Introduction to particle physics Lecture 1

Frank Krauss

IPPP Durham

U Durham, Epiphany term 2009

Outline

Topics of the lectures

Outline (subject to change)

1. Introduction; Concepts: Special relativity & quantum mechanics
2. Idea behind Feynman diagrams; Forces; Symmetry
3. Strong interactions I: Bound states and the Eightfold Way
4. Weak interactions I: Parity, Neutrinos, CP violation
5. Weak interactions II: Currents, Gauge bosons, Symmetry Breaking
6. Strong interactions II: Deep inelastic scattering & proton structure
7. Strong interactions III: QCD; QCD in e^+e^- collisions
8. The Standard Model
9. Physics at the LHC

Background reading

- Will follow closely:
  Coughlan, Dodd & Gripaios: "The ideas of particle physics"
- Further (suggested) reading:
  - Povh, Rith, Scholz & Zetsche: "Particles and Nuclei"
  - Halzen & Martin: "Quarks and Leptons"
  - Griffiths: "Introduction to Elementary Particles"
  - Zee's lectures at the African Summer Theory Institute:
    watch them at: http://www.asti.ac.za/lectures.php

Exam preparation

- The best preparation is the example classes and homework exercises.
- Lecture material (transparencies) and problems + solutions will be on DUO in due course.

Atoms and molecules

"Pre-particle physics"

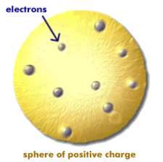
A **simplistic** view on matter at 1900:

- **Indivisible atoms** form the matter molecules around us, combining only in certain proportions (Richter and Dalton).
- Avogadro's law: At fixed temperature and pressure, **equal volumes of gas** contain **equal numbers** of molecules.
- **Atomic weights** are (roughly) **integer multiples** of the weight of the hydrogen atom (Prout).
- **Atoms** are associated with a specific electrical charge (Faraday).
- Order principle: **Elements** can be arranged in periodic families, with similar chemical properties but different weight (Mendeleev).
- Size of atoms: around 10^{-10} m (Loschmidt).

Atomic radiation

The discovery of the electron (J.J.Thomson, 1897)

- Experiment with cathode rays deflected by B-field $\longrightarrow$ **particles**!
- Direction implies negative charge.
- Determine velocity ($\approx 0.1c$) and huge charge-to-mass ratio (≈ 1850).
- Suggests indirect evidence for "new" negatively charged objects ("corpuscles") with very small mass (no ion/atom with similar properties known), charge dubbed "electron".
- Thomson's idea: part of the atom. His "plum pudding model" distributes them evenly over atom.



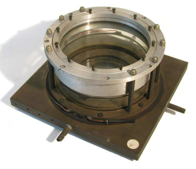
X-rays (Roentgen, 1895)

- A new form of extremely penetrating radiation, soon identified as electromagnetic radiation with short wavelength.
- Produced e.g. when electrons are abruptly decelerated.
- Roentgen's experiment: Boiling electrons out of a metallic electrode in vacuum, accelerating them by an electrical field into another electrode, where they are absorbed, emitting light.

- Demonstration of e.m. nature of X-rays by shooting them at crystals: diffraction pattern (waves!) emerges.
- Occurs when wavelength equals roughly the lattice spacing.

Radioactivity (Becquerel, 1896; Curie's 1898)

- Discovery of radiation **spontaneously** emitted by heavy elements (in this case uranium), darkening photo plates.
- Later technology: Scintillators, Geiger counters, electroscopes
- Real breakthrough: cloud chambers.
  Use water drops condensating from vapour around particles passing through it, ionising individual atoms.

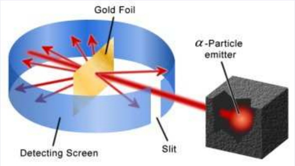


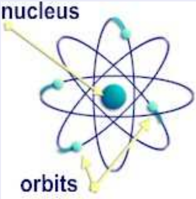
- Three different kinds of radioactivity: α, β, γ - different bending due to magnetic field and stopping in chamber.
- Important for two reasons:
  - First indication that atoms not indivisible, $\longrightarrow$ particle physics.
  - Three different kinds of radiation due to three different forces.

Rutherford's experiment

Atoms have structure!

- Idea: Fire α-particles (He-nuclei) on a thin gold foil and measure deflection pattern.
- "Plum-pudding" model predicts only slight deflections (no large fields in the atoms)
- But: Found **all** angles (up to π) $\longrightarrow$ strong fields in atoms!
- Because electrons so light w.r.t. α's: Deduce existence of a massive "core" - the nucleus - with size $\approx 10^{-15}$ m surrounded by the negatively charged light electrons with diameters up to $\approx 10^{-10}$ m.





Theoretical problems around 1900

- While the experiments above shattered the "atomistic" view in favour of a richer inner structure of matter, theory was unable to come to grips with two other problems:

Speed of light

- Classically: medium needed for wave propagation.
- Hypothesise "ether" for light.
- Must be able to measure relative velocity w.r.t. this absolute frame - failed!
- Therefore: Constant speed of light (in vacuum).

Interactions

- Light was interpreted as a form of heat.
- Thermodynamical description.
- Yields infinite emission of energy if all wavelengths allowed!
- Therefore: Quantise energies of electromagnetic radiation.

Frames of inertia

Galilei relativity

- Relativity discusses how changes in the coordinate set influence physical events. Coordinates specify positions in time (t) and space ($\vec{x}$) - meaningful only if system (reference frame) is specified.
- Example (a la Galilei): A man dropping a stone from a ship's mast. The man's perspective: trajectory accelerates along a straight line. A bystander at the shore: trajectory is a parabola.
- Since both perspectives describe the same event, the math behind the respective description must be connected: Transformations.

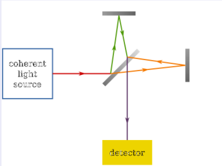
Galilei transformations

- Basic idea: Space and time are decoupled.
- Consequence: A time interval of one hour remains invariant, irrespective of the choice of reference frame. This allows only transformations of the type $t \to t' = t + \Delta t$.
- Similarly, at a time t_0 the origins of the two reference systems may be displaced: $\vec{x}(t_0) \to \vec{x}'(t_0) = \vec{x}(t_0) + \Delta\vec{x}$, and only a constant velocity $\vec{u}$ between them is allowed.
- Ignoring Δt and $\Delta\vec{x}$, therefore $\vec{x}(t) \to \vec{x}'(t) = \vec{x}(t) + \vec{u}t$.
- Consequence: Velocities are strictly additive.
  Assume system A (man on mast) is at rest and B (man on shore) moves with velocity $\vec{u}$ w.r.t. A, then velocities are related by $\vec{v}_B = \vec{v}_A + \vec{u}$.

The speed of light is constant

Michelson-Morley experiment

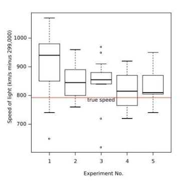
- Idea: Check existence of ether. Use earth's velocity orbiting around the sun. Leads to different relative velocities.



- Send coherent light along two directions, check for shifts in interference pattern due to different run times:

$$t_{\|} = \frac{2L}{c(1-v_E^2/c^2)} \text{ and } t_{\|} = \frac{2L}{c\sqrt{1-v_E^2/c^2}}.$$

- But: No variation seen.



- Conclusion: Speed of light is a constant, verified by a number of Michelson-Morley-type experiments.
- This contradicts Galilei relativity.
- New transformations necessary.

Lorentz transformations

- Basic idea: Space and time are entangled.
- Consequence: Relative velocities between reference frames affect both space and time coordinates.

$$\vec{x} \to \vec{x}' = \frac{\vec{x} - \vec{u}t}{\sqrt{1 - \frac{\vec{u}^2}{c^2}}} \text{ and } t \to t' = \frac{t - \frac{\vec{u}\vec{x}}{c^2}}{\sqrt{1 - \frac{\vec{u}^2}{c^2}}}.$$

- Consequence of this: Velocities below c can **never** add up to a result larger than c:

$$\vec{v}_{\rm tot} = \frac{\vec{v}_1 + \vec{v}_2}{1 + \frac{\vec{v}_1\vec{v}_2}{c^2}}.$$

- Remark: This limits the maximal transmission velocity of information to c, therefore a perfectly rigid body cannot exist.
- Remark (2): Space-time is divided into causally connected ("time-like distances") and disconnected ("space-like distances") regions.

Mass, momentum and energy

- Note: From now on, we set $c = 1$.
- Demand conservation of mass, momentum and energy to be invariant under Lorentz transformations:

  $$\text{For mass: } m(v) = \frac{m_0}{\sqrt{1-v^2}} = m_0 + m_0\frac{v^2}{2} + \ldots .$$

  This is the original reason for the identification $E = mc^2$ - the second term in the expansion is just the kinetic energy.
- Using $\vec{p} = m\vec{v}$ therefore $E^2 = m_0^2 + \vec{p}^2$.
- This implies that for particles with no rest mass $E/|\vec{p}| = 1$.

Aside: Manifest Lorentz-invariance

(Not examinable)

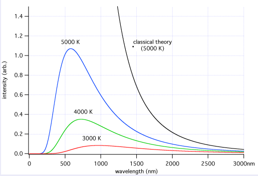
Four-vectors

- Since time and space on identical footing: Introduce "four-vectors"
$$x^\mu = (t,\, \vec{x}) \text{ and } p^\mu = (E,\, \vec{p}).$$
- Similar to $\vec{x}^2$ and $\vec{p}^2$ being invariant under Galilei transformations, we know that $t^2 - \vec{x}^2$ and $E^2 - \vec{p}^2$ are invariant under Lorentz transformations.
  Thus it is natural to introduce $x^2 = t^2 - \vec{x}^2$ and $p^2 = E^2 - \vec{p}^2$.
- But how can we construct this from, say x^μ?
  Answer: Define a **metric**
$$g^{\mu\nu} = g_{\mu\nu} = \begin{pmatrix} 1 & 0 \\ 0 & -\mathbf{1} \end{pmatrix}$$
  such that $x^2 = x^\mu x^\nu g_{\mu\nu}$.
- Remark: Gravity then acts by distorting the metric $g^{\mu\nu}$.

Quantising the electromagnetic field

Planck's hypothesis

- Problem in 1900: The electromagnetic spectrum emitted by a hot black body.
- Statistical physics (classical) failed completely in explanation, predicting the total energy emitted to be infinite.

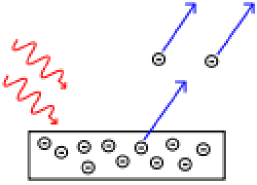


- Planck's ad hoc proposal: electromagnetic radiation not continuous, but "quantised".
- Relation of energy E and frequency ν is $E = h\nu$ with Planck's constant h (from now on: $\hbar = 1$).

- Remark: Most "perfect" black-body radiation is observed in cosmic microwave background.

Einstein's explanation of the photoelectric effect

- Quantisation is a natural, intrinsic property of electromagnetic radiation.
- Explains the photoelectric effect: Electromagnetic radiation "kicks" electrons out of metal. Process **depends on frequency of light only, not on intensity**.



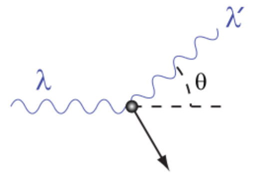
- Therefore it is the effect of a single photon.
- Energy of leaving electrons: $E_e = \omega - W_{\rm out}$. $W_{\rm out}$ is a material-specific energy needed for the electrons to leave the metal.
- Remark: One of four papers in Einstein's "annus mirabilis". (Others: Brownian motion and special and general relativity)

Discovery of the Compton effect

- Light scattered off a particle with mass *m* at rest changes wavelength:

$$\lambda \to \lambda' = \lambda + \frac{1-\cos\theta}{m}$$

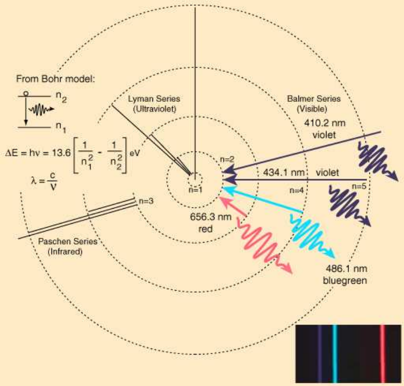
- Exactly the behaviour of a massless particle in relativistic physics (energy-momentum conservation).

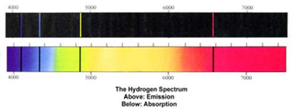


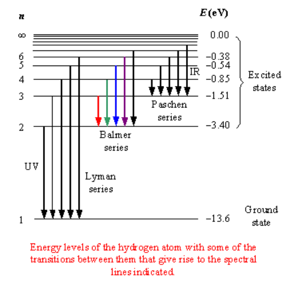
- Quanta of electromagnetic field are photons, symbolised by γ.
- First example of:

Interactions are mediated by exchange particles.

Bohr's atom model







de Broglie's matter waves

- Hypothesis: Waves (light) has particle character, therefore particles may have wave character, undergoing interference etc..
- Wavelength proportional to inverse momentum, $\lambda = 1/|\vec{p}|$.

- This applies to **all** particles, including us.
- Observation of the wave-like character of particles by diffraction of electrons on a lattice and emerging interference patterns.
- de Broglie's hypothesis motivates (a posteriori) Bohr's model of the atom: Only such orbits are allowed that can be filled with an integer number of wavelengths.

The essence of quantum mechanics

Schrödinger's wave function

- Using the matter waves of de Broglie, Schrödinger formulated a full wave mechanics for them.
- In his framework the wave of a particle with mass m (denoted by ψ) develops in space and time as
$$-\frac{1}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi = i\frac{\partial\psi}{\partial t}.$$
- Applying this equation to the hydrogen atom, he was able to reproduce Bohr's findings.
- Interpretation of the wave function: Its absolute value squared $|\psi(t,x)|^2$ gives the probability of finding the particle at x and t.
- Therefore: Replace Laplace's demon with a framework determining probabilities.

Heisenberg's uncertainty principle

- Alternative formulation by Heisenberg, centred around **observation**.
- Wave functions are replaced by (infinite dimensional) state vectors, observables are operators acting on them.
- Measurements are identified with expectation values of operators.
- Consequence: statistical/probabilistic treatment inherent.
- Also: Uncertainty relations

$$2\Delta p\Delta x \geq 1 \text{ and } \Delta E\Delta t \geq 1.$$

- Example: Confine a particle in a small volume $\Delta x = 1$ fm. Then: $\Delta p = \frac{1}{2\Delta x} \approx 100$ MeV.
- Used $\hbar c \approx 200$ MeV fm.

Spin

From observation to concept

- Discovery of small splitting of spectral lines in hydrogen spectrum - not explained by Bohr's model.
- Explanation: electron has "intrinsic magnetic moment" (spin), interacting with magnetic field produced by orbiting around nucleus.
- Distinctively quantum: In classical physics, all spin orientations are allowed, leading to a range rather than two lines.
- Therefore: spin must be quantised as well.
- By convention: $s = \pm 1/2$.
- Important: Spins always come in integers or half integers, at integer distance. Two different kinds of particles: bosons (integer spins) and fermions (half-integers), the latter enjoying the Pauli exclusion principle.

Summary

- Reviewed the experimental situation that led to the advent of particle physics - the study of sub-atomic structures.
- Two central ingredients: Special relativity and quantum mechanics.
- Will assume familiarity with the concepts presented today.
- To read: Coughlan, Dodd & Gripaios, "The ideas of particle physics", Sec 1-3.