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PROBLEMS OF CONTEMPORARY ELEMENTARY PARTICLE PHYSICS AND PROSPECTIVE ACCELERATORS

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1. Introduction

The present talk is devoted to some problems of elementary particle physics which seem to me to be most important ones.

It may be hoped that this review will help to throw light on the requirements which are to be imposed on prospective accelerators. My task is much facilitated by the fact that some time ago a group of theoreticians, on the main from our Institute, has contributed to this matter*. It is clear that this problem is difficult, and the present note might serve only as a basis for further discussions.

The discussion of the problem from the point of view of purely theoretical positions is nevertheless very important since the development of accelerators has its own logic partially predetermined by the already reached results: it is natural that every accelerator can be improved and developed. In these respects, the accelerator resembles a plant which gives naturally rise to new branches. But not always this process may be up to the interests of theory.

On the other hand, theoreticians too, can easily raise problems that can be realized on neither realistic accelerator.

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*This group consisted of D.I.Blokhintsev, S.S.Gershtein, G.V.Efimov, A.V.Efremov, V.G.Kadyshevsky, A.A.Komar, V.A.Matveev, V.A.Meshcheriakov, R.M.Muradyan, V.I.Ogievetsky and A.T.Filippov. See /1/.

In the past years we have greatly advanced in the development of accelerators both in our country and abroad. Let me remind the main facts demonstrating this development:

Proton accelerator in Serpukhov	76 GeV
Colliding proton beams in CERN	2 x 28 GeV
Proton accelerator in Batavia	400 GeV
Meson factory (Los Alamos)	800 MeV (high intensity).

It is clear that further there will be a tendency to overcome the limits achieved.

In Batavia, further advance to an energy 10^3 GeV is suggested. In Brookhaven a colliding 2 x 200 GeV beam system is being designed. In CERN a 300 GeV accelerator is planned. An interesting project is proposed in Stanford - a colliding 70 GeV proton beam with a 14 GeV electron beam. The project of an accelerator of an energy of some thousands of GeV is discussed in Serpukhov. The construction of a meson factory for neutrino studies is planned in Krasnai Pakhra.

These are the main trends; however, in the present talk I am not going to discuss to what extent these projects are real.

2. Some General Remarks

In what follows, I will dwell upon some physical problems. In this connection it is appropriate to recall the remark of E.Wigner about storeys of science. The uppermost storey is the storey of principles (fundamental symmetries of the world, principle of relativity, etc.) that underlie all our science. Then follows the storey of laws (for example, the laws of the Maxwell theory, hydrodynamic laws, etc.). The lowermost storey consists of phenomena and models of these phenomena (for example, optical nucleon model).

The deepest problems belong to the upper storey. At the same time, the principles are most steady and conservative. They form the basis of all our conceptions and, thus, change slowly.

It seems very important to look what ''passes'' (in the language of mountaineers) can occur from the height of which it would be possible to see new countries - the world of new phenomena and new principles. History gives us a lot of examples. In the first quarter of this century atomic physics and spectroscopy were a big field which was elaborated by physicists, till and now it has not been exhausted yet (for example, the optic spectrum of U_{92}).

But it happened that Rutherford paid attention to alpha particles and, on the basis of their study, discovered a new science, science about atomic nucleus. Investigating the alpha particle scattering he has advanced from energies of the order of dozens of eV to energies of the order of millions of eV.

It often comes in my mind whether the number of experiments which are being realized at present is too large. It seems to me that a more radical development of accelerators and the theory would eliminate many of them.

Taking over the job of discussing perspective problems I realize that the predictions of such a kind may turn out to be illusory. This is a linear making program, and the period of five years may turn out to bee too long. We may encounter unforeseen happenings on this way.

We are accustomed to the definite conception characteristic of physics however, there are other sciences, such as astophysics, biology, which are forced to take into consideration the evolution of the object under investigation. Physicists are not accustomed to such a view on things. But it is quite possible that the vacuum from which we extract particles is a result of the evolution of Universe at the early stage of its development.I give this as an example of possible surprises concerning our basic conceptions.

Without going so far, we have made an analysis of the future on the basis of the presently available data along two lines: physics of small distances between particles or, respectively, large momentum transfers and search for new particles.

3. Physics of Small Distances

Within this range of phenomena we may raise the problem of the existence of a certain "elementary length" a (using the commonly accepted terminology [2]). For the present it would be unjustified to impart to it a quite definite physical meaning.

From the point of view of the speculations we are aware of from the theory this length may have quite a different physical meaning. For example, in nonlinear field theory there is a certain scale of the field ϕ_0. Once the existence of an elementary charge e is assumed, there arises also a scale of the length $a = \sqrt{\phi_0 / e}$.

The elementary length may have the geometrical meaning. In Snydee's theory of quantized space the quantity h/a defines the curvature of the momentum space [3,4]. Finally, it is quite possible that generally the coordinates of particles cannot be determined precisely. Then there arises the notion of a stochastic space, and the length defines the scale of uncertainty in the particle coordinates $\Delta x \simeq a$. It appears to be possible to say generally that the elementary length a is a measure of the space-time domain in which causality commonly accepted in contemporary physics is violated [5,6].

This is still the field of theoretical investigations. Of more importance is the fact that there are two candidates on the title of elementary length, which can be constructed from universal constant in a purely phenomenological way without recourse to any theoretical conception. One of these lengths is that associated with gravitation

$$a = \Lambda_g = \sqrt{\frac{8\pi k h}{c^3}} = 0.82 \cdot 10^{-32} \text{ cm} , \qquad (1)$$

(k is the gravitational constant). The second one is associated with the Fermi weak interaction theory and is equal to

$$a = \Lambda_F = (G_F / m_p^2)^{1/2} = 0.66 \cdot 10^{-16} \text{ cm} , \qquad (2)$$

(G_F is the Fermi constant, m_p is the nucleon mass).

If these universal lengths have the physical meaning then it is natural to expect a sudden change in the course of physical phenomena in the region in which the particle energy W multiplied by the length a becomes larger than unity:

$$Wa > 1 . \qquad (3)$$

a) Gravitation

Now we turn to the first possibility - gravitation. A lot of serious arguments may be said in favour of the opinion that gravitation may play the predominant role in understanding the mass spectrum of elementary particles. At present many theoreticians are working on this problem /7,8/.

If gravitation turns out to be really important, the scales that should be studied will be so small that the accelerators necessary for this purpose go beyond the framework of any reasonable assumptions.

b) Weak Interaction

The second length $a = \Lambda_F$ may be a very probable candidate. The study of the appropriate scales needs accelerators which seem to be real already in the near future.

As early as in 1957 I proposed a criterion for the interaction force which is based on the comparison of the kinetic energy density ϵ with the interaction energy density w in the process of particle collision /9/.

According to this criterion, an interaction is strong if

$$|W| >> \epsilon . \qquad (4)$$

In the opposite case it is weak. The treatment of the interactions from this viewpoint leads to the conclusion that the interaction induced by meson fields (interaction constant $g^2/\hbar c$) at all interacting particle energies remains strong in the sense of criterion (4).

The electromagnetic interaction (constant $\alpha = e^2/\hbar c$) turns out to be always weak in the same sense. Finally, the weak interaction (Fermi interaction constant G_F) turns out to be weak at the particle energy in the c.m.s. $W << W_F = 300$ GeV, but for W comparable with W_F the weak interaction becomes strong. In particular, it begins to exceed the electromagnetic interaction.

If these theoretical conclusions are valud this fact will be of fundamental value for the problem of muon and electron masses. It seems stange that so far these particles show themselves to be quite identical at their mass difference by about a factor of 200.

c) Universal Interaction

For the time being we distinguish weak (constant $G \approx 10^{-5}$) electromagnetic (constant $\alpha = 1/137$) and strong (constant $g^2/\hbar c \approx 10–12$) interactions.

If with increasing energy these interactions are found to be comparable then the majority of present-day laws of conservation, such as conservation of isospin, hypercharge, etc., will be violated, the selection rules will change completely.

There might appear weak stars, i.e. leptons would be produced in particle collisions in a direct manner rather than at the expense of the decay of strongly interacting particles.

We would be faced with the fact of the existence of a superinteraction that is a unification of all the three interactions in one form. A revolutionary character of this situation needs no comments. The energy $W_F = 300$ GeV at which a weak interaction may become strong is called the energy of the unitary limit.

This limit can be reached on colliding beam accelerators, and appears to be reached only on them. The 300 GeV energy is the energy in c.m.s. The corresponding energy for an accelerator with a fixed target, is

$$E = \frac{1}{2} W^2 - 1 = 45000 \quad GeV \qquad (5)$$

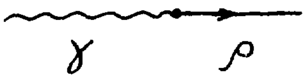
and cannot be discussed in a serious manner.

Hence it follows a forecast about perspective progress of accelerators with colliding beams of different types $(p+p,\ p+e^-,\ e^-+e^-,\ e^-+e^+)$ and an energy $W = 300$ GeV.

However, we should not forget that the study of high-energy secondary particles is also of considerable interest (beams, gamma-quantum, neutrino, mesons, hyperons, etc.). Therefore it is impossible to belittle completely the role of accelerators with fixed target ("laboratory" accerelators).

d) Electromagnetic Interactions

Besides the problem of the relationship between the muon and electron masses mentioned above there is the important problem of the study of vector mesons. The vector mesons, like ρ meson or, perhaps, recently discovered ρ' meson are interesting in that they connect the electromagnetic interactions with the strong ones according to the diagram



(6)

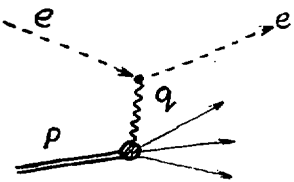
Thus, the electromagnetic interactions turn out to be surrounded by the weak interactions from the one side and by the strong interactions from the other side [10].

The idea about the possibility of constructing a "pure" electrodynamics isolated from other interactions is not realizable. The study of the relationship between the electromagnetic and weak interactions is one of the most interesting problems of contemporary theory and experiment. Of great interest is the study of the recently discovered "scale invariance" which will be discussed in more details in the next section.

e) Strong Interactions

The study of the high-energy behaviour of the cross sections πp, pp, Kp and $p\bar{p}$ is of fundamental value. As regards the asymptotic cross sections for strong interactions there are theoretical predictions based on the most important principles of the theory. In particular, it is important to know whether there is a universal common limit for such cross sections. What is the spectrum of produced secondary particles? On the basis of this information it is possible to draw conclusions about the structure of hadrons which are, to all appearance, rather complicated systems.

The study of the scattering at extremely small angles makes it possible to judge of the validity of causality (by checking dispersion relations). In reactions of the type $e + p \to e' + p'$ + any secondaries occuring according to the diagram



(7)

at large virtual proton momenta there is observed a scale invariance, i.e. the dependence of the reaction cross section σ on the ratio s/q^2 alone, where q is the momentum transfer, and s is the squared total energy:

$$\sigma = \frac{1}{s} f(s/q^2). \qquad (8)$$

As has recently been shown, the dependence (8) does not contradict the principles of local theory, but the mentioned process is associated with the behaviour of the amplitudes near the light cone /11,12/. Therefore the study of these processes is of fundamental value for the theory.

There are many other, more particular problems, concerning strong interaction which are not discussed here.

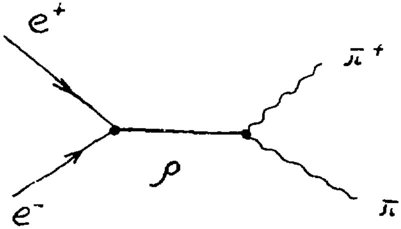
4. Search for New Particles

Starting with the most fundamental problems, first of all, we should point to the importance of the study of the vector meson spectrum. What is their spectrum?

What is their role in the relationship of the electromagnetic and strong interactions. Already now we know the processes of the type

$$e^- + e^+ \to \rho \,(\text{or } \rho') \to \pi^+\pi^- \,(\text{or } \pi^+\pi^-\pi^+\pi^-),$$

etc. In the language of the Feynman diagrams this reads



(9)

Next the problem of intermediate boson ("W boson") should be formulated. The problem of existence of this boson is of much value for understanding the dynamics of weak interaction. If such a boson exists, it is quite possible that the weak interaction will not develop up to its unitary limit. In this connection the question about its mass is important. According to the present-day information, a boson of mass $m_W < 5$ GeV has not been observed. If its mass is hundreds of GeV, then it will not significantly effect the weak interaction.

Among more general questions concerning the elementary particle spectrum we may point to the existence of the upper limit of the elementary particle mass (Does "maximon" exist, or does not?). In particular, if the lifetime of a particle becomes short which can occur with increasing weak interaction so as the decay width Γ becomes comparable with the particle mass M then the particle will cease to exist as a physically real object. The problem of the existence of the elementary particle mass M is of value in principle. If such a limit exists then the local field theory should have a limit of applicability arising due to restrictions on the accuracy of the determination of the coordinates imposed by $\Delta x \approx \hbar / Mc$ /13,14/.

Now I would like to dwell upon the last question, namely exotic particles. We may attribute to them "quarks" or "partons". These particles were the object of many laboratory searches. For the time being it may be asserted that free quarks with a mass $< 5-7$ GeV have not been found [15]. I always consider it that the search for quarks in vacuum is the same as the search for phonons (sound quanta) in vacuum. This assertion is rather based on my intuition and has not been proved. Therefore, those wishing can just as well continue to search for free quarks.

Also, on the basis of theoretical arguments Dirac predicted a magnetic dipole (which has not yet been observed, too, the cross section is smaller than $< 10^{-40}$ 10^{-42} cm^2) and it is quite possible that it does not exist in nature [16]. Yu.Schwinger suggested a possible existence of "dions", particles with fractional magnetic charge by means of which he tried to explain strong interactions.

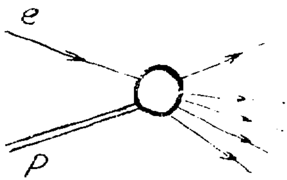
Both the possibilities, Dirac monopole and Schwinger dions, appear to be doubtful. They should rather be considered as an illustration of the possibilities of the theory.

For experimenters this is a hint for possible unexpected things and news in the elementary particle world.

5. Resume

To summarize it may be said that the possible "pass" from the height of which we can see quite new perspective is the unitary limit of weak interaction, i.e. $W_F \approx 300$ GeV. To reach this limit colliding beam accelerators of an energy $W_1 + W_2 \simeq W_F$ are needed. These colliding beams may be of different nature:
hadron, e.g., $p + p$ or $p + p$, lepton, e.g., or $e + e$ or mixed beams $p + e$.

The analysis of purely hadron collisions will, apparently, be very complicated. It should be more simpler to study phenomena in electron and positron beams. However, if in such beams it will be difficult to reach the unitary limit energy then it will be most interesting to study deep-inelastic processes of the type of that given in diagram (7) or processes involving neutrino



(10)

In this connection, mixed colliding beams (p - e) should attract special attention of experimentalists.

It is also appropriate to stress that there is no reason to distinguish between high energy physics and low-energy physics. It is more reasonable to distinguish elementary particle physics, nuclear physics, physics of the atom, etc. Therefore one should recall that the region of moderate or even low energies can yield important information on elementary particles.

In this connection, high-intensity accelerators (meson factories) and even reactors may turn out to be very useful installations.

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