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The Promise of High Energy Physics, Why More Accelerators?

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Almost always the construction of new accelerators at a higher energy level was followed within a period of a few years by a burst of new discoveries and insights. The construction of the Cosmotron led to a vast expansion of pion physics; the Bevatron was followed not only by the discovery of anti-nucleons -- that was the avowed aim -- but by the opening up of baryonic spectroscopy; the CERN-PS and the Brookhaven-AGS brought about the discovery of SU_3 symmetry and other aspects of the systematics of baryons which led to the quark hypothesis; the electron accelerators in Cambridge and Hamburg sparked the development of photoproduction of hadrons; SLAC initiated the amazing results of deep-inelastic electron scattering; the ISR revealed the rising total cross sections and the detailed structure of the perpendicular momentum distribution; the Frascati-CEA-Spear-rings opened up a great new field of hadron creation.

Surely, not all new and interesting discoveries are made at the latest energy frontier. The discoveries of the parity violations and of the recent Ψ-J particle at BNL are outstanding exceptions. Nevertheless, it is the essence of High Energy Physics to create access to new territories of knowledge. This was and will be achieved only by developing new ways and means of attaining energies that were hitherto out of reach, apart from the weak and restricted rays that nature sparingly allows to impinge on our atmosphere. Strange and unexpected ways of material behavior have been discovered and nature turned out to be much richer at high energies than anyone expected. Instrument construction was and will remain for some time the most important precondition to further progress of our knowledge of the basic structure of matter. High Energy Physics today is an exploratory science; it is still far from its explanatory stage. It may appear surprising to an outside observer that, in spite of this, theorists dominate the field and the names of the instrument builders do not appear on the title pages of the publications of discoveries.*

What is the present situation in our field and why do we need an extension of the energy frontier? In my view, hardly ever before did it seem so evident that such an extension will yield most significant new insights and surprises. In order to support this statement, let me start with a short description of the empirical situation in particle physics today, as compared with the situation in the "pre-subnuclear" era before, say, 1945. At that time the elementary particles (fermions) were considered to be the proton (p) and the neutron (n), the electron (e) and the nuetrino (ν). As interactions between them figure: a) the nuclear force acting between protons and neutrons, supposedly transmitted by the pion (no other meson was known); b) the electromagnetic forces transmitted by the photon and c) the weak interaction which transacts the emission of the lepton pair ($e\bar{\nu}$) by the nucleons. (Gravitational interactions will be left out as seemingly unimportant in particle physics.)

In the "subnuclear" era, from the 1940's to today, the world of "elementary particles was greatly enlarged (see Table 1). The two nucleons turned out to be only the ground states of a vast and probably infinite spectrum of baryon-states; the pion turned out to be the ground state of a probably infinite set of meson-states. The observed spectra and transitions exhibited a number of striking regularities which led to the introduction of new quantum numbers such as strangeness or hypercharge. The two leptons, e and ν, were found to be part of a quartet of leptons including the muon and the second neutrino. The nuclear force between p and n was replaced by seemingly complicated manifestations of strong interactions between baryons and mesons of all sorts (these strongly interacting entities are referred to as hadrons). The weak interactions are now a much wider array of effects, dealing with the interactions of leptons with each other, with hadrons and also of hadrons among themselves. A certain universality in the effects of the weak interactions was perceived; they all can be described by a common coupling constant named after Fermi. Our description of the electromagnetic interactions was not changed much except that it was deepened and put in a better form. The quantization of Maxwell's and Lorentz's equations of electromagnetism turned out to be a reliable theory even at the highest attainable energies. It is comforting to the conservative physicist that at least some of the fundamental ideas of old remain valid, as it is comforting that certain conservation laws also seem to remain exactly valid, such as the conservation of energy-momentum, of charge, of baryon number (assuring the survival of the universe) and of the number of leptons.

This rich array of new facts and relations in the subnuclear world has led to many theoretical speculations as to the basic foundation of this new world of phenomena. No definite and logically consistent foundation yet is found but it looks as if certain outlines are vaguely perceptible through the dense fog of facts. These outlines may lead to a true understanding of what is going on, but future discoveries may also prove that they were nothing but a mirage without base in reality.

These vague outlines can be described as follows (Table II): The quartet of leptons are "real" elementary particles whereas the hadrons are not. The analysis of the complicated hadron spectra and hadron reactions points towards the existence of hadron constituents: the quarks. All quarks are fermions with half-integer angular momentum. Recently, one was led to distinguish twelve different types of quarks. They are characterized by what may, more or less aptly, be called "flavor" and "color". There are four flavors called u, d, s, c; u and d refer to "up" and "down" in regard to an isotopic spin ½, s refers to strangeness and c to "charm"; s and c are supposed to have zero isospin. The most common assignment of electric charges is $\frac{2}{3}e$ for u and c, $-\frac{1}{3}e$ for d and s. The quartet of quarks is assumed to exist in three different "colors". This is necessary in order to explain the fact that the hadron

*The situation has been compared to Columbus trip to the West in 1492. The accelerator physicists are the ship-builders and navigators who made possible the crossing of oceans; the experimental physicists are the people who stepped upon the new territories exploring the plains, mountains, streams, and the strange peoples and animals; the theorists are those who remained in Madrid and predicted that Columbus would land in India.

states appear symmetric and not antisymmetric in respect to quark exchange as fermions ought to be. Indeed, the presently known hadron states appear to be antisymmetric in color but symmetric in respect to other quark properties. Color also helps to understand why quarks cannot appear singly as free particles: There probably exists a fundamental rule that only "colorless" quark configurations exist at all (or exist with reasonably low energy). A configuration is colorless if it is an equal mixture of the three colors, for example, by having triplets of quarks as in baryons, or by having quark-antiquark pairs as in mesons. Single quarks must carry color and therefore cannot exist or must have a very high mass. The leptons are not subject to this restriction since they are considered as colorless.

The fourth flavor of quarks -- the charmed quarks -- was introduced only recently. The interpretation of the presently known hadron spectra does not yet require a fourth type, with the possible exception of the newly discovered ψ/J particle which may be a "charmonium", that is a combination of a charmed quark and its antiparticle. The reasons for introducing charm were based upon arguments of general symmetry -- four leptons, four quark flavors -- and also upon the circumstance that the existence of a fourth type of quark provides a relatively simple way of explaining the observed absence of weak interaction transitions in which the hadron strangeness changes but not the charge. This absence was puzzling in view of the discovery of such transitions without strangeness change.

What are the interactions between these 16 elementary fermions supposed to be? The present description is modelled after quantum electrodynamics, to the effect that interactions are transmitted by vector fields whose quanta are often referred to as intermediate bosons. These fields are coupled to the fermions via the effects of generalized charges. There is, of course, the electromagnetic interaction itself which is known to be coupled to the electric charge and transmitted by massless photons γ. Then there is the weak interaction coupled to something like a "weak charge" and transmitted by the still hypothetical intermediate bosons of which there should be three types W^+, W^-, Z, the first two transmitting the charge changing interactions and the third transmitting the interactions without charge transfer. These field-quanta should be very massive particles because of the observed short range of weak interaction.

There exist interesting ideas about a common root of both electromagnetic and weak interactions. According to these ideas the γ, W^+, W^-, Z fields are all members of a multiplet with the same coupling constants. If this is so, one can estimate the masses M of the weak intermediate bosons, since the observed universal Fermi constant G would be connected with the electric charge by a relation $G \sim e^2/M^2$, which indicates a boson mass somewhere between 50 and 100 MeV. For energy exchanges way above this value, the electric and weak phenomena would be of the same order and would merge into a common realm of phenomena.

We now come to the strong interactions which, in this theoretical framework, are the interactions to which quarks only are subjected. First of all, there must be an agent which keeps the quarks confined in colorless configurations, preventing the separation into color carrying parts. It may be the consequence of some fundamental principle or the combined effect of some quark interactions. The agent producing the confinement has been referred to as "bag". Furthermore, there must be a direct interaction between quarks, transmitted by a vector field whose quanta are "gluons". The gluons are coupled to color, which acts as the generalized charge for this field. Since the hadrons are colorless, this interaction does not produce a direct force between hadrons, just as there is no direct electromagnetic force between neutral atoms. However, we know that the internal electrodynamic structure of atoms indirectly produces an attraction between atoms: the chemical bond. The nuclear force between hadrons may be the corresponding analogue to the chemical force.

There are many indications that the "gluonic" interaction between quarks seems to be not very strong. The strongest action upon quarks is the confinement. The latter, however, is an effect involving relatively small momentum transfers. The characteristic momenta involved in the confinement are those which correspond to the size of the hadron according to the Heisenberg principle (several hundred MeV/c). There are experimental indications of what one may call the "softness" of strong interaction, which is a name for small interactions at large momentum transfer and strong interaction at small momentum transfer. One indication is the deep inelastic scattering of highly energetic electrons on nucleons studied in the well-known M.I.T.-SLAC experiments. Here the experimental results can be interpreted as evidence for the fact that the quarks inside the nucleon act as if they were free particles in respect to large momentum transfers (> 1 GeV). Another indication is the fact that, in high energy proton-proton collisions the transverse momenta of the emerging hadrons are very low, namely of the order of a tenth of a GeV. Seemingly the internal interactions within a hadron are not capable to transmit large momenta to the emerging reaction products. On the other hand, it is known that hadron interactions at low momentum transfer are strong; this is why they received the name of strong interactions; the nuclear force is an example. Indeed, if hadrons can never be separated into single quarks, the force between quarks must go to infinity with increasing distance.*

The theoretical picture that emerges here, of 12 quarks and 4 leptons and their various couplings to different fields must be considered as very tentative and incomplete, in particular in respect to the fundamental root of the confining agent. Furthermore, the existence of the fourth flavor "charm" is still based upon very tenuous experimental evidence. No charm carrying mesons have yet been discovered. Nevertheless, this theoretical picture presents a system of connections between observed facts that, at this moment, does not seem to be obviously in contradiction with experiments, although its validity is far from being established. Whatever its eventual success, it may serve a purpose: it indicates the directions of research where new and relevant information may be expected. Such predictions must be taken with some reservations. If the theoretical ideas are wrong, the most important insights may come from the most unexpected direction (see footnote on page 1).

The first conclusion to be drawn is this: the experimental attack upon the unresolved questions must be carried out on a broad front. We expect important results from lepton beams, hadron beams and colliding beam facilities of all kinds. The outstanding problems will not be solved by one device only. Furthermore, it seems most probable that some of the most important

*This situation, softness at large Δq, strength at small Δq, seems to be theoretically not excluded - even in a field theory. A generalized electrodynamics in which the field carried "charge" may in fact lead to such effects if recent theoretical attempts turn out to be on the right track. The theorists call this effect "asymptotic freedom".

questions can be answered only by experimentation with higher energies; where we expect some new phenomena to appear. The creation of intermediate bosons is one example, the hypothetical merger of weak and electromagnetic effect is another. The establishment of the existence of new quantum numbers like charm may require at least the energies attainable by the Fermi lab or the SPS. However, one must never forget that further exploitation of lower energy beams has led and may lead again to decisive discoveries as it did recently with the discovery of the long-lived ψ/J mesons. The spectroscopy of hadron states is still in its very beginnings; only the lowest multiplets are well known. It is the foundation on which the quark hypothesis rests, and it must be further pursued in depth at presently existing accelerators.

Let us now look in greater detail at the different energy frontiers and their promises.

A. The electron, muon, and photon frontier.

The instruments working at this frontier are: electron accelerators with fixed targets, secondary electron-,muon-or photon-beams produced by proton accelerators, electron-proton colliding beams, electron-electron (positron) colliding beams. Experimentation with charged leptons and photons of higher energy first and foremost will tell us whether there is a limit to the applicability of quantum electrodynamics. So far no such limit has been found nor any indication of a structure within the electron or muon. Furthermore, the electromagnetic interaction is a sharp and reliable tool for probing hadron structure. Its reliability comes from the fact that we understand the interaction better than any other.

Electron and muon scattering at higher energy with hadrons will tell whether scaling breaks down, and if so, how. This is a way of looking into the question of quark interaction: Does it indeed remain to be a soft interaction at even higher momentum transfer? Does the assumption of a point-like elementary quark remain valid? What are the hadronic products of deep inelastic lepton scattering? A further extension of the electron-proton frontier into the 100 GeV region in the center of mass will have to take the way of electron-proton colliding beams; only such devices can attain that energy region.

The photon-hadron interactions are harder to interpret but the process of photoproduction at higher energy may yield important information about the new particles and perhaps about newer particles not yet discovered. After all, we would like to know whether those 16 elementary fermions is the correct list; there may be more (or fewer) quark flavors, there may be more than four leptons.

Electron-positron colliding beams represent one of those frontiers that turned out to be much richer than anyone expected. The high concentration of electromagnetic energy which one gets in the annihilation process is a most useful tool, in particular when one observes how this energy turns into hadrons. If the quark model is correct, the total cross section for hadron production is easily predictable and it should, in the high energy limit, be inversely proportional to the square of the energy. The proportionality factor should depend only on the number and charge of the quarks. At first this proportionality was not born out by the experiments at CEA, Frascati and SLAC; and the quark-model was thought to have encountered a serious setback. Recently, however, the deviations could be traced to identifiable resonances - the creation of the famous ψ/J particle. However, present energy limitations make it impossible to get a clear cut decision in regard to this question. Here observations at higher energy will make or break some of these ideas, or it will direct our thinking in completely new directions. The study of the details of hadron production at higher energy will provide many new clues as to the structure of these particles.

B. The proton-proton colliding-beam frontier.

A relatively simple way of achieving high center-of-mass energies between protons is the construction of p-p colliding beam devices. Many of the present question marks will be removed or replaced by bigger ones when center-of-mass energies of several hundred GeV become available. If our ideas are correct, this is the region in which the intermediate bosons should be produced and it should be possible to verify the existence of the charged and uncharged types. It is the region where the weak interactions should undergo qualitative changes in energy dependence and other properties, and where perhaps electrodynamics may change by exhibiting its connections with weak interactions. Some of these problems would be cleaner and more direcly investigated by means of electron-proton colliding beams with center-of-mass energies of several hundred GeV, but it seems to be easier to get such energies with p-p devices since it is difficult to accelerate electrons to sufficiently high energies.

Proton-proton collisions of that energy will tell us much more about the behavior of strong interactions at high momentum transfer and possible consequences of the softness. New entities such as single quarks, charmed mesons and other exotic particles may show up at these energies. We reiterate the importance of finding out whether the proposed list of 12 quarks and four leptons is correct and complete and whether our interpretation of hadron spectroscopy in terms of the assumed quark-flavors will remain valid.

C. The TeV fixed target frontier.

Colliding beam facilities restrict research to the effects of collisions of the accelerated particles; no secondary beams can be produced. In order to get at pion-, muon-, kaon-, electron-, photon, and neutrino-beams with energies higher than 200 to 300 GeV, a fixed target accelerator in the TeV region is needed. Such beams are necessary to fully investigate the new realm of phenomena which one expects to open up when the weak interactions become comparable to, and perhaps merge with the, electromagnetic ones, and when the strong interactions may reveal new features. All present indications point towards expectation that a very different behavior of elementary particles will appear at center-of-mass energies of several hundred GeV. Proton-proton colliding beams of that energy are a much too narrow window for looking into this new realm of phenomena.

This incomplete and sketchy description of the promises expected from new energy frontiers is supposed to show two points. First, our present ideas about the structure of the subnuclear world indicate strongly that the next steps in expanding the energy frontier should yield a number of important qualitatively new insights. Second, those new insights are expected to show up at different energy-frontiers and the information at one frontier alone will necessarily be incomplete without the results at other frontiers. The recent discoveries of the ψ/J-particles and their properties was a good example of the necessity of complementary information with very different beams. I close this series of predictions of future results with the obvious statement that nature is far more inventive than the human mind: Expect the unexpected!

Table I

"Elementary" Particles, Empirical

Particles

Pre-sub nuclear		Sub nuclear		
Proton, Neutron	⇒ Hadrons	Baryons $B = 1$; Mesons $B = 0$		infinite spectra, B-conservation
Electron, Neutrino	⇒ Leptons	electron e, neutrino ν	$L = 1$	Quartet, spin 1/2, $L(L')$ conservation
		muon μ, neutrino ν'	$L' = 1$	

Interactions

Nuclear force transmitted by pions	⇒	Strong interactions among hadrons
Electromagnetic transmitted by photons	⇒	Electromagnetic transmitted by photons
Weak emission of $(e\nu)$	⇒	Universal weak interaction emission of $(e\nu)(\mu\nu')$, π, K

Table II

Elementary Particles, Hypothetical

Particles (fermions)

Leptons	Quarks			
e	u	u'	u"	flavor ↓
ν	d	d'	d"	
μ	s	s'	s"	
ν'	c	c'	c"	
Color: 0	"red"	"blue"	"green"	

Interactions

Kind		Transmitted by	Coupled to
strong	Confinement of Quarks	——	——
	Quark-Quark interaction	gluons	color
el. mag		photons	charge
weak		$W^{\pm}$ charged, Z neutral	weak charge