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PHYSICS IN THE LAST CENTURY AND IN THE FUTURE

RUDOLF L. MÖSSBAUER

During the last century there were three major developments in physics: 1) the special and general theory of relativity; 2) quantum mechanics; and 3) the Standard Model of elementary particles. This paper will deal with these three developments and also with some new developments, in particular the Big Bang, Einstein's cosmological constant, accelerators, and some of the future realms of physics.

There have been several major developments in astronomy, starting with the Greeks. Physics proper started with Galileo Galilei because only in his time did there begin a systematic check of theoretical considerations through actual observation. During the last century there were three major developments in physics:

1) the development by Einstein of the special theory of relativity, i.e. of a new understanding of space and time and of the fact that the velocity of light is constant in all frames. This development included the famous relation between energy and mass: $E = mc^2$. This new development, which led in particular to the abandonment of the notion of an ether, had already been included in the description of electromagnetism by Maxwell, but it had been done then without comprehension. The last century also saw – again by Einstein – the development of general relativity, i.e. the development of a new geometry leading to a curvature of space and time due to the assembly of mass.

2) The development of quantum mechanics.

3) The development of the Standard Model of elementary particle physics, which in group theoretical notation reads $SU(3)_C \times SU(2)_L \times U(1)_Y$. Here, the indices stand as follows: C for colour, L for left-handed weak interaction, and Y for hypercharge. The first factor represents the strong interaction, while the other two factors represent a near unification of the

electromagnetic and the weak interactions. I say near unification, because the relative strength between both interactions, the so-called Weinberg angle, still had to be inserted by hand. I shall concentrate here for reasons of time on the more recent Standard Model. This model obviously does not contain the gravitational interaction. Gravitation plays at present only a role when bodies of astronomical dimensions are involved. We feel Gravitation only for that reason so strongly because we are attracted by the entire Earth, i.e. a body of astronomical dimensions. Gravitation at distances prevailing now on earth is negligible compared to the other interactions. It is only at much shorter distances, which are now not available, that Gravitation played a role. Such small distances prevailed in the vicinity of the Big Bang, which according to the majority of physicists is at the origin of our Universe. There are several arguments in favour of such a Big Bang: There is the primordial abundance of isotopes, there is the fact that most galaxies are receding from us (the Hubble-shift) and there is the electromagnetic background radiation held to be a leftover from the Big Bang. Until recently we have assumed that the mass content of the Universe, the so-called critical mass, just corresponds to that matter, where the Universe after an infinitely long time is neither receding nor approaching. We would speak in such a case of a Euclidian or flat Universe. It is well known that luminous matter plays only a minor role in the composition of our Universe. Exceeding the luminous part by some 90% is Dark Matter, and nobody knows what it consists of. We know of the existence of this Dark Matter very well from the observations of the Hubble red-shift phenomenon, which yields a much larger mass than is observed in the luminous part alone. There are indications, however, that Gravitation may be inverted at very long distances of our Universe – distances far exceeding our solar system. This leads to a renewed introduction of Einstein's cosmological constant, which is in agreement with the equations of the general theory of relativity. The cosmological constant was introduced by Einstein in order to explain a static Universe, long before the knowledge of an expansion of our Universe. Nowadays we know Hubble's law, which involves an expansion of our Universe, and it is suggested that at its rim this Universe undergoes an acceleration rather than an attraction, as implied by Gravitation. Even the vacuum has a non-vanishing energy according to the present quantum field theory. Why the vacuum energy density is not much greater than is presently observed is at present a mystery. This aspect of the cosmological constant is one of the fundamental mysteries of present fundamental physics. The presence of Einstein's cosmological constant or of an equivalent thereof is still an open question. It will presumably be dealt with in further talks.

We are presently capable of reaching the Big Bang by up to some 10^{-44} sec, but we cannot get closer because we do not known how to quantise Gravitation. At the high temperatures existing in the vicinity of the Big Bang, where Gravitation becomes of the same order as the other interactions, we necessarily must quantise Gravitation, which, however, is something which at the present nobody knows how to perform.

It might well be that all interactions reunite to one interaction if we get close to the Big Bang, at some 10^{19} GeV, leaving just one interaction constant. Let me make a joke here, which goes back to Gamov (who together with Lemaître is the father of the Big Bang): what did God do before he created our world by performing the Big Bang? He created hell in order to put in it those people who ask such questions.

We know that the Standard Model cannot be the final answer because of a large number of parameters which have to be inserted into this model by hand. A complete theory would have to explain all these parameters. People have tried experimentally to go beyond the Standard Model, but so far in vain, with one possible exception: the oscillations of atmospheric neutrinos as observed by the Japanese in the Super-Kamiokande experiment.

It might well be that deviations to the Standard Model appear usually only at much higher energies, close to the Big Bang, and that we are visualising a great desert between energies presently available in accelerators – some 10^2 GeV = 10^{11} eV – and energies close to the Big Bang – some 10^{19} GeV = 10^{28} eV. Such a phenomenon, in my opinion, is suggested by the fact that we presently measure the fourth and fifth decimals of the parameters entering the Standard Theory.

It is not clear whether string theories will provide a conclusive answer to the various questions which are raised. For example: why are we living in three spatial dimensions and one time dimension – altogether four dimensions – and not in other dimensions? String theory favours at the moment just eleven dimensions, with the exceeding dimensions being curled up. Or do dimensions beyond four extend to infinity, without leaving any experimental traces? A possible way out, which is favoured in the so-called superstring theories, would be the introduction of supersymmetric particles. We know that at present particles appear either as Bosons, in which case they carry an integer value of their spin – one way of saying that their intrinsic angular momentum is integer – or they appear as Fermions, in which case they carry a half-integer value of their spin. Theoreticians suspect that the arbitrary separation between Bosons and Fermions does not exist and that in reality we have a supersymmetry, i.e. a unification between both schemes. We do not know whether this is right or wrong, but the lightest supersymmetric particle, being of an order of 100-1000 GeV, should be observable in the near future, if it exists. These superstring theories have the additional advantage of quantising gravitation, but this feature still has to verified, with space and time losing their meaning when approaching the present theoretical limit.

There are in fact close ties between elementary particle physics and astrophysics, because many reactions happening in outer space are of relevance to particle physics as well. As an example, we may cite the dark matter problem, which means that the majority of matter is non-radiative, though well known to be there. It is clear that Dark Matter consists of unknown particles – perhaps super-symmetric particles?

In the present model of elementary particles all matter is made from quarks and leptons and there are four forces. These elementary particles and their interactions are shown in Fig.1. It might be, though this is very unlikely, that the present particles are not elementary, but such a feature would for its verification require accelerators of a higher energy than is presently available. This is because smaller distances, according to the uncertainty principle of quantum mechanics, require higher energies.

In addition, we have no ideas about the sizes of all of our natural constants. Are we living in just one Universe and are there many others, maybe an infinite number of them? Are these other Universes carrying other values of their natural constants? We just don't know.

I shall refrain here from making predictions about future experiments because most basic experiments are anyhow fortuitous. Yet there are several areas where progress will be made. First of all, there will be developments in biology, where physics will continue to make major contributions. It should be noted that all developments in biology so far have shown that everything can be explained on the basis of physics. Whether or not this also explains the process of living still has to be seen. A second area which promises real strides in the future is developments in astrophysics and cosmology, where we are still at the very beginning of our knowledge. Here we are beginning to do experiments and no longer have to rely on mere observations instead. A third area of great promise is that of synchrotron radiation. A fourth area – though of a more technical nature – is the development of nanostructures, which on the one hand make atoms visible and on the other deal with chemical reactions in the spikes of the used 'raster micoscopes'. A fifth area of interest will probably be neutrinos, because in contrast to the charged elementary particles we hardly know anything about these elementary particles and this in spite of the fact that they were already introduced into physics some seventy years ago. We suspect that oscillations lead to a mixture of such particles, attributing masses to them in a similar fashion to that done with quarks. Such a suggestion is made in connection with the observed solar neutrino deficit. The Japanese observation on atmospheric neutrinos is another hint on neutrino-observations. It will take many years to prove or disprove these experimental observations.

The existing circular accelerators have reached their limits, with linear accelerators still being projects of the future. This is a consequence of the fact that circular accelerators, because of their intrinsic acceleration, always produce synchrotron radiation, which with increasing energy reaches practical limits. We may mention here the LEP (large electron-positron) accelerator at CERN (Centre Etudes pour Radiation Nucleaire) near Geneva. It presently goes up to an energy of some 200 GeV, has a circumference of 27 km, and will be replaced in the same tunnel by a proton-antiproton accelerator called LHC (large hadron collider), which will start to resume operation in 2005 and presumably will be the last circular machine to be built at these high energies. We hope that we will achieve with this accelerator a measurement of the Higgs particle, which would be indicative for masses. Another big circular accelerator runs at the Fermi-Lab near Chicago, with a centre of mass energy of some 1.8 TeV (terra electron volts = 10^{12} eV). It will be surpassed by the LHC which when operative will carry a centre of mass energy of 14 TeV. I would like to mention in this context that DESY (Deutsches Elektronen-Synchroton = German electron synchrotron) at Hamburg/Germany was planning to built a linear accelerator with an energy of 750 GeV, which, presumably for financial reasons, may not be constructed. Only the stage with the free electron laser, producing synchrotron radiation in the 1 Å region, which requires much less energy and therefore much less money, will, it is supposed, be built.

Radioactive beams are presumably the only remnant in nuclear physics which are of real interest, because it is only with such beams that one can study reactions which do not persist on earth, yet are of relevance for stellar reactions.

You will well realise that we know a great deal in physics but that in principle we know very little about our world. Many of the crucial discoveries will be left for the future.

Figure 1. Present elementary particles and their weak interactions, arranged in three families, using for quarks and leptons the standard notations u, d, c, s, t, b = up, down, charm, strange, top, bottom quark, e, μ, τ, ν_e, ν_μ, ν_τ = electron, muon, tauon, electron neutrino, muon neutrino, tauon neutrino.A family lepton number can be attributed to each of the lepton families. The general interactions between elementary particles are also shown.

Elementary particles in electro-weak interaction (left-handed particles)

$$\begin{pmatrix}u\\d'\end{pmatrix}\begin{pmatrix}c\\s'\end{pmatrix}\begin{pmatrix}t\\b'\end{pmatrix}\quad\begin{pmatrix}\nu'_e\\e^-\end{pmatrix}\begin{pmatrix}\nu'_\mu\\\mu^-\end{pmatrix}\begin{pmatrix}\nu'_\tau\\\tau'\end{pmatrix}\ \text{where}\ \underbrace{\begin{pmatrix}d'\\s'\\b'\end{pmatrix}}_{\text{weak eigenstates}}=\underbrace{U}_{\text{mixing matrix}}\underbrace{\begin{pmatrix}d\\s\\b\end{pmatrix}}_{\text{mass eigenstates}}\ \text{and}\ \begin{pmatrix}\nu'_e\\\nu'_\mu\\\nu'_\tau\end{pmatrix}=\underbrace{V}_{\text{mixing matrix}}\underbrace{\begin{pmatrix}\nu_e\\\nu_\mu\\\nu_\tau\end{pmatrix}}_{\text{weak eigenstates}}$$

plus antiquarks (right-handed particles) and antileptons (right-handed particles)

Interactions between elementary particles

Example	Strong Interaction	Electromagnetic Interaction	Weak Interaction	Gravitational Interaction	Mediating particles
Proton	•	•	•	•	(3 quarks)
quark	•	•	•	•	gluons
electron		•	•	•	$W^{\pm}$, Z^0, photons
neutrino			•	•	
				•	graviton

Mixing matrix for three particles: Three mixing parameters and one phase yield altogether four parameters. There exist also two mass parameters $|\Delta m^1_0| = |m^2_1 - m^2_2|$

ad 1) The special theory of relativity started with the famous paper by Einstein in 1905, which had far reaching effects about all our physical measurements. In modern language, this paper contained the invariance of the product $\vec{r}'^2 - c^2 t'^2 = 0$, irrespective of an observer. This equation of a wavefront holds in any frame and thereby gives rise to the so-called

Lorentz transformations, which transform systems of different velocities into each other. In particular, the equality of time depends on the location, eliminating thereby the need for absolute time and of an 'ether'. The new theory means, in reality, abandoning the Galilean transformations, while Maxwell's equations for electromagnetism already contain the new form. The theory includes the principle of equivalence. The special theory of relativity is confined to motions, which are uniform relative to each other, corresponding to so-called inertial systems. This specific feature was dropped in the general theory of relativity., which had been established in 1915 by Einstein as well. This theory, which is too complicated to be presented here, boils down to the equation $R_{\mu\nu} = -kT_{\mu\nu}$, where $T_{\mu\nu}$ is an energy-momentum tensor describing the distribution of matter, k is a constant and $R_{\mu\nu}$ is a tensor describing a measure of the curvature of space. The curvature of space-time is thus related to the distribution of mass in space.

ad 2) The development of quantum mechanics started in 1900 with the famous paper by Max Planck on black body radiation, which on the one hand was correct, but on the other hand was performed without full comprehension. It was Einstein who introduced in his paper on the photo-electric effect in 1905 the proper relation between energy and frequency, although it was only in 1924 that deBroglie also introduced the relation between momentum and wavelength. Einstein in 1905 and deBroglie in 1924 thus established the laws $E = \hbar\omega$ and $|\vec{p}| = \hbar|\vec{k}| = \hbar/\lambda$, leading to a duality between waves and particles. This dualism was verified for electrons in 1927 by the experiment of Davisson and Germer. A non-relativistic quantum theory is traditionally specified as quantum mechanics, with the number of particles being constant. Radiative changes of particle numbers are in this theory performed in a semi-classical way. By contrast, a relativistic quantum theory is based on the principles of the theory of relativity. Again by contrast, a quantum field theory emphasises the creation and the annihilation, i.e. the changes in the number of elementary particles.

The sole interpretation of quantum mechanics, which is compatible with the Schrödinger function Ψ, is an interpretation of Ψ as probability amplitude. The quantity $|\Psi|^2$ then is the probability density dP/dV.

In a non-relativistic quantum theory, we may represent operators either in the form of differential operators or in the form of matrix operators. By consequence, there are in principle two descriptions of a non-relativistic wave equation, one is Schrödinger's wave mechanics and one is Heisenberg's matrix mechanics. Both descriptions really give the same result. A relativistic quantum theory was later on presented by Gordon and Klein for Bosons (particles with an integral number of intrinsic angular momentum or spin) and by Dirac for Fermions (particles with a half-integer number of spins), leading to the concept of antiparticles.

ad 3) The development of the Standard Model assumed, in particular, the existence of a renormalisation for the electroweak interaction, a theoretical development which led only last year to the Nobel prize for t'Hooft and Veltman. Their work was conducted within the framework of a relativistic quantum field theory. It has been well known since the fifties that QED (quantum electrodynamics) is quite suited to the calculation of electromagnetic interactions at any energy with high precision. This treatment leads to the fact that all infinities produced in the theory by quantum mechanical fluctuations can be eliminated by introducing changed (called renormalised) physical quantities such as charge and mass. The equations of QED necessitate a combination of Dirac's relativistic equation for fermions and of Maxwell's equations for photons. The quantum field theory of the colour force is known as quantum chromodynamics (QCD), which leads, in particular, to the SU(3) model.

Gauge theories are responsible for strong, electromagnetic and weak interactions. In particular, the gauge theory for both weak and strong interactions is non-Abelian, causing interactions between the particles mediating the interactions. In classical physics, gauge transformations mean that the relevant potentials are only defined up to arbitrary gradients, i.e. for a vector potential $\vec{A} \to \vec{A} + \vec{\nabla}\chi$ and for an ordinary potential $V \to V + \partial\chi/\partial t$. In quantum physics, gauge transformations mean in addition the replacement of Ψ by an arbitrary phase factor $\Psi \to \exp\{i\alpha)\Psi$,? where α is constant (global phase invariance). A local phase invariance $[\alpha \to \alpha(\vec{x}, t)]$ leaves the phase of the wave function open, though leaving the probability unchanged. Perhaps all the various gauge theories can be understood on the basis of a single gauge theory. A truly unified theory of all four interactions (called the 'theory of everything', TOE) would involve only one gauge coupling constant. Such a theory would also have to abandon the customary distinction between quarks and leptons, which holds at the present time. The notions of baryon and of lepton number conservation would have to be abandoned. These are notions which are in agreement with considerations but in disagreement with the fact that proton decay has not yet been found.