Mass Generation+Melting with the Strong Force

Or: Why the Vacuum is not Empty

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The Cosmic Pie of Matter and Energy

• Expanding Universe
  ↔ Dark Energy
  not at all understood!

• Star / Galaxy Motion
  ↔ Dark Matter
  New Particles?

• Mass of Visible Matter
  ↔ Weight / Inertia
  A Dense Vacuum?
Nuclear Physics and the Universe

- **Quark-Gluon Plasma**: $T > 200$ MeV ($<0.000001$ sec.)
- Phase transition to Hadronic Matter (Mass Generation, Quark Confinement), $T \approx 170$ MeV ($0.00001$ sec.)
- Low-mass nuclei: H (p), d (pn), $^3$He, $^4$He, $^7$Li (3 min.)
- Heavy elements in star collapses: Supernovae (today)
- Exotic forms of (quark) matter in Neutron Stars (today)
Outline

1.) The Atom and the Micro-Cosmos
   • Which Particles are Elementary?
   • What is the World Made of?

2.) Elementary Particles and Their Interactions
   • ”Matter Particles” vs. “Force Carriers”
   • Fermions vs. Bosons

3.) The Strong Interaction: Quarks and Gluons
   • The World of Hadrons
   • 2 Puzzles: Quark Confinement and Quark Masses
   • The Non-Emptiness of the Vacuum

4.) Heavy-Ion Collisions and Quark-Gluon Plasma
   • ”Evaporating” the Vacuum
   • Dissolving Mass into Energy

5.) Summary
1.) The Atom and the Micro-Cosmos: Which Particles are Elementary?

• What happens if one keeps dividing matter?
• Notion of the “atom” (ατομοσ = greek for “indivisible”)

But:

Rutherford (1911):
• most of the atom is “empty space”
• mass is concentrated in the atomic **nucleus**

⇒ subatomic particles
1.2 The Atom and the Micro-Cosmos: What is the World Made of?

- electrons elementary, atomic nucleus is **NOT**
- nuclei composed of **nucleons** = p, n
- each nucleon is made of 3 **quarks**:

\[
\begin{align*}
\text{proton}^+ &= (uud) \\
\text{neutron}^0 &= (udd)
\end{align*}
\]

- **up**-quark: charge $+\frac{2}{3}$, mass $m_u \sim 3 \text{ MeV/c}^2$
- **down**-quark: charge $-\frac{1}{3}$, mass $m_d \sim 6 \text{ MeV/c}^2$
- **electron**: charge -1, mass $m_e = 0.5 \text{ MeV/c}^2$

**But:** nucleon mass $m_p = m_n = 940 \text{ MeV/c}^2$
2.) Elementary Particles and Interactions

What holds Matter together?

- in addition to stable matter \((u, d, e^-, \nu_e)\)

  2 more “generations” of elementary particles
  (quarks + leptons):
  - charm + strange quark, muon + \(\mu\)-neutrino
  - top + bottom quark, tau + \(\tau\)-neutrino

**Force Carriers and Strength**

- **Electromagnetic**
  - \(e^-\) to \(e^-\)
  - Force Carrier: Photon
  - \(\alpha_{em} \approx 0.01\)

- **Strong**
  - \(u, d\) to \(d\)
  - Force Carrier: Gluon
  - \(\alpha_s \approx 1\)
2.2 Elementary Particles and Interactions

The Nature of Matter vs. Force Particles

- **Matter Particles** (quarks+leptons):
  - spin $S=\frac{1}{2}$ “Fermions” (half-integer $S$)
- **Force Particles** ($g$, $\gamma$, $W^\pm$, $Z$):
  - spin $S=1$ “Bosons” (integer $S=0,1,2,\ldots$)

- **Fermion Motel**:
  - only one identical fermion per room!
  - (Pauli Exclusion Principle)
  - $\Rightarrow$ electronic shell structure of atoms

- **Boson Inn**:
  - identical bosons per room preferred!
  - (Bose-Einstein Condensation)
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3.) The Strong Force: Quarks + Gluons

The Confinement of Quarks

• In Nature, quarks never observed in isolation: “Confinement”

• Quarks “glued” together by gluons (“rubber” band) → the interaction strength increases with distance!!

\[ F_s(r) = \text{const} \]

• theoretically not yet understood (recall electric force: \( F_e(r) = \alpha_{em}/r^2 \))

• “asymptotic freedom” at small distances explained → Nobel Prize in Physics 2004 [Gross, Politzer and Wilczek]
3.2 Strong Force: The World of Hadrons

• Quarks only appear as composites = hadrons

• two types of hadrons:
  - baryons: bound states of 3 quarks (fermions!)
    e.g.: \( S=1/2: \) \( p=(uud), \Lambda=(uds), \ldots \)
    \( S=3/2: \) \( \Delta^{++}=(uuu), \Omega^-= (sss), \ldots \)
  - mesons: quark-antiquark composites (bosons!)
    e.g.: \( S=0: \) \( \pi^+=(ud), \pi^0=(u\bar{u},d\bar{d}), K^-= (s\bar{u}), \ldots \)
    \( S=1: \) \( \rho^+=(u\bar{d}), \rho^0=(u\bar{u},d\bar{d}), \rho^-= (u\bar{d}), \ldots \)

Puzzle: Why are hadrons so much heavier than quarks?
(proton-mass = 940 MeV/c\(^2\) >> \( 3m_q = 15 \) MeV/c\(^2\))

Preliminary answer:
hadronic building blocks are “\textit{constituent quarks}”
= extended objects with mass \( M_q \sim 350 \) MeV/c\(^2\)
3.3 Strong Force: Mass Generation

- The **real question**: how to quarks become so massive? (note: this is asking for >98% of the **mass of all visible matter** – a very fundamental question!!)

**Our current best (most likely) answer:**
- **strong quark-antiquark attraction** (many gluons)
- **Bose-condensation** of \(qq\) pairs
- dense “liquid” fills the **vacuum**! \(\langle 0 | \bar{d}d + \bar{u}u | 0 \rangle \approx 5 \text{ fm}^{-3}\)
- quarks moving through the liquid have large mass (\(\approx \frac{1}{3}\) of the proton mass)!!

\[ m_q \sim 5 \text{ MeV} \]
\[ M_q \sim 350 \text{ MeV} \]

⇒ **our mass is due to a (very) dense vacuum!!**

Can we test this? E.g. evaporate the vacuum??
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5.) Summary
Nuclear Matter dissolves into Quark-Gluon Plasma (QGP):

• hadrons overlap, quarks liberated \( \Rightarrow \) Deconfinement!
• \( \langle \bar{q} q \rangle \) condensate “evaporates”, \( M_q \rightarrow m_q \) \( \Rightarrow \) Mass dissolves!

- required temperature \( \sim 200 \text{ MeV} \approx 4 \cdot 10^{12} \text{ °F} \)
- 100,000 times hotter than inside the sun!
- Early Universe \( \sim 0.00001 \text{ sec} \) after Big Bang!!

How do we pump this enormous amount of energy into the vacuum??
Answer: The Relativistic Heavy-Ion Collider!

Accelerate Gold-Nuclei to 100 GeV/nucleon and collide them!

(even more powerful accelerator (LHC) is running at the European Center for Nuclear Research (CERN) in Geneva)
4.2 Recreating the “Little Bang” in the Laboratory

Au + Au

QGP ?!
($\tau \approx 2 \cdot 10^{-23}\text{s}$)

How to look for particles inside the matter?

Watch out for electron-positron decays of the $\rho(770)$-meson!

Au + Au $\rightarrow$ X
4.3 The $\rho$-Meson in Vacuum and its Decays

In Vacuum:

- mass of the $\rho^0$-meson ($= u\bar{u}, d\bar{d}$) is well measured, $m_\rho = 770\text{MeV} 
\approx 2$ “constituent quarks”:
- $\rho$-meson unstable, lifetime $\sim 4 \cdot 10^{-24}\text{sec}$

But what happens to the $\rho$-meson mass in a hot medium (QGP)??
4.4 The $\rho$-Meson in a Hot Medium

Different theoretical predictions:

- $m_{\rho}$ “drops” to zero (quarks lose their mass)
- Interactions of the $\rho$ within the hot+dense gas: $\rho$-meson “melts” (broad mass distribution)

Which scenario is correct? Experiments have to tell us …
4.5 $e^+e^-$ Spectra in Nuclear Collisions

- account for $\rho \rightarrow e^+e^-$ decays over the entire “fireball” expansion history

**Recent $\mu^+\mu^-$ Data** [NA60 Experiment, CERN]

- experimental data favor the “melting” scenario
- advanced theoretical investigations required for definite conclusions … (ongoing at Texas A&M)

We are getting close to the secret of (visible) mass in the Universe…
5.) **Summary**

- Atom → Nucleus → Nucleons → Quarks (elementary!)
- Quarks are **confined** to Hadrons (baryons and mesons)
  - not yet understood!
- Quarks acquire a **large mass** within hadrons:
  - the vacuum is a “dense liquid” of \( \langle qq \rangle \) condensate!
  - more than 98% of the visible mass in the Universe!!
- Collisions of heavy nuclei at high energies:
  - Heat the vacuum and recreate the Early Universe:
    - deconfine quarks and gluons
    - evaporate vacuum condensate and **dissolve** mass into energy!
    - \( \rho \)-meson decays to dileptons to investigate the origin of mass

**very exciting research ahead …**
2.1 Hot+Dense QCD Matter in Nature

**Phase Diagram**

Early Universe (few $\mu$s after Big Bang)

Compact Stellar Objects (Neutron Stars)

In the laboratory: high-energy collisions of heavy nuclei!
Objective: to create matter at temperatures $T > T_c \approx 170\text{MeV}$ and energy densities $\varepsilon > \varepsilon_c \approx 1\text{GeVfm}^{-3}$