Introduction to Elementary Particle Physics

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Elementary Particle Physics

Lecture 5: Esfand 04, 1397

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Symmetries

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Symmetries:

- Space-time symmetries
  - **Continuous Lorentz transformation:** Rotation and boost
    Lorentz+translation invariance $\rightarrow$ Poincaré invariance
  - **Discrete Lorentz transformation:** C (Parity), T (Time reversal)

- Internal symmetries
  - Global transformation: Global $U(1_{em})$, $SU(N_f)$ and $SU(N_c)$
    $\curvearrowright$ **Conservation of (electric) charge**
  - Local transformation: Local $U(1_{em})$, $SU(N_f)$ and $SU(N_c)$
    $\curvearrowright$ **Gauge fields** (force carriers)

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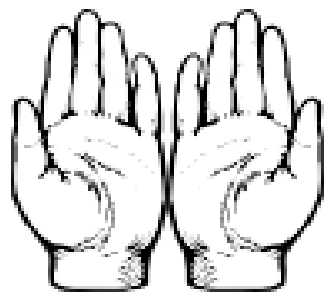
For **continuous** global and local symmetries, there are various **mechanisms of symmetry breaking**

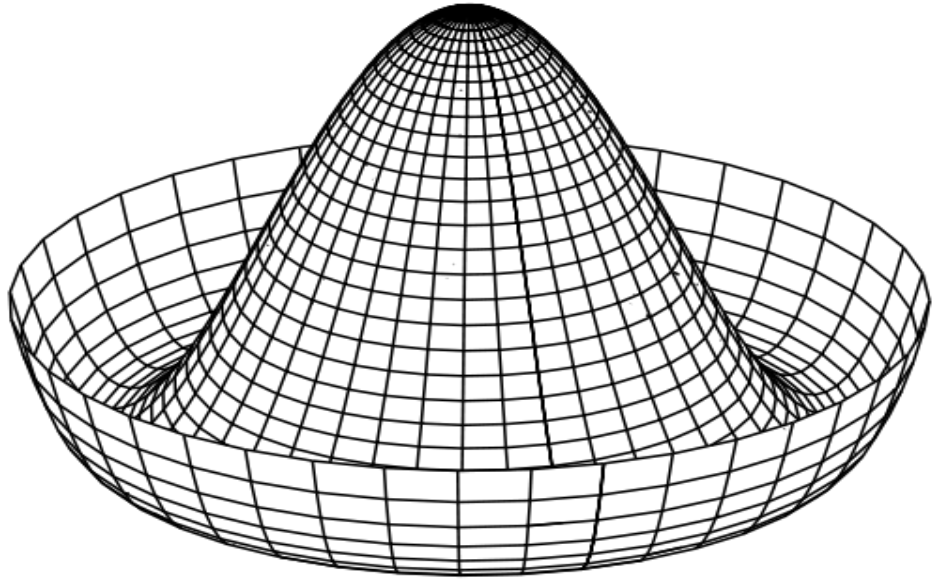
1. **Explicit symmetry breaking:** A term is added in the Lagrangian ($\mathcal{L}$) of the model that breaks explicitly the symmetry $\rightarrow$
   Example: Explicit chiral (left-right) symmetry breaking by adding a mass term in $\mathcal{L}$



2. **Spontaneous symmetry breaking (SSB):**

   Lagrangian of the model is invariant under certain symmetry, but the vacuum does not respect this symmetry $\rightarrow$

   Mexican hat potential



For $m^2 > 0$ and $\lambda > 0$

$$V(\varphi) = -\frac{1}{2}m^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$$

$$\frac{dV(\varphi)}{d\varphi} = 0 \Longrightarrow \varphi = 0 \text{ (max)} \quad \text{and} \quad \varphi = \pm\sqrt{\frac{m^2}{\lambda}} \text{ (min)}$$

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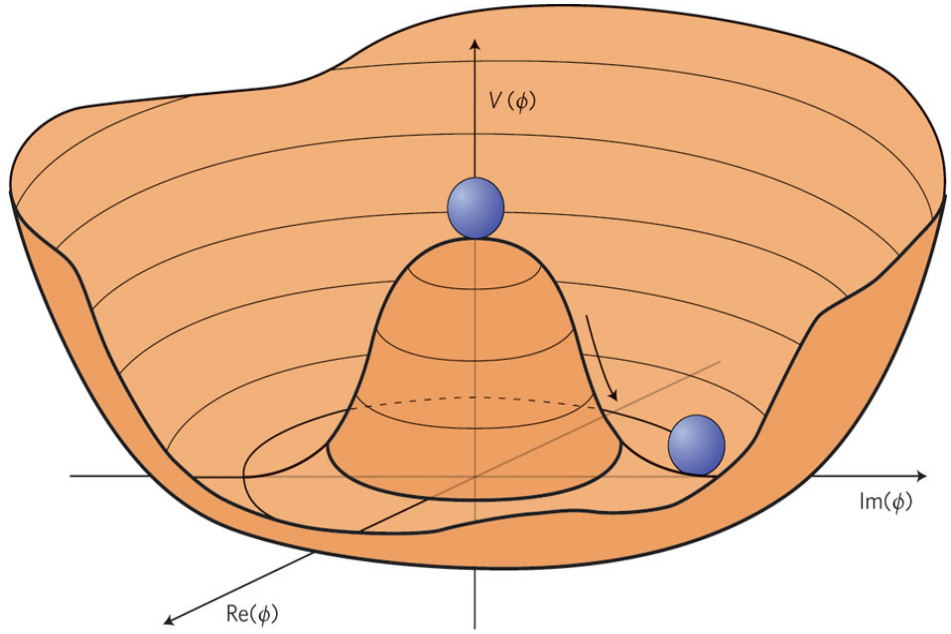

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Two categories of SSB:

a) Spontaneous breaking of **global** symmetries:

Goldstone mechanism

Example: Spontaneous chiral symmetry breaking (SχSB)

Consequence: *Massless* Goldstone modes $\rightarrow$

Example: Pions ($\pi^0, \pi^{\pm}$) are Goldstone modes of spontaneous $SU(2_L) \times SU(2_R)$ breaking [**QCD phase transition**]

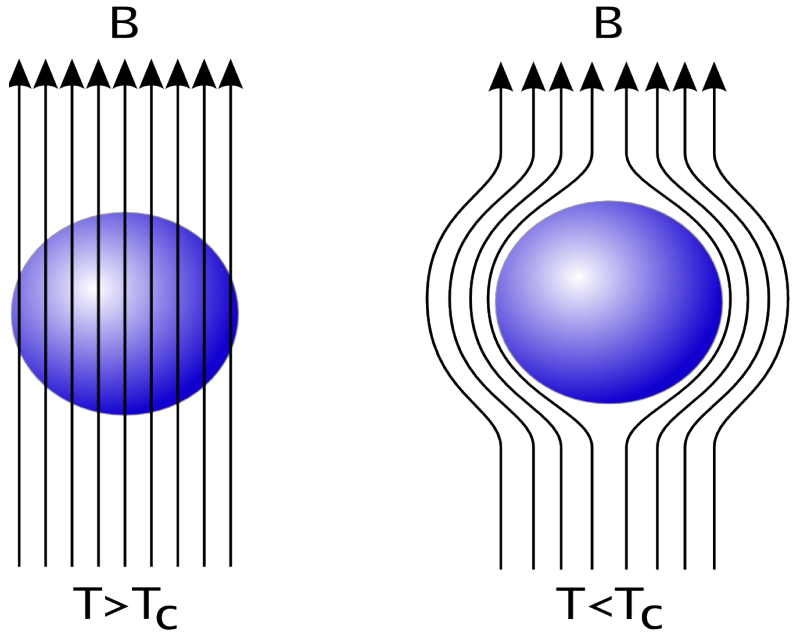
b) Spontaneous breaking of **local** (gauge) symmetries:

Higgs mechanism

Example: Spontaneous symmetry breaking of $SU(2_f) \times U(1_{em})$ [**Electroweak symmetry breaking**]

Consequence: *Massive* gauge particles $W^{\pm}, Z^0$

Superconductivity (Meissner Effect)



QED ($U(1)$) photons become massive because of the **Higgs mechanism** of SSB of local $U(1)$ symmetry

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3. **Dynamical symmetry breaking:** Classical model is invariant under certain symmetry, but the symmetry is broken by quantum corrections (external parameters T, B etc) $\rightarrow$
   Example: Dynamical mass generation
4. **Anomalous symmetry breaking:** A (global) charge that was conserved at classical level is not conserved at quantum level $\rightarrow$
   Example: Quantum anomaly
   Consequence: Pion decay $\pi^0 \rightarrow 2\gamma$
   Related to: **Baryogenesis** [Baryon-Antibaryon asymmetry]

QCD Phase Transition

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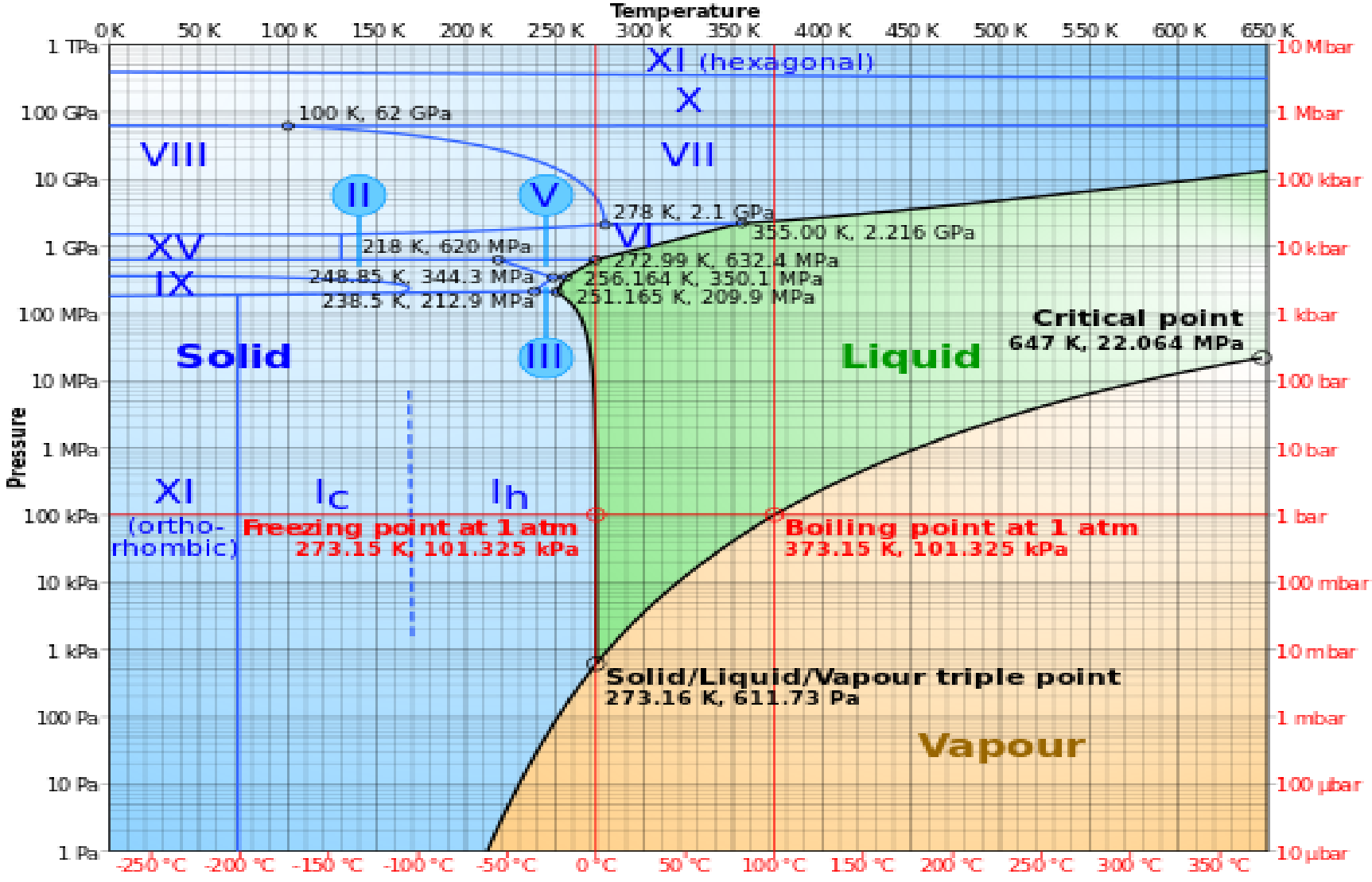
Phase diagram of Water



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Phase diagram of Quark Matter