PRESENT AND FUTURE OF HIGH ENERGY PHYSICS

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PRESENT AND FUTURE OF HIGH ENERGY PHYSICS

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**RESUME**

L'état actuel de la physique des hautes energies, et en particulier notre connaissance actuelle des particules fondamentales sont examinés afin d'évaluer les possibilités de progrès futur ainsi que le rôle à jouer par les futurs Grands Accélérateurs Européens.

**ABSTRACT**

The present status of high-energy physics, and in particular our present knowledge on fundamental particles and their interactions, are critically examined in order to assess what progress can be expected in the future and the role to be played by future European Accelerators.

In recent years spectacular developments have taken place in elementary particle physics. Both theory and experiment have met with great success in the past 3 years. We will try to give an outline of what happened, what are the current insights, and what is foreseen for the future. Some of it will be known, but we will tell it all to sketch a coherent tableau.

The "new physics", as it is sometimes called, started in 1971 with the proof of renormalizability of a class of theories, called gauge theories. In simpler words it meant this: it is possible to construct theoretically a consistent quantum theory for systems also containing vector particles with mass provided that all couplings and particle multiplets obey some symmetry. Differently stated: the Lagrangian of the theory must be symmetric under some transformations, and these transformations transform particles into each other. If these requirements are not fulfilled then the theory is non-renormalizable, which simply means that going beyond the lowest order approximation one obtains infinity for all kinds of perfectly sensible quantities.

Now it was already known for a long time that weak interactions are of a vector nature, that is they behave as if a very massive vector particle is exchanged (Fig.1)

- Neutron decay
  \[ N \rightarrow p + e^- + \nu_e \]

- Muon decay
  \[ \mu^- \rightarrow \nu_\mu + e^- + \nu_e \]
Neutrino process
\[ \nu_\mu + N + \nu^- + P \]

Fig. 1

At low energies the W is not explicitly observed, the whole looks like a 4-fermion interaction. One sees the spin 1, the vector nature of what is exchanged, but no actual propagation, and the mass has not been measured.

Up to 1971 no theory existed for this kind of process; everyone tried this model or that, and there existed many more or less phenomenological models. After 1971 we knew what the theory should be, and we knew what models were the best ones from a quantum field theory point of view. These models are nowadays known as the Weinberg model, and the G.I.M. (Glashow-Iliopoulos-Maiani) mechanism. We will very briefly describe these models.

In the Weinberg model the symmetry is SU_2, and particles are grouped in singlets and doublets (fig. 2). There are four vector-like particles, namely \( W^+, W^-, W^0 \) and photon \( \gamma \). Under SU_2 the particles of a multiplet transform into each other, and also the vector particles transform into each other. As a consequence invariance under the group implies that one sort of coupling generates others.

For instance the coupling \( W^+(e^-\nu_e) \) implies a coupling \( W^0(\bar{\nu}_e\nu_e) \); neutral currents are predicted. Pictorially this law can be represented as a race-track. This track must be closed (Fig. 3).

The reactions \( e^- + \nu^- + W \) and \( e^- + W^0 + \gamma \) imply the existence of \( e^- + \nu^- + W^0 \) and \( e^- + \nu^- + W^0 \). Similarly for the \( \mu^- + \nu^- \) system (Fig. 3).

The so-predicted neutral couplings imply the existence of the reaction:
\[ \nu_\mu + e^- \rightarrow \nu_\mu + e^- \]

(Fig. 4)

This reaction (and other similar reactions) have meanwhile been observed (Gargamelle, CERN). This very important experimental
discovery greatly enhanced the credibility of the model.

But now comes the question of coupling to hadrons. Nowadays most high energy physicists believe in quarks, and in any case it is an effective description. At that time three quarks were needed to explain the then known particles. These quarks were called the up, down and strange quark respectively, with charges \(\frac{2}{3}, -\frac{1}{3}\) and \(-\frac{1}{3}\). Each of these quarks comes in three varieties, and this is denoted by a color code. Thus there are three up-quarks called up-red, up-blue and up-green.

Most of the known hadrons are made up from three quarks with three different colors (thus making white altogether) or a quark and an antiquark from the same color (or rather color and the complementary color, thus again making white).

Examples (the bar denotes the antiparticle):

<table>
<thead>
<tr>
<th>Hadron</th>
<th>udd</th>
<th>(\pi^+) u(\bar{d})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>udd</td>
<td>(\pi^+) u(\bar{d})</td>
</tr>
<tr>
<td>Proton</td>
<td>uud</td>
<td>(K^+) u(\bar{s})</td>
</tr>
<tr>
<td>Lambda</td>
<td>uds</td>
<td></td>
</tr>
</tbody>
</table>

Neutron decay is thought to be due to \(d-u-W^-\) coupling (Fig.5)

\[
\begin{align*}
\text{N} & \rightarrow d & u & \nu_e & \text{e}^- & \text{p} \\
& \uparrow & \downarrow & \uparrow & \downarrow & \downarrow
\end{align*}
\]

New couplings needed to enlarge Cabbibo theory into gauge theory.

\[
\begin{align*}
N & \rightarrow p & e^- & \nu_e \\
& \uparrow & \downarrow & \uparrow & \downarrow & \downarrow
\end{align*}
\]

The reaction then known could all be understood as being due to the various couplings shown in Fig.6. The corresponding theory is the Cabbibo theory of weak interactions.

\[
\begin{align*}
d & \rightarrow u & W^- \\
u & \rightarrow d & W^+ \\
s & \rightarrow u & W^- \\
u & \rightarrow s & W^+ \\
\end{align*}
\]

Cabbibo model of weak interactions of hadrons

If gauge theory applies then there must be transitions such that the race-track closes:

This implies neutral couplings, such as

\[
\begin{align*}
u & \rightarrow u & W^O \\
\end{align*}
\]

\[
\begin{align*}
d & \rightarrow s & W^O \\
\end{align*}
\]

Fig.7

is experimentally excluded because it would lead to the decay:

\[
\begin{align*}
\Lambda(uds) & \rightarrow N(udd) & e^+ & e^- \\
\end{align*}
\]

Fig.8. And this reaction has not been seen.
The decay $A - N^+ e^- e^+$ following from the coupling $s + d + W^0$

Fig. 8

The cure to this problem is the G.I.M. mechanism. A new quark and an alternative route are introduced (Fig. 9):

A new quark of charge $2/3$ is introduced in the G.I.M. scheme

Fig. 9

Supposedly this new quark, called charmed quark, was rather heavy, thus not experimentally discovered.

In a famous paper M. Gaillard, B. Lee and Rossner analyzed the situation and pointed out that this quark should not be heavier than 3 GeV.

In 1974 a new particle was discovered with a mass of about 3.1 GeV and called the $J/\psi$. Soon the hypothesis was put forward that this $J/\psi$ particle was a bound state of a charm and an anti-charm quark, which would imply that the charmed quark has a mass of about 1.5 GeV. Since then many experiments have confirmed this idea, and we have learned that this G.I.M. idea is correct. Thus there exists a fourth quark, and in the past few years a whole spectrum of new particles, all in the 2-3 GeV region has been established. They are understood again as three-quark and quark-anti-quark bound states, but now with one or more of these quarks being the new heavy charmed quark. Needless to say that all this was a tremendous boost to the gauge idea.

Meanwhile, as usual in physics, the picture has changed again, and many question marks have appeared. Let us first discuss a very fundamental problem.

One of the very outstanding and intriguing problems is this: why is electric charge quantized? Why have proton and electron so precisely opposite charge?

This feature finds some explanation in gauge theories. There is a class of gauge theories where the electric charges of all the elementary particles are related to each other. In these theories the sum of the electric charges of all the elementary particles must be zero. Let us make up the balance including the new charm quark and also taking into account that every quark occurs in three color types

<table>
<thead>
<tr>
<th>leptons</th>
<th>quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>3 $\times$ $u$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>3 $\times$ $d$</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>3 $\times$ $s$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>3 $\times$ $c$</td>
</tr>
<tr>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>

Indeed, the sum total is zero! This is
very satisfactory, even if we know very little about the underlying theory.

However, the experimentalists from SLAC had another surprise coming: they discovered yet another lepton, the \( \tau \) with its own neutrino. This \( \tau \) particle behaves really precisely as an electron, except that it is much heavier. It has the same charge as the electron, it seems to be coupled in weak interactions precisely like the electron, and furthermore, like the electron, it ignores the strong interaction. And finally, like the electron, it has its own neutrino, as was subsequently discovered. This experimental discovery, unasked for by theorists had one undesired consequence: the \( \tau \)-lepton upsets our electric balance.

How to cure this electric unbalance? If we try to cure this with quarks we need another two quarks, \( t \) (top, charge \( 2/3 \)) and \( b \) (bottom, charge \( -1/3 \)), each again in three color varieties. Then, by just duplicating the configuration seen with electron and muon the electric balance can be restored. Of course, there are other responsibilities, but in the present theoretical scheme that was the simplest possible extension.

Another miracle occurred. Very recently Lederman et al., discovered another new particle that looked very much like the first symptom of a bottom quark with a mass of about 5 GeV. In fact, they discovered the upsilon, with a mass of about 9.5 GeV, and this upsilon was speculated to a bottom-anti-bottom quark bound state. If this is true then we must expect another round of spectroscopy in the 5 GeV region. Meanwhile DESY in Hamburg has confirmed and augmented this discovery. And very soon PETRA, the new electron machine in Hamburg, will hopefully give us all the details.

Aside from the bottom quark we still need another quark, the top quark. By now most high energy physicists are prepared to believe that it exists, and we will also assume that it will be discovered in due time. But now one gets the uneasy feeling that leptons and quarks are like rabbits, multiplying in an uncontrolled way. Is there a limit to this game? Will more and more leptons and quarks turn up as we go to higher and higher energies? Is there a limit? What do we know?

Let us make an inventory of things discovered so far. A picture resembling three flagpoles emerges (Fig.10)

\[
\begin{array}{cccccccc}
| & u_r & u_b & u_g & c_r & c_b & c_g & \tau_r & \tau_b & \tau_g \\
|---|---|---|---|---|---|---|---|---|---|
| \| d_r & d_b & d_g & s_r & s_b & s_g & b_r & b_b & b_g \\
| ---|---|---|---|---|---|---|---|---|---|
| v_e & v_\mu & v_\tau \\
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>e &amp; \mu &amp; \tau</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\end{array}
\]

The three flagpoles

Fig.10

Forces between those particles are due to gluons that mediate strong interactions and couple only to quarks, and the weak forces are due to three very heavy vector bosons \( W^+, W^- \) and \( W^0 \), with a mass of 80-90 GeV. These vector bosons couple to quarks and leptons. The electromagnetic forces are mediated by photons that couple to charged particles. There is another
force and other particles required by the theory, but we will discuss that later.

The first question that comes to mind is: are there still more leptons and quarks? Is there perhaps an infinite sequence of flagpoles?

Concerning this there is an argument coming from astrophysics, from an idea due to Shartsman. The argument was carried further by Steigman et al., and finally by Hut (Phys.Let.69B(1977)85). The idea is that the thermal equilibrium at the time of the big bang depends on what particles take part in the partition. And after the "freeze in" this reflects itself in the neutron/proton ratio, which in turn can be observed from Helium abundance in the Universe. And secondly, if it comes to weakly interacting neutral particles such as mass-less neutrino's then there cannot be too many kinds of them, because, being stable, they would still be around and add to the energy content of the Universe. That however can be tolerated only up to some extend.

The conclusion from these arguments is that there are at most 8 degrees of freedom available for stable massive neutral leptons. As for mass-less neutrino's there is still room for 2 of these. Thus if new flagpoles contain also mass-less neutrino's then we can tolerate at most two new flagpoles. In any case, the number is limited, and there can be no infinite series of flagpoles with mass-less neutrino's.

The above argument depends on cosmology, and furthermore the new neutrino's could have mass, be unstable, and so escape this argument. If however these neutrino's are part of a flagpole, with certain mass differences between the particles of such a flagpole, then another argument applies. It has been shown that the sum of the mass differences cannot exceed a certain number, and to be specific, if there is only one new flagpole then the mass difference must be less than 500 GeV. While this number is large, it is nevertheless not infinite, and again we conclude that the number of flagpoles is limited. In fact, including also some other, much vaguer considerations, one gets the feeling that there is maybe one, or perhaps two new flagpoles, but no more.

So this is as far as things have come today. The very exciting past 8 years have brought us gauge theories, as well as a massive amount of experimental data showing that these ideas apply to weak, e.m. and strong interactions. And gradually we have come to a new situation, with new questions and new perspectives. Again nature puts new mysteries in front of us, and again plans are made to probe experimentally for further information.

Altogether what we know to exist, or believe to exist, can be taken altogether in a very simple three flagpole picture. These three flagpoles contain fermions, that is quarks and leptons, of spin 1/2 only. Further there are forces between these particles, and associated with these forces there are additional particles, namely:
photon, intermediating e.m. interactions,
\( W^+, W^-, W^0 \), intermediating weak interactions,
8 gluons, intermediating strong interactions.

The theory predicts masses of 80 and 90 GeV for \( W^+ \) and \( W^0 \) respectively. All these particles have spin 1.

A symmetry is associated with each interaction, namely \( U(1) \), \( SU(2) \) and \( SU(3) \) respectively.

In addition to all this the theory requires the existence of at least one more particle, of spin 0 and of as as yet undetermined mass. This particle is called the Higgs particle and in the theory this particle is there to mediate a new force. This force is introduced as a means to give masses to all particles, fermions and vectorbosons. As a consequence this Higgs particle is coupled to all massive particles, with a strength proportional to the masses of these particles.

Looking at all this many questions arise. First of all, believing everything stated so far, there are still general understood facets of the theory. For instance, we do not understand yet completely quark confinement. It seems an experimental fact, the theory also contains some strong suggestions in this sense, but up to now nothing has been proven.

Secondly, there are some facts predicted by the theory that have not yet been tested experimentally. For instance, the W-bosons of weak interactions have, not yet, been shown to exist. And absolutely nothing is known for sure about this new force associated with the equally hypothetical Higgs particle.

Thirdly, there are facts observed for which we have no explanation. To be precise they are not in conflict with the theory, but on the other hand they are not needed either. Let us concentrate for a moment on these extra features.

The first question is: why are there three flagpoles (or maybe four or five)? Is there a deeper structure underlying this? For instance, the periodic system of atoms is a thing that we now understand as being due to the fact that the atoms are build up from protons, neutrons and electrons. Perhaps the flagpoles are due to some further internal structure of the particles. If this is so, to what energy must we go before this structure shows up? For example, if hydrogen atoms collide with an energy of a few eV then they break up (ionise), and we see the constituents (proton and electron). Can we expect something similar for electrons or quarks, but at much higher energy?

Another great mystery shows in the masses of the various particles. The quark masses are not well known (due to the fact that no free quarks have been observed), but we have some ideas. The following results obtain for the three flagpoles (we ignore the complications due to Cabbibo mixing).

\[
\begin{array}{ccccccc}
\text{u} & 10 & 10 & c & 1500 & 1500 & 1500 & t \\
\text{d} & 5 & 5 & s & 250 & 250 & 250 & b \\
\nu_e & 0 & \nu_\mu & 0 & \nu_\tau & 0 \\
\nu_e & 0.5 & \nu_\tau & 105.6 & \tau & 1782
\end{array}
\]

It must be stated that we do not know which
lepton pair goes with what quark pair, but we have arranged them in order of increasing mass.

Concerning now these masses we really have no idea where they come from. In the theory they correspond to free parameters and it is really this feature that is disturbing. The theory has too many free parameters. It seems impossible to escape the idea that there must be a deeper structure, which then naturally gives rise to this large number of things.

If we accept this view then the very fundamental question of this moment is: at what energy will this deeper structure show up?

Very little can be said on this matter. The only clue discovered so far is in the Higgs system. Now this system is responsible for the particle masses, and it seems natural to suppose that this is the segment of the theory that is the most interesting from the above point of view. Here the following fact has been discovered if the Higgs particle is heavier than 1000 GeV then the Higgs forces become very strong forces that could well give rise to bound states and composite systems. This is then the number suggested by the theory: something in the range of 1000 GeV. We expect that at an energy below, or not much above this value things will crack up, we will see a new structure, and heaven knows what it will be.

What can be done from an experimental point of view? An energy of 1000 GeV is by itself not beyond technical possibilities. At CERN, Geneva, protons are accelerated to an energy of about 300 GeV. Right now construction is underway to pull antiprotons of the same energy into the same ring, turning however in the opposite sens. In this way collisions involving hundreds of GeV will be possible by the end of 1981.

However, the proton (and the antiproton) is not an elementary particle, but is made up from three quarks and a cloud of gluons. And each of these quarks carries only a part of the energy. The collisions will therefore be complex reactions, involving colliding quarks, and quarks passing on, and masses of gluons exchanged and emitted (in the form of pions, ultimately). Altogether we expect a complex situation, and it will be very difficult to observe the effects that we are interested in.

It is for these reasons that high energy physicists have turned to electron machines, in fact to electron-positron colliding beams. In European context a proposal for a large electron-positron machine (LEP) is being prepared, and we hope that this machine will give us some answers to the fundamental issues. The energy will probably not be beyond 300 GeV in total, but this is enough to explore for further flagpoles, and to establish the existence of the vector bosons. Moreover, we may reasonably hope to get more insight in the Higgs forces, because such a machine would be capable of the production of a pair of vector bosons, and since these particles are so heavy also the Higgs force between them is appreciable and
perhaps detectable.

The machine mentioned is really very big, very difficult to construct and expensive in exploitation. To given an idea of the problems it is perhaps instructive to discuss some features of this machine.

The version presently under study at CERN consists of a large ring with a diameter of 10 kms. In this ring there circulate two beams in the opposite sens. Each beam is made up from 4 bunches. The electrons and positrons have an energy of 85 GeV implying a \( \beta = \sqrt{1-\frac{E^2}{c^2}} \) of \( 17 \times 10^8 \). Each beam contains about \( 5 \times 10^{12} \) particles.

In itself from a macroscopic point of view, the energy residing in each beam is not very large, namely about \( 2.2 \times 10^{-2} \) kwh. The trouble is that electrons going around lose energy through synchrotron radiation and this loss is big because \( \beta \) is so large. In fact, with the radius given the loss is about 1.5 % per turn, which means that per turn \( 3 \times 10^{-4} \) kwh must be provided. Now the electrons turn 10,000 times per second, that is \( 3.6 \times 10^7 \) turns per hour, and we so find an energy loss of \( 10.8 \times 10^3 \) kwh = 11 Mw. Since there are two beams we have a loss of 22 Mw, which must be provided continuously. This sets the scale of 'things. The power must be provided through cavities that are fed by klystrons, oscillating at a frequency of 353 Mhz. Of course, losses also occur here, and furthermore there is energy consumption also in the bending magnets. All together the machine will need more than 100 Mw to generate, in the end (going to higher energy) perhaps as much as 300 Mw.

Apart from all other difficulties also this energy consumption (about 10-30 % of the output of an electricity central) may well be an obstacle. In any case, we are clearly coming to the limits of the possible. If ever we want to go to higher energies we will need other principles. A possibility is colliding linear accelerators; this will be possible provided low temperature physicists succeed in building good super-conduction cavities (see U.Amaldi, Physics Let. 61B(1976)313).

The machine envisaged, costing about \( 10^9 \) Swfr. can be paid out of the current CERN budget over a period of about 8 years. The plan is not to ask for more money, but to do it with the present means. Whether this is really possible, and whether governments will agree with this will become clear within the next two years. And then perhaps around 1988 experiments will start probing further into those very, very deep mysteries of nature.