

Schlüsselexperimente der Elementarteilchenphysik: The Standard Model

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What particles do we know about and what are their properties? How do they interact? We will discuss Feynman diagrams, fundamental interactions of the electromagnetic, weak and strong forces between particles and finally some open questions in the prevailing Standard Model.

Particles and properties:

Short history review:

The electron was detected already 1897 by Joseph John Thomson. In 1911, the famous experiment by Ernst Rutherford (with helium atoms bombarded on a gold foil) revealed that the most of the atoms is in fact empty space, and the nucleus inside the atom was discovered. Dirac anticipated antiparticles 1928, to explain the negative energy solutions of his equation. They would be identical in mass but bend opposite to the electrons in a magnetic field. 1932 the neutron was discovered by Chadwick; the same year Dirac's positron was found by Anderson. This was only the beginning of the particle era.

An elementary particle is a smallest constituent; it cannot be destroyed into smaller parts and must be structureless (pointlike).

We classify them into two kinds; fermions and bosons. Ordinary matter consists of fermions. In this group, there are two families called quarks and leptons. Both have 3 generations. The leptons cannot combine into bound states, but the quarks can. They actually cannot be detected without being bound (we think). The bound states are called hadrons, and formed either by one quark and one anti-quark (meson) or by 3 quarks (baryon). The hadrons are the only particles able to interact via strong force.

Fundamental not only for how the nature works, but also for the detection of particles, is how they interact. Relevant forces here are the electromagnetic, strong and weak forces. In SM, interactions are mediated by virtual particles. These mediators are "interchanged" between the particles and cause interaction. All mediators are bosons.

What tells the elementary particles apart?

Spin: All the fermions have spin $\frac{1}{2}$; their wave-functions are asymmetric and they obey the Pauli principle. Bosons have even-integer spin, symmetric wave-functions and do not obey the Pauli principle.

Charge: Leptons have charge 0 (neutrinos) or $-1e$ (e , μ^- , τ^-). The quarks have fractional ($\frac{2}{3}$ or $-\frac{1}{3}$) and the mediators have 0 or 1. Unit is the measured charge of an electron, with the full effect of EM screening incorporated in the value.

Mass: Most particles are given masses, or at least an upper limit, corresponding to experimental results. Neutrinos need not have mass according to the standard model. β decay gives an upper limit of neutrino masses, but neutrino oscillations imply that the mass is nonzero.

For every *particle* there is also an *antiparticle*, with equal spin and mass as their particle, but with all other properties reversed. Interchanging a quark \rightarrow anti-quark corresponds to *charge conjugation operation C*.

Conservation rules:

Initial energy must exceed the rest energies of the reaction products. The reaction must also conserve momentum. Other conserved quantities: Charge, e^- , μ^- and τ^- -lepton number, and baryon number. Special conserved quantity: flavor; a conserved quantity in EM and strong interaction, but not in weak!

Interactions:

We have mentioned the 3 fundamental forces of nature. In SM, extending quantum mechanics to force fields, there are 3 very important, corresponding theories;

QED Quantum Electrodynamics, theory of the force between electric charges,

QCD Quantum Chromodynamics, the general theory of how quarks interact,

QFD Quantum Flavourdynamics of the weak interaction.

The strong force has the by far strongest *coupling strength*. The EM strength is a factor of α less, and the strength of weak force only 10^{-6} of the strong force. Gravity may be neglected in elementary particle physics with strength only $6 \cdot 10^{-39}$ as compared to the strong force. The stronger the interaction that is possible for a particular decay, the shorter the lifetime of the decaying particle. Note also: EM force and gravity have infinite range; but the nuclear forces have very short range.

Feynman diagrams:

A tool to visualize interaction processes. They also contain mathematics of the process, making possible calculations of e.g. cross section. The calculations are done by applying the "Feynman's golden rules". A Feynman diagram is drawn with time as an arrow pointing in a specified direction; a particle as an arrow in time-direction, and an anti-particle as an arrow in the direction opposite to time. An interaction (that is, a virtual mediating boson) is drawn either as a wave (EM), a dashed line (Weak) or a spiral (Strong) depending on the interaction. Both charged and neutral weak forces are drawn as dashed lines.

QED

EM force is the one force that we, together with gravity, notice in everyday life, it also holds atoms and nuclei together. An electrically charged particle interacts according to the Coulomb force; or if in a magnetic field, the Lorenz law. Interaction is due to exchange of virtual photons. We could not draw Feynman diagrams if they were not (violation of momentum conservation in 1 vertex alone).

Following Feynman's golden rules, every vertex in an EM Feynman diagram introduces multiplication of a factor e to the '*scattering amplitude*'. *Cross-section* is proportional to the square of the scattering amplitude; e^2 for 1 vertex, which in turn is proportional to the EM coupling constant α , also called the fine structure constant (since it determines the magnitude of the fine structure (spin orbit splitting) in atomic spectra).

But there are infinitely many Feynman diagrams! The problem is solved by the smallness of $\alpha = 1/137$; diagrams with more vertices (more factors of α) contribute less to the scattering amplitude and we need only consider lower order diagrams.

α is not exactly constant because of charge shielding. The charge we measure is therefore an effective charge; $q_{\text{eff}} = q/\epsilon$, where ϵ is the dielectric constant of the material. q_{eff} increases at very small distances (screening vanishes). Vacuum is a dielectric, creating electron-positron pairs and reducing the field of an electric charge.

QCD

In the 1950's and 60's, many new baryons and mesons were found. Attempts to order them in patterns, led to the *eightfold way*; where particles got place in geometrical structures depending on strangeness and charge. This approach led to a correct prediction of the Ω^- . But *why* did particles fit into these patterns? Solution by Gell-Mann and Zweig in 1964: hadrons have an *elemental substructure*, of two or three so called *quarks*. The original theory contained 3 quarks; up, down and strange, all with fractional charges and spin $1/2$, combining to form mesons and baryons, held together by gluons. This was successful in classifying the new particles, but some remaining questions (and the Zweig rule) lead to the proposal of a fourth quark, charm (Bjorken, Glashow). In 1974 a new, heavy particle was found independently by two groups at SLAC and Brookhaven; now called the J/ψ -particle. It had properties of a c-anti-c-meson; more massive than all other mesons known and with a much greater lifetime (as expected, due to Zweig-rule). Together with the discovery of the first charmed baryon Λ^+ (1975), it constituted firm evidence for a fourth quark, as well as for the quark theory in general.

After the tau lepton was discovered, which was completely unexpected, two further quarks were proposed to maintain the lepton-quark symmetry; bottom and top quarks have now also been detected. The latter preferably decays from t-anti-t into W bosons and b quarks, with subsequent decay to leptons, neutrinos and hadrons (Fermi National Laboratory). The top quark is the heaviest known elementary particle; its detection was a great triumph for theory as well as for modern accelerators and detectors.

Still one important problem remained. There are particles (like the Ω^-), with 3 identical quarks (sss). Quarks are *fermions* and *should obey the Pauli principle*; we should not detect a bound state of 3 identical quarks! Introducing three *colour charges* r, g, b saved quark theory. Colour is an additional quantum

number making the quarks non-identical. Only *colourless combinations* would exist in nature, the mesons with colour-anti-colour and the baryons with three different colours (analogous to white light). Gluons carry colour and anti-colour, which are changed in every interaction, and it can couple to itself, forming “glue balls”. It has been detected at SLAC that electrons incident on a proton target interact with only half of the protons mass, indicating that half of the proton mass comes from gluons.

Estimations of *strong coupling* from the decay probability or with Γ of unstable baryons, gives a value ~ 1 (at relatively low energies). According to the Feynman golden rules, every vertex in a Feynman diagram of strong interaction introduces factor $\alpha_s \rightarrow$ more contribution for higher order diagrams! Solution: strong coupling is not constant, but running. The reason is somewhat analogous to the screening in QED; now with color. (Origin: q-anti-q colour shielding + gluon colour antishielding. Self-coupling of gluons “spreads out” colour; effect larger with higher momentum.) Calculations imply that the coupling decreases at high momentum \sim short distances, although being large at lower momentum; at some separation. Inside of some small distance quarks are nearly free, but to separate them would take more and more energy as the separation grows. The idea of *asymptotic freedom* was awarded Nobel price 2004. The origin of *quark confinement*, explains why quarks never occur alone, but always colorless combinations. With high enough energy in a collision, two quarks (or a gluon ball) may be torn apart, but the confining potential makes it easier to create new quark-pairs until the energy is low enough. *Jets* of hadrons are created; experimental signatures of quarks and gluons.

Important proof of the number of colours is given by experiments on total cross-section rate $R = \sigma(ee \rightarrow \text{hadrons}) / \sigma(ee \rightarrow \text{muons})$. The denominator can be calculated using Dirac’s equation, and is $4\pi\alpha^2 / 3E_{\text{CMS}}^2$. In the quark model, the numerator is given by $\sum q_i^2$; so we sum the squared charges of all relevant flavours. For energies below the cc-threshold, only u, d and s contribute, giving $R = 2/3$. At high energies, counting all but the top quark, we get $R = 11/9$. But results from experiments on the cross section rate have given results 3 times as big. If the quarks also have a colour degree of freedom, it would fit!

Another notable estimation from this ratio: Measurements of the cross-sections yield an estimate for the number of neutrino species. An example is experiments with Z bosons, whose lifetimes are found consistent with exactly 3 very light (or massless) neutrinos.

QFD

All quarks and leptons can interact weakly. In EM and strong interactions, flavour is always conserved, but this does not hold for the weak force. The mediators are called intermediate vector bosons; W and Z. Any process that changes the flavour of a given quark or lepton type is a weak, charged decay process. Weak decays are thus responsible for the fact that ordinary stable matter contains only up and down type quarks and electrons. Matter containing any more massive quark or lepton types is unstable. For quarks, color exchange between generations is possible but suppressed. This is, according to SM, not allowed for leptons.

One complication in detection of W decay is that they more often decay into quarks; harder to separate from background of strong interactions. There is less background in leptonic decay.

Neutral currents are in general also harder to detect than flavor changing, since it must compete with the much stronger electromagnetic interaction.

In the 1960’s, Glashow, Weinberg and Salam proposed the *electroweak theory*; combining EM and weak force at high energy. Physicists believed that weak forces were closely related to EM forces since they have comparable strengths at very short distances (10^{-18} m). But the strength depends strongly on both mass of the force carrier and distance of interaction; the huge mass difference of W and Z compared to photons could explain the weakness of weak force at greater distance. The theory predicted the existence and masses of intermediate vector bosons W^+ , W^- and the neutral Z_0 , as well as charm-quark. Neutral currents were indirectly seen in 1973, W and Z particles were discovered 1983 at CERN, giving a Nobel price 1979. But if the photons and the intermediate vector bosons are the same at high energies, why are the latter so heavy, weighing 80 times the proton mass? The masses may be explained by the *Higgs-mechanism*. It introduces a 4-component scalar field with a vacuum expectation value of 246 GeV, resulting in spontaneously broken (hidden) local gauge invariance; **symmetry breaking**, giving masses to all particles. The interactions are still gauge invariant. The 4th degree of freedom introduces the spin 0 Higgs boson, which couple to fermions and is responsible for their masses (and its own). It’s the simplest mechanism that can give mass to the gauge bosons, that is also compatible with gauge theories. The

detection of Higgs boson is one important goal for experiments such as the LHC at CERN. Its decay to b anti- b should dominate, but be screened by much background. Detection should be possible if the Higgs boson was produced in association with W , Z or t anti- t . The decay to 2γ is rare but has little background. It is the most promising channel but requires excellent calorimeter resolution. The fact that it has not yet been detected puts a lower limit on its mass; 114 GeV.

Three important examples of weak interactions:

1. Hydrogen burning in the sun. See slide. In total: $4p + 2e^- \rightarrow \text{He-4} + 2\nu_e + 6\gamma$.
2. Weak beta-decay builds up nuclei.
3. Causes decay of heavier quarks (c, s, b, t) and leptons (μ, τ) into lighter.

Another thing than flavour that is conserved by strong and EM forces, but not by the weak force, is parity; inversion of space. Parity breaking in weak decay was discovered in the 1950's. That parity together with charge conjugation gives a total CP-invariance gave comfort first, but then a special case was detected; neutral kaons. These are not CP-eigenstates, only the linear combinations K_L and K_S of them are. K_L has a 39% probability of decaying to 1) $\pi^+ + e^- + \text{antineutrino}$, or 2) $\pi^- + e^+ + \text{neutrino}$. But the latter is $3,3 \cdot 10^{-3}$ times more common than the first; a difference in matter and antimatter!

Quantum field theories put up CPT as the ultimate invariance, where T is (direction of) time.

Beyond the standard model

The current SM describes many features of the subatomic world remarkably good.

But fundamental questions are left open; the many free parameters in SM (masses), the asymmetry between matter and antimatter, number of elementary particles, how to include gravity...

Some possible extensions of SM are:

GUT: An attempt to join electroweak force with the strong force. In SM, extrapolation of the coupling strength for the 4 interactions, with data from LEP, does not lead to a coincidence at high energies. In Grand unified theories, this would be possible. Idea: Quarks and leptons are states of leptoquarks; this brings the same amount of leptons as of quarks. It also means that quarks and leptons can be changed into each other, given sufficient time. Makes proton decay possible (although lifetime of about 10^{32} y).

SUSY: Higher order loops in Feynman diagrams contribute to the Higgs mass. If no new physics, loops must cancel without reason. If SUSY is correct, they would cancel naturally. According to SUSY, each SM particle has a super symmetric partner with $\frac{1}{2}$ a unit difference in spin. The Higgs field gets more complex, with 5 physical Higgs bosons. The lightest particle might be stable, and take part in the explanation of dark matter. SUSY has not been detected, it might just be too heavy. Therefore we hope it will be discovered through missing transverse energy (momentum) at the high energies of LHC, CERN.

TOE: Even a GUT is incomplete because it would not include space-time and therefore gravity. It is hypothesized that a "Theory of Everything" will bring together all the fundamental forces, matter and curved space-time in one unifying picture. For cosmology, this will be the single force that controlled the Universe at the time of formation. The current approach to the search for a TOE is to attempt to uncover some fundamental symmetry.

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