Foundations of Physics III Quantum and Particle Physics Lecture 8

Frank Krauss

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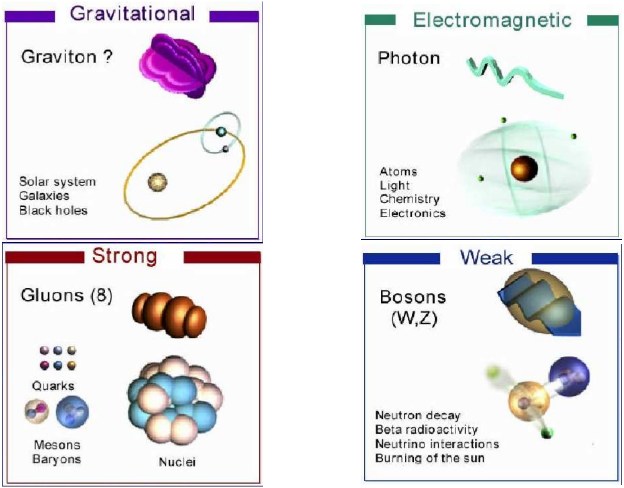
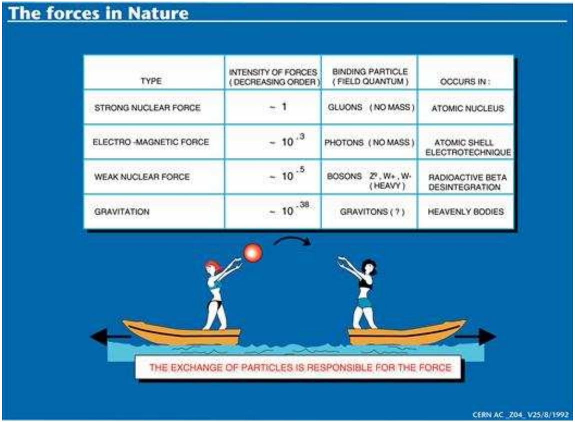
Fundamental forces



Exchange particles

- **Forces act through exchange particles** associated with them.



TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, $W+$, $W-$ (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES

Gravity

- Most familiar force, but: Important only in macro-world!
- Newton's law: $F = G\frac{Mm}{r^2}$ (G = Newton's constant)
  (implicit: gravitational = inertial mass)
- General relativity: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$,
  where $G_{\mu\nu}$ = metric, and $T_{\mu\nu}$ = energy-momentum tensor.
- Carrier of gravity (hypothetical): **massless spin-2 graviton**
- Up to now: No good quantum theory of gravitation.
- Gravity becomes quantum at roughly the Planck mass:

  $$M_{\rm planck} = \sqrt{\hbar c/G} = 1.2209 \cdot 10^{19}\ \text{GeV} = 2.17645 \cdot 10^{-8}\ \text{kg}.$$

  $M_{\rm planck}$ too large to be phenomenologically important - beyond direct reach of all experiments (LHC probes about 10^4 GeV)

Electromagnetism

- Force that we understand best - both classically and quantum. (Because the coupling strength e, $e^2/(4\pi) = \alpha \approx 1/137$ small enough for perturbation theory!)
- Coulomb force law for static charges: $F = K\frac{q_q q_2}{r^2}$.
- Equations governing the laws of classical electromagnetism:

  Maxwell's laws.
- Structure: Two fields ($\vec{E}$ and $\vec{B}$ - vector and axial vector), all first derivatives, currents and charges $\longrightarrow$ 4 equations:
  Differ in **Parity**: pseudoscalar, vector, axial-vector equation.
- Sources are asymmetric (no magnetic monopole!).
- Classically: Electromagnetic waves - theory of light.
- Carrier of electromagentism: **massless spin-1 photon**

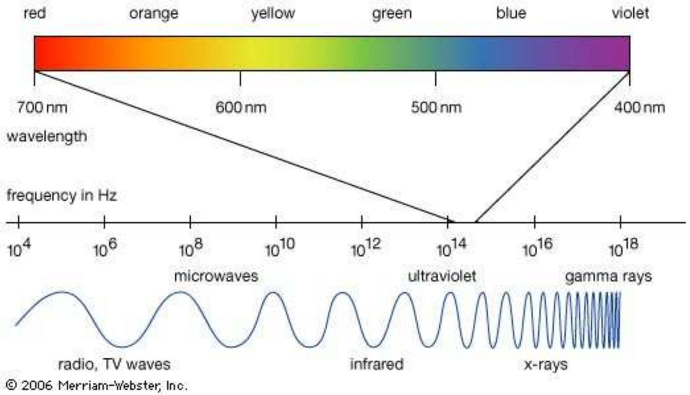
Aside: Parity

- Parity is invariance under
$$\psi(\vec{x},\, t) \longleftrightarrow \hat{\mathcal{P}}\psi(\vec{x},\, t) = \lambda\psi(-x,\, t):$$
- This translates into $|\psi(\vec{x},\, t)|^2 = |\psi(-\vec{x},\, t)|^2$.
- Therefore, $\lambda = \pm 1$ corresponding to even $(+)$ or odd (-) parity.
- If a force (e.g. electromagnetism) respects parity, parity-even states cannot emerge during interaction from odd states and vice versa.
- Note: Electron orbits in an atom have a defined parity.
- In addition, particles have **intrinsic** parity.
- Parity is multiplicative.

Parity at work

- Atomic physics example:
  Since orbitals have definite parity and because electrodynamics respects parity, not all transitions are allowed. This manifest itself in "missing" spectral lines (although the orbitals exist and the transition is energetically allowed): Parity selects allowed transitions.
- Particle physics example:
  A J/ψ is a vector particle, it therefore has $P = -1$. If it decays into two particles, they must always form an s-wave (even parity). To see this consider the c.m. system of the decaying particle - the two outgoing ones are back-to-back with no angular momentum. Therefore a decay of a vector into two vectors is forbidden.

Electromagnetic waves



The first quantum field theory: QED

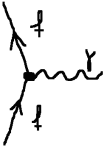
- Quantum ElectroDynamics (QED) describes the interactions of electrically charged particles (electrons, ...) with the electromagnetic field.
- **One interaction vertex only:** $ee\gamma$

Propagators

Fermions ($e^{\pm}$, ...)

Photons

Vertex



- First realistic quantum field theory, example for all others
- Important principle for construction: gauge invariance

How to draw Feynman diagrams in QED

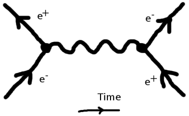
(highly examinable)

Rules for QED

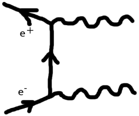
- For simplicity: Fix a time-axis.
- Fermions (electrons and positrons) are represented with straight lines and arrows and photons with wavy lines.
- If the arrow points (anti-)parallel to the time-axis: (anti-)particle. This is relevant only for external particles.
- Along a fermion line, "clashing arrows" are not allowed - they are related to fermion number (charge) violation.

Examples

- Bhabha-Scattering ($e^- e^+ \to e^- e^+$)



- Pair annihilation ($e^- e^+ \to \gamma\gamma$)

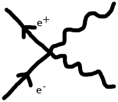


Illegal Feynman diagrams

(highly examinable)

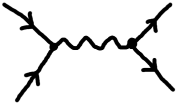
Illegal vertex

- Rule: Use only vertices that are present in the theory. They exactly correspond to the interaction terms in the Hamiltonian.
- In QED: Only $ee\gamma$ vertex.
- In example: Used an $ee\gamma\gamma$ vertex.



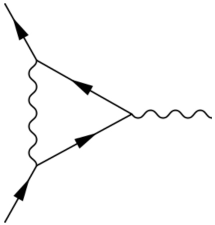
Clashing arrows

- Rule: Don't revert the arrow along a fermion line (flow of quantum numbers and conservation laws).
- In QED: fermion number and electrical charge.
- In example: globally okay, locally (at each vertex) wrong.



Precision QED: Electron's anomalous magnetic moment

(not examinable)



- "Classically", intrinsic magnetic moment of a particle with charge q, mass m and spin s given by:
$$\vec{\mu} = g\frac{q}{2m}\vec{s} \text{ with } g = 2.$$
- However, g is altered by quantum corrections, necessitating renormalisation and also giving rise to finite corrections.
- First calculation by Schwinger in 1948 (diagram above), yielding
$$\frac{g-2}{2} = \frac{\alpha}{2\pi} \approx 0.0011614.$$
- By now, one of the most precise number in physics:
$$\left.\frac{g-2}{2}\right|_{\rm exp} = 0.00115965218085(76)$$
- 10 digits-agreement with theory $\Longrightarrow$ used for precise value of α.

Learning outcomes

- Four fundamental forces: gravitational, electromagnetic, weak and strong.
- Forces mediated by exchange particles.
- Summary of gravity (beyond scope of course)
- Fearures of electromagnetism
- Feynman diagrams, once again, this time for QED
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