Nuclear physics and QCD

Michael C Birse

(The University of Manchester)

NuPECC long range plan 2004: Perspectives for nuclear physics research in Europe in the coming decade and beyond

- Chapter 4 Quantum Chromodynamics
- Chapter 5 Phases of nuclear matter

http://www.nupecc.org/nupecc/lrp02/

Nuclear physics is QCD

Quantum Chromodynamics (QCD) is the theory of the strong interaction
– the force responsible for binding nuclei

Theory of quarks and gluons, carrying colour charges
– but these are trapped inside colour-singlet states: hadrons
(at least in the vacuum surrounding us)
– mesons ($q\bar{q}$) and baryons (qqq)
(plus clouds of gluons and $q\bar{q}$ pairs)

Nuclei: large numbers of quarks, but still strongly correlated in threes
→ many properties can be understood just in terms of nucleons,
interacting via phenomenological forces

But . . .

We want to understand:

- the nature of colour confinement
- the mechanism of mass generation for hadrons
- the origin of the forces between nucleons

And to look for places where the standard picture breaks down:

- responses of nucleons to external fields
  (polarisabilities, three-body forces)
- existence of "exotic" states
  (glueballs, hybrids, "molecules", pentaquarks?)
- transitions to new phases of strongly interacting matter
  under extreme conditions of temperature and density
  (quark-gluon plasma, colour superconductors)

All of these need QCD degrees of freedom and symmetries

Outline

- Some rudiments of QCD
    - Lagrangian
    - Running coupling
    - Confinement
    - Hidden chiral symmetry
    - Phase diagram
- Hadrons in the ordinary vacuum
    - Chiral dynamics
    - Parton distributions
    - Heavy-quark states
- Strongly interacting matter
    - Quark-gluon plasma
    - Dense baryonic matter

Quantum Chromodynamics

QCD is a gauge theory (like electromagnetism)

- spin-1/2 particles: quarks
- interacting by exchange of spin-1 bosons: gluons

Gauge symmetry group is colour SU(3)

- quarks: triplets (“red, green, blue”)
- gluons: octet
- nonabelian: when a quark emits a gluon, its colour changes

→ gluons must carry colour → must interact with each other

Lagrangian

$$\mathcal{L} = \sum_{f=u,d,\dots} \bar{q}_f \left[i\gamma^\mu \left(\partial_\mu - i g t^a A^{a\mu} \right) - m_f \right] q_f - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$

in terms of quark fields: $q_f(x)$, gluon fields: $A^a_\mu(x)$ ($a = 1, \dots, 8$) and

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

m_f: “current” masses, from EW Higgs mechanism

Quarks come in six flavours

Up, down: current masses $m_{u,d} \simeq$ 5–10 MeV

- dominant constituents of ordinary matter
- form a pair under SU(2) isospin symmetry (weak interaction)

But also two extra heavier copies (generation problem)

- charm (1.3 GeV), strange (100 MeV)
- top (178 GeV), bottom (4.3 GeV)

→ s, c and b quarks all form hadronic states

→ s could play a role in normal matter – virtual $s\bar{s}$ pairs

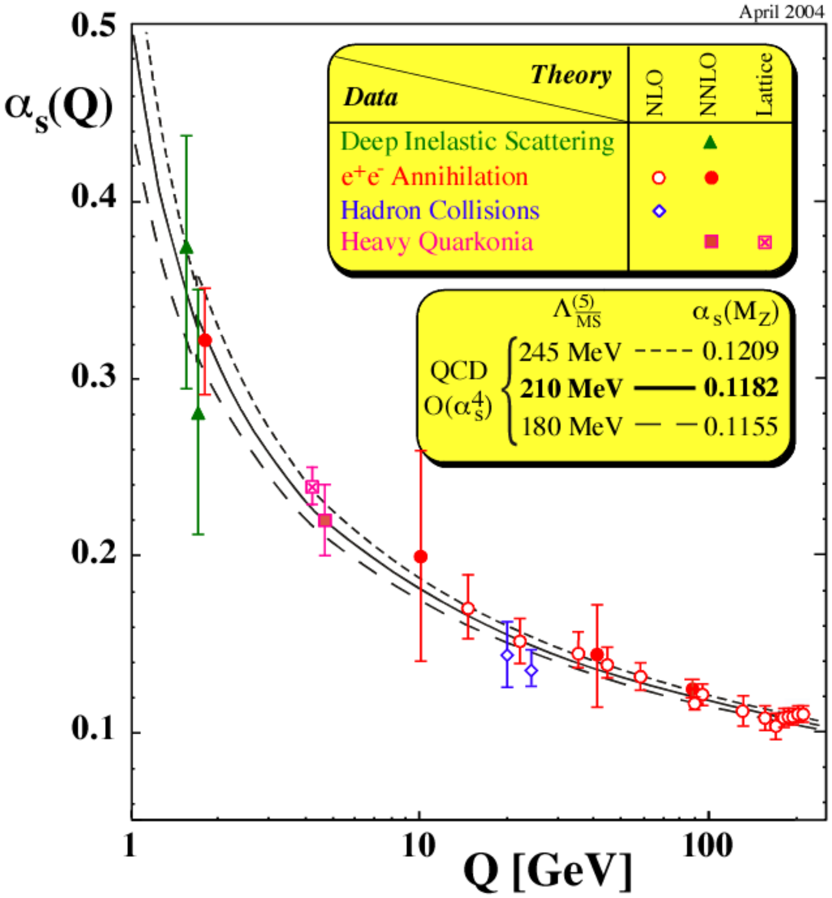
→ c and b can act as $\sim$ static sources of gluon fields

(t decays too fast to do much in hadrons or nuclei)

Running coupling

Cloud of virtual gluons and quarks around colour charge → antiscreening

Strong coupling constant $\alpha_s = g^2/4\pi$ runs with momentum scale Q



S. Bethke, hep-ph/0407021

High momenta, $Q \gg 1$ GeV

- asymptotic freedom [Gross, Politzer and Wilczek, 1973]
- perturbation theory can be used
  hard scattering processes, evolution of DIS structure functions

Low momenta, $Q \lesssim 1$ GeV (nuclear and hadron physics)

- QCD is nonperturbative
- "empty" space like a complicated condensed-matter system

Theoretical tools include

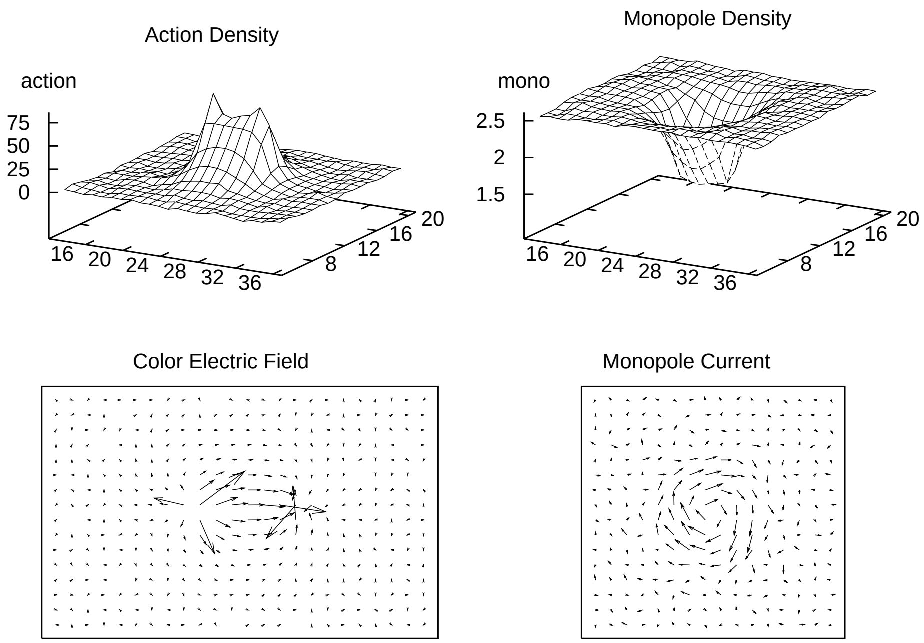
- lattice simulations
  define fields on a discrete lattice in Euclidean space-time
  evaluate path integrals numerically using Monte-Carlo methods
- renormalisation group and effective field theory
  expand in powers of ratios of low- and high-momentum scales
- QCD-inspired models
  nonrelativistic quarks, bags, solitons, NJL, hadronic strings . . .

Confinement

Quarks and gluons trapped inside colour-singlet hadrons
Emerging picture: dual superconductor

- vacuum is condensate of magnetic monopole-like gluon configurations
- Meissner effect confines colour electric fields to flux tubes

→ linear potential between $Q\overline{Q}$ (hadronic string)



H. Ichie *et al*, DIK Collaboration, hep-lat/0212036

Full QCD with 2 light flavours

Maximal Abelian gauge

Hidden chiral symmetry

u and d quarks almost massless in QCD Lagrangian

(EW Higgs not the origin of mass as we know it!)

$\longrightarrow$ interactions with gluons preserve quarks' helicity

$\longrightarrow$ hence conserve chirality (handedness)

Theory $\sim$ symmetric under two copies of isospin: right- and left-handed

- $q \rightarrow \exp\left[i\boldsymbol{\alpha}\cdot\boldsymbol{\tau}(1\pm\gamma_5)\right] q$
- chiral symmetry group $\mathrm{SU}(2)_R\times\mathrm{SU}(2)_L$

But at low energies

- quarks seem to have masses $\sim$ 300 MeV
- hadron spectrum shows no sign of this symmetry (no parity doublets)

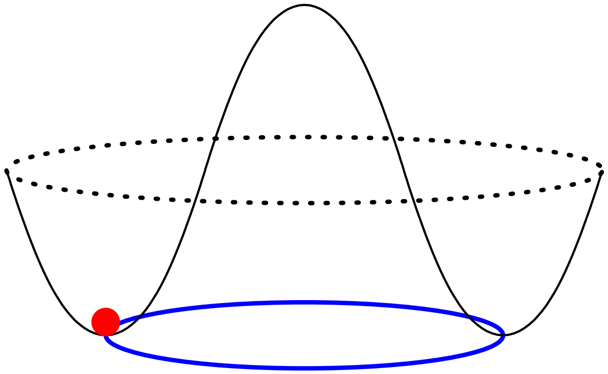
$\Rightarrow$ Symmetry is hidden (spontaneously broken)

QCD vacuum contains a condensate of quark-antiquark pairs

$$\langle 0|\overline{q}_L\, q_R + \overline{q}_R\, q_L|0\rangle \simeq -3\ \text{fm}^{-3}$$

Odd chirality ($q_R \leftrightarrow q_L$) → quarks get dynamical masses

Potential energy: “Mexican hat” (like Higgs in EW sector)



Exact chiral symmetry ($m_{u,d} = 0$)

→ massless pions (Goldstone bosons)

→ pion interactions vanish at threshold

Real world: current masses break symmetry explicitly

→ small pion masses $m_\pi^2 \propto m_{u,d}$ ($m_\pi \simeq 140$ MeV $\ll m_\rho,\ M_N$)

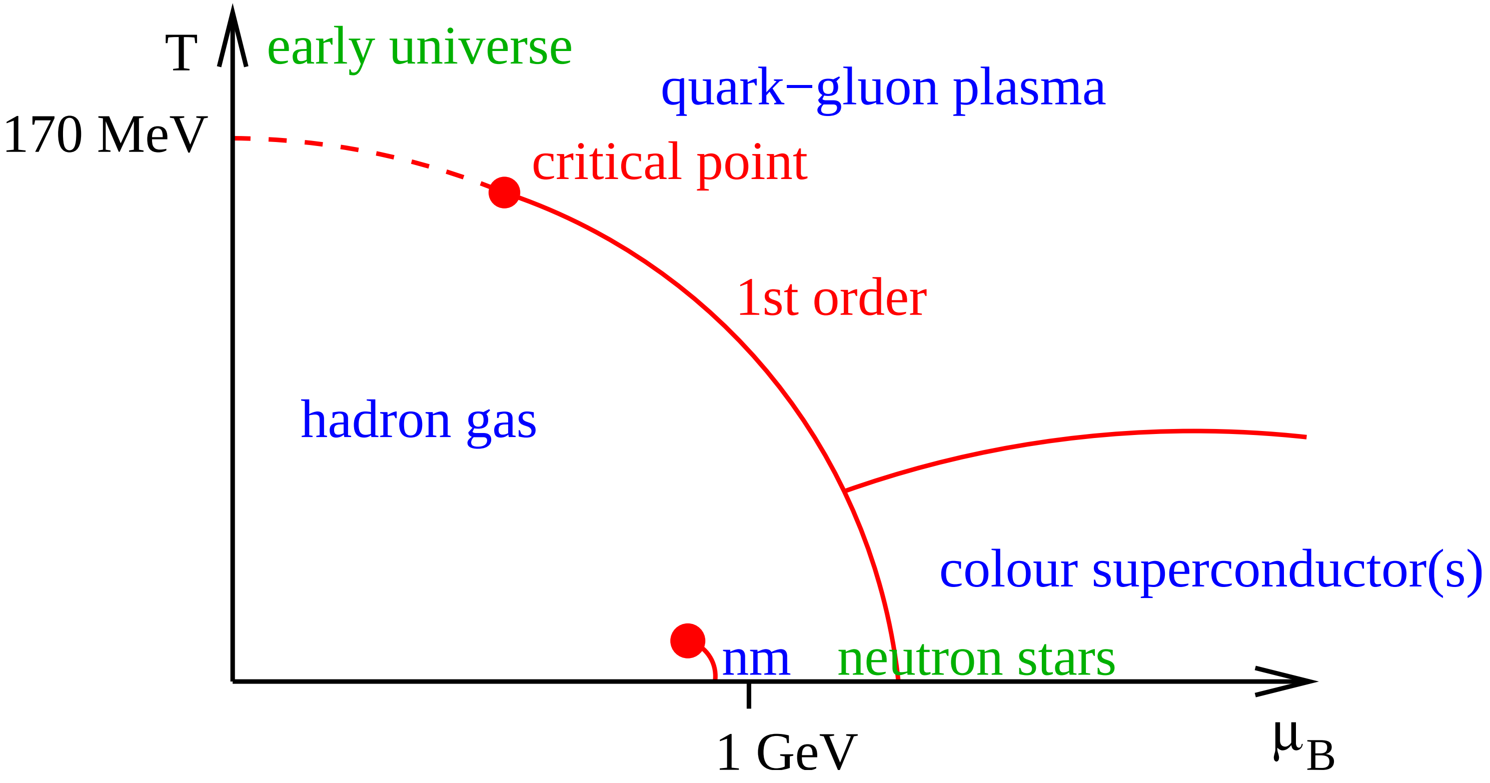
→ pions interact weakly at low energies

QCD phase diagram

Vacuum surrounding us now

- quarks and gluons are confined (“monopole” condensate)
- chiral symmetry is hidden (quark condensate)

Extreme temperatures or densities can destroy condensates → new phases



Lattice methods work well for $T \neq 0$, $\mu_B = 0$

For two flavours of light quark (u, d), and one lightish (s)

→ rapid crossover at $T_c \simeq 175$ MeV, energy density $\epsilon_c \simeq 0.7$ GeV/fm^3

(no sharp phase transition)

→ unconfined quarks and restored chiral symmetry

- a quark-gluon plasma
- above T_c: energy density $\epsilon(T) \propto T^4$ (ideal massless plasma)
- but growing evidence for strong $q\bar{q}$ correlations up to $T \sim 1.5T_c$

Lattice extrapolations to $\mu_B \neq 0$, $T \neq 0$ becoming more reliable
→ hints of critical point at $\mu_B \sim 400$ MeV

Cold dense matter: no lattice calculations (sign problem)

- only models (or perturbative QCD at asymptotic densities)
- transition to unconfined quark matter expected
- attractive forces between quarks → pairing → colour superconductivity
- wide variety of possible phases (2SC, CFL, LOFF, . . .)

Chiral dynamics

Small pion mass → pions play important roles in nuclear physics

- structure of nucleon

  pion cloud → EM form factors, negative $\langle r^2\rangle_c$ for neutron
- nuclear forces

  pion exchange → longest-range forces between nucleons

At energies $\sim m_\pi$ quarks and gluons interact strongly

But chiral symmetry → interactions of pions are rather weak

→ systematic expansion in powers of pion mass and momenta:

chiral perturbation theory

Example of an “effective field theory”:

- embodies all symmetries of QCD (eg: SU(2)$_R$×SU(2)$_L$)
- in terms of low-energy degrees of freedom:
  pions, nonrelativistic nucleons
- nonrenormalisable $\longrightarrow$ infinite number of couplings
- but at each order only a finite subset contribute

Can provide a bridge between experiment and lattice QCD

- extraction of relevant low-energy parameters from data
- extrapolation of lattice results from $m_q \sim m_s$ ($m_\pi \sim$ 400 MeV)
  to realistic u, d masses ($m_\pi =$ 140 MeV)

Important applications

- $\gamma\gamma \to \pi\pi$ and $\pi\pi$ scattering
- photo- and electroproduction of pions from nucleons
- responses of nucleons to EM fields

Example: low-energy Compton scattering from proton

→ electric and magnetic polarisabilities Beane et al, nucl-th/0403088

$\alpha_p = 12.1 \pm 1.1 \pm 0.5 \times 10^{-4}$ fm^3

$\beta_p = 3.4 \pm 1.1 \pm 0.1 \times 10^{-4}$ fm^3

Also polarised Compton scattering → 4 spin-dependent polarisabilities and virtual Compton scattering $ep \to e'p\gamma$ → “generalised” polarisabilities

(form factors for these responses)

→ demand high-precision experiments MAMI, ELSA, Jlab

Parton distributions

Deep-inelastic scattering $e + p \to e' + X$

Bjorken region: large momentum transfer Q^2 and energy transfer ω, finite

$$x = \frac{Q^2}{2M_N\omega} \qquad (\sim \text{momentum fraction of struck parton})$$

Systematic expansion in powers of $1/Q^2$ (soft-collinear effective theory)

Leading (twist-2) terms → parton distributions $q(x, Q^2)$

- logarithmic evolution with Q^2 calculable from perturbative QCD
- but initial shapes at low Q^2 given by nonperturbative physics

Moments of these distributions $\int_0^1 x^n q(x)\, dx$

- matrix elements of local operators

→ another bridge between experiment and lattice

- include operators not coupled to EW fields

Important example: flavour-singlet axial coupling

- total quark spin in proton $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ $(\Delta q = q_\uparrow - q_\downarrow)$
- polarised DIS → $\Delta\Sigma \sim 0.13 \pm 0.10 \pm 0.10$ SMC

  (naive analogy with $g_A = \Delta u - \Delta d = 1.26 \to \Delta\Sigma \sim 0.6$)

Questions:

- what carries remaining angular momentum $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$?
  - gluons ΔG?
  - orbital motion of quarks L_z?
- is $\Delta\Sigma$ small because of polarised strange sea $\Delta s < 0$?

First information on ΔG coming from evolution of $\Delta\Sigma$

More direct probe: photon-gluon fusion $\gamma^* g \to q\bar{q}$

→ $D\bar{D}$ or high-p_T pair of light hadrons HERMES, COMPASS

Deeply virtual Compton scattering $ep \to e'p\gamma$

→ generalised parton distributions (↔ form factors)

- some of these sensitive to L_z HERMES, CLAS

Heavy-quark states

c, b quarks act as slow (nonrelativistic) sources of gluon fields

→ expansions in powers of $1/m_Q$

($Q\bar{q}$: heavy-quark effective theory; $Q\bar{Q}$: NRQCD)

- third bridge to lattice calculations
- spectrum of excited states → quark-antiquark forces

Charmonium region

- bound states below $D\bar{D}$ threshold very sharp
- states above threshold can also be narrow if $L \neq 0$
- new states not reachable from e^+e^- (CLEO) now being found
  $\eta_c'(2\,^1S_0)$ 3638 MeV; $h_c(^1P_1)$ 3526 MeV; X 3872 MeV Belle, ...
- possible hybrid states with $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$ not allowed for $Q\bar{Q}$
- narrow $Q\bar{Q}$ states → cleaner region to hunt for glueballs

Mapping out this spectrum calls for

- production in $p\bar{p}$ annihilation (all quantum numbers)
- very good beam resolution (narrow states)
- a catch-all detector GSI/PANDA

Quark-gluon plasma

Primordial matter: high temperature, very small baryon density

– hope to recreate in ultrarelativistic heavy-ion collisions $E/A \gtrsim$ 100 GeV
  RHIC, LHC/ALICE

Immediate questions:

- what energy densities are reached?
- does matter reach thermal equilibrium?
- at what temperature?

Answers so far:

- transverse energy → initial $\epsilon \gtrsim$ 5 GeV/fm^3 (well above ϵ_c)   RHIC
- large elliptic flow (sideways expansion) → hydrodynamics
  → high degree of thermalisation at early stage
- hadron yields → "chemical" freezeout at $T \simeq$ 160 MeV, $\mu_B \sim$ 25 MeV

→ all suggest RHIC is reaching relevant region for QGP formation

Dense baryonic matter

Very dense cold matter exists inside neutron stars

- baryon densities several times nuclear matter, $T \lesssim 10$ MeV
- could be colour superconducting quark matter (quark stars?)
- but hard to probe inside these objects
- not possible to recreate conditions on Earth

Instead use relativistic heavy ions with $E/A \sim 20$ GeV SPS, GSI/CBM

→ dense, warm matter: $\rho_B \sim$ few times nuclear matter, $T \gtrsim 100$ MeV

→ look for signals of

- first-order transition (collective flow effects)
- possible critical phenomena (event-by-event fluctuations)
- changes to hadron properties in dense matter (reduced masses)

Summary

Nonperturbative nature of QCD vacuum

- lot of interesting physics (confinement, hidden chiral symmetry)
- determines the structure and interactions of hadrons
- rich phase diagram
- still not well understood theoretically
- experiments only starting to probe with any precision

Important physics:

- controls structure of nuclei and nuclear reactions
- needed in astrophysical systems (early universe, neutron stars)
- origin of our mass

As universe cooled from Planck temperature $T \sim 10^{19}$ GeV
various phase transitions in gauge theories expected to have occurred

- QCD $\rightarrow$ only one we can hope to recreate here on Earth
- and study related condensation phenomena in any detail