Aspects of Modern Nuclear Physics

NuPECC Long Range Plan « Perspectives of Nuclear Physics in Europe » Brussels, Dec. 9, 2010

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Modern Nuclear Physics

Nuclear physics is an old discipline

- It has undergone significant renewal and diversification in recent years (because of its internal dynamics, and its position at the cross-road of many fields, with rapidly evolving frontiers)

- It spans a vast area of activities (from the most applied to the most fundamental)

- It contributes in an essential way to the advance of knowledge
Advance of knowledge

Vital interplay between
- experimental developments (accelerators, detectors)
- theoretical efforts (ECT*, JSC)

This talk focusses on two issues
- nuclear matter
- quantum chromodynamics

Nuclear physics ‘point of view’: emphasize many body aspects rather than elementary processes.
As one goes back in time, the universe becomes denser and hotter.

Rough orders of magnitude:

- Temperature: $T \sim 10,000,000,000 \text{ K}$
- Energy: $E \sim 1 \text{ MeV}$
- Time: $t \sim 1 \text{ second}$
One can break an atom into electrons and a nucleus.
One can break a nucleus into protons and neutrons
But one cannot extract a free quark from a proton.

Still, we do see the quarks inside the proton!
Quarks are confined within hadrons
« So there must be an ultimate limit to bodies, beyond perception by our senses. This limit is without parts, is the smallest possible thing. It can never exist by itself, but only as a primordial part of a larger body, from which no force can tear it loose. »

Lucretius, De rerum natura, ~ 55 B. C.
If we cannot isolate free quarks, can we imagine conditions under which they behave as (almost) free particles?

Ordinary matter: quarks are confined in protons and neutrons

Quark-Gluon Plasma: quarks roam freely over the entire volume of the plasma

Such conditions have existed in the early universe, and can be created in collisions of nuclei at high energy
The QCD phase diagram

$T_c \simeq 170 \text{ MeV}$

- Hadronic matter
  - confined, $\chi$-SB
- Quark-Gluon Plasma
  - deconfined, $\chi$-symmetric
- Colour superconductor
- Nuclei

$T$ and $\mu_B$ axes.
Large computers are needed to calculate the predictions of QCD.
Phase transition(s) (crossover)

(from Z. Fodor, arXiv:0711.0336)

(from M. Bazavov et al, arXiv:0903.4379)
the RHIC at Brookhaven Lab visible from space
Relativistic Heavy Ion Collider RHIC @ BNL

3 km ring

major international enterprise: thousands of scientists and engineers
The “little bang”

Nucleus at 0.99999 the speed of light

Two such nuclei collide

Quark Gluon Plasma formed

Decays into 1000s of sub-atomic particles
By studying these images.....

...one can reconstruct the properties of the quark-gluon plasma.
Matter flows like a fluid

Initial momentum distribution is isotropic

Without interactions, the particles would escape isotropically, irrespective of the shape of the interaction zone.

Strong interactions induce pressure gradients. The expansion becomes anisotropic, and the momentum distribution reflects the anisotropy of the initial interaction region.
Elliptic flow

\[ v_2 = \langle \cos(2\phi) \rangle \]

(Quark-Matter 02)

(Quark Matter 09)
The low viscosity of the quark-gluon plasma

\[ \frac{\eta}{s} < 5 \times \frac{1}{4\pi} \]

(M. Luzum and P. Romatschke, arXiv: 0804.4015)
viscosity at weak and strong coupling

perturbation theory

\[ \eta = \frac{1}{3} np \lambda \quad \lambda = \frac{1}{n \sigma} \]

AdS/CFT duality

\[ \frac{1}{4\pi} \]
News from the Large Hadron Collider
First Elliptic Flow Measurement at LHC

- $v_2$ as function of $p_t$
  - practically no change with energy!
  - extends towards larger centrality/higher $p_t$?

- $v_2$ integrated over $p_t$
  - 30% increase from RHIC
  - $<p_t>$ increases with $\sqrt{s}$
  - pQCD powerlaw tail?
  - Hydro predicts increased ‘radial flow’
  - very characteristic $p_t$ and mass dependence; to be confirmed!
From the very hot

From the very large

...to the very small

...to the very cold

The beauty of (theoretical) physics

The same ideas/analysis apply....
Elliptic flow of cold interacting Fermi gas of atoms

Conclusions

- the study of ultra-relativistic heavy ion collisions is only one particular aspects of modern nuclear physics.

- the field is lively and the perspectives outlined in the LR plan are truly exciting