Planning of new accelerators and the problems of contemporary elementary-particle physics[1)]

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In the first part of the article (chapter 2) a brief review is given of the characteristics of existing and projected accelerators. The second part (chapter 3) is devoted to enumeration of the main problems of elementary-particle physics whose solution depends substantially on the maximum energy achievable in the center-of-mass system: a) the search for an elementary length, i.e., a hypothetical dimensional quantity which provides an energy scale at ultrahigh energies. b) The search for quarks, Schwinger dyons, and other unusual particles. c) The study of self-similar behavior in lepton-hadron and hadron-hadron collisions, particularly the search for deviations from self-similarity which would indicate the appearance of a new energy scale in high-energy physics. d) Further precision experiments in lepton physics in which deviations from the predictions of quantum electrodynamics at ultrasmall distances could be observed. e) The study of weak and weak-electromagnetic processes at high energies. In conclusion a discussion is given of the desirability of constructing a complex of colliding beams of protons, antiprotons, electrons, and positrons with a center-of-mass energy greater than 300 BeV.

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1. INTRODUCTION

The development of accelerators has its own logic, which is a consequence of a previous history and which does not always correspond to the requirements of physics. The history of development of accelerators shows that their energy increases by roughly an order of magnitude every seven years.

With the beginning of the epoch of storage rings and colliding beams, this rate of rise of energy can increase substantially. The typical energy of cyclic proton accelerators may approach 1000 BeV in the coming decade.

However, it is clear that the planning and contribution of new accelerators should be very closely connected with the problems raised by the contemporary development of elementary-particle physics and with the level of knowledge which has been achieved. It is also necessary to take into account the already existing machines both in our country and in the West, the plans for their modernization, and the possibilities opened up by use of new principles of charged-particle acceleration. Therefore, before discussing the physical problems, we will dwell briefly on a review of existing and planned accelerators and their modernization. As far as the physical problems are concerned, the authors realize that their expectations and advice may turn out to be in many respects illusory, since they refer to a significant degree to terra incognita. Nevertheless, we hope that this review of the physical problems will turn out to be useful in selection of the types of future accelerators.

2. EXISTING AND PLANNED ACCELERATORS

The 76-BeV proton accelerator at Serpukhov continues to be the largest accelerator in the USSR[1,2]. In its intensity and stability it has turned out to be one of the best accelerators in the world in its class of machines. In three years of operation it has succeeded in giving physicists a great deal of useful information, part of which (for example, the very sharp arrival of the πN-scattering cross section at a constant value) has turned out to be so unexpected that no satisfactory explanation has been obtained up to the present time. Experiments in this accelerator will undoubtedly remain at the center of attention for a long time, in spite of the fact that it has already yielded the palm of preeminence in energy to the 300-BeV accelerator at Batavia[3]. We discuss later the modernization of this accelerator with conversion to superconducting magnets, which will permit its energy to be increased to the order of 1000 BeV.

The successful achievement of storage of proton beams will permit still further advance toward the high-energy region—to several thousand and even tens of thousands of BeV. The already existing colliding beams at CERN[4] with 2 × 28 BeV are equivalent to an energy of 1700 BeV in the laboratory system, and the beams planned at Batavia with 2 × 100 BeV are equivalent to 20 000 BeV. A proton accelerator with 2 × 200 BeV (80 000 BeV lab) is being planned at Brookhaven[5]. However, because of the very substantial loss of intensity the group of problems which can be solved in such accelerators is significantly restricted. This means, naturally, that it is already impossible to produce very intense secondary beams, and only the various aspects of proton-proton collisions can be studied.

The colliding proton-antiproton beams with 2 × 23 BeV whose construction is planned at Novosibirsk[6] belong to this same group but are applicable to a somewhat broader group of problems.

Another important direction of accelerator development is the increase in beam intensity. In the near future it is proposed to obtain π-meson beams comparable in intensity with those produced by meson factories. These intensities will permit observations and measurements to be carried out with much higher accuracy and will permit the details of phenomena to be more deeply penetrated.

The rise in energy which we have noted is more modest in the acceleration of electrons. The largest electron accelerator (if we do not include the secondary γ beam at Serpukhov with energy $E_{\gamma} = 35$ BeV) remains the SLAC two-mile linac at Stanford (20 BeV), which will retain for a long time its leading position. In addition, it will be improved by technical refinement of the machine (replacement of the klystrons), which in the near future will raise the electron energy to 35 BeV. In Novosibirsk a beam is operating with energy 2×700 MeV, and colliding electron-positron beams of 3.5 BeV will apparently soon be obtained[7]. Similar accelerators but with much lower energy are operating at present at Orsay, France: 2×0.5 BeV, and at Frascati, Italy: 2×1.2 BeV[7].

The Kiev and Amsterdam conferences on high-energy physics have emphasized the great value of experiments in colliding electron beams.

In addition to the operating accelerators mentioned, the Stanford storage rings with energy 2×2.5 BeV and high luminosity (10^{31}—10^{32}) have now begun to operate. A complex of ee, $e\bar{e}$, and $\overline{ee}$ colliding beams is also being built in West Germany: 2×3 BeV, with very high luminosity (10^{32}). In Stanford the idea is being discussed of collision of beams from the linear accelerator (without storage) with energy 2×20 BeV. In addition there is a plan to build a complex of ee, $e\bar{e}$, and ep beams with energy 15 BeV for electrons and positrons and 72 BeV for protons (the PEP project in California).

This in its general features is the situation with accelerators at the present time.

3. THE MOST IMPORTANT PROBLEMS OF ELEMENTARY-PARTICLE PHYSICS

In this section we discuss the most general and at the same time fundamental problems of elementary-particle physics.

It is natural that we proceed from contemporary ideas, and therefore our opinions should be taken with a grain of salt. It is clear that we can in no way exclude the possibility that nature will present us with some kind of surprise which goes beyond the fantasy of theoreticians. Furthermore, for ourselves we would like to consider this very likely. With these reservations, we note two directions of research which we can expect to be followed by fundamental discoveries—the study of phenomena occurring at small distances, and the search for new unusual particles.

a) The elementary length. By this term we mean some fundamental length a which can characterize the scale of nonlocality or any other scale which may have a geometrical value (for example, the curvature of momentum space, the discreteness of space-time instead of a continuum, and so forth)[9]. A quite natural candidate for the role of elementary length is the length associated with the weak interaction: $a_W = 6 \times 10^{-17}$ cm, which corresponds to a center-of-mass energy $W = 300$ BeV. The possibility of observing the elementary length in extremely accurate measurements at low energies, for example, by means of the Mössbauer effect, is an extremely interesting question. However, analysis shows that very general variants of nonlocality are compatible with the small spectral line width $\Delta\omega/\omega \approx 10^{-16}$ observed by means of this effect. For observation of nonlocal effects, the ratio of the frequency ω to the frequency $\omega_a = c/a$ which determines the nonlocality turns out to be important. It follows from experiments at high energies that $a < 10^{-15}$ cm, and $\omega_a > 10^{25}$. Therefore the Mössbauer effect turns out to be uncritical.

We can expect that the existence of an elementary length will lead to a radical change in the behavior of phenomena in comparison with the established behavior. First of all, the formulation of the problem of the asymptotic behavior of cross sections would change substantially in this case. In fact, according to existing data, the length a satisfies the condition $am \ll 1$, where m is the mass of any of the known particles or resonances. In the case of existence of a length a, the region $W \gg m$ could be divided into subregions $Wa \gg 1$ and $Wa \ll 1$. It is natural to expect that the behavior of the cross sections in them will be quite different. It is difficult to say at what energies such a break in the cross sections may appear. However, we should apparently not expect this up to energies of the order of hundreds of BeV in the c.m.s.

If the weak interaction is not suppressed by the existence of an intermediate boson, the length $a_W = 6 \times 10^{-17}$ cm can have a fundamental value. In this case for $W > 300$ BeV we can expect the prevalence of weak interactions over electromagnetic and even strong interactions. This circumstance may play a decisive role in construction of the theory of elementary particles.

At the present time three types of interactions are clearly distinguishable (strong, weak, and electromagnetic) which are in no way related to each other. If it turns out that with increasing energy all three of these interactions are comparable in strength, we will turn out to be in the face of some universal strong interaction in which most of the ordinary conservation laws (isospin, hypercharge, space and charge parity) are violated. The ordinary selection rules for strong, electromagnetic, and weak processes will turn out to be only low-energy approximations, and a real possibility will arise of studying the characteristic features of such a hyperinteraction. The revolutionary nature of the change in the physical picture associated with this development of events hardly needs explanation.

One of the possible manifestations of this interaction could be weak stars—the direct (and not as the result of hadron decay) production of leptons, including neutrinos. In this connection colliding proton beams with energy of the order of hundreds of BeV and also $p\bar{p}$ and ep beams may present no less interest than $e\bar{e}$ and $\mu\bar{\mu}$ beams. The possibility of reaching this critical limit for weak interactions in accelerators with fixed targets lies beyond the limits of our imagination ($E \gtrsim 5 \times 10^{4}$ BeV).

b) Unusual particles. Also belonging to the same class of "lottery" problems as the search for the elementary length, with high stakes but also high winnings, is the search for unusual particles: quarks and Schwinger dyons[10], intermediate bosons, the Dirac monopole, and heavy leptons.

Quarks are particles with fractional electric and hypercharge and, according to current ideas of hadron symmetry, are the building blocks of which hadrons are constructed. However, all attempts to observe these particles both in cosmic rays and accelerators and in electrostatic experiments searching for fractional charges have ended in complete failure. It is very likely that quarks themselves are not elementary particles, but are excitations which are convenient in description of the states of hadrons.

Dyons are essentially the same as quarks but possessing in addition a fractional magnetic charge. They form the basis of Schwinger's magnetic theory of matter, the essential part of which is a superstrong long-range magnetic interaction characterized by a dimensionless constant $g = 36 \times 137 \approx 5000$. According to Schwinger, this interaction binds dyons into a hadron. Theoretical considerations favoring the existence of particles with magnetic charge were advanced by Dirac already in the 1930's (the so-called Dirac monopoles), the electric and magnetic charge in them being automatically connected by the relation $eg = n$, where n is an integer.

There is as yet no convincing reasoning as to the mass of these hypothetical particles except, perhaps, the mass of the intermediate boson, which according to the approximate estimates of T. D. Lee amounts to 37.3 BeV and, consequently, requires colliding beams with $W > 40$ BeV.

These, in our opinion, are the two main directions in which we can expect revolutionary discoveries.

Let us further discuss more specific problems in the physics of strong, weak, and electromagnetic interactions. These problems are closely related to the current state of elementary-particle physics, and without their solution it is difficult to conceive of its further development.

c) Strong interactions. Here the main problems must be considered the discovery of the hadron interaction mechanism and the mass spectrum of hadrons[8,11]. We have evidently become acquainted so far only with the lower portion of this spectrum, and it would be important to understand how far it extends into the high-mass region. Current experimental data and theoretical ideas (duality) permit us to expect that as we move forward we will observe more and more relatively stable states with large masses and spins. A detailed knowledge of a rather wide portion of the spectrum is necessary for construction of a complete picture of strong interactions.

The presently existing experimental data and theoretical studies on hadron scattering indicate that the classification of reactions on the basis of transferred quantum numbers correctly reflects the main features of hadron interaction and the difference in the behavior of the cross sections: $\sigma \sim E^{2\alpha-2}$. On the basis of this criterion the following classes are distinguished:

1) Transfer of vacuum quantum numbers, $\alpha_P \approx 1$. This is characteristic of elastic and quasielastic processes whose cross sections are approximately constant.

2) Transfer of quantum numbers of vector mesons (ρ, ω, A_2, K^*), $\alpha_V \approx 0.6$–0.3 which is characteristic of charge exchange, photoproduction, and so forth. These cross sections fall off.

3) Transfer of baryon quantum numbers $\alpha_B \approx 0 - -1$ (meson-baryon backward scattering, and so forth).

4) Transfer of quantum numbers of pseudoscalar mesons (π, k, η), $\alpha_m \approx 0 - -0.3$ (photoproduction by a γ ray polarized parallel to the reaction plane, and so forth).

5) Transfer of so-called exotic quantum numbers $\alpha_{ex} < -1$ (double charge or baryon number, double isospin, etc.).

The study of the details of these transfers, however, is hindered by the fact that we are ordinarily dealing with a mixture (for example, in elastic scattering in the diffraction region not only vacuum numbers are transferred but also meson and even exotic numbers). It is clear from this how complex and ambiguous is the problem of choosing parameters and of the details of the transfer mechanism. In addition, it is complicated by the difficulty of polarization measurements, which could provide information not only on the absolute values of the amplitudes but also on their phase shifts.

This structure of the strong interactions compels us to think that an unmasking of the details of transfer must be approached from the high-energy end where only vacuum number transfer "survives". But where does this "end" begin?

At sufficiently high energies, as a result of the Lorentz contraction, a hadron appears as an infinitely thin disk with finite effective transverse size. On the basis of an analogy with the dynamics of a planar explosion, we can suppose that at extremely high energies an interaction must be characterized by definite scale relations[12]. This leads to interesting experimental predictions, in particular, to constancy of the cross section, which is characteristic for transfer of vacuum numbers, and to a constant slope of the diffraction cone.

The first preliminary results from the CERN colliding pp beams with $E_{lab} \approx 1000$ BeV show that the cross section at these energies has apparently already reached its asymptotic value ≈ 38 mb (or is slowly approaching it logarithmically). The slope of the diffraction cone either remains constant or has a tendency to reach a constant value. Together with the rather smooth behavior of cross sections in the 30–70 BeV region, this provides a basis for thinking that the region of the order of a thousand BeV is already asymptotic. In the coming years the Batavia accelerator will permit these energies to be approached, and will provide the possibility of checking this expectation and clarifying the mechanism for transfer of vacuum quantum numbers.

However, final solution of this problem will require, in all probability, experiments at energies of several thousand BeV in the laboratory system. Here it would be most interesting to verify the still existing difference in cross sections (more accurately, the unusually weak falloff) for π^+p and π^-p scattering observed at Serpukhov. If this phenomenon is retained also at the Batavia energies and it is not possible to explain it by an unusual electromagnetic correction, it may lead to a review of our ideas about strong interactions.

The most suitable phenomena for bringing to light the laws of transfer of meson quantum numbers are inelastic πN and NN charge-exchange reactions, photoproduction, and production of resonances in the 20–1000 BeV region. The cross sections associated with these transfers are still rather large here, and transfers of the remaining numbers are already appreciably suppressed. However, discovery of the details of the transfer mechanism will require rather careful and many-sided measurements not only of cross sections and angular distributions but also of polarizations. As a good lesson we can use the example of πN charge exchange, in which the angular distributions have been described by many models, but the recently measured polarization has been a stumbling block for many of them. Another example is the angular distribution in photoproduction of π and K mesons in the region of very low momentum transfer and πN backward scattering, which will help to solve the problem of the elementarity of mesons and nucleons.

Such comprehensive measurements require intense secondary beams, an abundance of electronic and automation equipment, and extensive use of computers. We have no other means of pursuing the difference among the many theoretical models of the transfer mechanism.

An alternative to the existence of an elementary length may turn out to be so-called self-similarity or scale invariance, which means the absence of any parameters with the dimensionality of length (or mass) in description of interaction at small distances. An experimental indication of the possibility of this phenomenon is the behavior of the cross section for deep inelastic ep scattering[13]. This hypothesis is also favored by arguments associated with the problem of field quantization in curved space-time. More clear-cut information could be obtained, apparently, from the E dependence of the differential cross sections for scattering at high energies and momentum transfers ($s \sim t \gg M^2$).

d) Electromagnetic interactions. At the present time we can consider as central problems, first, the search for deviations from quantum electrodynamics and the problem of the difference between the μ meson and the electron and, second, solution of the question of how universal is the behavior observed in inelastic scattering of electrons by protons and which has received the name self-similarity or scale invariance[12,14].

In regard to the first problem, a most effective experiment would be the precision measurement of the hyperfine splitting of the levels in muonium—a system where there are no strong interactions. Such measurements in hydrogen are being carried out at present with an accuracy to 12 places, of which only 6 can be accounted for by electromagnetism. In the remaining experiments the strong interaction, which is known less accurately, turns out to be important.

Here we are also bordering on one of the most important problems of contemporary physics—the mass difference of electrons and μ mesons, which perhaps is also not due to the electromagnetic interaction. If this is so, a similar interaction should contribute to the hyperfine splitting and anomalous magnetic moment of the μ meson, which are known at present with an accuracy to 7 places. The absence of deviations from quantum electrodynamics compels us to shift the search for a difference to the high-energy region, comparing the behavior of the μ meson and electron in electromagnetic processes at increasing energies. Here it would be of very great value to have colliding electron and μ-meson beams of the highest possible energy and reasonable intensity.

The phenomenon of scale invariance was first observed in inelastic electron-proton scattering at high energy and momentum transfer q^2 and consists of the fact that the dimensionless amplitudes of this process turned out to be functions only of one parameter, W^2/q^2. This led to the hypothesis of the self-similar behavior of processes at high energies. It follows from this, in particular, that the total cross section for annihilation of electrons and positrons behaves as $1/W^2$. This hypothesis urgently requires experimental verification, and such verification will be partially provided at Serpukhov and Batavia in planned experiments on the deep inelastic scattering of electrons and μ mesons. However, the best thing, in our opinion, would be verification of self-similarity in deep inelastic ee or $e\bar{e}$ scattering in the region of large W and large momentum transfer. Observation of these processes will become possible when the energy of the colliding beams is increased to several tens of BeV and will provide the possibility of clarifying the mechanism whereby self-similarity arises.

e) Weak interactions. The central problem remains the dynamical nature of weak interactions. Are they four-fermion or are they accomplished through an intermediate boson? Experiments on the search for the intermediate boson which we have mentioned above, on the one hand, and the study of the behavior of weak processes at energies of the order of 300 BeV in the center-of-mass, on the other hand, are turning out to be extremely important in this connection. The specific behavior of the cross sections for weak processes at these energies may be the key to understanding the dynamical nature of these interactions[15]. In particular, we should expect the appearance at high energies of characteristic features of the behavior of cross sections (for example, for interaction of neutrinos with nucleons) due to self-similarity.

No less fundamental are the problems of verifying the laws of conservation of electronic and muonic lepton numbers, and also the violation of C, P, and T parity, and in particular the mechanism of CP-parity violation, which has been observed so far only in the decay of K^0 mesons. Here a rather large number of possible mechanisms have been collected at present, and only precision measurements and observation of rare decays can assist in making the choice among them.

To solve these problems it is necessary to have intense beams of secondary particles, first of all K mesons and hyperons, which can be obtained in presently operating accelerators (in particular, at Serpukhov) if the intensity of the main beam is raised.

For the most part we have been speaking above only of the phenomena which from our point of view are most fundamental, leaving aside a number of interesting questions involving, for example, study of the so-called "nuclear structure" of light, which begins to appear at BeV energies, a number of interesting electrodynamic effects of higher order, precision measurements of weak decays, and so forth. They also may turn out to be unexpectedly interesting and may compel us to reconsider and improve the picture of the interaction.

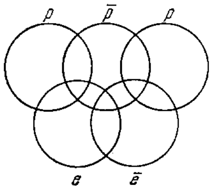
A good example is the recently raised problem of $K_L \to 2\mu$ decay[16], whose probability turns out to be much smaller than follows from the ordinary ideas of weak interactions and the probability of the $K_L \to 2\gamma$ decay. It indicates surprises awaiting us in weak-electromagnetic processes. Thus, one of the possible explanations of the $K_L \to 2\mu$ puzzle is the strong violation of CP invariance in $K_{LS} \rightarrow 2\mu$, 2γ processes and an anomalously high probability of $K_S \rightarrow 2\mu$, 2γ (three to four orders of magnitude greater than the similar decay of K_L).

4. FUTURE ACCELERATORS

On the basis of the review presented above of accelerators and the main problems of elementary-particle physics, it is clear that it hardly makes sense at the present time to plan the construction of proton accelerators with energy below a thousand BeV. Most promising from the point of view of maximum coverage of interesting problems, expected results, and competitive capability would be the following directions of development:

a) Modernization of already existing machines with a sharp increase in the intensity of the primary beams, and consequently also of the secondary beams, or with acceleration of polarized particles and simultaneous complete provision of experiments with means of detection and analysis of information, with maximum possible saturation of the experiments with the newest electronic techniques and complete automation. Measures of this type will play a decisive role in the further development of experimental investigations, since the requirements of modernity make most important not so much individual achievements as a general high scientific and technical level.

b) Construction of proton accelerators (with superconducting magnets) with proton energies $E > 1000$ BeV ($W > 40$ BeV), with subsequent arrangement of colliding beams with c.m.s. energy $W \gg 300$ BeV. In this same direction of further planning it is desirable to consider the possibility of $p\bar{p}$ colliding beams, and also ep and $e\bar{p}$ beams. Such a complex could be pictured symbolically in the form of an Olympic complex of five rings (which of course can also be superimposed:



It would permit a great advance in the study of fundamental properties of particles and could be done much more cheaply than construction of individual pairs of rings. In an ideal system of this complex it would be desirable to have also a muon storage ring; however, this problem still appears far from solution technically. In any event, the authors consider it extremely important in the study of hadron collisions to go beyond the limit W = 300 BeV.

c) To produce secondary beams of hadrons and leptons of extremely high energy, it appears necessary to pursue research on collective methods of acceleration to superhigh many-thousand-BeV energies, and first of all the Veksler-Sarantsev method[17] as the most highly developed and promising.

d) As we have already noted above, the creation of $e\bar{e}$, $\mu\bar{\mu}$, and $p\bar{p}$ colliding beams with energy W as close as possible to 300 BeV unconditionally remains the fundamental problem of the coming decade. The conditions for study of electromagnetic and weak interactions in collisions of the $e\bar{e}$ or $\mu\bar{\mu}$ type are particularly simple[2)].

e) The large expenditures on contemporary high-energy physics, in our view, should not in any case be oriented only toward possible fundamental discoveries capable of revolutionizing all of science.

The essence of the matter is that for contemporary elementary-particle physics, as for any fundamental science, although it does not lead directly to the realm of production, the achievement of its goal nevertheless involves the solution of many extremely complex technical problems. Therefore a contemporary center of nuclear investigations is, in essence, not only a leading scientific center but also an advanced technical center capable of solving complex technical problems. Utilization of the achievements of such scientific centers in the national economy can have revolutionary consequences.

An example of such utilization of spinoffs of nuclear physics is the mastery of methods of working with liquid hydrogen and liquid helium, and the introduction to industry of superconducting magnets, whose development is presently carried on in almost all the nuclear centers of the world. Cybernetic systems of analysis and collection of information, without which contemporary experiments would be unthinkable, can find broad application in control of the national economy and its planning, and investigations with μ-mesic atoms open up vastly promising possibilities in the study of chemical-reaction kinetics, which also can have great practical value. We should also not forget the progress which accompanies the application of the methods of theoretical nuclear physics in other fields. The recent achievements in solid-state physics is a beautiful example of this. In our opinion it is necessary to utilize more widely this aspect of the work of the nuclear centers.

The same can be said about medical-biological studies and their applications. We are speaking of the treatment of cancer by beams of mesons and multiply charged ions, the early diagnosis of the degeneration of tissue, and so forth. Work in the nuclear centers of the West in this exceptionally important direction has become very active recently. In many centers special groups have been created who are occupied with medical-biological problems. The possibilities of our centers are still inadequately utilized.

In this connection it is extremely important to construct meson factories as a source of beams of extremely high intensity and to produce beams of relativistic multiply charged ions[18].

The authors hope that they have reflected sufficiently completely the work of the entire group, and they express their gratitude to its members for their observations.

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[2)] Incidentally, as noted above, all interactions may become comparable at very high energies.

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