The Origin of the Visible Mass in the Universe

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

• Scientists (Philosophers) have always been wondering:
  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 are elementary (as far as we know), atomic nucleus is NOT.
- Nuclei are composed of nucleons = protons and neutrons.
- Each nucleon is made of 3 quarks: u, d, u.

**Proton**

\[ \text{proton}^+ = (uud) \]

**Neutron**

\[ \text{neutron}^0 = (udd) \]

- **Up-quark**: charge \( \frac{2}{3} \), mass \( m_u = 3 \text{MeV/c}^2 \)
- **Down-quark**: charge \( -\frac{1}{3} \), mass \( m_d = 6 \text{MeV/c}^2 \)
- **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 + neutrino
    - top + bottom quark, tau + neutrino

**Force Carriers and Strength**

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<tr>
<td>Strong</td>
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<td>Quarks and Gluons</td>
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\[ \alpha_{em} = 0.01 \]

\[ \alpha_S = 1 \]
2.2 Elementary Particles and Interactions

The Nature of Matter vs. Force Particles

- **Elementary Matter** Particles (quarks+leptons):
  - spin $S = \frac{1}{2}$ “Fermions” (half-integer $S$)

- **Elementary 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)
3.) The Strong Force: Quarks + Gluons

The Confinement of Quarks

- In Nature, quarks have never been observed in isolation: “Confinement”
- Quarks “glued” together by gluons (“rubber” band) → the interaction strength (charge) increases with distance!!
  \[ F_s(r) = \text{const} \]

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

- “asymptotic freedom” at small distances explained → Nobel Prize in Physics 2004
  [Gross, Politzer and Wilczek]
3.2 The 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.: $S=1/2$: $p=(uud)$, $\Lambda=(uds)$, …
    $S=3/2$: $\Delta^{++}=(uuu)$, $\Omega^-=(sss)$, …
  - mesons: quark-antiquark composites (bosons!)
    e.g.: $S=0$: $\pi^+=(u\bar{d})$, $\pi^0=(u\bar{u},d\bar{d})$, $K^-=(s\bar{u})$, …
    $S=1$: $\rho^+=(u\bar{d})$, $\rho^0=(u\bar{u},d\bar{d})$, $\rho^-=(u\bar{d})$, …

Puzzle: Why are hadrons so much heavier than quarks?
(proton-mass = 940MeV/c² >> 3$m_q$ = 15MeV/c²)

Preliminary answer:
hadronic building blocks are “constituent quarks”
= extended objects with mass $M_q \sim 350\text{MeV}/c^2$
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 \((q\bar{q})\) 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 \((\sim \frac{1}{3} \text{ of the proton mass})!!\)

\(\Rightarrow\) our mass is due to a (very) dense vacuum!!

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

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

- required temperature is \( \sim 200 \text{MeV} \approx 4 \cdot 10^{12} ^\circ\text{F} \)
- 100,000 times hotter than inside the sun!!
- early universe \( \sim 0.000001 \text{ sec} \) after the Big Bang!!

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

Accelerate Gold-Nuclei to 200GeV/nucleon and collide them!
(even more powerful accelerator (LHC) to start soon at the European Center for Nuclear Research (CERN) in Geneva)
4.2 Recreating the “Little Bang” in the Laboratory

How to look for particles inside the matter?

Watch out for electron-positron decays of the $\rho(770)$-meson!
4.3 The \( \rho \)-Meson in Vacuum and its Decays

**In Vacuum:**
- The mass of the \( \rho \)-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)??

Energy of decay products \((\pi^+\pi^-)\) = mass of the parent particle \((\rho)\)!
4.4 The $\rho$-Meson in the 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

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

- experimental data favor the “Melting” scenario
- advanced theoretical investigations required to arrive at definite conclusions (ongoing at Texas A&M)

**(We are getting closer to the origin 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 (q̅q) 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 condensates and dissolve mass into energy!
    - ρ-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 μs 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 $\varepsilon > \varepsilon_c \approx 1\text{GeVfm}^{-3}$