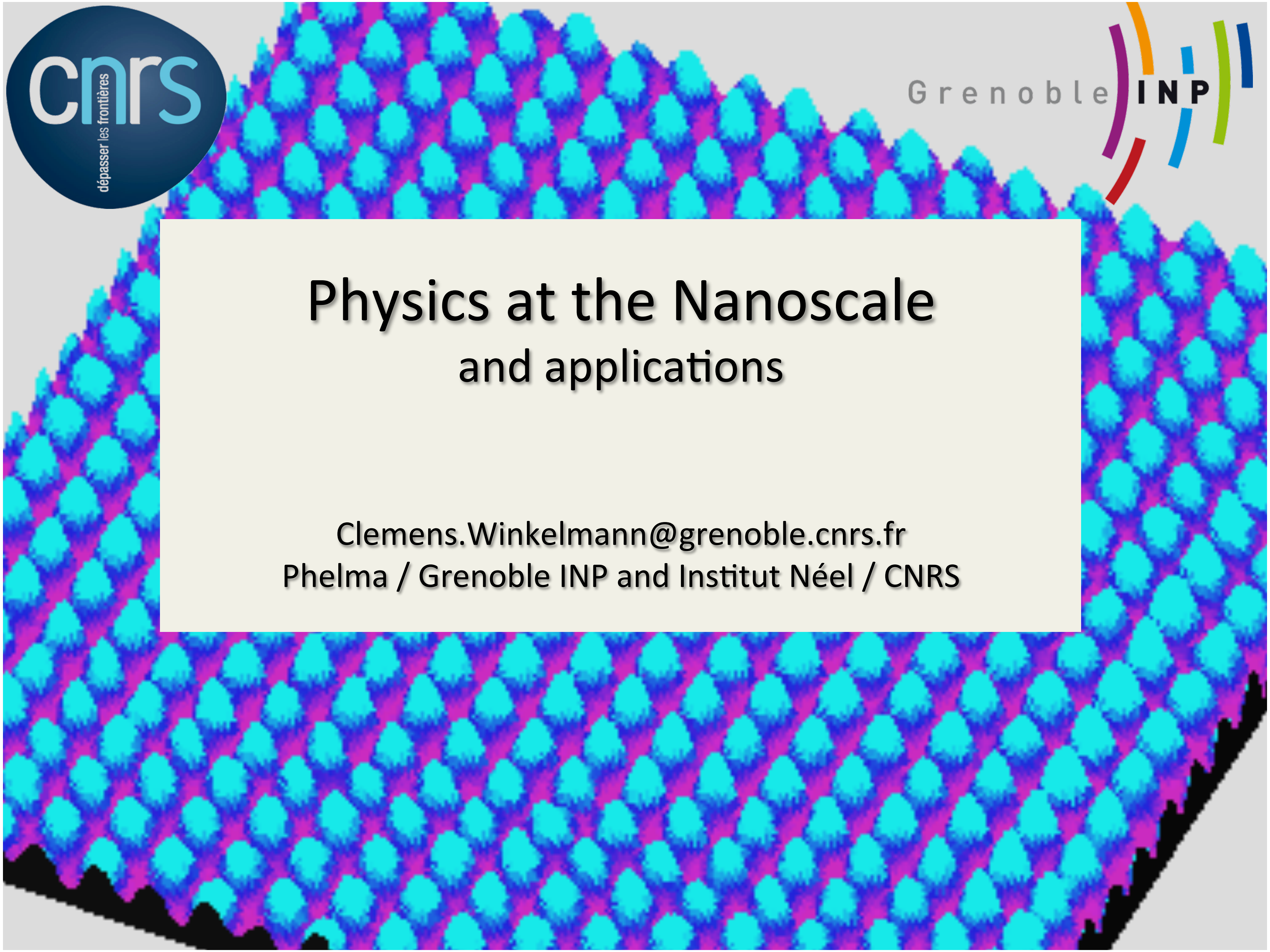

Physics at the Nanoscale

and applications

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Physics at the Nanoscale

I Basics of quantum mechanics
II Statistical physics
III Forces at the nanoscale
IV Electron tunneling and applications
V Quantum electronic transport

Statistical Physics

Large numbers and fluctuations

Macroscopic world:
ensembles of $N \approx 10^{23}$ particles

Fluctuations concern $\approx\sqrt{N}$ particles

Relative fluctuations amount to $\sqrt{N}/N = 1/\sqrt{N} \approx 10^{-11}$

« In a big group, you only care about the mainstream »

In nanoscience, there's room for fluctuations.

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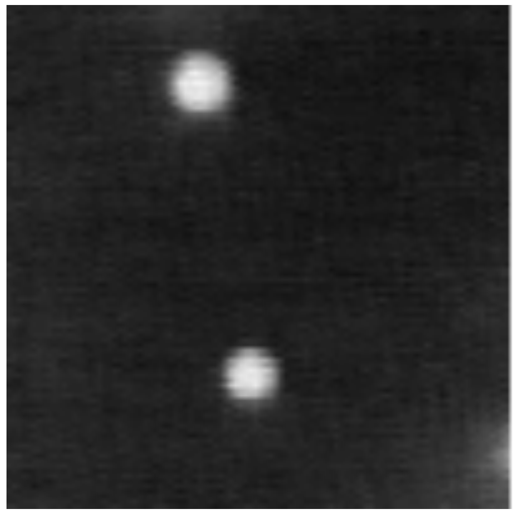
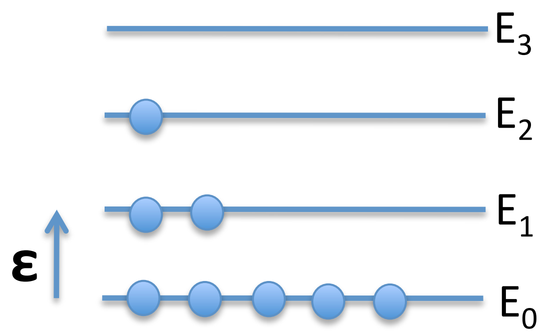


Brownian motion of 2 µm spheres in water.
Courtesy Professor Eric Weeks, Emory University

Statistical Physics

Boltzmann distribution



At fixed temperature, probability of a given particle to be in a given state of energy E

$$P(E) = \frac{1}{Z}\exp(-\frac{E}{k_B T})$$

Boltzmann constant
k_B=1.38 10^{-23} J/K

At room temperature (300K)

$k_B T$ = 4.1 10^{-21} J
= 26 meV
= 4.1 pN.nm

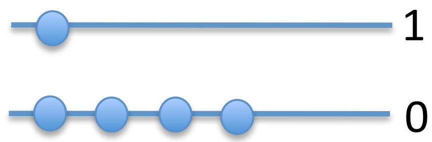
Exercise:
In the above drawing, assume T=300K and ε=100 meV. How much more is state 0 populated than state 1 ?
How about if ε=1 eV ?

Statistical Physics

Quantum statistics

○ Quantum particles are entirely described by their quantum state

-classically, 5 ways of realizing



- in the quantum world, they're one and the same thing

- How many particles can be in the same quantum state?

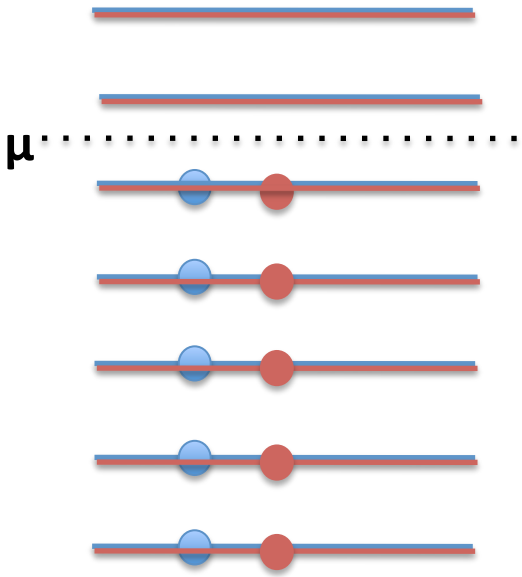
Pauli exclusion principle: Two fermions cannot be in the same quantum state.

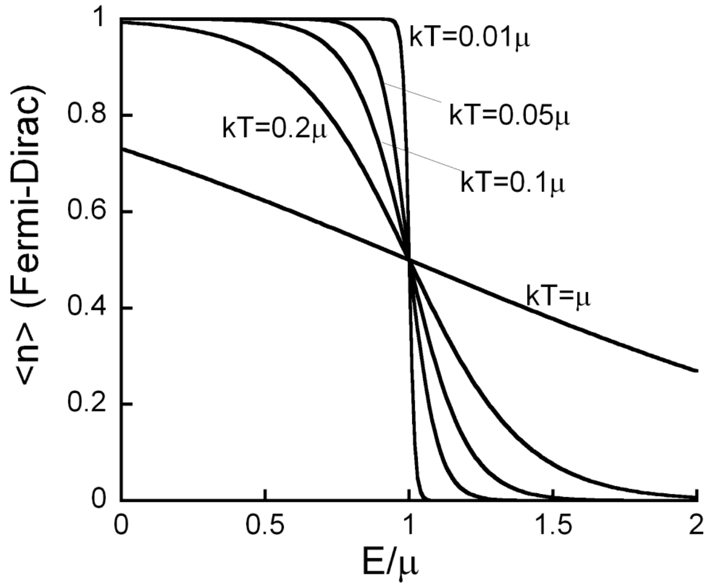
Fermi-Dirac distribution $$n(E) = \frac{1}{\exp\left(\frac{E-\mu}{k_B T}\right)+1}$$

Statistical Physics

Fermi-Dirac distribution

$$f(E) = \frac{1}{\exp\left(\frac{E-\mu}{k_B T}\right)+1}$$

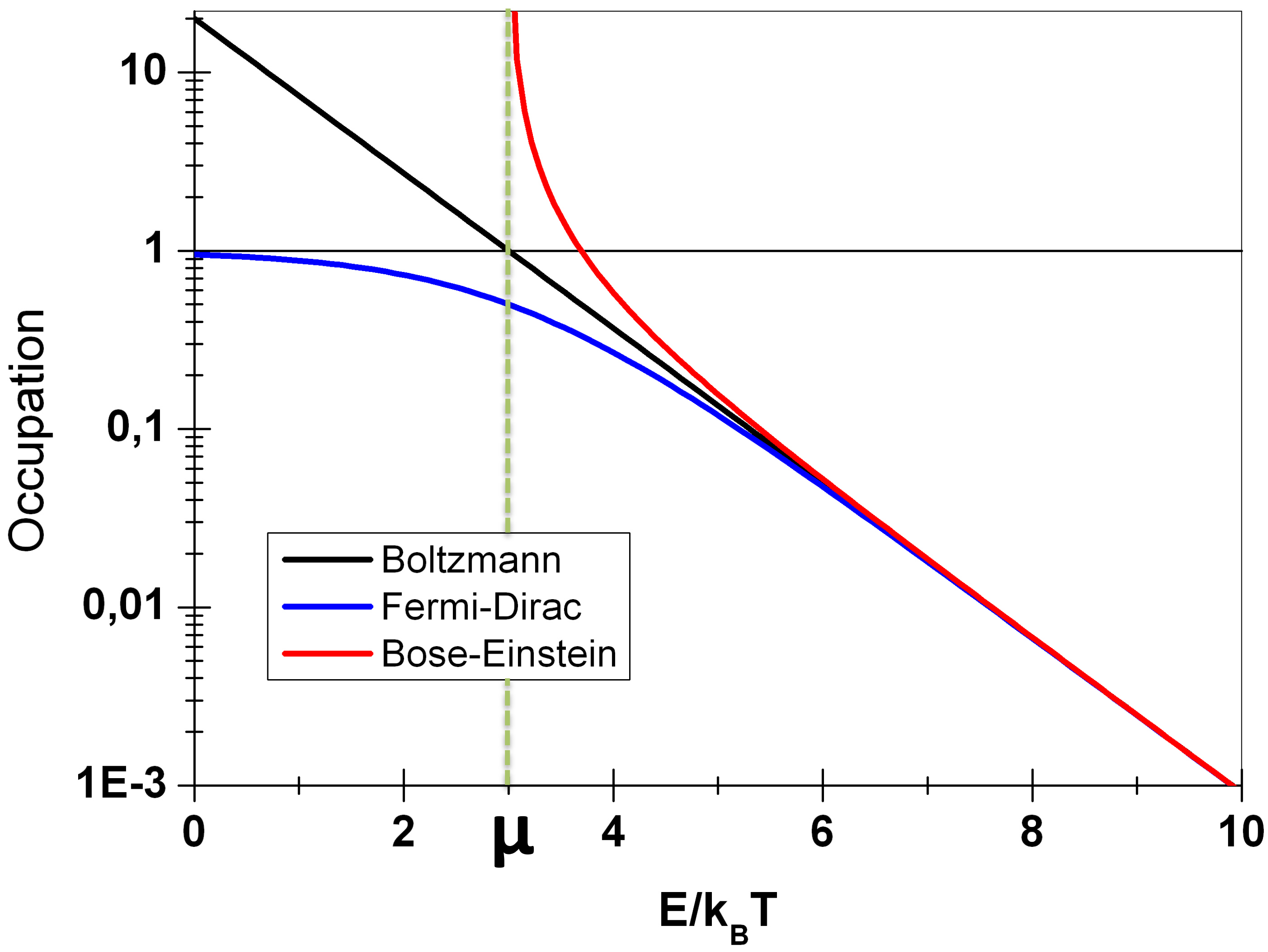




○ Low-energy states are filled with probability ≈ 1.

○ For E > μ, occupation probility decays similarly to Boltzmann distribution.

○ Orbital states may be spin degenerate.



10
1
0,1
0,01
1E-3
Occupation
0
2
μ
4
6
8
10
E/k_B T
Boltzmann
Fermi-Dirac
Bose-Einstein

Statistical Physics

Thermal distribution of fermionic ensembles

- Fermions: electron, proton, neutron, ^{3}He, …

- At $T = 0$, all states below μ are filled, all above are empty.

- At $T > 0$, thermal excitations around $E=\mu$.

  States filled with finite probability $0 < p < 1$.

  Thermal smearing: df/dE
  Full width at half hight $\approx 3.5 k_B T$

- At high $T \approx \mu/k_B$, recover Boltzmann statistics.