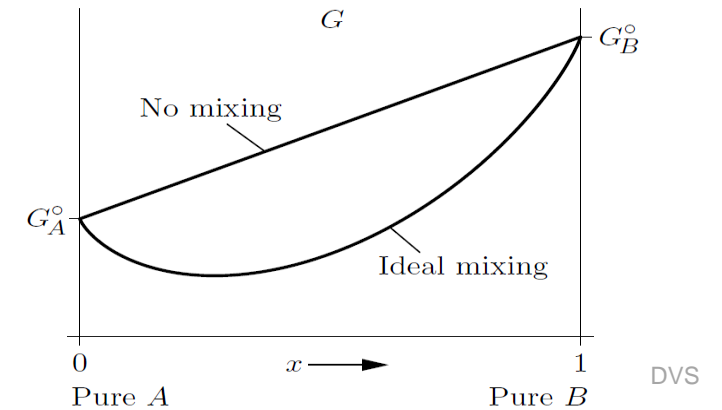
$$R = 8.3145 \text{ J/(mol} \cdot \text{K)}$$

Avogadro number

$$N_A = 6.022 \cdot 10^{23} \text{ 1/mol}$$

$$N_A k = R$$

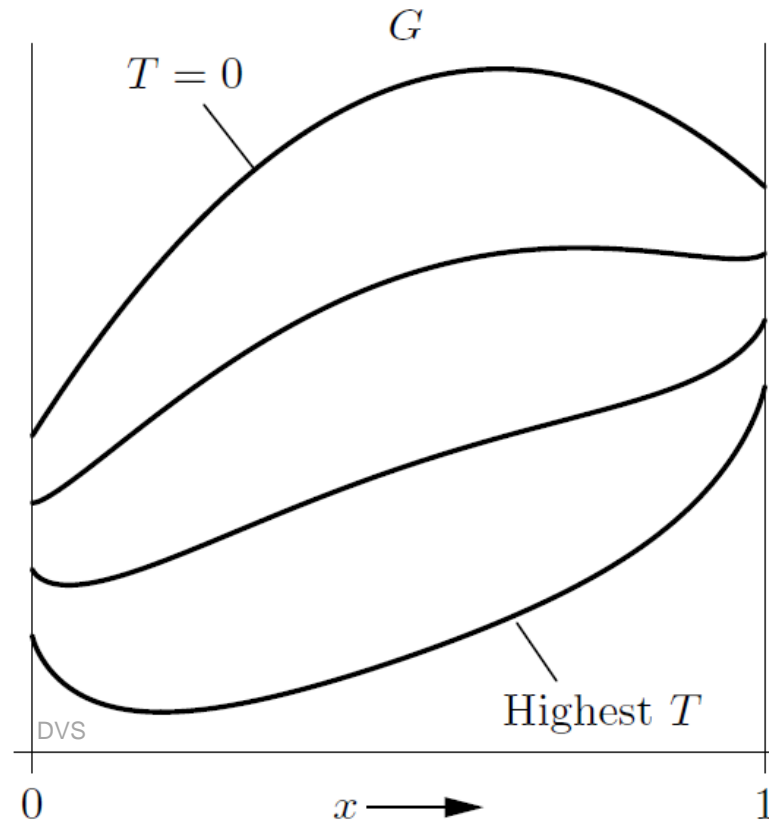
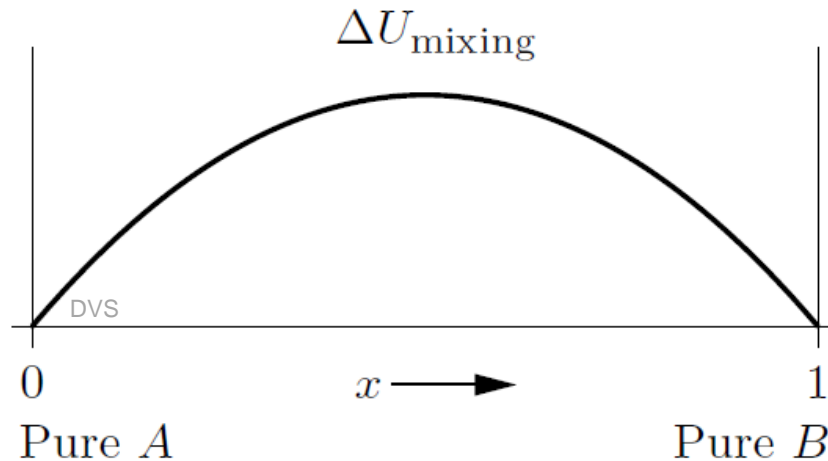
Ideal mixing



- There is minimum in the function $G_{mixing}(x)$.
- Its derivative with respect to x goes to infinity at $x = 0$ and to minus infinity at $x = 1$.
- The graph of this expression therefore has a vertical slope at each endpoint.
- Because $G_{mixing} < G$, **system will always be in the mixed state.**

Mixing with increase of energy

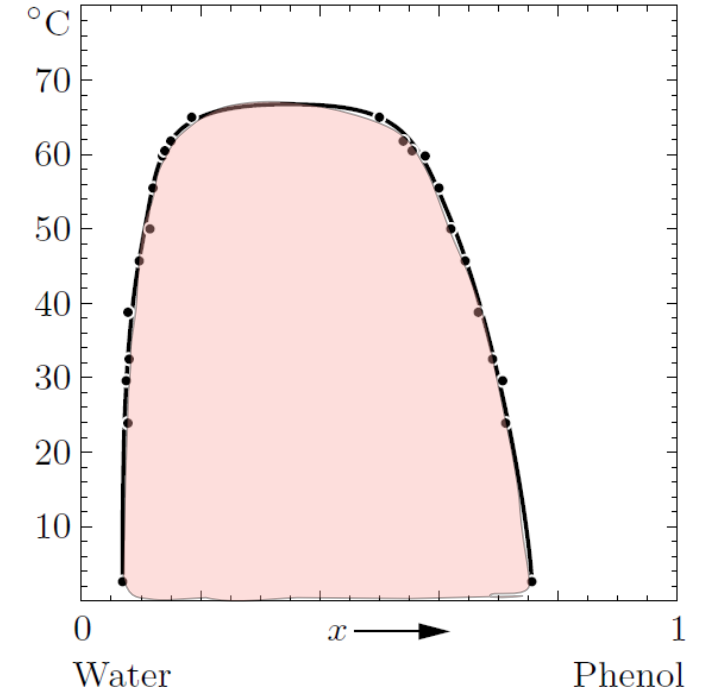
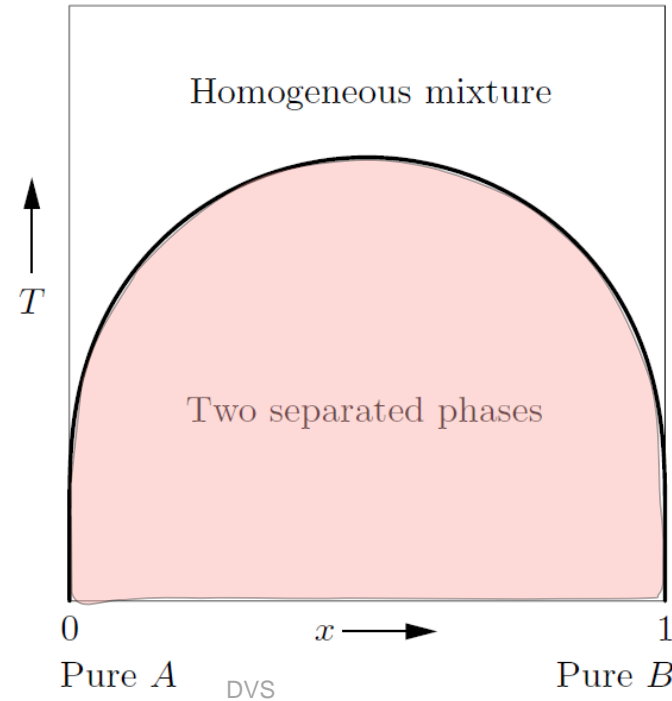
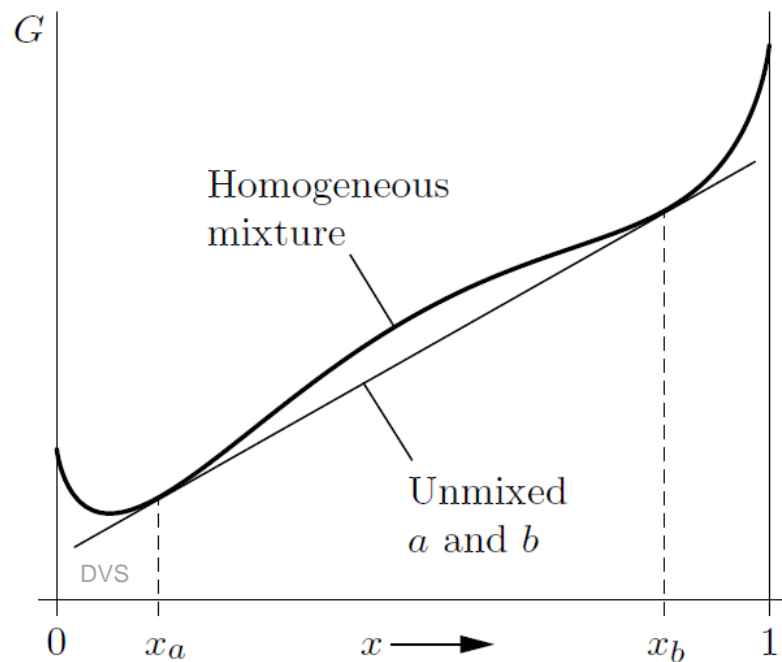
$$G = U - TS + PV$$



Mixing A and B can often increase the energy of the system. **The concave-down free energy function indicates an unstable mixture.**

Solubility gap

$$G = U - TS + PV$$



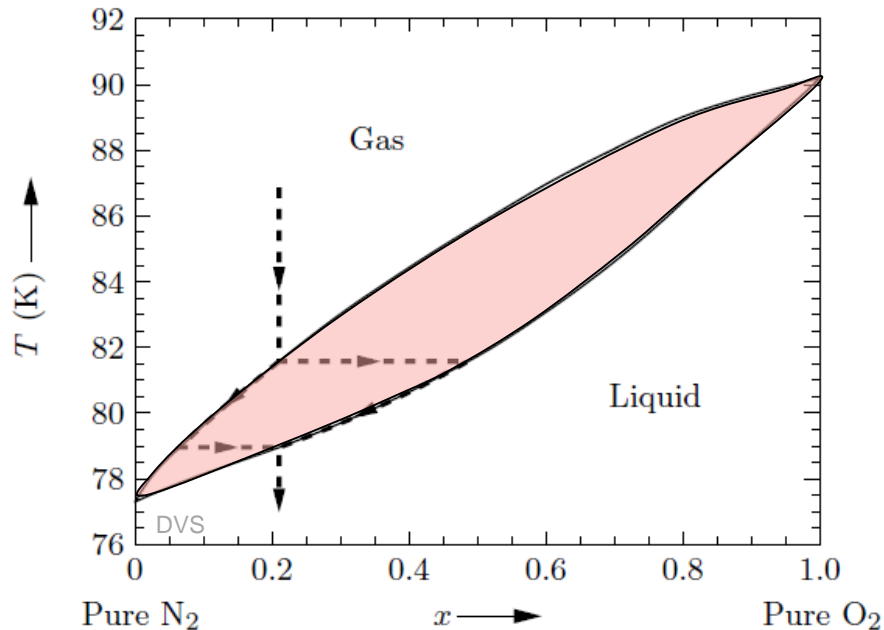
If the composition of the system lies between x_a and x_b , it will **spontaneously** separate into an A-rich phase of composition x_a and a B-rich phase of composition x_b . One says that the system has a solubility gap, or that the two phases are immiscible. **Decreasing the temperature of this system widens the solubility gap.**

Phase Changes in a Miscible Mixture

Air: 78% N₂ and 21% O₂. Boiling temperature of O₂ (T_B) is 90.2 K and boiling temperature of N₂ is 77.3 K (T_A). But transition into the liquid state does not happen in two steps: at 90.2 and 77.3 K. It starts at 81.6 K only. Why?

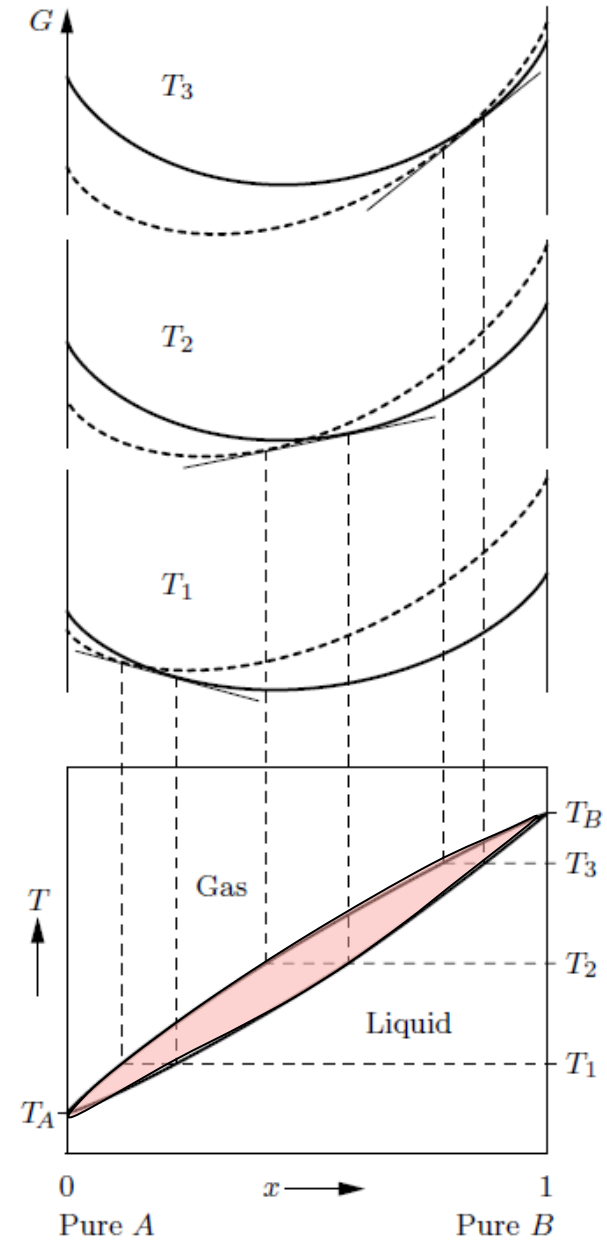
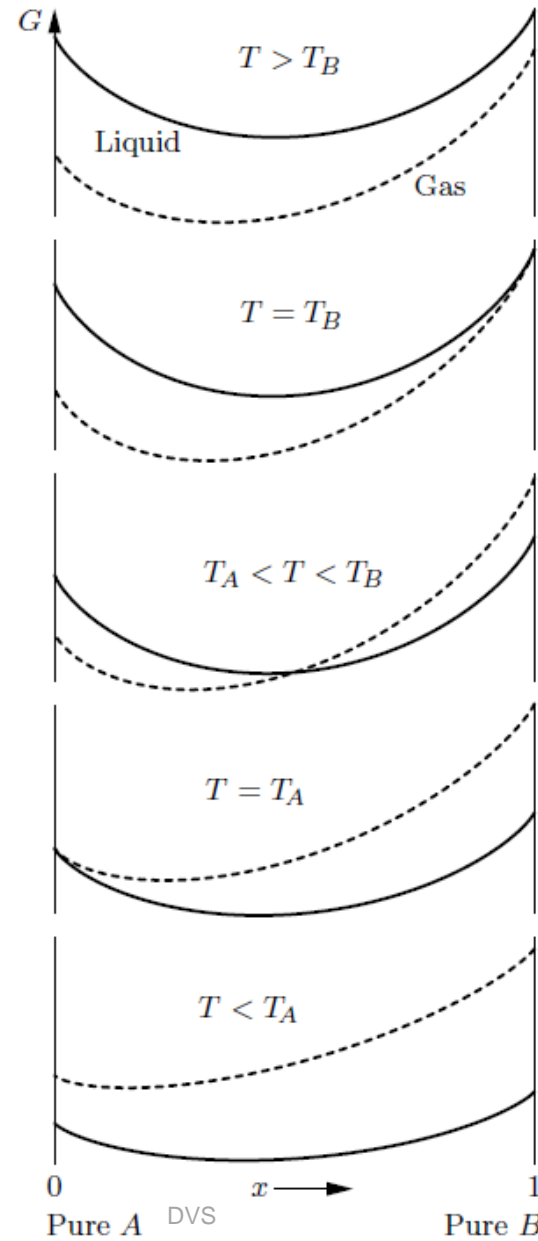
Answer is in Gibbs free energy of mixtures.

$$G = U - TS + PV$$



Ideal behavior of the mixture of N₂ and O₂ in liquid and gas states.

At 81.6 K, a liquid consisting of 48% oxygen begins to condense.

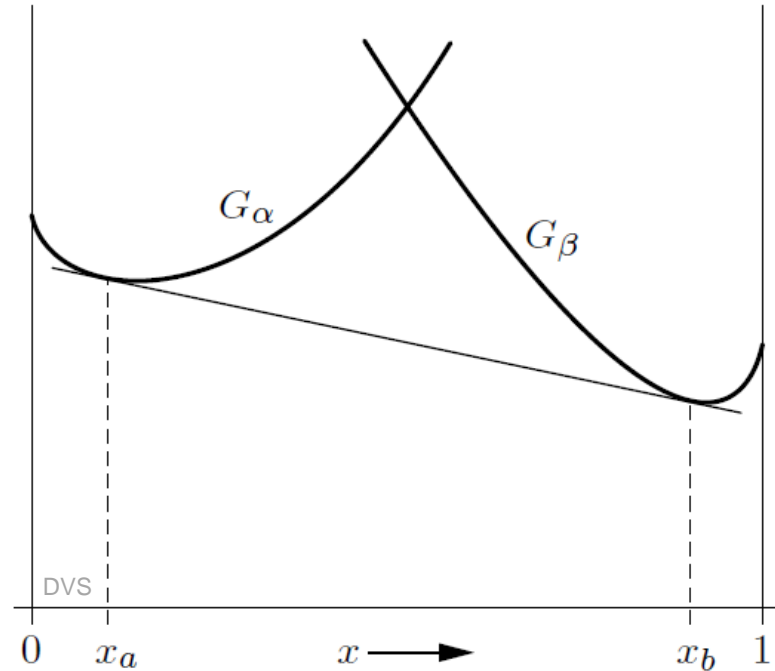


Phase Changes of an Eutectic System

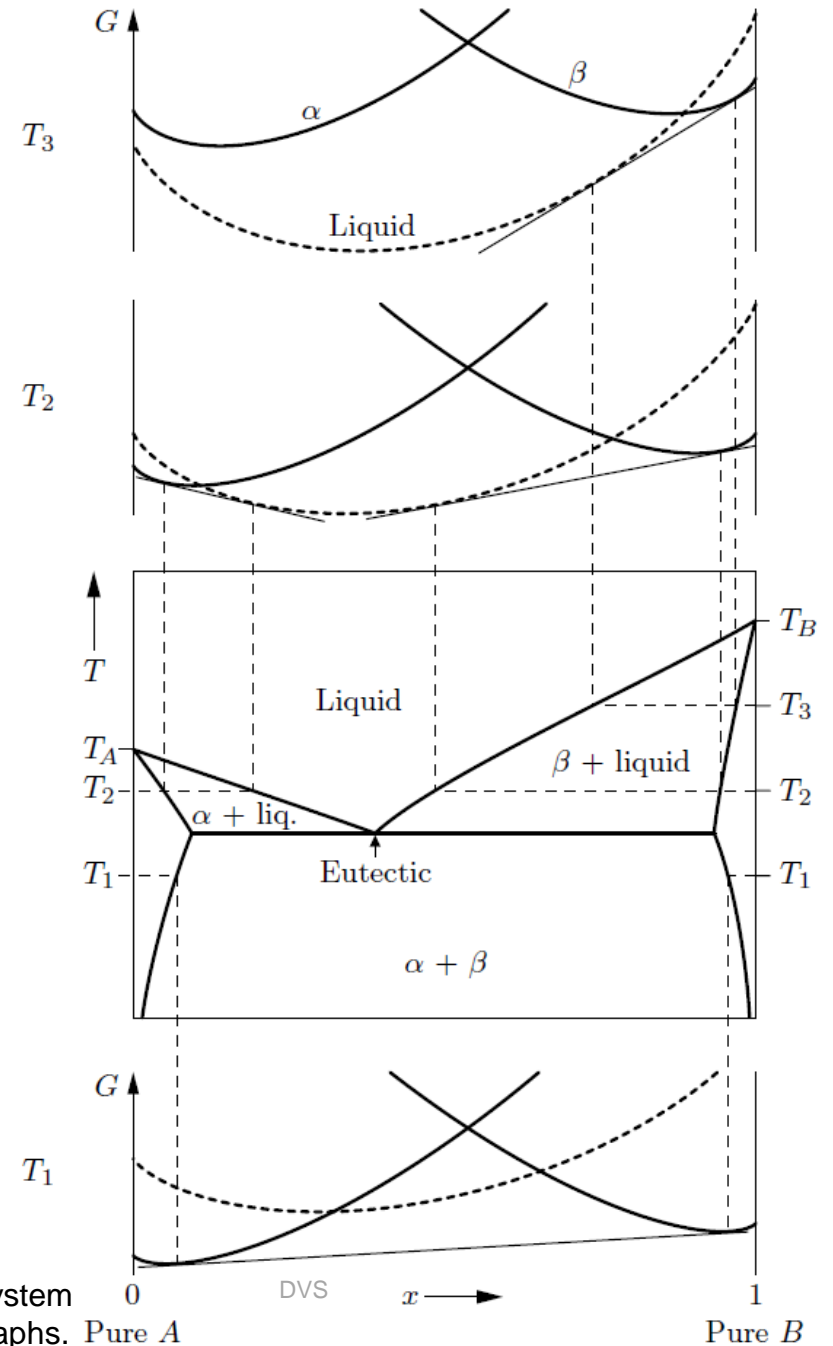
“easily melted”

An eutectic system from the Greek eu = well and taxis = melting is a heterogeneous mixture of substances that melts at a temperature that is **lower than the melting point of any of the constituents.**

The most common case is when the mixed solids have different crystal structures, and the unmixed combination of phases close in composition to pure ones is stable at intermediate concentrations.



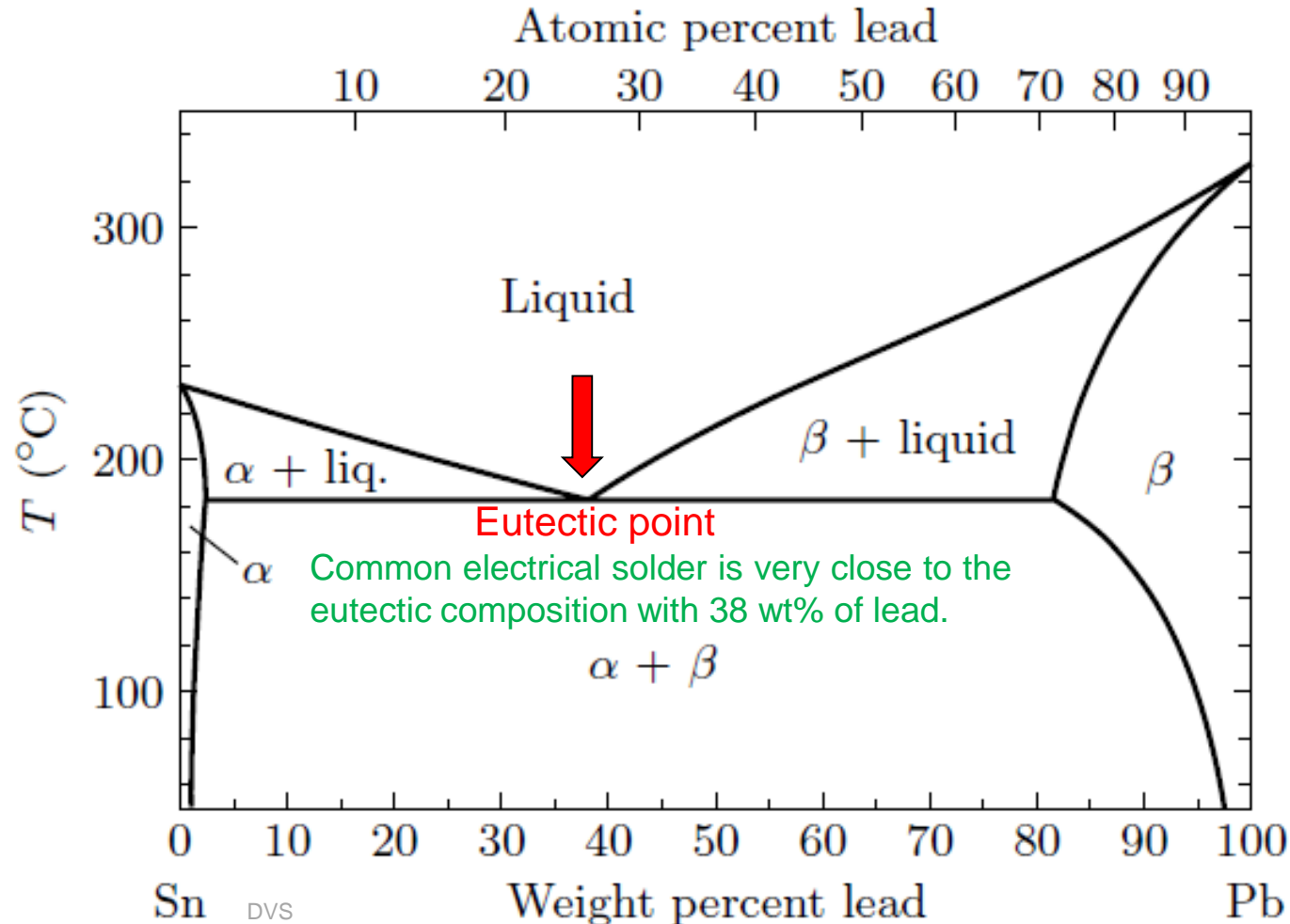
Free energy graphs for a mixture of two solids with different crystal structures: α and β .



Phase diagram of an eutectic system reconstructed from free energy graphs. Pure A

Pure B

Example of an Eutectic System

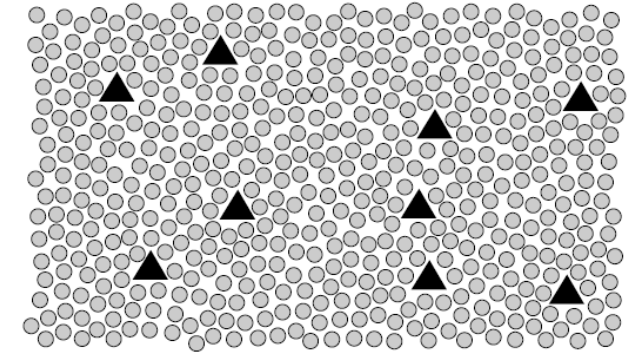


The eutectic point corresponds to a special composition at which the melting temperature is the lowest, lower than that of pure substances. A liquid near the eutectic composition remains stable at low temperatures because it has more mixing entropy than the unmixed combination of solids.

There is an unmixed combination of Sn-rich and Pb-rich phases in the solid solution.

Phase diagram for the mixture of tin and lead.

Dilute solutions



DVS

- A **dilute solution** is a mixture, in which one component (the **solvent**) is dominant or primary and the other component (the **solute**) is minor or secondary.
- There could be several solute components in a solvent.
- The solute molecules are **much less abundant** than the solvent molecules.
- The solute molecules are “always” surrounded by solvent molecules and **rarely interact directly with other solute molecules**.
- The solute in a dilute solution behaves **like an ideal gas**.

Molality and molarity

$$\text{Molality } m = \frac{\text{Number of moles of solute}}{\text{Number of kilograms of solvent}}$$

- **Molality** is the number of moles of solute per number of kilogram of solution.
- **Molality** is dimensionless unit.
- **Molarity** is the number of moles of solute per number of liters of solution.
- **Molality** and **molarity** are different parameters, but for dilute solutions in water, the two are almost identical.
- The pH of a solution is defined as **minus the base-10 logarithm** of the **molality** of H^+ ions:

$$\text{pH} \equiv -\log_{10} m_{H^+}$$

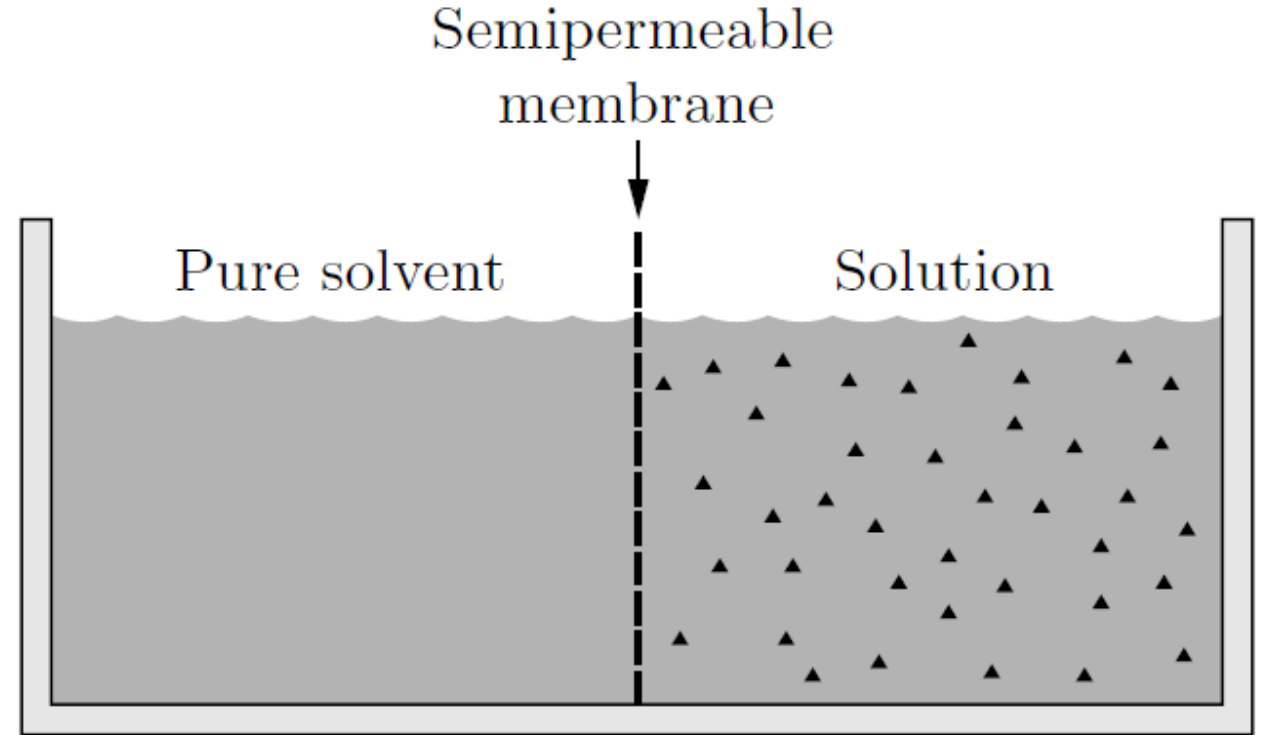
For pH = 7, number of H^+ (and OH^- in water) ions is 10^{-7} .

When the pH is less than 7 (indicating a higher H^+ concentration) we say the solution is **acidic**, while when the pH is greater than 7 (indicating a lower H^+ concentration) we say the solution is **basic**.

Osmotic pressure

The solvent molecules will spontaneously flow from the pure solvent into the solution. This flow of molecules is called osmosis.

Examples of semipermeable membranes: membranes surrounding plant or animal cells, which are permeable to water and small molecules but not to larger molecules, and the membranes that are used in industry for the desalination of seawater.



DVS

The osmotic pressure is described by Van't Hoff's Formula:

$$(P_2 - P_1) = \frac{kTN_B}{V} = \frac{RTn_B}{V}$$

Examples of osmotic pressure

Van't Hoff's Formula: $(P_2 - P_1) = \frac{kTN_B}{V} = \frac{RTn_B}{V}$

In biological cell, there are about **200 water molecules for each molecule of something else**. The difference of pressure being in water:

$$\frac{n_B}{V} = 278 \frac{\text{mol}}{\text{m}^3}$$

An animal cell membrane would burst, but plant cells can withstand such a pressure.

$$\frac{n_B}{V} = \left(\frac{1}{200}\right) \left(\frac{1 \text{ mol}}{18 \text{ cm}^3}\right) \left(\frac{100 \text{ cm}}{1 \text{ m}}\right)^3 = 278 \text{ mol/m}^3$$

$$(P_2 - P_1) = 6.9 \text{ bar}$$

$$(278 \text{ mol/m}^3)(8.3 \text{ J/mol}\cdot\text{K})(300 \text{ K}) = 6.9 \times 10^5 \text{ N/m}^2$$

Seawater has a salt concentration of about 35 kg/m³, corresponding to an osmotic pressure of about 27 × 10⁵ Pa (**27 bar**). This pressure value corresponds to the pressure exerted by a water column of 270 m high.

For 1 m³ of pure water: $U = PV = 27 \times 10^5 \text{ Pa} \times 1 \text{ m}^3 = 2.7 \text{ MJ} (0.75 \text{ kWh})$

In Norway, electric power consumption (kWh per capita) is ~66 kWh per day.

This is an amount of energy needed to lift 1 m³ of water (1000 kg) to a height of about 270 m.

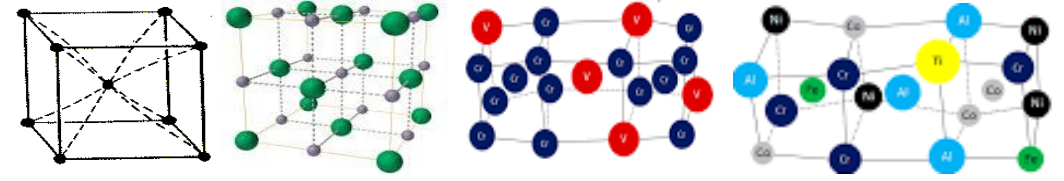
For NaCl the maximum solubility is about 360 kg/m³. Then, in principle, extracted osmotic energy could be one order of magnitude higher.

Mixtures in High Entropy Alloys (HEAs)

High Entropy Alloys (HEAs): Alloys that contain at least 5 principal elements, each having an atomic percentage between 5 - 35 at.%.

Project “MAGNIFICENT - Additively manufactured magnetic high entropy alloys for renewable electricity”, funded by the Research Council of Norway (pr. nr 287979) within the Nano2021 Program

Chemical and structural complexity / Desired properties



Pure metals

Binary compound
s

Conventional alloys

HEAs

$$\Delta G = \Delta H - T \cdot \Delta S$$

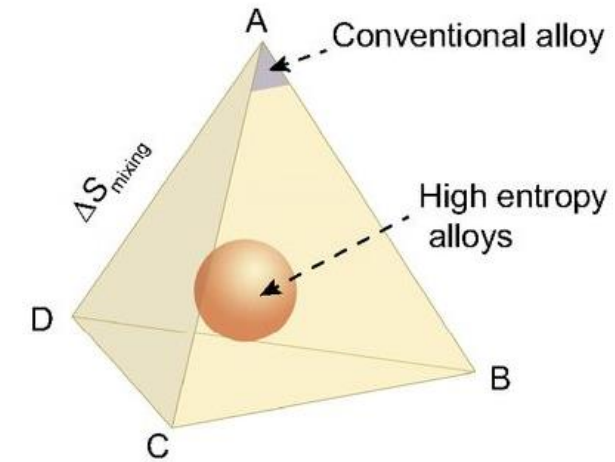


ΔH
(IM compounds)



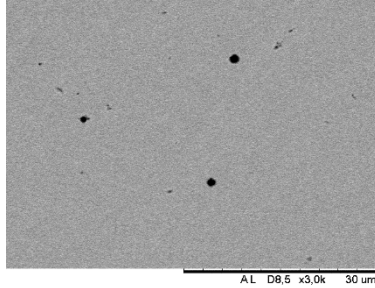
ΔS

(Increase of the constitutional elements)

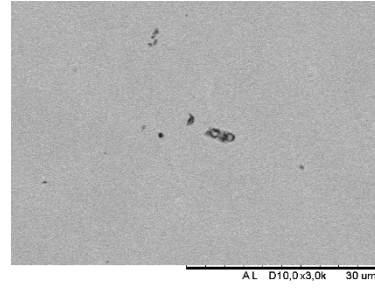


SEM evidence of spinodal decomposition

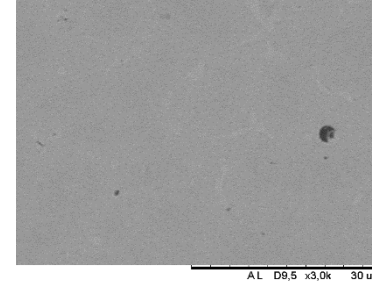
Sample 1



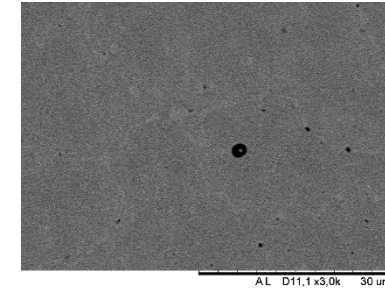
Sample 2



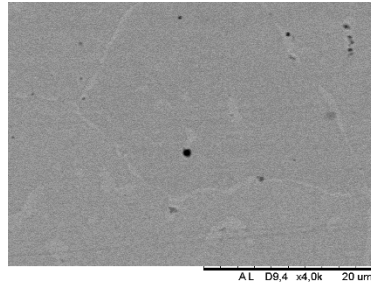
Sample 3



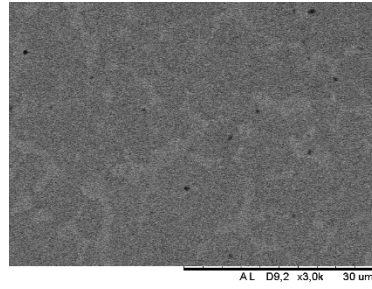
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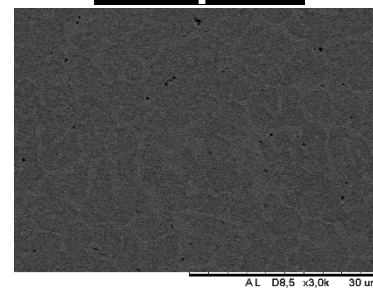
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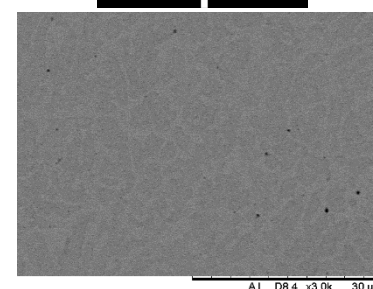
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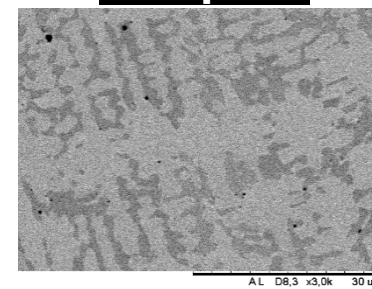
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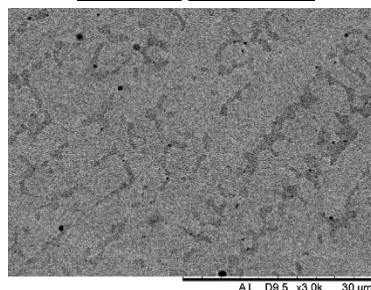
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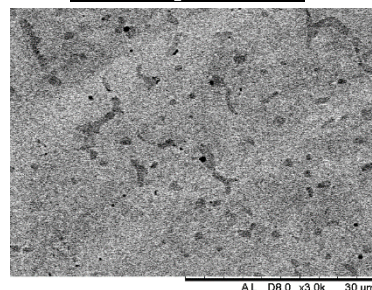
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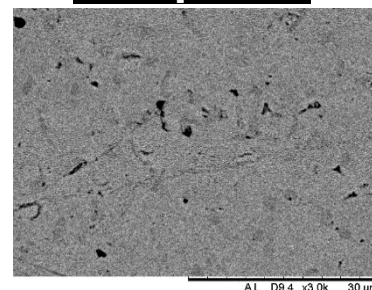
Sample 10



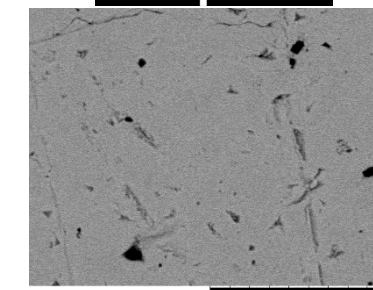
Sample 11



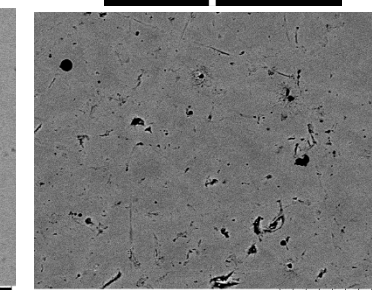
Sample 12



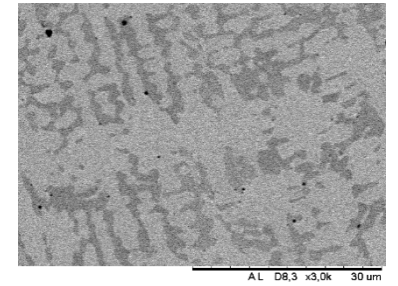
Sample 13



Sample 14



Spinodal decomposition



- Spinodal decomposition occurs when one thermodynamic phase **spontaneously** (i.e., without nucleation) separates into two phases. Decomposition occurs in the absence of nucleation because certain fluctuations in the system reduce the **free energy**. As a result, **the phase change occurs immediately**.
- Spinodal decomposition is observed, for example, in **mixtures of metals**. When the two phases emerge in approximately equal proportion (each occupying about the same volume or area), they form characteristic **intertwined structures** that **gradually coarsen**.
- Spinodal decomposition occurs when a **homogenous phase becomes thermodynamically unstable**. An unstable phase **lies at a maximum in free energy**.

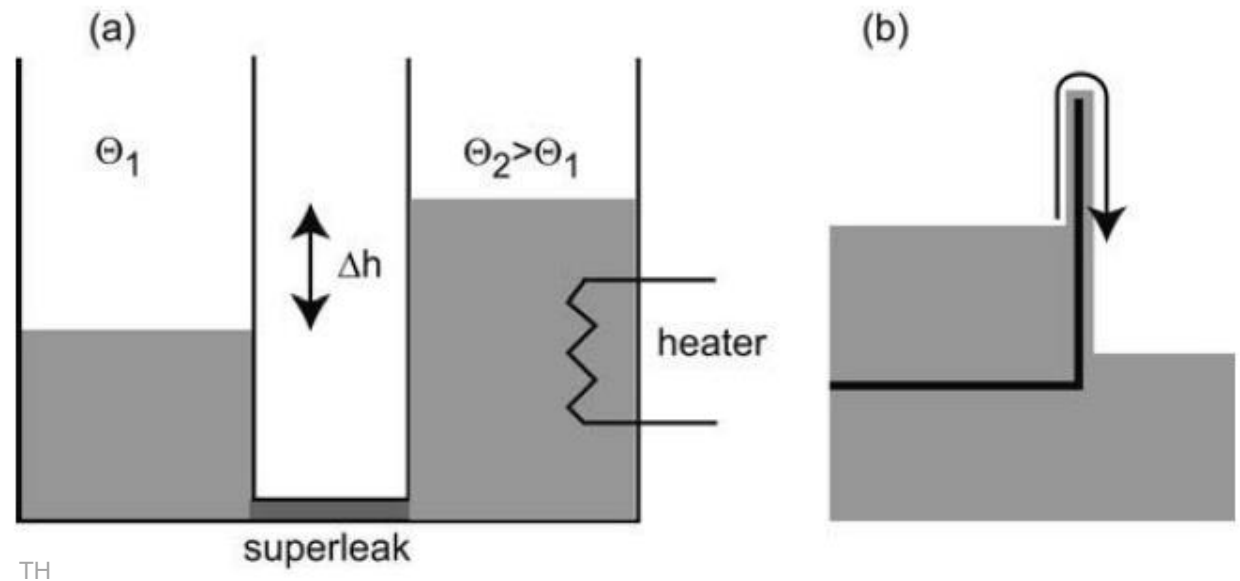
Summary

- **Mixtures** of phases **are common** in physics and the mixing strongly influences phase transitions of pure phases.
- It is the **entropy of mixing** that influence phase transitions.
- Key for understanding phase transitions in mixtures is in **concentration dependence of Gibbs free energy**.
- The entropy of mixing, together with the increase of total energy, leads to appearance of **solubility gap** in the phase diagram of the mixture.
- The solubility gap leads to the **split of homogeneous mixture** into co-existing phases.
- A **dilute solution** is an important type of mixtures, in which the solute molecules are much less abundant than the solvent molecules.
- A contact of a dilute solution with solvent through a membrane blocking solute molecules leads to the phenomenon of **osmotic pressure**.
- The unique properties of mixtures are **intensively used** in the modern science and technology.

Properties of superfluid helium

- The superfluid helium has zero entropy and zero viscosity, which means, for example, that there is no flow resistivity. The thermal conductivity of the superfluid is in theory infinitely large.
- In He II, the thermal conductivity is very large, and evaporation takes place at the surface only. Hence, He II is perfectly quiet, even if it boils off.

- Phase transition to superfluid helium is a Bose–Einstein condensation process.
- Superfluid helium displays phenomenon of superleak.
- Superfluid He tends to creep over any wall and shows extreme adhesion to surfaces and “complete wetting” effect.

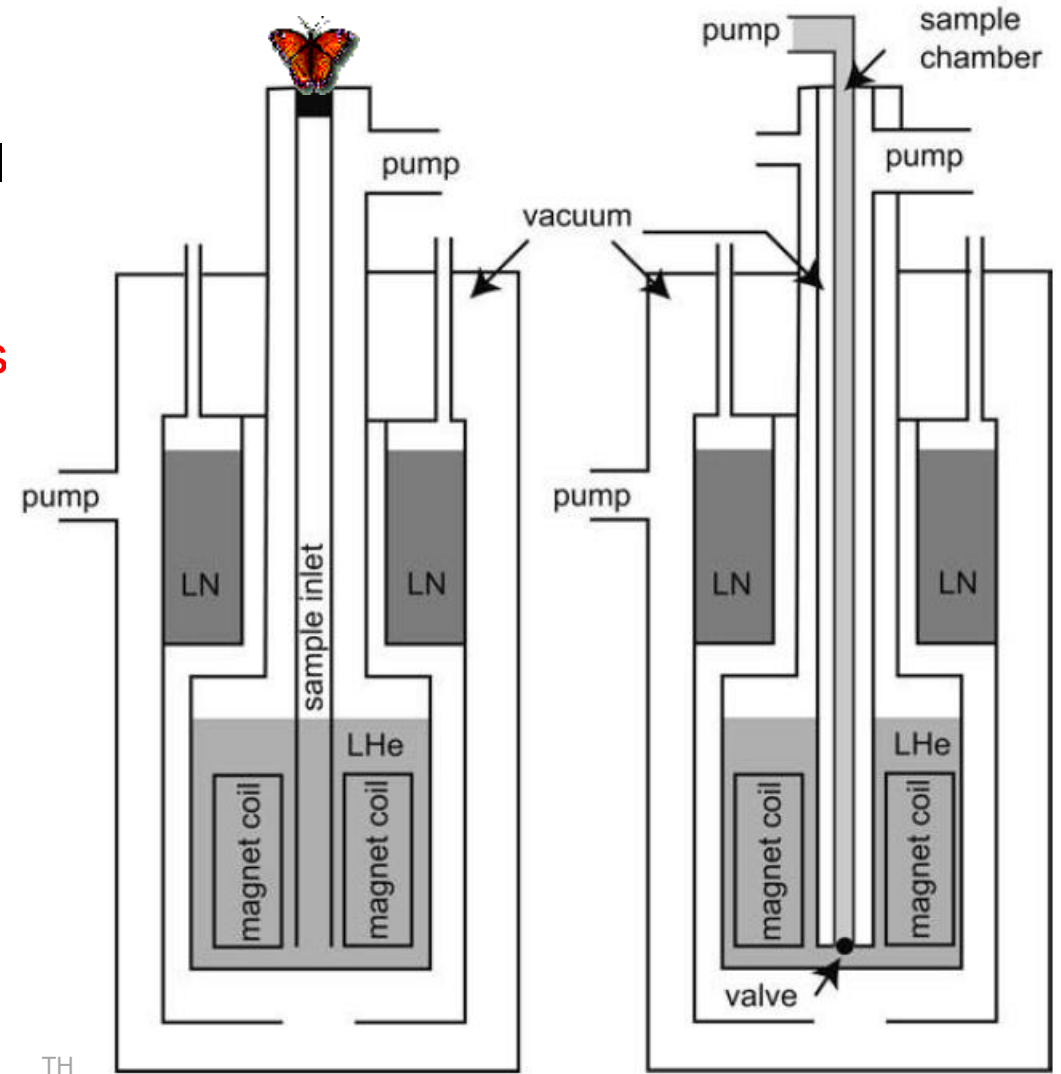


(a) Sketch of a He II osmotic cell. (b) Superfluid film creeping across a wall.

^4He cryostats

- In a cryostat, He is **isolated** from the environment by a vacuum jacket. LHe container is made of a material with a poor thermal conductivity, such as glass or stainless steel.
- Main types of ^4He cryostats are **bath cryostat** and **gas flow cryostat**.
- In a bath cryostat temperature is reduced by **pumping**.
- He vapour pressure p drops exponentially as temperature Θ decreases:

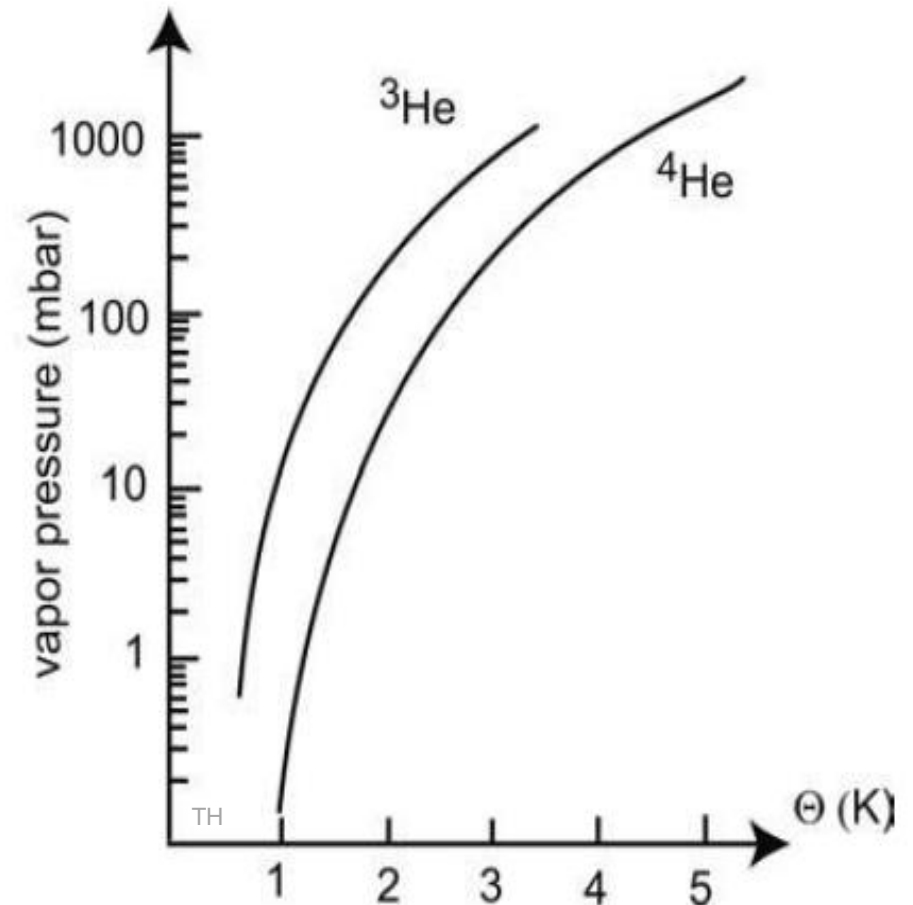
$$p(\Theta) = p_0 \exp(-L/k_B\Theta).$$
- Low pressure and high pumping speed is necessary to reach low temperatures. $\Theta \sim 1.2\text{K}$ at $p = 1\text{mbar}$.
- **Continuous variation** of temperature between 1.2 K and room temperature is possible in a gas flow cryostat.



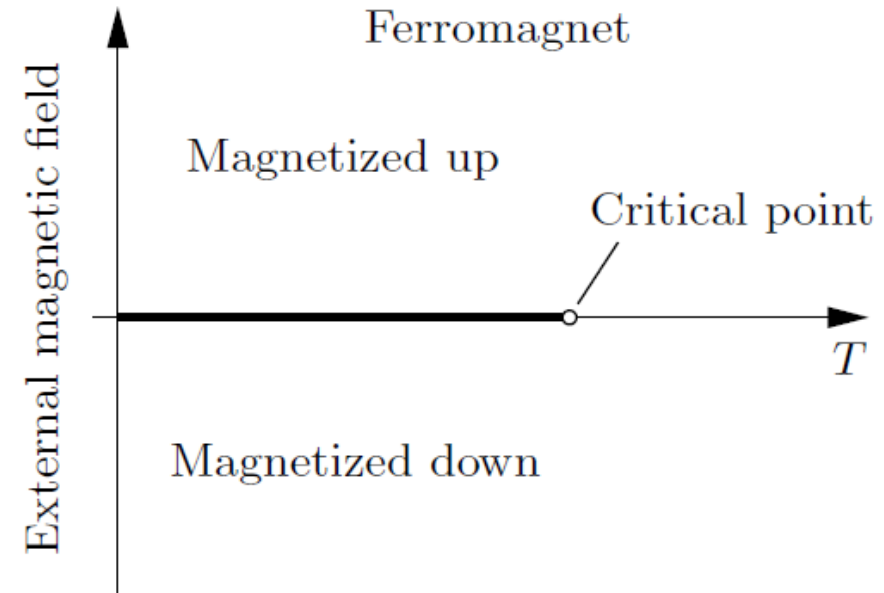
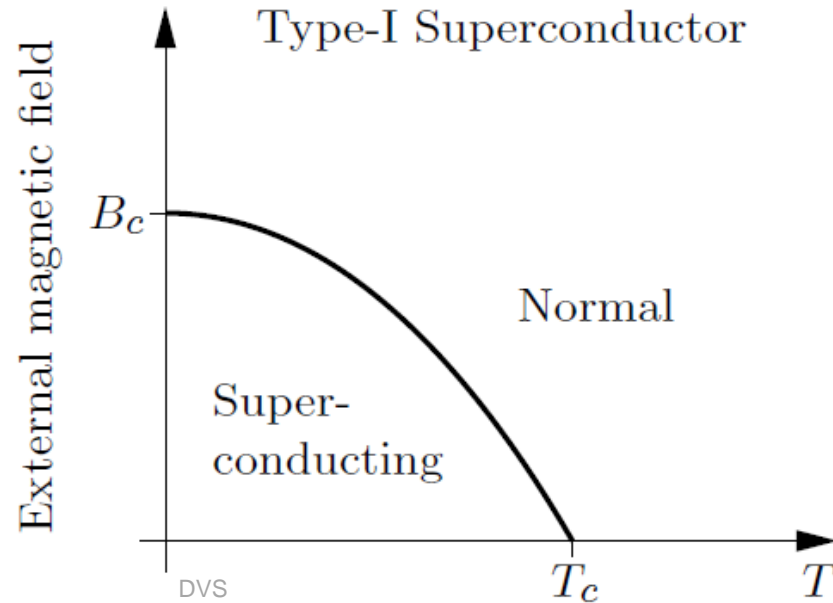
TH
Sketches of a ^4He bath cryostat (left) and a ^4He gas flow cryostat (right).

^3He cryostats

- Below 1 K, the vapour pressure of ^3He is much higher than that of ^4He . Temperatures down to about **270 mK** can be reached by pumping L^3He .
- ^4He is used for a precooling stage.
- ^3He is kept in a **closed cycle**.
- Evaporated ^3He gas can be **condensed** by a small, pumped ^4He pot, which is connected to the ^4He bath via a needle valve, such that its temperature stays well below 3.2K.
- Some cryostats are equipped with a **continuous flow option**, where, the pumped ^3He is immediately re-condensed.
- With somewhat higher base temperature, **measurement period becomes unlimited**.



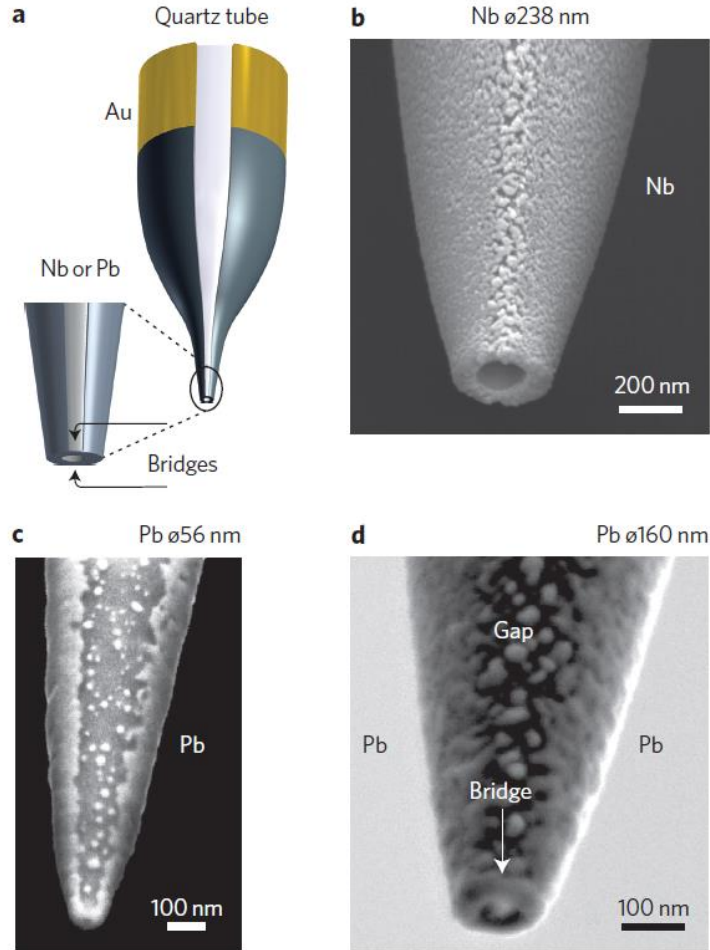
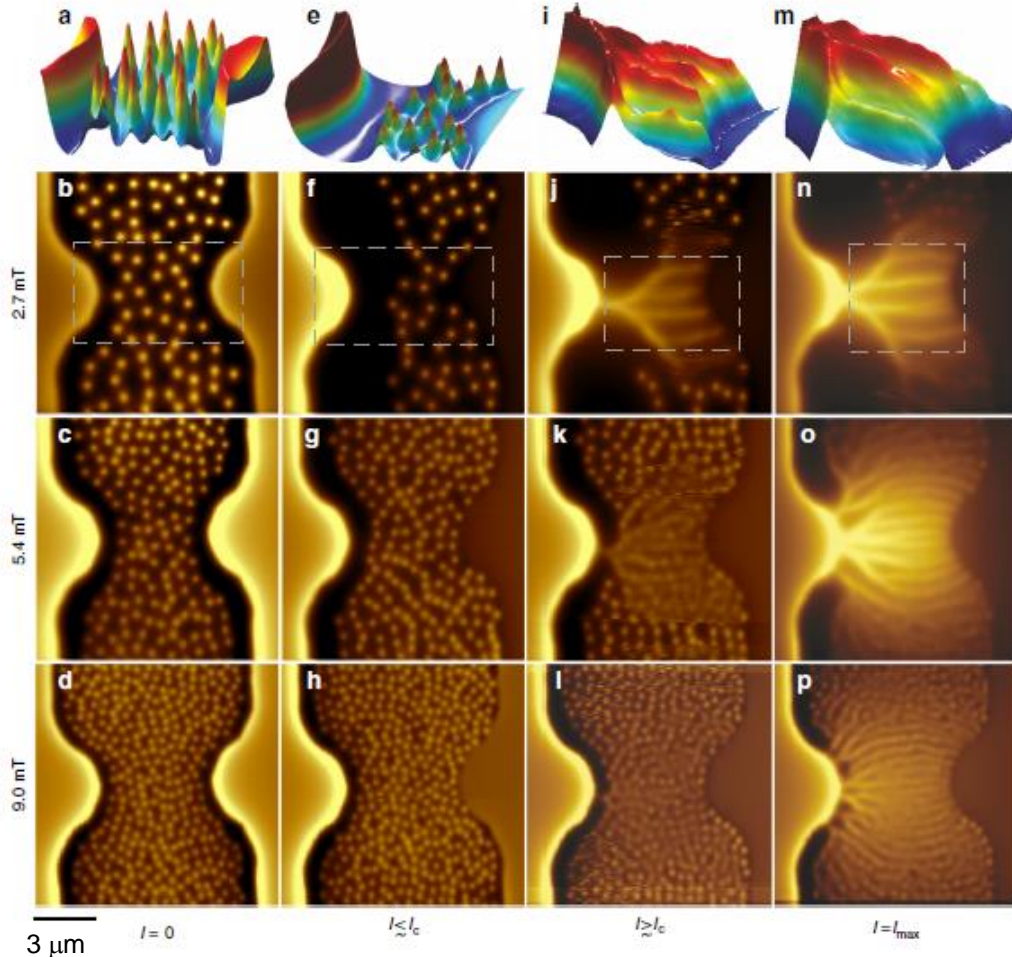
Other phase diagrams



Phase diagrams for two magnetic systems: type-I superconductor (tin, mercury or lead) and a ferromagnet such as iron, which has magnetized phases pointing either up or down, depending on the direction of the applied field.

Imaging of super-fast dynamics and flow instabilities of superconducting vortices

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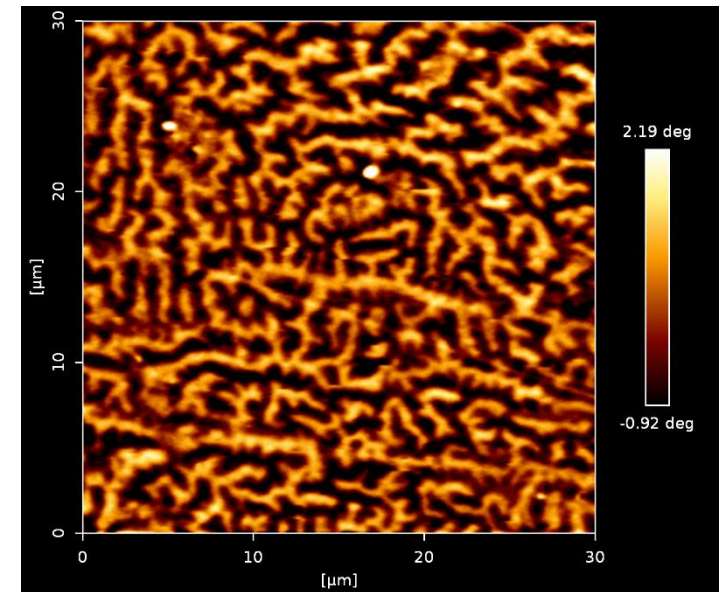
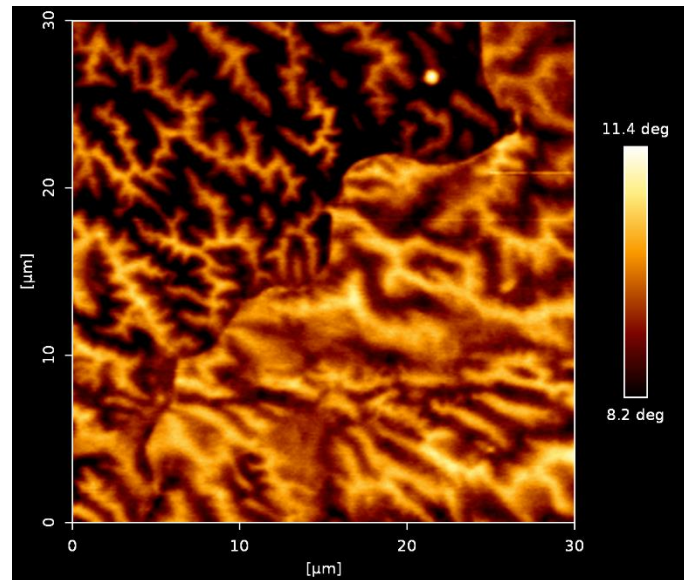
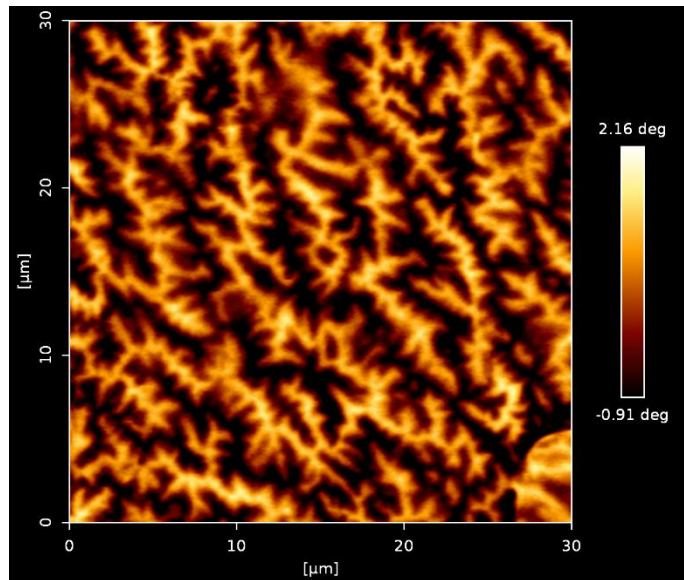
Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 7610001, **Israel**, The Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 9190401, **Israel**, Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, **Belgium**, Département de Physique, Université de Liège, B-4000 Sart Tilman, **Belgium**, Departments of Physics and Electrical Engineering, University of Colorado Denver, Denver, Colorado 80217, **USA**, Verkin Institute for Low Temperature Physics & Engineering, Ukrainian Academy of Sciences, Kharkov 61103, **Ukraine**, Department of Physics, Old Dominion University, Norfolk, Virginia 23529-0116, **USA**.

Magnetic imaging of stationary and fast moving vortices in Pb film at 4.2 K.

SEM images of SOT devices.

Domain structure and Magnetic Force Microscopy

The domain structure of a material is the one which **minimizes the Gibbs free energy of the material.**

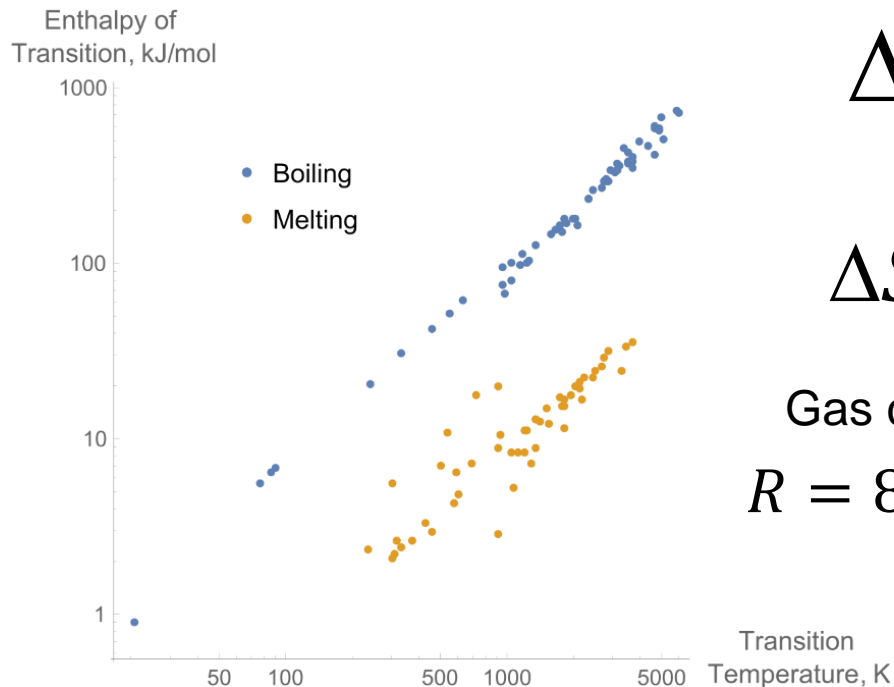


Examples of magnetic domains in $\text{FeNiCoAl}_x\text{Mn}_x$

Trouton's rule

The enthalpy of vaporization ΔH_{vap} is the latent heat of vaporization or simply heat of evaporation.

Trouton's rule states that the entropy of vaporization ΔS_{vap} is almost the same value, about **85–88 J/(K·mol)**, for various kinds of liquids at their boiling points T_b . ΔS_{vap} is defined as the ratio between the enthalpy of vaporization and the boiling temperature. It is named after Frederick Thomas Trouton.



$$\Delta G = \Delta H - T\Delta S$$

$$\Delta S_{\text{vap}} = \frac{\Delta H}{T_b} \approx 85 \frac{\text{J}}{\text{mol} \cdot \text{K}}$$

Gas constant

$$R = 8.3145 \frac{\text{J}}{\text{mol} \cdot \text{K}}$$

$$\frac{\Delta S_{\text{vap}}}{R} = \frac{\Delta H}{RT_b} \approx 11 \pm 1$$

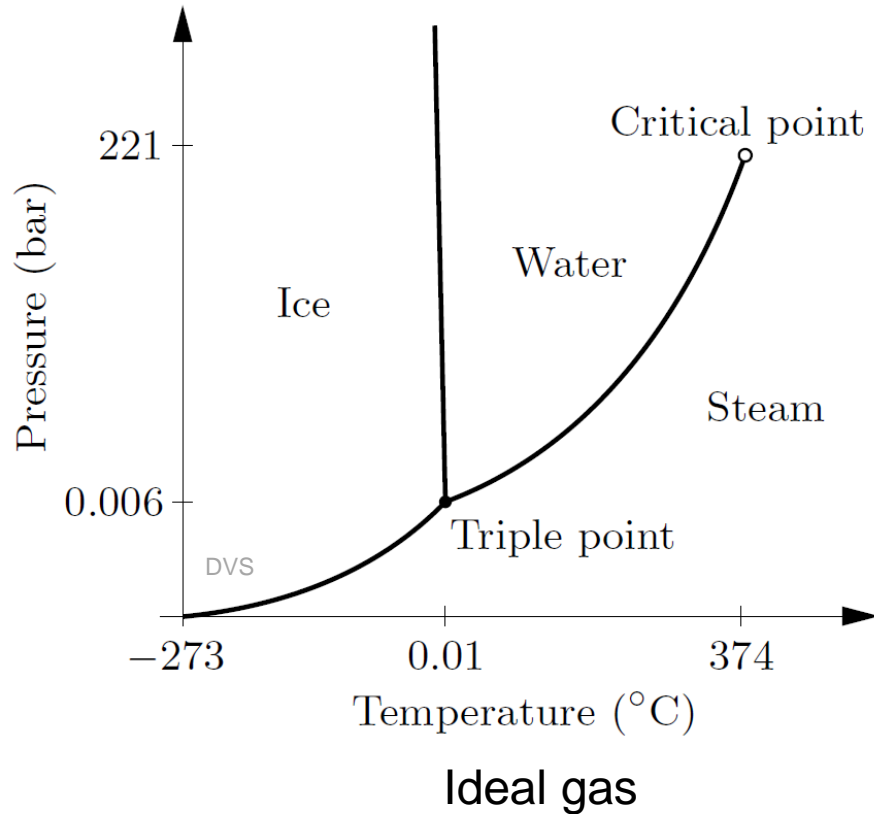


Frederick Thomas Trouton

Born	24 November 1863 Dublin
Alma mater	Trinity College, Dublin

https://en.wikipedia.org/wiki/Frederick_Thomas_Trouton

Clausius-Clapeyron relation



$$\frac{dP}{dT} = \frac{\Delta H}{T_b \cdot \Delta V}$$

$$\Delta G = \Delta H - T\Delta S \quad \Delta S_{vap} = \frac{\Delta H}{T_b}$$

$$\Delta G = \Delta U + P\Delta V - T\Delta S_{vap}$$

$$\frac{dP}{dT} = \frac{\Delta S_{vap}}{\Delta V} = \frac{\Delta H}{T_b \cdot \Delta V}$$

$$P\Delta V = RT$$

$$\frac{dP}{P} = \frac{dT \cdot \Delta H}{RT^2}$$

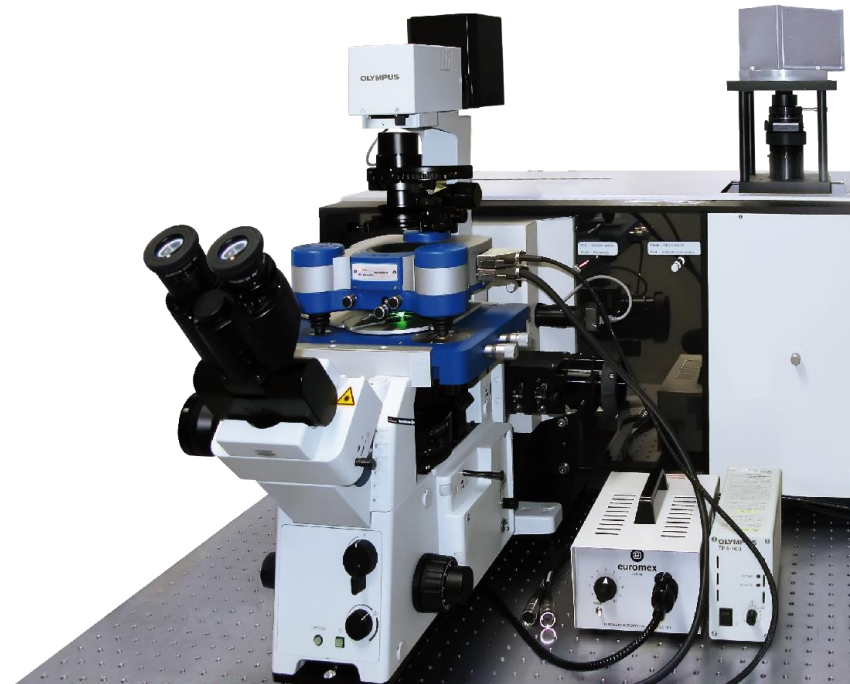
$$\ln \frac{P_1}{P_2} = -\frac{\Delta H}{R} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

Magnetic Force Microscopy (MFM)

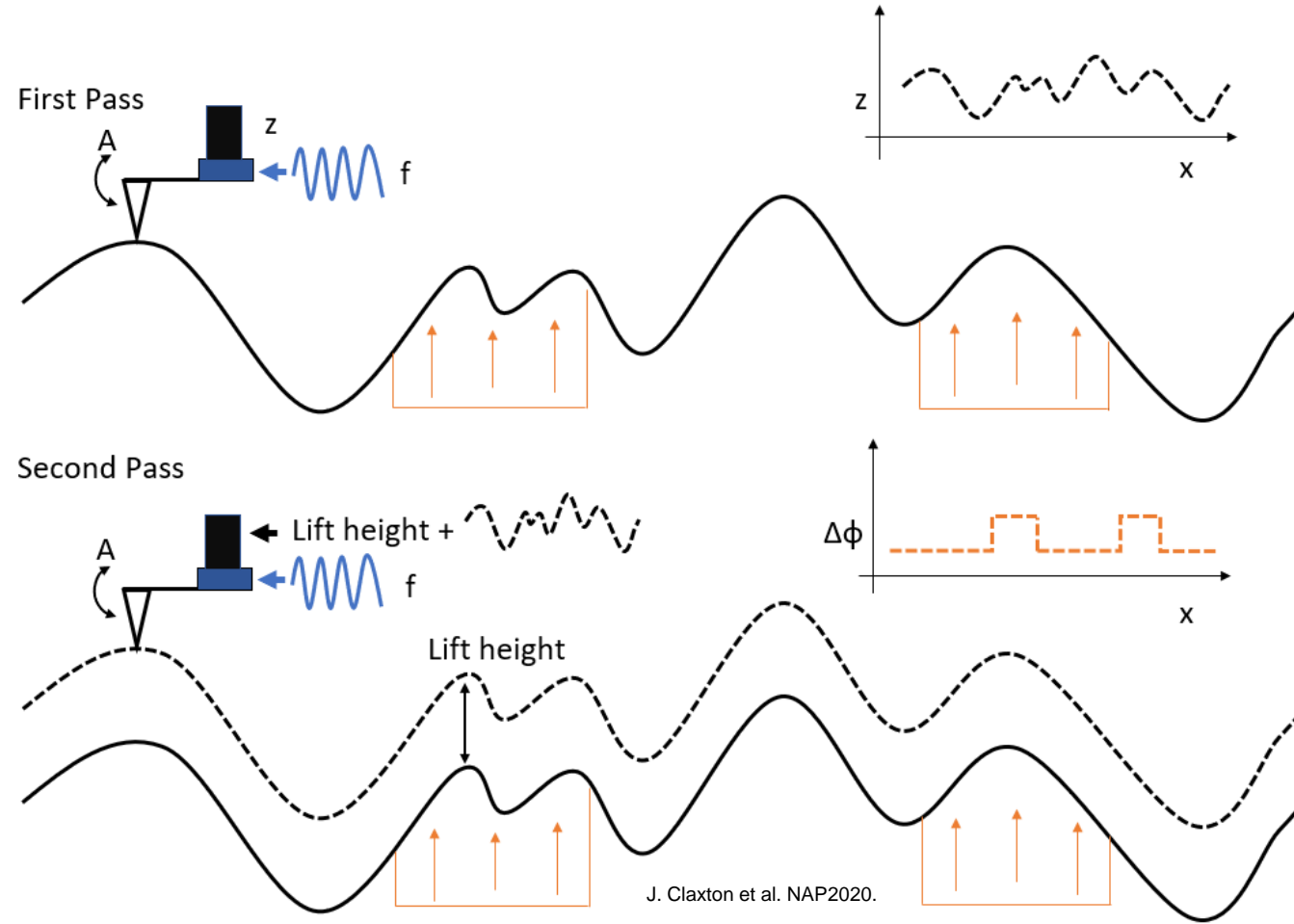
- Scanning probe technique
- Measures probe-sample interaction using magnetic tips

**A tool for measuring
magnetic properties of
High Entropy Alloys**

Image Source: jpk.com



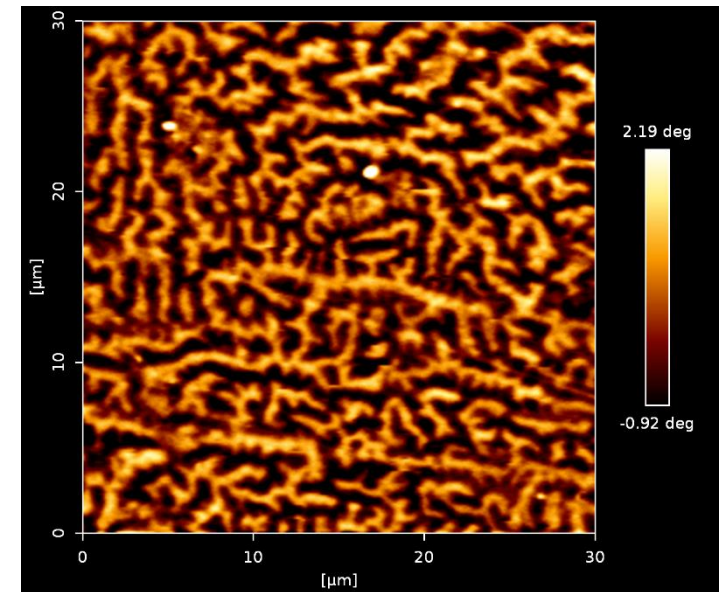
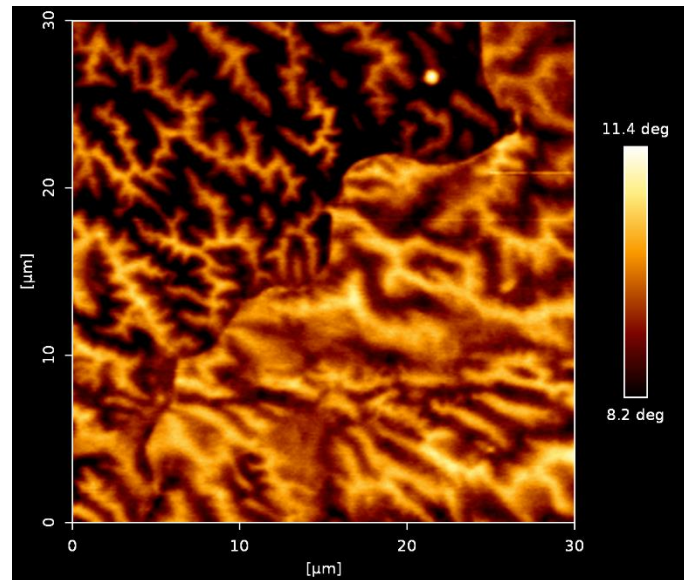
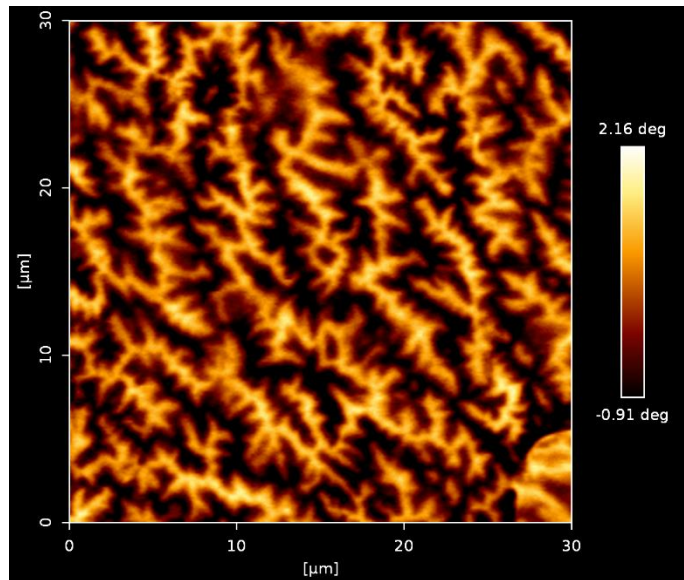
Two Pass Technique



Magnetic material

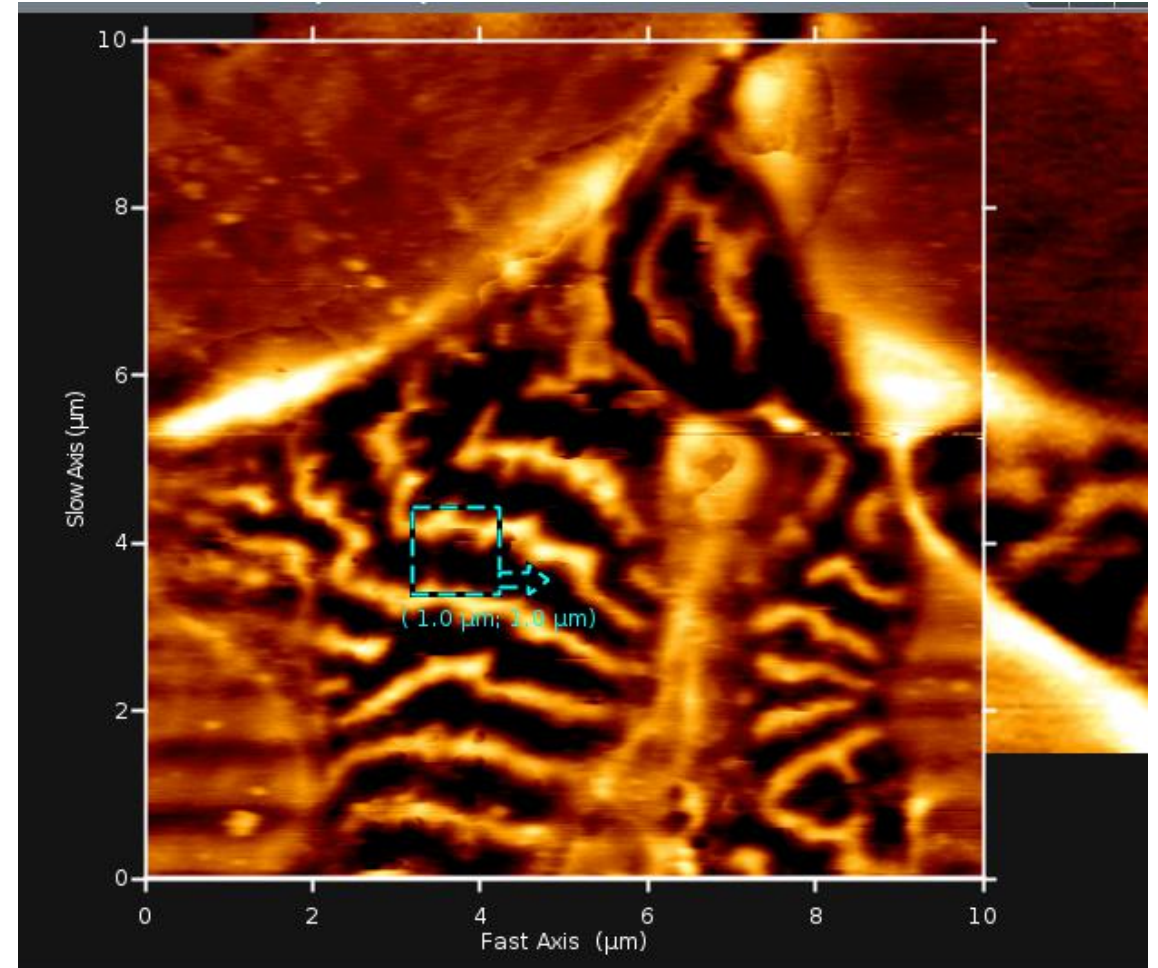
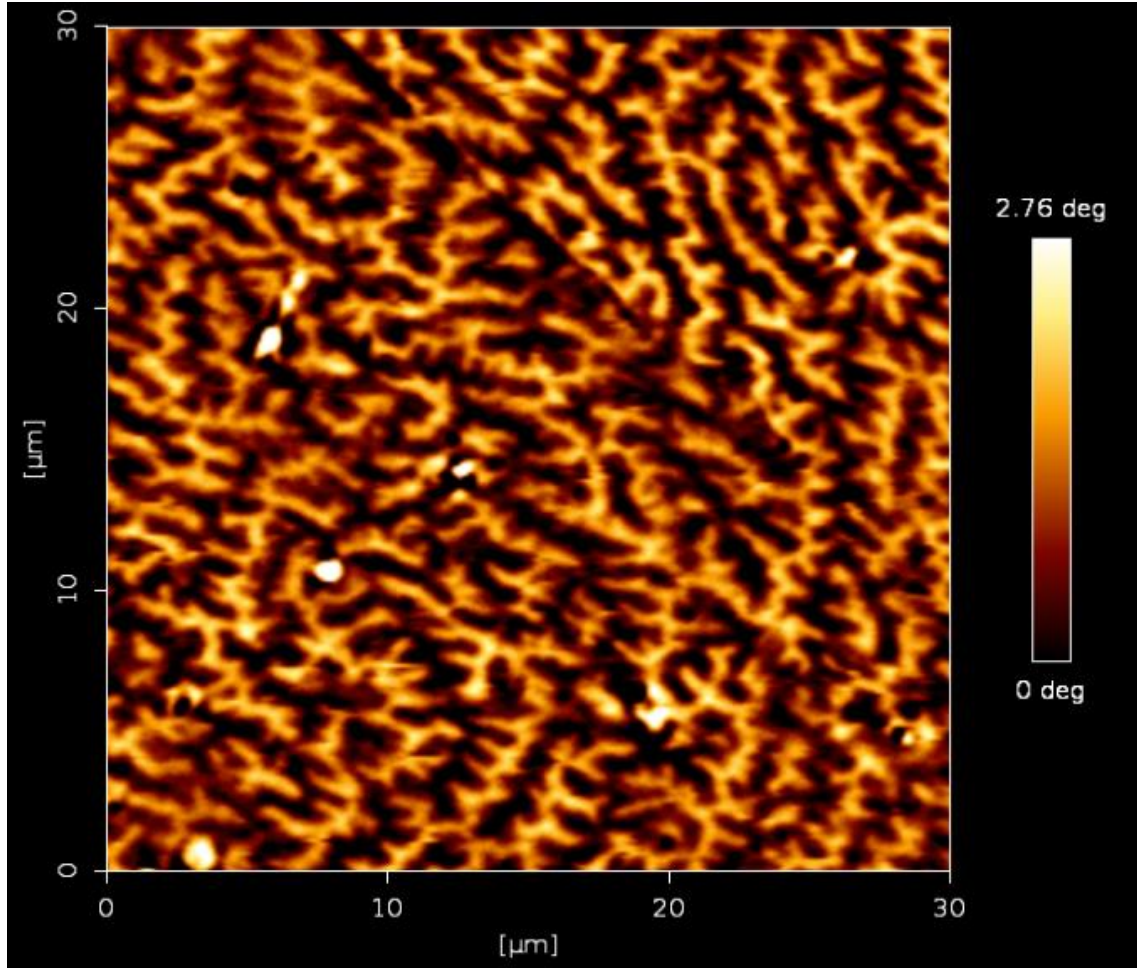
Domain structure and Magnetic Force Microscopy

The domain structure of a material is the one which **minimizes the Gibbs free energy of the material.**

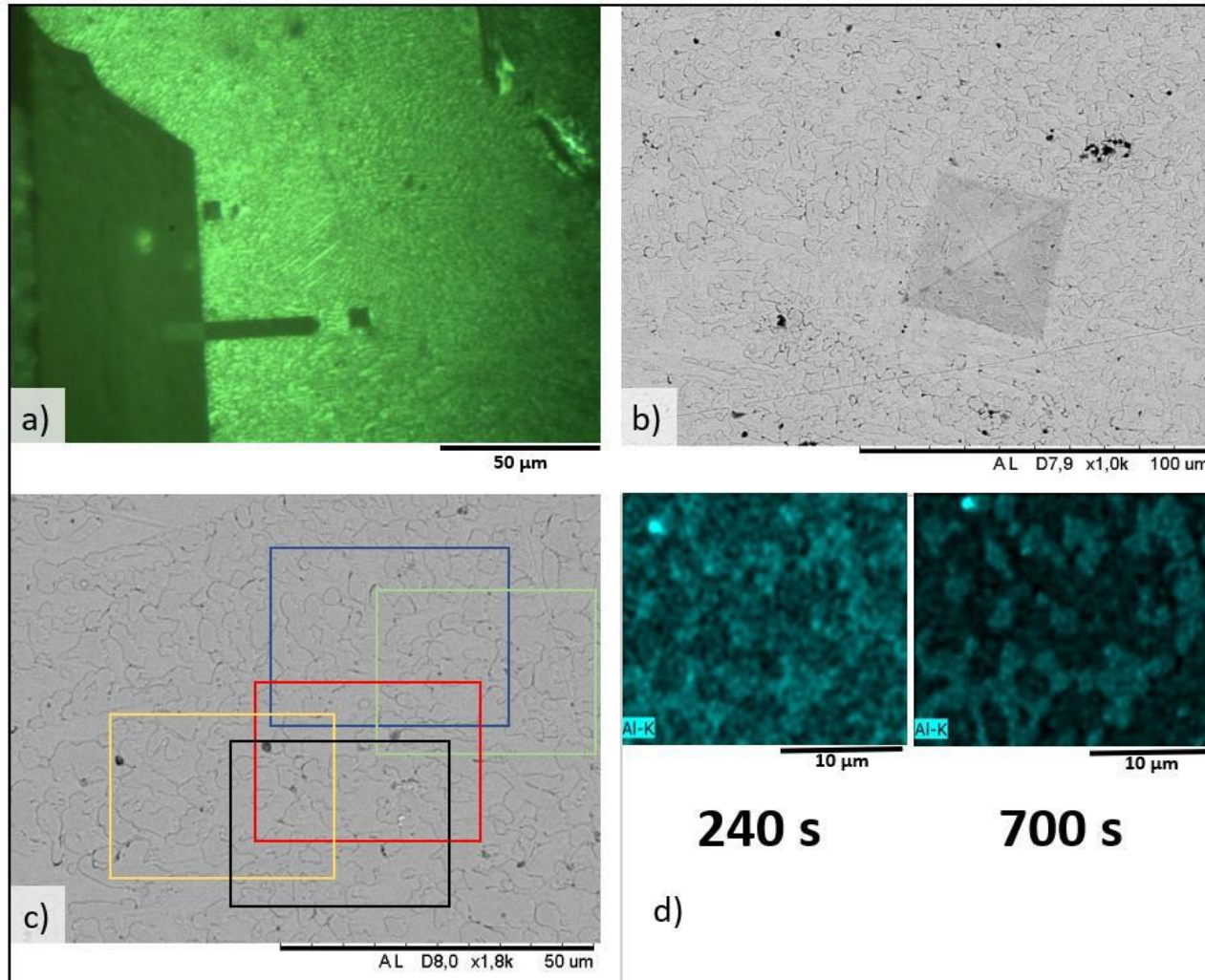


Examples of magnetic domains in $\text{FeNiCoAl}_x\text{Mn}_x$

MFM Results

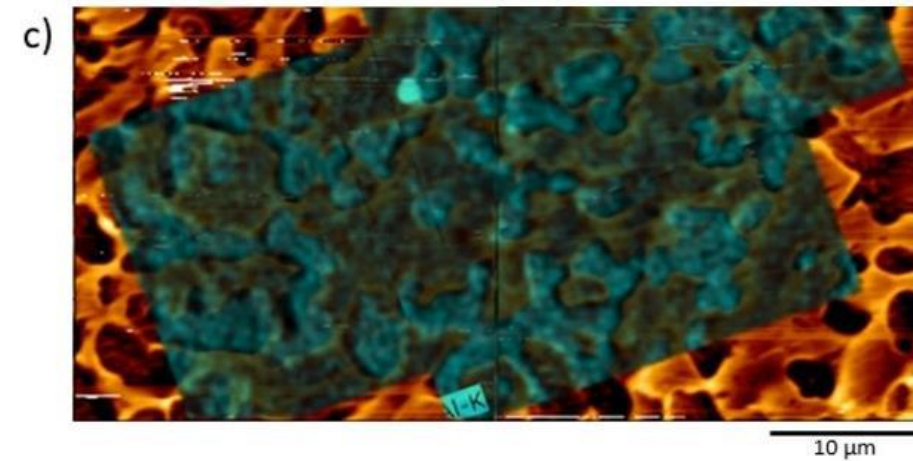
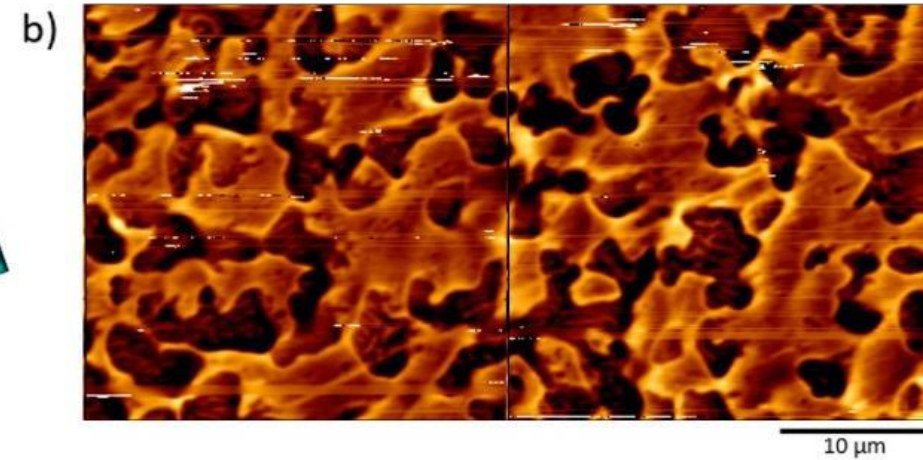
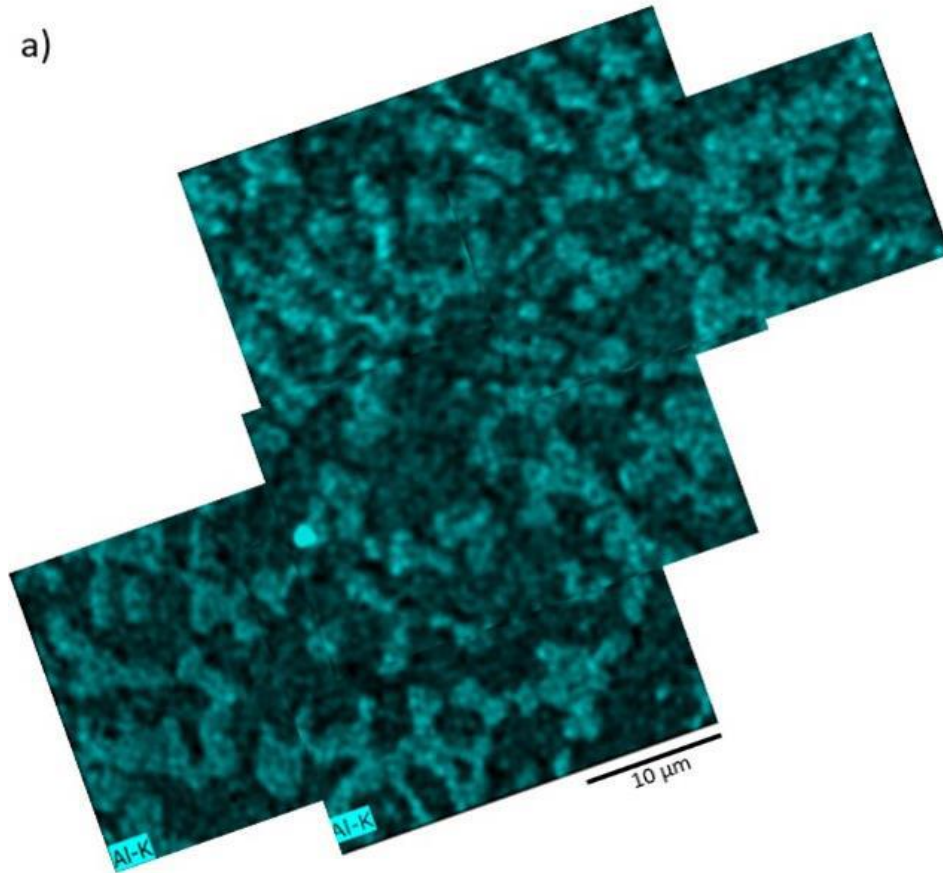


MFM and SEM measurements



a) Optical image from MFM showing the cantilever next to an indentation mark. b) An SEM image of the corresponding indentation mark. c) The area of each recorded EDS map surrounded by rectangular frames of different colour. d) Two Al EDS maps of the same area, but with different times of acquisition.

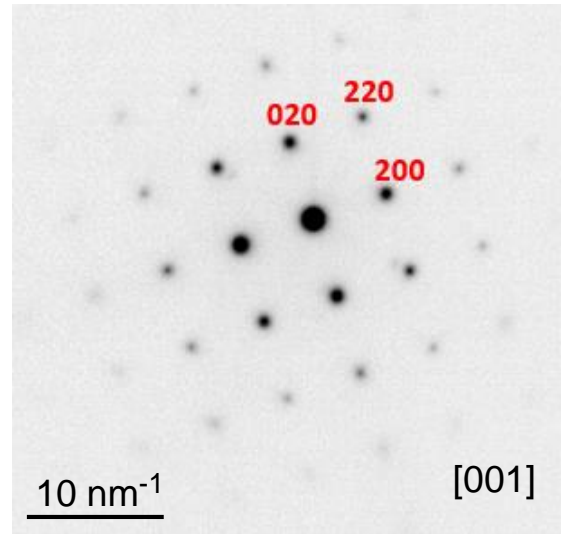
Correlation in MFM and SEM measurements



a) Al elemental map from EDS, b) MFM map from the same region as the Al elemental map and c) MFM map overlaid with the elemental map, having 30 % transparency.

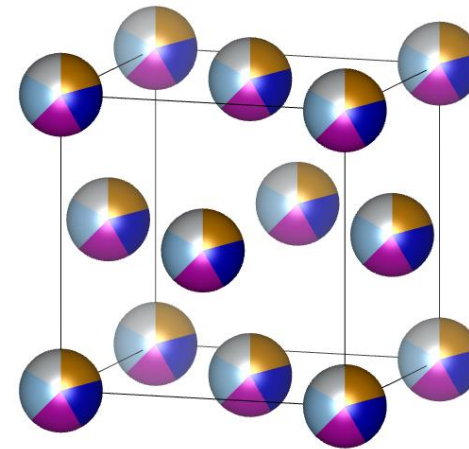
Crystal structure determination with TEM

Selected Area Diffraction (SAD)



Fe-rich

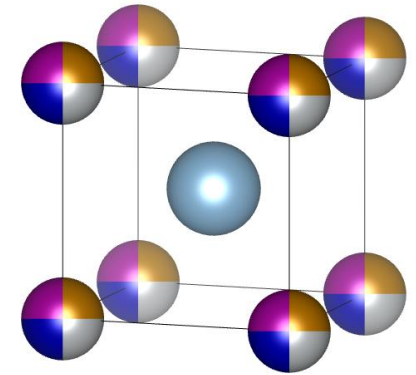
FCC



$a = 0.36 \text{ nm}$

Al-rich

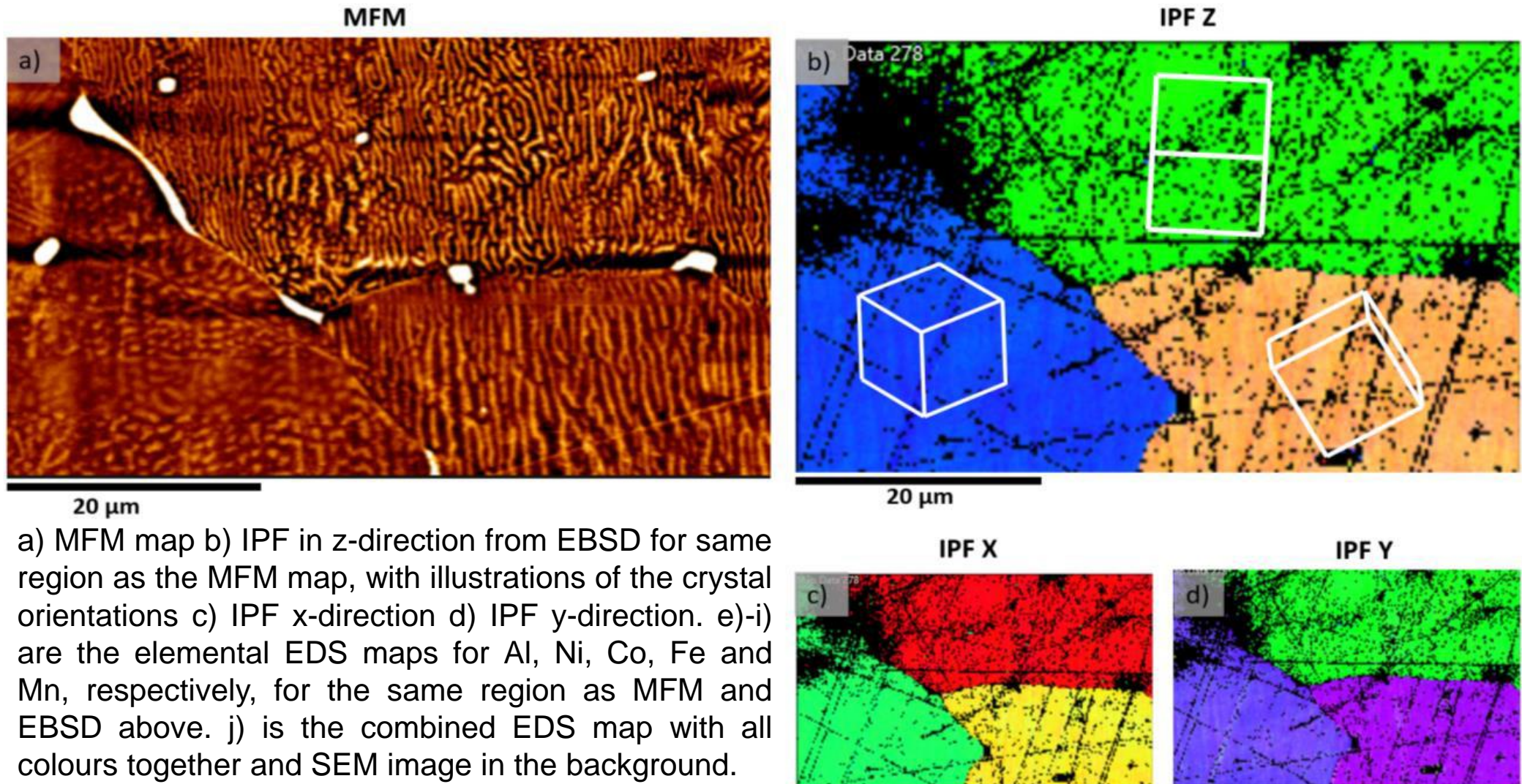
B2



$a = 0.29 \text{ nm}$



Correlation in MFM and EBSD measurements



Free energies in van der Waals fluid

$$P = \frac{NkT}{V - Nb} - \frac{aN^2}{V^2}$$

$$G = -NkT \ln(V - Nb) + \frac{(NkT)(Nb)}{V - Nb} - \frac{2aN^2}{V} + c(T)$$

$$G = F + PV \quad F = G - PV$$

$$F = -NkT \left(\ln \left(\frac{n_Q(V - Nb)}{N} \right) + 1 \right) - \frac{aN^2}{V}$$

$$n_Q(T) = (2\pi mkT/h^2)^{3/2}$$