Extreme Matter

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Outline

The reductionist method

The reductionist checklist

Always pack a microscope when you go exploring

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Always pack a microscope when you go exploring

In order to understand something, first find what it is made of.

- To understand chemistry, start with the chemical elements
- For life: understand the working of cells
- Matter: examine elementary particles

The well-known story of matter

- **1789**: conservation of mass. Along with laws of stoichiometry, can be used to deduce the existence of atoms.
- Connection with the Gas Laws: kinetic theory of gases, Avogadro's number. The length scale of atoms: 0.1 nm.
- The atom split in 1897: electrons (negatively charged) seen. Rutherford's experiments in **1911** reveal positively charged atomic nucleus: length scale of 1–10 fm.
- In 1913 X-ray spectroscopy established that the periodic table is ordered by the nuclear charge Z (Moseley).
- Great developments in nuclear physics: β-decay, fission, fusion: energy generation, understanding of the mechanism of stars, transmutation of elements, artificial elements.

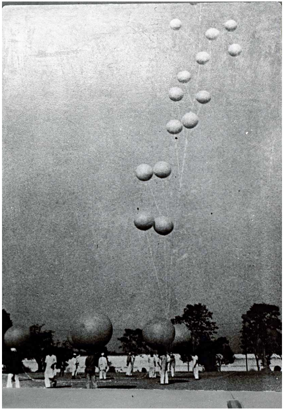
The puzzling behaviour of strong interactions

Protons are positively charged, but nucleus is usually stable. In fact, β-decays increase Z!

Neutrons discovered in 1933 (Chadwick).

In 1935 Yukawa proposed a new interaction to stabilize nuclei; called strong interactions: mediated by a new particle— a meson. In 1947 π observed in cosmic rays: Yukawa's **meson**.

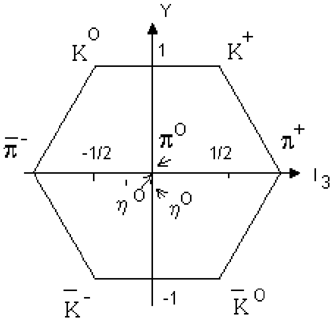
In 1947 entirely different mesons also found in cosmic rays. Through the '50s lots of new particles found. Baryons (like proton and neutron): fermions, mesons: bosons.

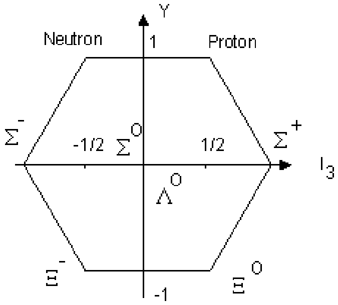


TIFR, 1950s

The hadron periodic table

Gell-Mann and Ne'eman built hadrons from true elementary particles: quarks. Mesons = quark and anti-quark, baryons = three quarks. (**1961**)
Three varieties of quarks: up, down and strange.





The Discovery of the Strong Interactions

1911: the discovery of the atomic nucleus

The scattering of α and β particles by matter and the structure of the atom, E. Rutherford, Phil. Mag. 21 (**1911**) 668–88.

1961: quarks underly the visible world

Axial Vector Current Conservation in Weak Interactions, Y. Nambu, Phys. Rev. Lett. 4 (**1960**) 380–2.
The Eighfold Way: A Theory of strong interaction symmetry Murray Gell-Mann CTSL-20, TID-12608, Mar. **1961**, 49 pp.
Derivation of strong interactions from a gauge invariance, Yuval Ne'eman, Nucl. Phys. 26 (**1961**) 222–9.

A quantum particularity

Statistics

Truly elementary particles of the same kind indistinguishable.

- Exactly one particle per state: **Fermions**
- Any number particles in the same state: **Bosons**

Spin

Quantum mechanics allows only discrete angular momenta: $\hbar/2$ (Planck's constant).

- Fermions have angular momenta $\hbar/2$, $3\hbar/2$, $5\hbar/2$ *etc*.
- Bosons have angular momenta 0, $\hbar$, $2\hbar$, *etc*.

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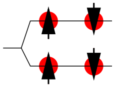

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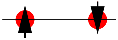

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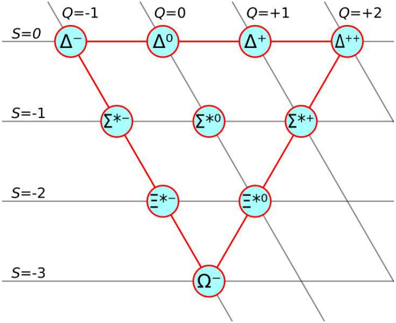
A small puzzle: the gateway to the standard model



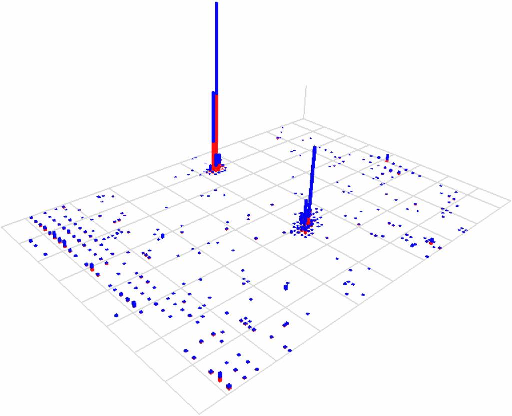
Baryon Δ^{++} contains three up quarks in the same state.

Quarks are fermions. Cannot be in the same state.

There must be three types of quarks. What distinguishes them?

New charge. Called **colour**. Turns out to be the charge of the strong interactions.

Seeing is believing



Single quarks are never seen in experiment: the only strongly interacting particles ever seen are hadrons.

Quantum ChromoDynamics

Quarks carry colour charge. Interact by exchanging gluons. Gluons also have colour charge. No other elementary particle has colour charge. The quantum theory of "coloured particles" is called QCD.

Binding of quarks into hadrons the true strong interaction; the binding of the nucleus a much weaker "van der Waals" remnant force.

From energy scales of a few MeV to TeV no substructure to quarks found!

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1908–2008: 30 Nobel prizes to almost 50 people!

The Discovery of the Theory of Strong Interactions

Asymptotic freedom in QCD

Ultraviolet Behavior of Nonabelian Gauge Theories, D. J. Gross and F. Wilczek, Phys. Rev. Lett. 30 (**1973**) 1343–6.
Reliable Perturbative Results for Strong Interactions? H. D. Politzer, Phys. Rev. Lett. 30 (**1973**) 1346–9.

Confinement in QCD

Confinement of Quarks, K. G. Wilson Phys. Rev. D 10 (**1974**) 2445–59.

Parameters of QCD

Fundamental theory: very few parameters.

1. Λ: an intrinsic mass scale. $\Lambda \simeq 200$ MeV; corresponding length scale: 1 fm. Strength of interaction distance dependent: $\simeq 1$ at 1 fm, decreases with distance: **asymptotic freedom**
2. Up and down quark masses: m_u, $m_d \simeq$ 5–10 MeV. Is that natural— $m_{u,d} \ll \Lambda$? No. Approximate symmetry forces light quark masses almost to zero: **chiral symmetry**
3. A medium heavy quark: $m_s \simeq \Lambda$. Natural; no special symmetry.
4. Several very heavy quarks: m_c, m_b, $m_t \gg \Lambda$. Important at very short distances; unimportant at length scale ≥ 1 fm. Origin of heavy masses related to **Higgs boson**

Outline

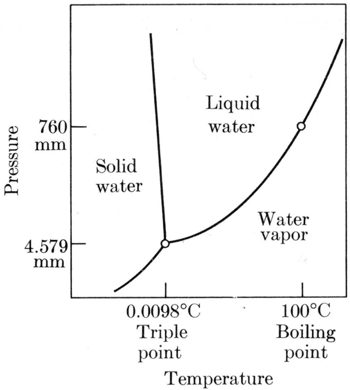
1. Extreme reductionism
2. Building things up
   - The phase diagram
   - Cold and dilute: particle physics
   - Cold and dense: nuclei, stars, supernovae
   - Hot matter: early universe
3. Future

Emergent behaviour

At macroscopic distances and times thermodynamics emerges from all theories of matter: universal laws.

Microscopic theories explain characteristics such as the specific heat or bulk compressibility.

Various kinds of matter also undergo **phase transitions**: location of phase transitions come from microscopic theory.



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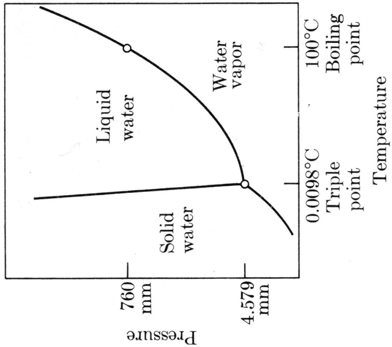

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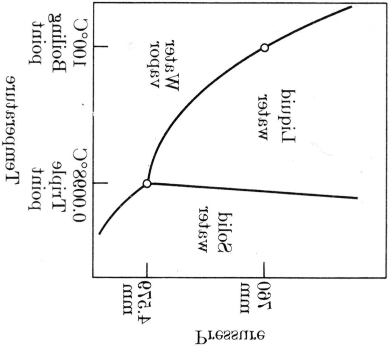

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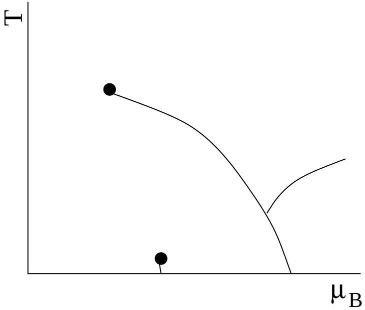

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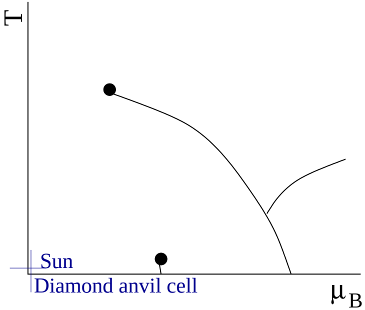

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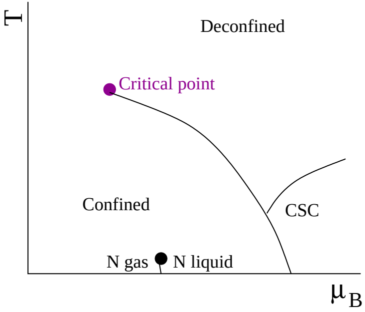
$\mu = 300 \pm 30$ MeV
Gavai and SG, 2008



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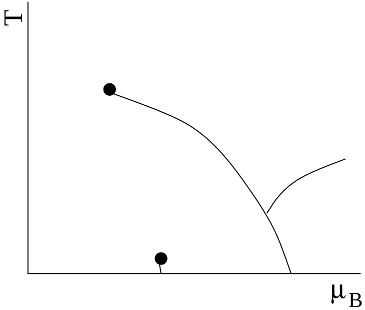

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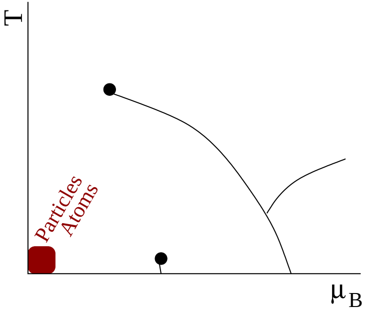

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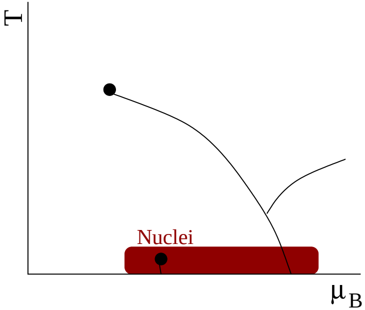

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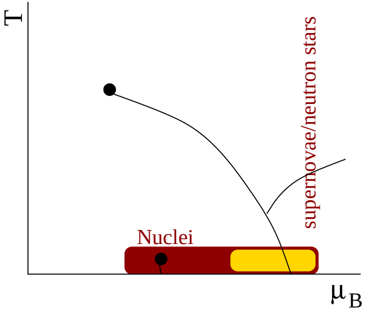

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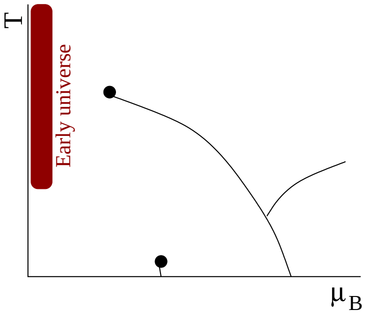

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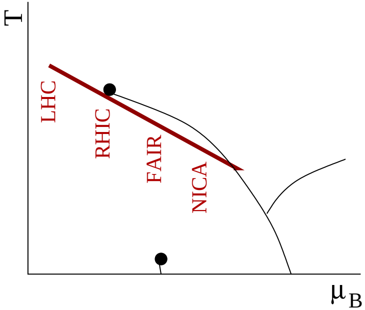

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Extreme computing

QCD mathematically intractable: prize for proving that colour charge cannot be produced in a lab: **$ 1,000,000**

Alternative: put it on computers. Tremendous computing challenge: multi Eflops year. All future developments require base of supercomputing.

- Humans: $\simeq$ 0.1 flops
- Desktops: $\simeq$ 1 Gflops
- QCD today: $\simeq$ 1–10 Tflops
- QCD in 5 years: $\simeq$ 1 Pflops
- US long-range plan: $\simeq$ 1 Eflops

IBM Blue Gene: designed in collaboration with QCD practitioners.

1 flops: adding two 8-digit numbers in 1 sec

The mass of matter

Can the mass of this system be computed from the standard model of particle physics?

1. Protein folding and other entropic terms ≈ 1 eV
2. Binding energy of electrons ≈ 1 KeV
3. Electron rest mass ≈ 1 MeV
4. Proton mass ≈ 1 GeV

QCD answers the question with accuracy of about 1 part in 10^3. This involves computing the mass of the proton from first principles.

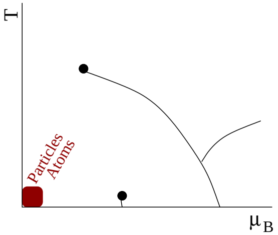
Exotics

Lesson from the '60s: meson = 1 quark + 1 anti-quark; baryon = 3 quarks. Nothing else known.

Excitement of the '00s: pentaquark baryons = 4 quarks + 1 antiquark. Weak evidence at present.

Future: glueballs = multiple gluons; hybrid mesons = 2 quarks + 2 anti-quarks; others?

Mathur *et al.*, Basak *et al.*



Nuclear accidents

The next-to-simplest nucleus: ^2H very lightly bound. Why?

	$a(^1S_0)$ fm	
	pp	*np*
Expt*	-7.8098 (23)	-23.748 (10)
Bonn	-7.82	-23.75
Paris	-7.85	-23.72

*:Dumbras *et al.*, 1983

$^1S_0$ scattering lengths in fm. The natural scale for nuclear binding is 1 fm, so the scattering lengths are unnaturally large. Why?

Many similar coincidences known. Some very important for stellar nucleosynthesis. Understanding from QCD? Beginning of a new subject.

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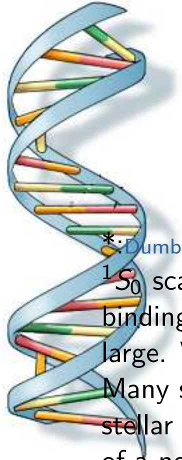

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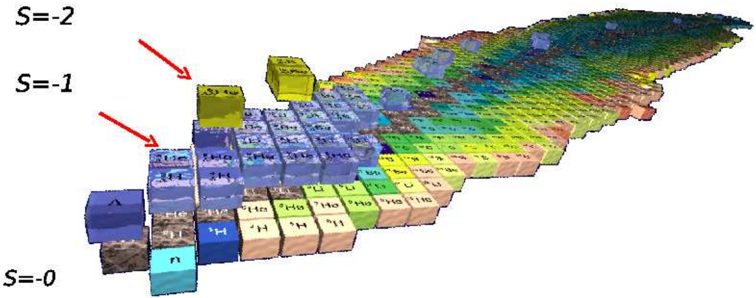
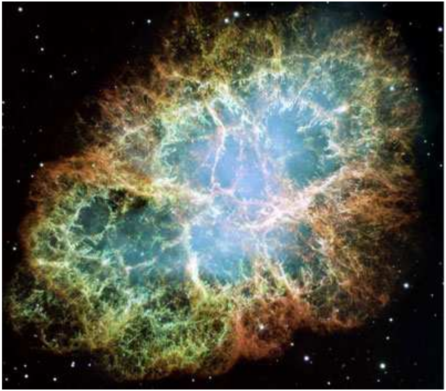
Nuclear physics: new dimensions



STAR Collaboration, 2009: includes several Indian groups

A possible supernova signal



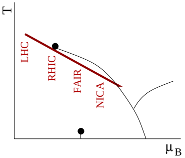
If the core of a supernova turns into dense quark matter then a burst of $\overline{\nu}$ may be detected in neutrino observatories on earth.

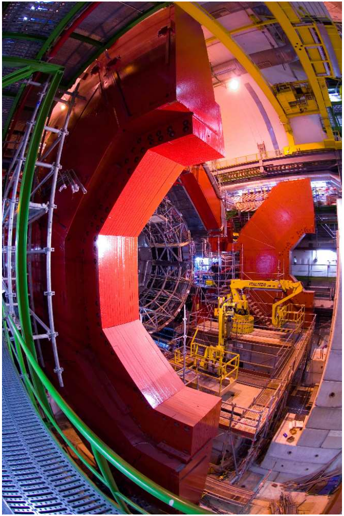
Dasgupta *et al.*, 2009

Hydrodynamics

Matter at long distances and long times almost always obeys hydrodynamics: almost universal theory. More generally: coupled advection-diffusion equations.

The role of microscopic theories of matter is to explain the equation of state, the viscous coefficients, *etc*.





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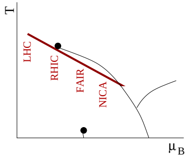

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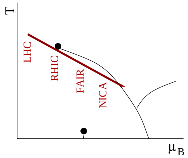

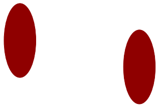

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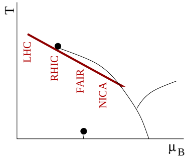

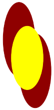

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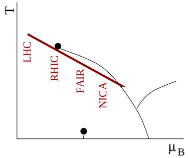

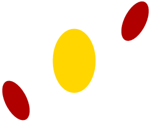

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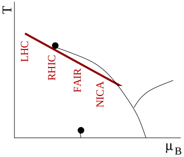

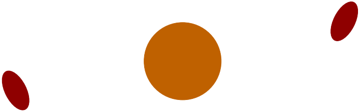

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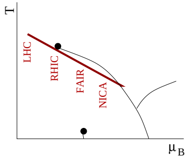
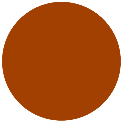




Extreme viscosity

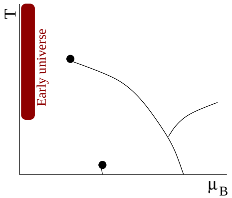
Shear viscosity of different materials cannot be directly compared. Instead compare “kinematic viscosity”: η/n; relativistically η/S.

This has the same dimension as $\hbar/k_B$. So $\eta k_B/(S\hbar)$ is dimensionless. How small can it be?

$$\frac{\eta}{S} \times \frac{k_B}{\hbar} \begin{cases} \simeq 0.8 & \text{(liquid He)} \\ \leq 0.5 & \text{(BEC)} \\ \leq 0.5 & \text{(hot QCD)} \end{cases}$$

Danielewics & Gyulassy 1985

Son *et al.*, 2001; Schaeffer, 2010



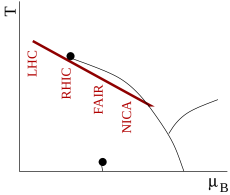
Femtophysics is nanofluidics

Knudsen number is $K = \lambda/L$. When $K \ll 1$ coarse-graining possible. As $K \to 0$ kinetic theory $\to$ fluid dynamics.

In colliders $\lambda \simeq 0.1$–1 fm expected. L measured less than 10 fm. Hence $K \simeq 0.1$–1. Microscopic dynamics may be important: causal viscous fluid dynamics.

Nanofluidics, gas dynamics, neutrino flow in supernovae all have $K \simeq 0.1$–1.

Bhalerao *et al.*2005, SG 2005

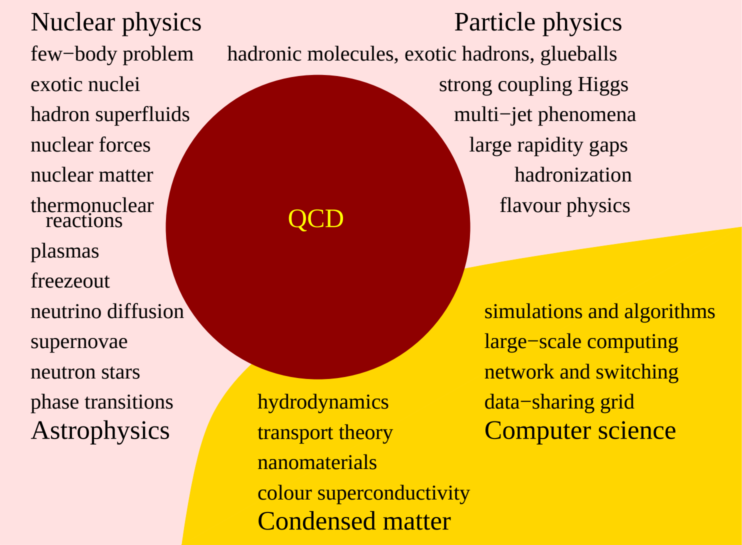


Outline

Beyond

Matheran: SG, 2009

QCD today


Nuclear physics
few−body problem
exotic nuclei
hadron superfluids
nuclear forces
nuclear matter
thermonuclear reactions
plasmas
freezeout
neutrino diffusion
supernovae
neutron stars
phase transitions
Astrophysics
Particle physics
hadronic molecules, exotic hadrons, glueballs
strong coupling Higgs
multi−jet phenomena
large rapidity gaps
hadronization
flavour physics
QCD
simulations and algorithms
large−scale computing
network and switching
data−sharing grid
Computer science
hydrodynamics
transport theory
nanomaterials
colour superconductivity
Condensed matter