PARTICLE PHYSICS PROSPECTS: AUGUST 1981

L.B. OKUN

Institute of Theoretical and Experimental Physics
Moscow, USSR

Instead of giving a general overview of the prospects I decided to choose and discuss in some details just one problem, which could be considered as problem No. 1 in particle physics. To be No.1 this problem has to be theoretically advanced and urgent. It should be also experimentally accessible.

<u>What is the problem No.1?</u>

There are several competitors for this title.

Of course, the problem of confinement is very fundamental. It is imperative to understand the structure of the QCD vacuum with its quark and gluon condensates. However, it seems that in spite of many unsolved intriguing puzzles we have already past the QCD crest: we know the Lagrangian.

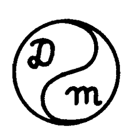
Electroweak gauge bosons if not observed at CERN in the near future may become problem No.1, but I hope they are at the right place.

Grand unification is exciting, but at the moment it has not so much connections with our everyday particle physics. After all, proton decay may be too slow to be detectable, and there is no reliable estimate of the abundance of relic magnetic monopoles on the earth, moon, planets and in cosmic rays.

Superunification (including gravity) is fascinating, but even in our dreams we cannot hope to run experiments on a Planck mass accelerator. The situation may change drastically as soon as very heavy magnetic monopoles are discovered. Their annihilation may bring us quite close to the experiments near the Planck threshold. But meanwhile supergravity does not look as a problem No.1 for experimentalists.

I am aware that many physicists would place on the top of the list the so called preons, hypothetical structure elements of leptons and quarks, called by many other names. When and if discovered, preons will represent a major step on our way into the nature of matter. However, they do not look ripe enough.

It seems to me that the problem No.1 of high energy physics are scalar particles. The search for these particles is extremely important mainly because of their vital role in symmetry breaking. The whole picture of the physical world consists of two parts, which are complementary like yin and yang brought in another context into quantum physics by Niels Bohr:



Here the yang comprises the principles of local symmetry which could be symbolized by the gauge derivative $\mathcal{D}$ . It represents the kinetic terms of the Lagrangian and interactions with the (and of the) gauge fields. The yin, which is not less important, comprises symmetry breaking which gives masses $m$ to various particles including the gauge particles.

It seems now that the way to the understanding of the symmetry breaking inevitably goes through the land of scalars: scalarland. Fundamental scalars protect the renormalizability of the theory by moderating the cross-section growth and hence, the loop divergencies. They give masses to all particles. They violate CP- and may be, even P-invariance. There are theoretical models, which contain no fundamental scalars. In such models nevertheless tightly bound spinless particles inevitably appear.

At present the scalarland exists only in the dreams of theoreticians, who describe it in many ways, which are quite far from being selfconsistent. The aim of this talk is to urge experimentalists and accelerator builders to join their efforts in discovering this land, which lies below and not far above 1 TeV.

## One elementary scalar

The simplest way to break the electroweak symmetry is known to be the introduction of a doublet of scalar "tachions" with imaginary mass. Gauge interactions of these scalars give masses and longitudinal components to W, Z bosons. The Yukawa interactions of the scalars give masses to quarks and leptons and lead to weak mixing angles. The remaining scalar particle $H^\circ$ is neutral and has real mass $m_H$. This "tachion" model is described by the well-known potential $V(\varphi) = \lambda(|\varphi|^2-\eta^2/2)^2$ where $\lambda$ is a dimensionless self-coupling constant, and $\eta/\sqrt{2}$ is the vacuum expectation value of the field $\varphi$:

$$\eta = (\sqrt{2}\ G)^{-1/2} \cong 250 \text{ GeV} , \quad m_H \sim \sqrt{2\lambda}\ \eta .$$

Although the number of theoretical papers dealing with this mechanism reaches several thousands, there are still important unsolved theoretical problems in the Higgs model.

1. The scale problem. We don't understand why $\eta \simeq 1/4$ TeV. In a renormalizable theory such as the standard electroweak model and QCD, the natural value for $\eta$ would be $m_{Pl}$. Thus the scale problem may be formulated as a question: why is the Fermi coupling constant $G_F$ different from the Newton coupling constant $G_N$? The possible answers to this question lead to very interesting physical predictions.

2. The selfcoupling problem. We don't know the value of $\lambda$ and have no physical or mathematical principle which would allow us to predict it. The value of $\lambda$ determines the mass of the $H^\circ$. If $H^\circ$ is heavy, much heavier than W, than $\lambda$ is large and a new strong interaction is waiting for us at energies above $\eta$ . The interaction will manifest itself in a strong WW-scattering. In the case of a light Higgs particle the WW-scattering is moderated by Higgs exchange. In the

case of a very heavy Higgs boson this scattering is not moderated and becomes strong at $\sqrt{s} \gg 2m_W$.

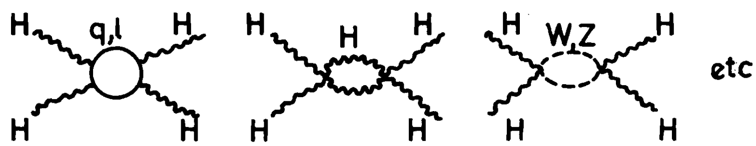
On the other hand, the manifestations of a heavy Higgs boson in low energy processes are negligible: of the order of $\alpha \cdot \ln(m_H/m_W)$ with a small additional numerical factor.

3. The Yukawa pattern problem. A host of arbitrary Yukawa couplings present a challenge to theorists. The problem is especially conspicuous if the neutrino masses are in the eV range. There are suggestions to explain the smallness of some quark and lepton mass ratios by radiative corrections mechanism. According to this idea, for some of the light particles the Yukawa couplings are equal to zero and the corresponding masses come from the heavier particles through radiative corrections. For instance, numerologically, $m_e \sim \alpha m_\mu$, $m_u \sim \alpha^2 m_t$.

A tiny admixture of very heavy neutral fermions may explain the small but nonvanishing neutrino masses.

The understanding of the lepton and quark mass pattern is especially important from the so-called "anthropocentric" point of view. The most "anthropocentric" are the masses of the lightest leptons and quarks: $\nu$, e, u, d. It suffices to mention that the mass of the neutrino may determine the formation of the galaxies and the fate of the Universe and that for $m_p - m_n + m_e > 0$ hydrogen is unstable. The last inequality depends crucially on the relation between the masses of u- and d-quarks.

The "tachion" mechanism, which breaks symmetry at the tree level, looks too ad hoc. Much more attractive is the idea that the symmetry breaking effective potential has the form $\varphi^4 \ln \varphi$ and is caused by the loops of vector, spinor and scalar particles:




This loop mechanism places a lower limit of about 7 GeV on $m_H$. For the lighter Higgs boson the vacuum is unstable.

The stability of the vacuum in the framework of one-loop approximation places also an upper limit on quark and lepton masses: ~ 70 GeV and ~ 100 GeV, respectively. These limits may be violated in the non-minimal Higgs models.

## Several elementary scalars

The simplest extension of the single Higgs doublet model is a model with several Higgs doublets. Its main virtue from the experimental point of view is the existence of charged scalar particles $H^\pm$, which are easy to detect as soon as their threshold is reached (i.e. $e^+e^- \to H^+H^-$). From the theoretical point of view the model does not solve any of the above-mentioned problems and adds a couple of new headaches. Special care should be exercised within the model to get rid in a natural way of the flavor changing neutral currents (FCNC), which give too strong $K \to \bar{K}$ transitions and give decays like $K^0 \to \mu^+ e^-$ or $\mu \to e\gamma$.

The model with three Higgs doublets allows for spontaneous CP-violation. This mechanism taken by itself calls for very light $H^{\pm}$ -bosons, which are well within the range of PETRA and PEP. It predicts also a large electric dipole moment of the neutron: $d_n \sim 10^{-25}$ e·cm (the experimental upper limit is $6 \cdot 10^{-25}$ e·cm), and strong deviations (of the order of 6 %) from superweak predictions for $K_L \to 2\pi^0$ and $\pi^+\pi^-$ decay amplitudes (experimental value is $3 \pm 4$ %).

I want to remark here that in the framework of the minimal single doublet Higgs model, CP could be violated only explicitly: through complex Yukawa couplings into the quark mass matrix and then into the matrix of weak charged currents. Such an explicit CP-violation predicts an unmeasurably small neutron dipole moment (of the order of $10^{-33}$ e.cm) and

$$|\eta_{+-} - \eta_{00}| / |\eta_{+-}| \sim 1\% .$$

Spontaneous CP-violation in the framework of the big bang picture predicts a domain structure of the vacuum: domains with $\mathrm{Im}\langle\varphi\rangle = +\eta$ and $\mathrm{Im}\langle\varphi\rangle = -\eta$. Such a "chess-board" vacuum seems to be excluded by the isotropy of the black body relic radiation. All these unwanted features could be removed by adding some imaginary Yukawa couplings and by marrying spontaneous and explicit "soft" CP-violation. But I see nothing attractive in this marriage of spontaneous and explicit. As for the existence of several scalar doublets their raison d'être may lie in the supersymmetry, which will be discussed later.

## Technicolor

The dynamical symmetry breaking known under the registered trademark Technicolor was invented in order to solve the scale problem. It is assumed that elementary scalars do not exist and that the Fermi scale is produced from the Planck scale by some new gauge interaction. Namely, it is assumed that masses of W and Z bosons are generated by a special set of particles: techniquarks and technigluons, with the confinement radius of the order of $10^{-16}$ - $10^{-17}$ cm. Confined techniquarks form technihadrons with masses $\gtrsim 1$ TeV. However chiral symmetry breaking in the TC sector generates massless Goldstone bosons (GB) and light pseudogoldstone bosons (PGB). The goldstones are "eaten up" by W and Z and serve as their third components; the pseudogoldstones must be observed as relatively light spinless bosons. Thus spinless bosons appear again though now they are composite and pseudoscalars (contrary to the case of elementary Higgs scalars). The expected number of the pseudogoldstones should be very large in any realistic TC-model, because of the large number of techniquarks. Consider, for example, a simple model of one family of 8 technifermions: U, D, E, N, where U, D are color triplets and E, N are color singlets. With the gauge group $SU(N)_{TC}$ this model has global $SU(8)_L \times SU(8)_R$ symmetry. TC-confinement breaks this symmetry and gives 60 pseudoscalar PGB's :

4 colored octets with M ~ 240 GeV

4 colored triplets + antitriplets with M ~ 160 GeV

4 colorless singlets with M ~ few GeV

Two of the latter are charged: $P^+$ and $P^-$, and two are neutral: $P^0$ and $P^3$. The charged ones should be observed at PETRA and PEP: $e^+e^- \to P^+P^-$.

It is quite probable that the number of PGB's should be much larger in a realistic TC-model due to a larger number of techniquarks. The expected proliferation of techniquarks has the following origin. There are no arbitrary Yukawa couplings in the TC-model. Any non-universality of the values in the sector of quark and lepton masses and mixing angles (and there is no sign of any universality in this sector!) should result from one of two possible sources. First from the corresponding difference in the patterns of extended technicolor (ETC) multiplets containing both our fermions and technifermions. Second, from radiative corrections. The emerging structure has to be quite complex.

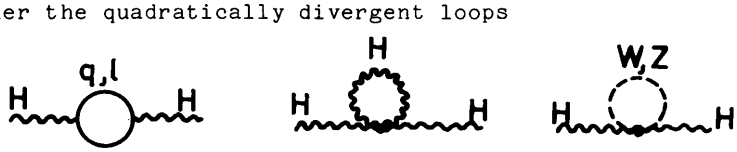
Local ETC symmetry alongside with gluons and technigluons has gauge bosons, coupled to currents transforming fermions into technifermions. These ETC gauge bosons with masses of the order of 100 TeV participate in the mechanism giving masses to our fermions. Local ETC symmetry has also gauge bosons coupled to currents, transforming fermions of one generation into their counterparts of other generations, for instance, d into s, or μ into e. The exchange of both types of ETC gauge bosons trigger processes looking like flavor changing neutral currents (FCNC), and this brings the whole TC-model into a dangerous contradiction with experiment. I have never seen an adequate TC-model giving a realistic spectrum of fermion masses and weak mixing angles and naturally explaining the absence or smallness of FCNC. To make a TC-model more or less realistic we may need such a large number of light technifermions that the very TC-confinement is in danger: screening may overcome antiscreening.

Nevertheless some of the TC ideas may turn out to be relevant and fruitful.

## Compensations and superparticles

One can try to solve the scale problem in the framework of elementary scalars. In that case, however, a host of new particles appear, which are lighter than one TeV and possess rather unusual combinations of quantum numbers. The idea of this approach, which is based on the fermion-boson symmetry looks very promising.

Consider the quadratically divergent loops




where different lines correspond to particles with different spins: wavy to 0, solid to 1/2, and dashed to 1. These are the quadratic divergencies that bring us in a non-stop flight to the Planck mass.

Dimensional regularization bypasses the divergencies but does not solve the scale problem. In some aspects the hierarchy of scales reminds me the problem of small mass-difference of the neutral kaons that existed in the 60's and was solved by the discovery of charm.

To solve the scale problem we must compensate the quadratic divergencies. The possibility of such compensation is suggested by the observation that the sign of the first loop is negative, while the signs of the two remaining loops are positive. (The negative sign is connected with the negative Dirac sea.) Of course, one can assume that the compensation between the three types of diagrams is accidental. But it is very strange to have such an accidental cancellation with an accuracy of the order of $10^{-34}$ (in squared masses of Higgs particles). It is much more reasonable to assume that the compensations take place because each known field has a supersymmetry partner or partners with coupling constants determined by supersymmetry. Let us designate these partners by the suffix "ino":

| | | | | |
|---|---|---|---|---|
| goldstone | (0) | --- | goldstino | (1/2) |
| higgs | (0) | --- | higgsino | (1/2) |
| lepton | (1/2) | --- | leptino | (0) |
| quark | (1/2) | --- | quarkino | (0) |
| photon | (1) | --- | photino | (1/2) |
| gluon | (1) | --- | gluino | (1/2) |
| W | (1) | --- | wino | (1/2) |
| Z | (1) | --- | zino | (1/2) |

The terminology here is not yet established. For instance, some authors use the term nuino for various neutral neutrino-like spinor particles. According to our notation, nuino, muino and electrino refer to the spinless partners of neutrino, muon and electron, respectively.

In order to prevent the Higgs boson from becoming heavier than 1 TeV, the "inos" in the loops have to be lighter than 1 TeV. Thus, if the low energy supersymmetry is the custodian of the low Fermi scale, a real superzoo of new exotic creatures awaits us around the corner.

We cannot exclude at present that some of these superparticles are very light. For instance, the mass of the gluino could be not much larger than 5 GeV. It is not yet excluded that down- quarkinos are in the range of PETRA and PEP. Gluinos and quarkinos are colored. Combined with ordinary quarks and gluons they form colorless superhadrons. The lifetime of these particles depends radically on the pattern of supersymmetry breaking. For some patterns superparticles are produced in pairs, and the lightest of them are stable.

A satisfactory theoretical mechanism of supersymmetry breaking is still unknown. Spontaneous breaking is accompanied by a massless goldstino and in the tree approximation gives unacceptably light quarkinos and leptinos (half of them lighter than quarks and leptons).

It is possible to break supersymmetry explicitly and "softly", by hand, by introducing in the Lagrangian the mass terms of the lower supersymmetry partners: spinors in gauge multiplets (1, 1/2) and scalars in chiral multiplets (1/2, 0). Unfortunately, this procedure is too arbitrary and the value of the Fermi constant $G_F$ remains unexplained.

## Supersymmetry and Unification

The early supersymmetry essentially modifies the standard estimates of the proton lifetime. Gluinos reduce the antiscreening of the color charge and thus increase the mass of grand unification towards the Planck mass. On the other hand, the higgsinos contribute to the screening of the electric charge and thus reduce the mass of grand unification. With only two higgsino multiplets we have $\sin^2\theta_W \cong 0.23$ and the expected value of $M_{GU}$ is of the order of $10^{17}$ GeV, which makes the proton lifetime unobservably long ( $\sim 10^{37}$ years). With 4 higgsino multiplets $m_{GU} \sim 10^{15}$ GeV, $\tau_p \sim 10^{31}$ years, but $\sin^2\theta_W \sim 0.25$, which is too high.

It is interesting that while suppressing the usual grand unification mechanism of proton decay, models of early supersymmetry potentially contain another mechanism, which without special precautions could lead to an instantaneous proton decay. The dangerous elements are (anti)down-quarkinos. These particles may be coupled to the diquark channel (ud). If in addition they have couplings with the (anti)quark-lepton channel ($\bar{u}e^+$), they will trigger a very fast proton decay, unless the couplings are extremely weak. These considerations add some extra spice to the experiments searching for proton decay.

The above mentioned growth of the unification mass towards the Planck mass may be considered as an indication of superunification covering not only electroweak and strong interactions, but gravity as well.

On the other hand the supersymmetry discussed above is the simplest N = 1 supersymmetry. It is at present an open question how to embed such N = 1 model in larger-N theories, among which especially symmetric and attractive are N = 4 and N = 8. As it is well known, the first one gives some signs of being conformal. The second is a maximal extended supergravity theory, generally considered as a basis of superunification.

When speaking about the prospects of supersymmetry, it is impossible not to mention the famous problem of the cosmological term: why is the energy density of the vacuum equal to zero? Another direction of thought is the extra (compact) space dimensions; their existence is suggested by the extended supergravity. But let us return to the scalars.

## Quest for scalars

I have deliberately refrained from speaking about the scalars of grand unified theories. These grand scalars are behind such fascinating objects as magnetic monopoles. The decays of the grand scalars are suspected to be responsible for the baryonic asymmetry of the world. Even the sacred Planck mass may be a secondary manifestation of some scalar condensate.

All this is grand and supergrand, but the really great thing are the ordinary light scalars. We are extremely lucky that alongside with the grand scalars there must exist a rich region of new phenomena below and around 1 TeV. Ordinary scalars provide a link that would enable us to pull out the whole chain. The discovery of scalars will be the experimentum crucis of the quantum field theory.

Scalars are at the epicenter of particle physics. The theoretical seaquake, the eruption and tumbling of numerous theoretical models herald the birth of a new physical continent.

It is evident that our theoretical picture of the origin of particle masses still lacks an important clue, a new theoretical idea, a new principle. I doubt whether this principle could be discovered by pure theoretical insight without a new experimental breakthrough.

Painstaking search for light scalars should be considered as the highest priority for the existing machines such as CESR, PETRA, PEP and the CERN $p\bar{p}$-collider, and even more so for the next generation of accelerators, such as LEP, Tevatron, UNK and HERA. Especially promising is the project of a very high energy electron-positron linear collider. The future of theoretical physics depends on the energy and luminosity of these machines.

During the last 50 years physicists solve problems by inventing hypothetical particles, which eventually become real. It took 14 years to discover the first hypothetical spinless particle: the pion. It is now precisely 14 years that we live with a new type of hypothetical spinless bosons. Isn't it about time to discover them?

## References

The following references are intended to help the reader to get in touch with the literature on the subject which contains thousands of papers.

For various aspects of the Higgs boson physics as well as for the list of references see the review papers:

M.K. Gaillard, Comments Nucl.Part.Phys. 8, No.2, 31 (1978). A.I. Vainshtein, V.I. Zakharov, M.A. Shifman, Uspekhi Fiz.Nauk, 131, 537 (1980); Sov. Phys. Uspekhi 23, 429 (1980).

-----

For a recent discussion of spontaneous CP-violation see

A.A. Anselm, N.G. Uraltsev, Yadernaya Fiz. 30, 465 (1979), Sov.Journ.Nucl. Phys. 30, 240 (1979)

G. Senjanović in Proceedings of the XX HEP Conference, Madison, 1980, p. 524. (Edited by L. Durand and L.G. Pondrom).

-----

A thorough discussion of very heavy Higgs bosons is given by T. Appelquist in Lectures at 21st Scottish Summer School, St. Andrews 1980.

-----

A very lucid review of technicolor is given by K.D. Lane, M.E. Peskin in Electroweak Interactions and Unified Theories, Proceedings of the XV Recontre de Moriond (Ed. by J. Tran Thanh Van) 1980, Vol. II, p. 469;

see also recent papers on FCNC and PGB's: S. Dimopoulos, J. Ellis, Nucl.Phys. B182, 505 (1981).

J. Ellis, M.K. Gaillard, D.V. Nanopoulos, P.Sikivie, Nucl.Phys. B182, 529 (1981).

A. Ali, M.A. Beg, DESY 80/98, October 1980.

-----

The role of color and electroweak radiative corrections as a source of quark and lepton masses is discussed by S. Weinberg, Phys.Lett. 102B, 401 (1981)

Reviews on supersymmetry:

P. Fayet, S. Ferrara, Physics Reports 32C, No.5, 249 (1977)

P. van Nieuwenhuizen. Physics Reports 68, No.4, 189 (1981).

-----

The phenomenology of light supersymmetric particles is discussed in the preprints:

G. Barbiellini et al., DESY 79/67 October 1979.

P. Fayet, TH 2864-CERN, May 1980.

-----

The scale problem from the point of view of supersymmetry is analyzed in a number of recent preprints:

S. Dimopoulos, S. Raby. Supercolor, SLAC-PUB-2719, March 1981.

M. Dine, W. Fischer. M. Srednicki,"Supersymmetric technicolor",Inst. Adv. Study preprint, Princeton 1981.

S. Dimopoulos, S. Raby, F. Wilczek,"Supersymmetry and the scale of unification", University of California, Santa Barbara, NSF - ITP-81-31, April 81.

S. Dimopoulos. H. Georgi,"Softly broken supersymmetry and SU(5)", Harvard University preprint HUTP-81/A022, May 1981.

E. Witten,"Dynamical breaking of supersymmetry", Princeton University preprint, 1981.

E. Witten,"Mass hierarchies in supersymmetric theories",preprint ICTP, IC/81/106 Trieste, July 1981.

-----

For the latest experimental searches of Higgs bosons, TC,PGB's and leptinos see talks at this conference by J. Bürger and A. Silverman. The results of searches for very light scalar particles decaying into two photons were presented at this conference by H. Faissner.

## Discussion

H. Faissner, TH Aachen: The $2\gamma$-events, about which I reported yesterday, are obviously candidates - not only for axions - but also for the other eight scalars Professor Okun mentioned: the leptino, the quarkino and the light technicolors. The evidence we derived from comparing frequencies of $2\gamma$ and $1\gamma$-events is clear: these objects do decay into $2\gamma$'s (not into 3 or 4, and not into $1\gamma$ + something else)! - This, by itself, proves they are not vector particles. And for their properties we know they did penetrate 10 to 20 m of shielding, in the high- and medium energy experiments, i.e. they interact more weakly than strong or electromagnetic. The mass determination at the Jülich reactor (~ 50 km from here), albeit coarse, is a direct measurement of $m_{\gamma\gamma}$, independent of theory, and gave $m_{\gamma\gamma} \approx m_e/2$.

Tzu-hsien Chang, Peking: I, as a chinese, am deeply grateful to your introduction of chinese philosophy in your talk. I want to use this occasion to make an appeal to the audience to name the Goldstone boson into 'Nambu-Goldstone'-boson as Gell-Mann did. On the problem of $e^+e^- \to H^+ + H^-$ I would like to ask, whether people have searched for leptonic decay modes of the Higgs.

J. Branson, MIT: In Bürgers talk and in my talk we presented evidence from JADE which rules out a technipion or $H^\pm$ which decays into $\nu$ and is in the mass range between 5 and 14 GeV. This is true for the most relevant branching ratios.