STRUCTURE OF MATTER

Discoveries and Mysteries

Rolf Landua
CERN
PREFACE

This is a lecture about 100 years of particle physics. It covers about 100 years of ideas, theories and experiments.

More than 50 Nobel prize winners on particle physics
This is a broad overview about the main discoveries.

In the early 1900s, most physicists believed that physics was complete, described by classical mechanics, thermodynamics, and the Maxwell theory.

“There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. “ (Lord Kelvin, 1900)

DARK CLOUDS:
1) Blackbody radiation - Quantum Physics
2) Michelson-Morley experiment - Special Relativity
MATTER IS MADE OF PARTICLES

1897: ELECTRON - the first ‘discrete’ building block of matter

J.J. Thomson

1905: ATOMS ARE REAL - Explanation of Brownian Motion (Perrin)

A. Einstein
ENERGY COMES IN QUANTA

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA

\[ \varepsilon = h \nu \]

M. Planck

1902: PHOTOELECTRIC EFFECT

“The electron energy does not show the slightest dependence on the light intensity”

P. von Lenard

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

\[ E_{\text{max}} = h \nu - W \]

“Amy only revolutionary contribution to physics”

A. Einstein
1905: SPEED OF LIGHT IS ALWAYS CONSTANT

\[ c^2t^2 = v^2t^2 + w^2 \]

1) Time dilation, space contraction
2) Modification of Newton’s laws, relativistic mass increase.

\[ E = mc^2 \]
1909: NUCLEI: very small + heavy within (almost) empty atom

1913: BOHR MODEL- (empirical) explanation of discrete spectral lines
(using Planck’s constant h) to quantize angular momentum

1923: DE BROGLIE

Particles are waves

\[ \lambda = \frac{h}{p} \]
QUANTUM MECHANICS

1923: UNCERTAINTY RELATION

\[ \Delta x \Delta p \geq \frac{\hbar}{2} \quad \Delta E \Delta t \geq \hbar \]

Heisenberg

1926: SCHRÖDINGER EQUATION

\[ \mathcal{H} \psi (\mathbf{r}, t) = (T + V) \psi (\mathbf{r}, t) = \left[ -\frac{\hbar^2}{2m} \nabla^2 + V (\mathbf{r}) \right] \psi (\mathbf{r}, t) = i\hbar \frac{\partial \psi}{\partial t} (\mathbf{r}, t) \]

(electrons in atoms form ‘standing waves’)

Schrödinger

Interpretation (Born, 1927):

\( \psi = \) probability amplitude

\( |\psi|^2 = \) probability
Electron spin 1/2 explained
Antiparticles must exist!
Spin 1/2 particles (fermions) must obey exclusion principle
ANTIPARTICLES

When energy converts to mass, particles and antiparticles are produced.

1932: Positron discovery

Every particle has an antiparticle

E = mc²

When energy converts to mass, particles and antiparticles are produced.
QUANTUM FIELD THEORY (1927 - 1948)

It was known that the **electromagnetic field consists of photons**

How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?

Many people worked on this problem ...
Quantum Electrodynamics (QED)
VACUUM FLUCTUATIONS

Quantized fields: Ground state energy is \( \neq 0 \)

Photons and particle-antiparticle-pairs populate empty space!

[Remark: should give rise to (lots of) “vacuum energy”]

UNCERTAINTY RELATION:

\[ \Delta E \times \Delta t \geq \hbar/2\pi \]
Vacuum fluctuations have observable effects

The world record for the most precise calculation in physics goes to:

Electron anomalous magnetic moment “g”

\[ \mu = g \frac{e}{2m} S \]

“Leading order”

Second order

Fourth order corrections

\[ g = 2 \]

\[ a = \frac{(g-2)}{2} = \frac{1}{2\pi} \times \frac{1}{137} \]

\[ \sim 0.0011614 \]

Current precision (theory and experiment agree)

\[ a = 0.00115965218073(28) \]
CASIMIR EFFECT

\[ p_c = \frac{F_c}{A} = \frac{\hbar c \pi^2}{240 \cdot d^4} \]

\( p = 100 \text{ kPa} \) (d=11 nm)

SPOOKY: at 11 nm distance, the pressure is 1 atm.
NUCLEAR PHYSICS

1895-1900: RADIOACTIVITY - strange radiation phenomena

1903: Alpha-, Beta-, Gamma-Radiation known
(different penetration depth)

1911: Nucleus positive, small - surrounded by electrons

1932: DISCOVERY OF THE NEUTRON

Alpha particle = He nucleus
What keeps protons and neutrons together?

Why is the range of nuclear forces finite? (maximum size of nuclei ~ 5 fm)

Yukawa model:
- New “strong” interaction
- Exchange of “pion”
- Pion has mass: finite range of 1-2 fm
Toy model:

UBS offers you a loan of

1000 Euro x Seconds

UNCERTAINTY RELATION:

$\Delta E \times \Delta t \geq \frac{\hbar}{2\pi}$
Electromagnetic vs Nuclear Exchange Forces

Nuclear vs Yukawa potential ~ Modified “Coulomb” law

Coulomb law

\[ V(r) = -e^2 \frac{1}{r} \]

Yukawa potential ~ Modified “Coulomb” law

\[ V(r) = -g^2 \frac{e^{-mr}}{r} \]

\[ \Delta E \Delta t \geq \hbar \quad (\Delta E \sim m) \]

\[ r = c \Delta t = \frac{\hbar c}{m} \sim \frac{200 \text{ MeV fm}}{m} \]
An accelerator is a giant microscope ....

... and can also produce new particles:

\[ E = mc^2 \]
1948 - 1960s: New accelerators and detectors

PARTICLE ZOO contains ~ 200 'elementary particles'

Mesons

\[ \pi^+ , \pi^- , \pi^0 \]  
Pions

\[ \eta' \]  
Eta-Prime

\[ \eta \]  
Eta

\[ \rho^+ , \rho^- , \rho^0 \]  
Rho

Kaons

\[ K^+ , K^- , K^0 \]

BARYONS

\[ \Delta^{++} , \Delta^+ , \Delta^0 , \Delta^- \]  
Delta

\[ \Lambda^0 \]  
Lambda (strange!)

\[ \Sigma^+ , \Sigma^0 , \Sigma^- \]  
Sigma (strange!)

\[ \Xi^0 , \Xi^- \]  
Sigma(very strange!)

Underlying structure?
Classification scheme based on ‘quarks’

3 types of “quarks”: up, down, strange (and their anti-particles)

- u: +2/3
- d: -1/3
- s: -1/3

electric charge

Meson

\( \pi^+ \)

Baryon

\( p \)
Discovery of quarks
Electron-Proton scattering at Stanford

1956 Hofstadter: proton radius \( \sim 1 \text{ fm} \)

1967 Friedmann, Kendall, Taylor: three ‘point-like particles’ inside a proton

Measured cross-sections perfectly compatible with presence of 2 up- and 1 down-quark in proton
The concept of “Colour” charge

How can you explain this particle?

A new concept: “colour charge”

1) Colour charge is source of ‘strong force’
2) There are three types of colour (e.g. “red”, “green”, “blue”)
3) Only colour-neutral states can exist

(Bardeen, Fritzsch, Gell-Mann)
Quarks carry a “colour” charge - in addition to their electric charge

(that makes them different and hence exclusion principle does not apply)
Quarks interact by exchanging ‘gluons’ that carry colour (and anti-colour)

Total number of gluons: 3 x 3 - 1 = 8

(1 combination is a ‘colour-singlet’, i.e. neutral)
Since gluons carry a (colour) charge:

Gluons can interact with other gluons
The self-interaction of the gluons results in the energy of the gluon string increasing with distance between quarks. This produces a force that keeps the quarks as ‘prisoners’.
Gluon ‘strings’ break: new quark-antiquark pairs

Analogy to breaking a magnet into two halves: does not produce a magnetic monopole

Meson

excited state of meson

string breaking: two mesons