Standard model of particle physics

Lukas Maczewsky (Jena)

The standard model of particle physics represents the currently accepted theory about the smallest particles of matter. This article gives a brief historical survey about the formation of this model. Furthermore, it shows some characteristics of our elementary particles. At the end of the paper the model is summarized in one table. This abstract is only an introduction to particle physics and covers only selected topics.

Joseph Thomson, in 1897, detected the electron. Thus began the discovery of the inner structure of atoms. Ernest Ruhterford countinued this progress with the detection of the first free proton outside of an atomic nucleus in 1919. With the neutron, the existence of which was proven experimentally by Walther Bothe and Herbert Becker 1930, and the photon we have the first *model kit* for matter. A lot of phenomena can be discribed with the three particles electron, proton, neutron and their mediator, the photon.

Table 1: The smallest known particles in 1932.

particle (1932)	el. charge (e)	mag. moment (J/T)	restmass (kg)
electron e^-	-1	$-9,27 \cdot 10^{-24}$	$9,109 \cdot 10^{-31}$
proton p	$+1$	$1,4 \cdot 10^{-26}$	$1,673 \cdot 10^{-27}$
neutron n	0	$-0,96 \cdot 10^{-26}$	$1,675 \cdot 10^{-27}$
photon γ	0	0	0

Already in 1932 scientists guessed that our matter had a smaller inner structure. They detected for example a magnetic moment of the neutron, despite it is being electrically neutral. Then there was a problem with the energy at the beta decay. Wolfgang Pauli solved the problem by postulating the neutrino. Furthermore, Paul Dirac forecasted the antimatter with the equation, that now bears his name, and physicists detected new particles in the higher atmosphere, e.g. muons and pions. These new particles initiated new conservation laws and quantities, like the *strangeness*. These was discovered as secondary radiation in pictures of cloud chambers.

Figure 1: First picture of antimatter: the track of a positron [2].

This *particle zoo* of more than ten different known types of particals can be put into an order. On one hand we have particles with half-integer spin, like baryons (proton, neutron, etc.) and leptons (electron, muons, neutrinos, etc.) which are called fermions. And on the other hand there are particles with an integer spin like mesons (pions, kaons, etc.) and mediator particles (photon, etc.) called bosons. The main difference between fermions and bosons, because of their spin, is the fact that only the fermions are subject to the Pauli exclusion principle. Moreover there are more conservation laws for fermions like for parity conservation or strangeness.

These two groups of particles interact via four fundamental forces. The four fundamental forces (or better interactions) are the gravitational, the electromagnetic, the weak and the strong interaction. All four of them have a specific strengh, compared with the other forces, a specific range and specific mediators. For example, the electromagnetic interaction has an infinite range, and photons as mediator particles. These four fundamental interactions with their mediatiors are an important part of the standard model of particle physics. They allow for the explaination
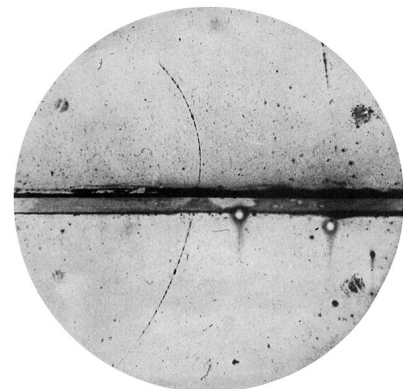
of the interactions between the particles, but not, however, of the structure and the order of the particles.

In 1954 MURRAY GELL-MANN and indepently of him GEORGE ZWEIG created the quark model. Gell-Mann named these elementary particles after a word in the novel *Finnegans Wake* by JAMES JOYCE. The theory says that some of the six elementary particles (up, down, strange quark and their antiparticles) form any baryon and any meson. The quarks' electric charge is a fraction of the elementary charge. Gell-Mann and Zweig solved the problem of the strangeness taking into account strange quarks with the quantum number -1 or 1 for the anti-strange quarks. Any meson is a quark-antiquark pair and therefore these particles have a baryon number

Table 2: The three quarks, known in 1964, and their antiparticles.

quark	electr. charge	baryon number	isospin	strangeness
u	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	0
d	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	0
s	$-\frac{1}{3}$	$\frac{1}{3}$	0	-1
$\overline{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	0
$\overline{d}$	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	0
$\overline{s}$	$\frac{1}{3}$	$-\frac{1}{3}$	0	1

$\frac{1}{3} - \frac{1}{3} = 0$. For example, the meson K^+ consists of one up and one anti strange quark. So the kaon has the electric charge $\frac{2}{3} + \frac{1}{3} = 1$, the isospin $\frac{1}{2} + 0 = \frac{1}{2}$ and the strangeness $0 + 1 = 1$. Likewise any baryon consists of three quarks and any antibaryon of three antiquarks, e.g. two up quarks and one down quark make a proton.

If we look closely at this model, we see that different quarks in one particle can have the same quantum numbers like the three strange quarks in the Ω^- hadron. But since quarks are fermions, we need an additional quantum number due to the Pauli exclusion principle. This new quantum number is called *color charge*. The values of the color are red, green, blue and antired, antigreen, antiblue. Since we cannot measure these colors in the composed particles, i.e. all of them are colorless, we can conclude that the color of the quarks annihilate each other. Therefore the two quarks in mesons have one color and the corresponding anticolor. And the (anti)baryons there appear either all three colors or all three anticolors. Because of the additive color mixture we observe the baryons and the mesons to be white or rather colorless. However, this color charge can be described within the theory of quantum chromodynamics. According to this, the *really strong interaction*, of the quarks has its origin in the color charge. The mediators of this force are so-called gluons. Any gluon is a mediator of two colors. The color of a quark could be changed by gluons, e.g. a blue up quark becomes a red up quark. A gluon with blue and antired acts as a mediator:

$$u_b \longrightarrow u_r + G_{b\overline{r}}$$

Whenever the quarks change their colors in the particles, thus *glue* is always between the quarks and we cannot seperate the quarks. Thus we either don't have enough energy to break up the bond or we have so much of it that it is enough to create a new pair of particle and antiparticle. For example, if we want to separate an up quark from a proton (consisting of two up, one down quark), we create a pair of quark and antiquark, so that e.g. a neutron and a positive pion will be created (figure 2). The well-known strong interaction is the weak part of this really strong interaction that can be observed, like the sea foam is the visible part of big water waves. The experiments confirmed this theory, so till today no test came up with a shows
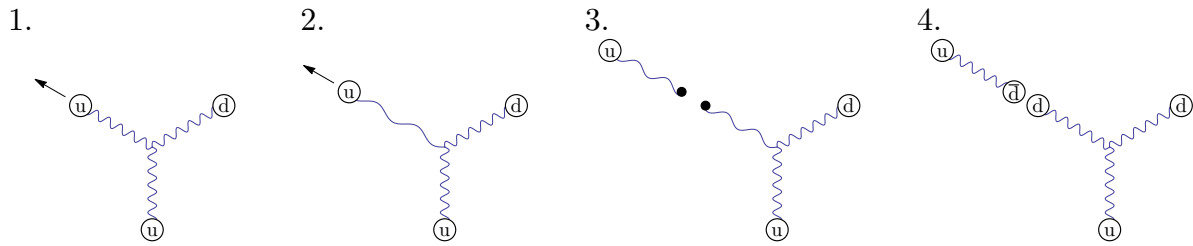
Figure 2: Trying to separate an up quark off a proton (uud) with the result of a neutron (udd) and a π^+ (u$\bar{\text{d}}$) [1].

a free, single quark. At DESY, Hamburg, and SLAC, Stanford, scientists tried isolate quarks, but they could only indirectly measure an inner structure of hadrons.

Table 3: Standard model of particle physics. The table displays the three generations and the area of influence of the fundamental interactions.

	I	II	III	interaction (mediator)		
quarks	u	c	t	strong (gluon)	el.-mag. (photon)	weak $(W^\pm, Z^0)$
	d	s	b			
leptons	e	μ	τ			
	ν_e	ν_μ	ν_τ			

With these new elementary "bricks" the standard model of particle physics is complete (Table 3). We have, on one side, the quarks with the gluons as mediators. However, three more quarks named charm, top and bottom are neccessary to describe all phenomena. The other six particles are the leptons with the τ lepton and the tau neutrino ν_τ. Moreover, the table shows the relationship between the elementary particles and the fundamental interactions. The strong interaction acts only on the quarks. The electromagnetic interaction affects the quarks and also the electron, muon and tauon. Analog patterns are valid for the weak interaction. Furthermore, the scheme displays the three generations of particles. The generation I is the group of elementary particles that build up the stable matter. The generations II and III classify the remaining elementary particles which, however, shall not be discribed any further now.

By reconstructing the historical development of the standard model of particle physics we saw on one hand the fundamental character and on the other hand the groundbreaking progresses of this theory. It enables us to explain the broad range of phenomena in this field. Therefore, it is currently the most acknowledged model and was publicly honored with the Nobel prize of physics for PETER HIGGS and FRANÇOIS ENGLERT this year.

References

[1] Ne'eman, Y., Kirsh, Y.: *The particle hunters*; Cambridge University Press 1986.

[2] Anderson, C.: *The positive electron*; Physical Review 43(1933)491-494.

[3] Bleck-Neuhaus, J.: *Elementare Teilchen. Moderne Physik von den Atomen bis zum Standard-Modell*; Springer Berlin Heidelberg 2010.

[4] Gasiorowicz, S.: *Elementary particle physics*; Wiley New York 1966.