ON THE 90TH ANNIVERSARY OF L D LANDAU'S BIRTH

PACS numbers: 10, 11, 13.90.+i, 14

556

Current status of elementary particle physics

L B Okun

Contents

1. Sixteen fundamental particles	553
2. Fundamental fermions	553
3. Fundamental vector bosons	554
4. Running coupling constants	554
5. Colliders	555

6. Why do we need still larger colliders?

<u>Abstract.</u> A brief review is given of the state-of-the-art in elementary particle physics based on the talk of the same title given on January 22, 1998, at the seminar marking the 90th anniversary of the birth of L D Landau. (The seminar was hosted by the P L Kapitza Institute for Physical Problems in cooperation with the L D Landau Institute of Theoretical Physics).

1. Sixteen fundamental particles

Elementary (or fundamental) particles are defined as particles that are not composed, at the current level of knowledge, of other elementary particles.

Experiments have revealed twelve elementary fermions (with spin s = 1/2) and four bosons (with spin s = 1) (not counting the respective antiparticles).

2. Fundamental fermions

Table 1 shows that the twelve fermions form three generations, each comprising two leptons and two quarks.

The last column of Table 1 gives the electric charge of the particle in the given row. The names and notation of quarks stand for the English words: u for up, d for down, c for

Table 1.

Ger	nerations	1st	2nd	3rd	Q
Quarks	upper	u	с	t	+2/3
	lower	d	s	b	-1/3
Leptons	neutrino	ve	ν_{μ}	ν_{τ}	0
	charged	e	μ	τ	-1

L B Okun State Scientific Center of Russian Federation "Institute of Theoretical and Experimental Physics"

ul. B. Cheremushkinskaya 25, 117218 Moscow, Russia E-mail: okun@heron.itep.ru

Received 26 March 1998 Uspekhi Fizicheskikh Nauk **168** (6) 625–629 (1998) Translated by V Kisin; edited by L V Semenova charmed, s for strange, t for top (or truth), b for bottom (or beauty).

Each charged fermion has an antiparticle counterpart: \bar{u} , \bar{d} , \bar{c} , \bar{s} , \bar{t} , \bar{b} , e^+ , μ^+ , τ^+ . It is not yet known if the neutrinos have antiparticles. They (at least some of them) may even be truly neutral, that is, they constitute their own antiparticles. These truly neutral neutrinos are known as Majorana neutrinos, as against the ordinary ones, known as Dirac neutrinos. A search for neutrinoless double beta-decay is being actively pursued now. The highest accuracy was achieved in the search for the neutrinoless decay of ⁷⁶Ge ($T_{1/2} \gtrsim 10^{25}$ years). If neutrinoless double beta-decay is discovered at an improved level of instrument sensitivity, it will indicate the Majorana nature of the neutrino and also that its mass is non-zero.

Looking at Table 1, we cannot help marveling at how far elementary particle physics has gone since fate snatched L D Landau first from physics (January 1962) and then from life (1 April 1968). Landau knew only three leptons (e, v_e and μ). The discovery of the muon neutrino was first announced in July 1962 at the Rochester conference in Geneva; all the participants of the conference sent Landau a letter, wishing him the speediest recovery.

As for the hadrons, in 1962 physicists knew, in addition to nucleons, π and K mesons, plus a number of strange hyperons and resonances. However, the composite hadron model based on three sakatons failed to provide an adequate description of baryons, even though it gave an adequate description of weak hadron currents and mesons. That only came in 1964 when M Gell-Mann introduced three quarks: u, d and s.

It would of course be possible to say that both the world around us and ourselves are built of nucleons and electrons; the fact that nucleons consist of three quarks (p=uud, n=ddu) cannot change anything in the 'everyday' life of a human being. For our world to function, it also needs, in addition to p, n and e, the electron neutrinos v_e , without which hydrogen could not burn in the Sun and the stars:

$$2e + 4p \rightarrow {}^{4}He + 2\nu_e + 27 \text{ MeV}$$

This is the source of all the energy we can count on. Neutrinos are born in the Sun in enormous numbers and immediately fly away into the surrounding space. Seventy billion neutrinos cross each square centimeter of the surface of the Earth each second. We do not notice this, though: we are transparent to neutrinos. Huge detector systems had to be erected to record several hundred solar neutrinos. This number was roughly what was expected, which was a triumphant success of science. But the triumph was not complete: the number of neutrinos was less than that calculated by a factor of 2-3. We will return to this puzzle later. At the moment we can emphasize that out of the three generations of fermions in Table 1, a 'pedestrian' would be quite happy if the first was the only one. We can only guess what the second and third generations are needed for. According to some very simple models, for example, CP invariance cannot be violated without them. And without this violation of CP invariance the Universe could not have generated the baryonic asymmetry at the early stages of its evolution: it would contain equal numbers of protons and antiprotons, electrons and positrons; they would all be converted by annihilation into photons and neutrinos and we would never have appeared!

3. Fundamental vector bosons

The tradition of science-popularizing literature is to treat fundamental fermions as 'building blocks' of the Universe (even though very few of them justify this term). As for the four vector bosons, they are usually described as interaction carriers, as a glue that fixes the 'building blocks' to one another. This comparison describes some of them extremely well. Experiments have thus established four vector bosons (we again ignore their antiparticles): the photon γ , the gluon g, the neutral weak boson Z⁰, and the charged weak bosons W[±], which are antiparticles to each other.

The photon has been studied better than the rest. Free photons create free electromagnetic fields: radio waves, light, x-rays, and gamma-quanta. The photon mass is zero. Consequently, the photon energy E in vacuum equals the absolute value of **k**, of its momentum (times c): $E = c|\mathbf{k}|$. Photons with $E^2 \neq c^2 \mathbf{k}^2$ are said to be virtual. The Coulomb field in the hydrogen atom is created by virtual photons with $-c^2 \mathbf{k}^2 \gg E^2$. The electric charge e is the source of photons. We know from optics and atomic physics that $e^2/\hbar c = \alpha \simeq 1/137$. (Here $\hbar = h/2\pi$ and h is the Planck quantum of action). All electromagnetic interactions are due to photon exchange. The theory describing electromagnetic interactions is known as quantum electrodynamics (QED).

The carriers of the strong interactions are the gluons. Gluons' sources are the so-called 'color' charges. These charges have no relation to ordinary color and were given this name only for convenience of talking about them. Each of the six species of quarks (also known as quark flavors, u, d, c, s, t, b) exists in three color forms: yellow, blue or red (y, b, r). Antiquarks carry the corresponding color anticharges: \bar{y} , \bar{b} , \bar{r} . It is important to emphasize that the three charges (y, b, r) and the three anticharges (\bar{y} , \bar{b} , \bar{r}) are completely independent of quark flavors. We have hidden part of the truth when stating that there exist six different quarks: in fact, they are twelve if antiquarks are taken into account and 36 if color charges are. However, this 'sextupling' can be interpreted as six different states of one particle.

The color states of gluons are even more complicated. A gluon has two color indices, not one. It is easy to show that the number of different gluons is eight: $3 \times \overline{3} = 8 + 1$. The combination $y\overline{y} + b\overline{b} + r\overline{r}$ is 'snow-white' and thus carries no color charge. In contrast to photons in QED, which are electrically neutral, gluons in quantum chromodynamics (QCD) are carriers of color charges and thus have to emit and absorb gluons. The result is a completely unfamiliar

behavior for the strong interactions of gluons and quarks: their interaction energy increases in response to attempts to separate them.

As a result, free gluons and quarks cannot exist: they are 'self-confined' within colorless hadrons. The complete quantitative theory of this confinement has not been constructed yet but qualitative confirmations have been obtained by computer simulations on four-dimensional lattices and by the so-called QCD sum rules.

4. Running coupling constants

The dimensionless quantities $\alpha = e^2/\hbar c$, $\alpha_s = g^2/\hbar c$, $\alpha_{\rm W} = g_{\rm W}^2/\hbar c$, $\alpha_{\rm Z} = g_{\rm Z}^2/\hbar c$ are often referred to as coupling constants. It was established as early as in the 1950s that $\alpha \approx 1/137$ is a constant only at zero (or very low) momentum transfer q^2 . Owing to vacuum polarization, α grows with increasing q^2 and tends to infinity at high but still finite q^2 . This phenomenon is known as the Landau - Pomeranchuk pole and was interpreted as a manifestation of the non-selfconsistency of QED. Once QCD was born, it became clear that $\alpha_s(q^2)$ [in contrast to $\alpha(q^2)$] tends to zero as $q^2 \to \infty$. This phenomenon is known as asymptotic freedom. As a result of the asymptotic freedom, the perturbation theory provides an adequate description of gluon and quark collisions at small distances (at high q^2), generating the so-called jets of hadrons. The reverse face of asymptotic freedom is confinement: color attraction becomes irresistibly strong at large distances. Of considerable experimental significance for studying the confinement is the search for the so-called 'exotic hadrons' that contain, in addition to three valent quarks (in the case of a baryon) and a quark and an antiquark (in the case of a meson), additional quark – antiquark pairs or valent gluons. Of special interest are the so-called glueballs that consist only of gluons.

In comparison with the fast-running α_s , the weak interaction constants α_Z and α_W crawl rather than run: they grow by about one per cent from $q^2 = 0$ to $q^2 \simeq 100$ GeV². However, if the progress of all constants is extrapolated towards higher q^2 , they show a tendency to coming together at a single point somewhere around $q^2 = 10^{15} - 10^{16}$ GeV, where $\alpha_s \sim \alpha_W \sim (8/3)\alpha \sim 1/40$. We can hope, therefore, that a unified theory of the electroweak and strong interactions exists at such high q^2 . Such theories are described by symmetry groups that incorporate leptons and quarks in a single multiplet and predict proton decay. The search for proton instability was especially intense 10-15 years ago but unfortunately failed to discover the expected effect.

To complete the survey of the sixteen fundamental particles, we give in Table 2 the particle masses (or the upper

$\begin{array}{l} \nu_e < 10 \; eV \\ 1956 \end{array}$	$\begin{array}{l} \nu_{\mu} < 170 \; KeV \\ 1962 \end{array}$	$\begin{array}{l} \nu_\tau < 24 \; MeV \\ 1975, 1998 \end{array}$	$\begin{array}{l} \gamma < 10^{-15} \text{ eV} \\ 1926 \end{array}$
e 0.51 MeV 1897	$\mu 105.7 \text{ MeV}$ 2 × 10 ⁻⁶ s 1937, 1947	$\tau 1777 \text{ MeV} 3 \times 10^{-13} \text{ s} 1975$	g 0 1973
u 5 MeV 1964	c 1300 MeV 10 ⁻¹² s 1974	t 176 GeV Γ = 2 GeV 1994	Z 91.2 GeV $\Gamma = 2.5 \text{ GeV}$ 1983
d 10 MeV 1964	s 150 MeV 1964	b 4.3 GeV 10 ⁻¹² s 1977	W 80.4 GeV $\Gamma = 2.1$ GeV 1983

limits for the masses of the neutrinos and the photon), their lifetimes (or decay widths) and the years of their experimental discovery.

The quark masses in Table 2 should not be taken too literally; indeed, quarks do not exist as free isolated particles. These values characterize quark masses deep inside hadrons. Quark lifetimes should not be interpreted literally either. The only quark that is 'born free and dies free' is the heaviest of them, the t quark. Its lifetime is so short that it simply has no time to form hadrons with the quarks that accompany its birth.

5. Colliders

The heavy quarks c, b, t, the τ leptons, the gluons and the W and Z bosons were mostly discovered and studied in experiments with colliding particle beams. Storage ring accelerators with colliding beams are known as colliders. Table 3 lists twelve electron – positron colliders that have been functioning (or functioned) from the beginning of the 1970s, and one electron – proton collider. We list in Tables 3 to 5 the name of the collider, the institute, the center or town where it is located, the duration of operation, and the energy of each beam in GeV.

Table 3.

SPEAR	SLAC	1972-1990	4×4
DORIS	DESY	1973-1993	5.6×5.6
CESR	Cornell U.	1979-	6×6
PETRA	DESY	1978 - 1986	23.4×23.4
PEP	SLAC	1980 - 1990	15×15
BEPC	Beijing	1989-	2.2×2.2
VEPP-4M	Novosibirsk	1994 -	6×6
TRISTAN	KEK	1987 - 1995	32×32
SLC	SLAC	1989-	50×50
LEP I	CERN	1989-1995	50×50
VEP - 2M	Novosibirsk	1992-	$0.7 \times 0.7 \ (0.55 \times 0.55)$
LEP II	CERN	1996 - 2000	up to 100×100
HERA	DESY	1992 -	$e^{\pm}30 imes p820$

The ψ meson, the first of the numerous energy levels of charmonium (the system consisting of c and \bar{c}), was discovered at the SPEAR collider in 1974. The same particle, christened J, was discovered simultaneously at the Brookhaven accelerator in an experiment with a fixed target.

The Υ meson, the first of the numerous levels of upsilonium (or bottomonium, the system consisting of b and \bar{b}), was also discovered in a collider. To study the properties of b quarks, e^+e^- colliders were built with beam energies around 6 GeV.

LEP I and SLC were constructed for precision measurements of the properties of Z bosons. The four detectors of LEP I recorded 20 million events of the resonance creation and decay of Z bosons. The number of Z bosons at the SLC collider is fewer by two orders of magnitude but they are produced by a polarized electron beam, which makes it possible to conduct unique measurements of Z-boson properties.

The LEP II collider, which operates in the same 27 kmlong ring tunnel in which LEP I worked before it, was built to study the creation of W^+W -boson pairs and also to search for new particles: the scalar Higgs boson and the so-called supersymmetric particles that we will discuss later. To conclude the comments to Table 3, we note that the highest precision in measuring the τ lepton mass was achieved with the Beijing accelerator, and that the experiments at the lowest energies in Novosibirsk are required for the high-precision testing of QED.

Three high-current e^+e^- colliders listed in Table 4 will start operation in 1999 specially to study the mechanisms of CP-invariance violation.

Ta	ble	4.

DAΦNE	Frascati	1999	$\begin{array}{c} 0.51 \times 0.51 \; (0.75 \times 0.75) \\ 8 \times 3.5 \\ 3 \; 1 \times 9 \end{array}$
KEKB	KEK	1999	
PEP II	SLAC	1999	
PEP II	SLAC	1999	3.1 × 9

The collider in Italy will study K mesons and those in Japan and USA, B-meson decays. Note that to be able to observe B-meson decays in flight (not at rest), the colliding electrons and positrons must have unequal energies.

The proton – antiproton colliders are shown in Table 5.

Table 5.

SppS	CERN	1981 - 1990	315 imes 315
Tevatron	FNAL	1987 -	1000×1000

The European collider was used to discover, in 1983, the W and Z bosons (the first publications contained less than ten events). This collider was designed on the basis of the already existing proton accelerator SpS, specially for the discovery of the W and Z bosons whose masses were predicted by the theory of the electroweak interaction. The t quark was discovered in 1994 at the American collider.

The fate of the proton – proton colliders proved to be rather sad. The largest of them, with a ring tunnel more than 80 km long and an energy for each proton beam of 20000 GeV = 20 TeV, was called the SSC: the superconducting supercollider. In 1993 the US Congress canceled the decision to build the SSC after three billion dollars had been spent on its construction near Dallas in Texas.

The superconducting acceleration-storage complex UNK of the Institute of High Energy Physics (in Protvino, near Serpukhov, Russia) was expected to reach colliding beam energies of 3 TeV. The ring tunnel longer than 20 km was completed; however, further building work was discontinued, owing to lack of funding.

There are grounds for hoping that the LHC — the Large Hadron Collider at CERN with a proton energy of 7 TeV, whose construction is to begin in the tunnel in which LEP II is now operating, will be completed in 2005. Not only the CERN member countries but also many others are participating in the construction of LHC, including USA, Japan and Russia.

The design plans for the construction of linear electron – positron colliders are still at a much earlier stage; the colliders may start operation after 2010. The energy range involved is 250 to 1000 GeV in a beam. The beam energy is only limited by the collider's length. In contrast to electron – positron ring colliders, the synchrotron radiation in linear machines is insignificant.

The $\mu^+\mu^-$ colliders, discussed since the early 1960s, would be truly tiny in comparison to the electron-positron colliders. The main difficulty here is the short lifetime of muons (two microseconds); however, a muon with energy 1 TeV lives for 20 ms and can travel up to 6000 km.

6. Why do we need still larger colliders?

The first goal is to search for new particles that are required for theorists to achieve self-consistency in the description of nature. The so-called Standard Model is based on the local (gauge) symmetry described by the $SU(3)_c \times SU(2)_W \times U(1)_V$ group. Here $SU(3)_c$ is the symmetry of the strong color interaction of quarks and gluons. $SU(2)_{W} \times U(1)_{V}$ describes the electroweak interaction. All fermions and vector gauge bosons in non-broken symmetry are massless. As a result of a spontaneous breaking of the $SU(2)_W \times U(1)_Y$ symmetry the neutral bosons W^0 and B^0 are mixed. One of their superpositions describes a massless photon that corresponds to the non-broken gauge invariance of electrodynamics, as discovered by V A Fock in 1926. The other superposition describes the massive Z^0 boson. Charged W^{\pm} bosons also gain masses as a result of spontaneous symmetry breaking.

In each generation massless fermions form isotopic doublets if they are left-handed (the spin points against the momentum) and singlets if they are right-handed (the spin points along the momentum). (Left-handed neutrinos and right-handed antineutrinos were first discussed by LD Landau in 1956.) The 100% breaking of the mirror symmetry P and the charge symmetry C is thus built into the theory 'by hand'.

In the Standard Model fermions gain masses, just as the Z and W bosons, via the spontaneous breaking of the $SU(2)_W \times U(1)_Y$ symmetry realized by the Higgs mechanism. The Higgs mechanism in quantum field theory is a relativistic version of the Ginzburg–Landau mechanism in superconductors. The electrically neutral Higgs field forms a non-zero vacuum mean field — the 'vacuum condensate' filling the entire Universe. The quanta of this field are particles with spin s = 0: Higgs bosons, or simply higgses. The masses of all particles in the model are $m = f\eta$, where m is the mass of a given particle, f is the coupling constant for the particle and the Higgs field, and η is the value of the condensate. We have no theoretical predictions for the values of f but we know the value of η with high accuracy:

$$\eta = (\sqrt{2}G_{\rm F})^{-1/2} = 246 \,\,{\rm GeV}\,.$$

(Here G_F is the familiar constant of the week four-fermion interaction.)

On the η scale, the most natural is the mass of the t quark: it corresponds to $f \simeq 1$. However, the hierarchy of fermion masses (of coupling constants f) remains unclear. The smallness of the neutrino masses looks especially baffling.

The W and Z boson masses were predicted using the Standard Model. The t quark mass was predicted on the basis of a theoretical analysis of high-precision data obtained by measuring electroweak radiative corrections in Z boson decays (20 million events!). Predictions of the higgs mass are much less reliable because it affects the radiative corrections much less than the t quark mass. The simplest variants of supersymmetric models predict 130 GeV for the upper bound on the higgs mass. The schemes of Grand Unification of the strong and electroweak interactions predict this limit to be 200 GeV (the prediction is based on renormalization group equations). Most theorists expect that $m_Z < m_h < 2m_Z$. If $m_{\rm h} < 2m_{\rm W}$, the principal decay signal of higgs creation must be the decay to two gamma-quanta. Although this is an extremely rare decay, other decays are very hard to extract from the background. The hunt for the higgs at LEP uses the

reaction $e^+e^- \rightarrow Z^0h$. If LEP II fails to find higgs, LHC will. The scenarios with a very heavy higgs appear to be too ugly to a theorist. If $m_h > 800$ GeV, the Landau – Pomeranchuk pole in the higgs sector shifts to a physically observable region.

The search for the higgs is Problem No. 1 of high-energy physics. Once the higgs is discovered, it will be necessary to find out whether there are additional types of higgs. If there are several of them, the properties of the Higgs sector of the theory will become an area of detailed analysis.

Problem No. 2 of high-energy physics is the search for supersymmetry (SUSY). There are three arguments in favor of believing that SUSY exists:

1. The cancellation of quadratic divergences in the higgs sector: they threaten to transform the Fermi scale ($\sim 10^2 \text{ GeV}$) into the Planck scale ($\sim 10^{19} \text{ GeV}$, see clarification below).

2. The unification of all interactions, including gravitation (see below).

3. The mathematical elegance of SUSY.

A host of supersymmetric theories is available. The simplest of them is the N = 1 SUSY in which each of 'our' particles has a supersymmetric partner differing only in the value of spin (in a non-broken SUSY) and mass (in a broken SUSY; we know that the SUSY in nature is indeed broken!). Here is a brief list of supersymmetric pairs:

- 1. Photon; s = 1 photino; s = 1/2.
- 2. Gluon; s = 1 gluino; s = 1/2.
- 3. Z boson; s = 1 zino; s = 1/2.
- 4. Higgs; s = 0 higgsino; s = 1/2.
- 5. Neutrino; s = 1/2 sneutrino; s = 0.
- 6. W boson; s = 1 wino; s = 1/2.
- 7. Leptons; s = 1/2 sleptons; s = 0.
- 8. Quarks; s = 1/2 squarks; s = 0.

The 3 through 5 superparticles are also known as neutralinos, and the 6 through 8 superparticles, as chargino. The lightest of the superparticles must be stable, provided the so-called R-parity is conserved. Such stable particles may constitute the main component of the so-called 'dark matter' which comprises from 90% to 99% of the total mass of the Universe. The search for dark matter is conducted both on the Earth, in low-background laboratories, and by astronomical methods (in the search for gravitational lenses). Superparticles may be discovered at LEP II, Tevatron, and LHC.

Another particle, in whose existence theorists firmly believe but which will never be detected by experimenters, is the graviton. It is the quantum of the gravitational field, a neutral massless particle with spin s = 2. Gravitational antennae will soon be able to detect gravitational waves but the individual particles of these waves interact sufficiently strongly only at fantastically high (Planckian) energies in the center-of-mass reference frame:

$$E \sim m_{\rm P} c^2 = \left(\frac{\hbar c}{G_{\rm N}}\right)^{1/2} c^2 = 1.22 \times 10^{19} \,\,{\rm GeV}\,,$$

where G_N is Newton's constant.

The quantum theory of gravitation has not yet been constructed. In the supergravity theory, the graviton is accompanied by the gravitino (s = 3/2).

The studies devoted to the particles already discovered and those likely to be discovered in the foreseeable future are known as 'phenomenological'. Those devoted to particles that will never be observed in experiments are known as 'theoretical'. This group of studies assumes that the quantum field theory in general and the Standard Model in particular are phenomenological theories. The fundamental theory is then not a theory of pointlike particles but one dealing with strings whose size is of the order of $\hbar/m_Pc \sim 10^{-33}$ cm. These strings move in multidimensional spaces and possess boson – fermion symmetry, that is, they are superstrings. Superstrings are coupled in ten-dimensional space to multidimensional supermembranes (branes). The latest achievement in this field is the idea that there exists an all-encompassing M-theory. Various versions of superstring models suggested previously have been generated by perturbative expansions at different points in the parameter space of the future M-theory.

Can theorists succeed in devising, by a shear mental effort, a unified theory in which all the experimentally observed masses, mixing angles and coupling constants will be fixed by the imposed self-consistency of the theory, instead of being free parameters? In my opinion, theorists cannot do it without experimenters' help. The foremost problem is to study the properties of higgses and superparticles in the mass range up to and of the order of 1 TeV. It is necessary to understand the mechanism of violation of CP invariance. We need to clarify how the neutrino sector works (masses, mixing angles, phases). Taken together, this may offer a launching pad for extrapolation from 10^3 to 10^{19} GeV. But we will also need luck.