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*THE MAIN RESEARCH TRENDS IN ELEMENTARY PARTICLE PHYSICS**

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In recent years the efforts of physicists studying elementary particles have been, perhaps more than previously, concentrated on the study of processes referring to high energies (above 1 BeV). A study of these processes has already led in the past to the discovery of several interesting peculiarities in the world of elementary particles and it continues to yield new unexpected results. Basically there are two sources of new information on elementary particles: higher energies for the colliding particles and higher precision of quantitative measurements at low and intermediate energies. It is difficult to say which of these two approaches will give rise to decisive discoveries for our basic understanding of the properties of elementary particles. But in recent years qualitatively new results have been obtained mainly by going to regions of higher energy.

Recent studies in the high energy region have considerably enriched our notions about elementary particles. A new family of unstable elementary particles —"resonances"—has been added to the previously known particles. New unusual symmetry properties of the strong interactions have been discovered. Recent data on weak interactions are threatening to do away with our well established notions on the symmetry properties of space-time. Significant advances have been made in the study of nucleon structure, leading further and further away from the picture of a point particle. Lastly, in a number of cases investigations have brought physicists close to the possibility of verifying the main principles on which modern elementary particle theories are based, in particular the principle of locality.

The grandiose task of discovering the fundamental regularities of the micro-world, lying at the foundations of motion of all matter, requires no less grandiose machinery. To study elementary particle physics the USSR and major countries of the world (USA, England, France, Italy, West Germany, Japan, Sweden) have constructed gigantic electron and proton accelerators, at which are working huge groups of scientists. The research front is unusually wide, and the amount of information produced is such that its analysis is beyond the capacity not only of a single person but even of a group of specialists. In this connection international conferences on high energy physics, in which past achievements are summarized and most promising directions for the future are outlined, acquire special significance. The last of such conferences took place in August 1964 at Dubna. On the basis of materials presented at that conference, and also a number of later papers, the authors of the present article have attempted to give a review of the main directions in which investigations are carried out in elementary particle physics.

The authors are fully aware that in an article of this nature it is difficult to avoid being subjective, to preserve balance, and to give each important result its due—particularly since the importance of a result is often a function of time.

It was not the aim of the authors to give a detailed description of all papers presented at the Dubna conference,* and therefore in the text, as a rule, the names of individual scientists and countries, where the work was done, are not given.

1. GENERAL CHARACTERISTICS OF THE PRESENT STAGE OF RESEARCH

It is natural to call the main direction of investigation in the field of elementary particles that direction which leads most directly to the main goal—the construction of a theory of elementary particles. At the moment it is far from clear what that theory will be like, what will be its main concepts and what problems will be of central importance for it. One may only formulate a number of questions which appear at the moment to be most relevant. We shall define as "main" those lines of research which are most intimately connected with the resolution of these questions. Somewhat arbitrarily they can be classified into three groups:

1. What elementary objects exist in nature and to what extent are they indeed elementary? (Is their number finite?) What are their quantum numbers (spatial-mass, spin, parity; "internal"-isospin, hypercharge, etc.)? How many are the "internal" dynamic variables and how are they connected with

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*This article was written at the request of the editor and does not pretend to be a complete report on all the papers presented at the conference; only the main directions and the principal results are noted. (Editor)

*For more details the reader may consult the reports of the rapporteurs issued by the Joint Institute for Nuclear Research.

Table I. Stable and quasistable particles

Symbol	Mass, MeV	$(I)\ J^{PG}$	Lifetime, sec.	Principal decay modes		
				Type	Fraction, %	Q, MeV
Photon						
γ	0	1^-	Stable			
Leptons						
ν_e	$0\,(<0{,}2\cdot 10^{-3})$	$^1/_2$	Stable			
ν_μ	$0\,(<4)$					
$e\pm$	0.511006 ± 0.000002	$^1/_2$	Stable			
$\mu\pm$	105.659 ± 0.002	$^1/_2$	$2.2001\cdot 10^{-6}$ ± 0.0008	$e\nu\nu$	100	105.66
Mesons						
$\pi\pm$	139.60 ± 0.05	$(1)\ 0^{--}$	$2.55\cdot 10^{-8}$ ± 0.26	$\mu\nu$	100	33.95
				$e\nu$	$(1.24\pm 0.05)\times$ $\times 10^{-4}$	139.60
				$\mu\nu\gamma$	$(1.24\pm 0.25)\times$ $\times 10^{-4}$	33.94
				$\pi^0 e\nu$	$(1.5\pm 0.3)\times$ $\times 10^{-8}$	4.08
π^0	135.01 ± 0.05		$1.80\cdot 10^{-16}$ $\pm 0{,}29$	$\gamma\gamma$	100	135.01
$K\pm$	493.8 ± 0.2	$(^1/_2)\ 0^-$	$1.229\cdot 10^{-8}$ $\pm 0{,}008$	$\mu\pm\nu$	63.1 ± 0.5	388.1
				$\pi\pm\pi^0$	21.5 ± 0.4	219.2
				$\pi\pm\pi+\pi^-$	5.5 ± 0.1	75.0
				$\pi\pm\pi^0\pi^0$	1.7 ± 0.1	84.2
				$\pi^0\mu\pm\nu$	3.4 ± 0.2	253.1
				$\pi^0 e\pm\nu$	4.8 ± 0.2	358.3
				$\pi\pm\pi\mp e\pm\nu$	$(4.3\pm 0.9)\times$ $\times 10^{-5}$	214.1
				$\pi\pm\pi\pm e\mp\nu$	$<0.1\cdot 10^{-5}$	214.1
K^0	498.0 ± 0.5		$50\%\,K^0{}_1+$ $+50\%\,K^0_2$			
K^0_1	mass difference $-0.91\cdot{}^1/\tau_1$ ± 0.07		$0.92\cdot 10^{-10}$ $\pm 0{,}02$	$\pi^+\pi^-$	(69.4 ± 5.1)	218.8
				$\pi^0\pi^0$	30.6 ± 1.1	228.0
K^0_2			$5.62\cdot 10^{-8}$ ± 0.68	$\pi^0\pi^0\pi^0$	27.1 ± 3.6	93.0
				$\pi^+\pi^-\pi^0$	12.7 ± 1.7	83.8
				$\pi\mu\nu$	26.6 ± 3.2	252.7
				$\pi e\nu$	33.6 ± 3.3	357.9
η	548.7 ± 0.5	$(0)\ 0^{-+}$		$\gamma\gamma$	35.3 ± 3.0	548.7
				$3\pi^0{}_+\pi^0 2\gamma$	31.8 ± 2.3	143.7
				$\pi^+\pi^-\pi^0$	27.4 ± 2.5	134.5
				$\pi^+\pi^-\gamma$	5.5 ± 1.3	269.5

the spatial dynamic variables? To what extent can these elementary objects be described by fixed proper values of these dynamic variables? (This last may turn out to be relevant for the understanding of the nature of unstable particles.)

2. What types of interactions do elementary particles have? Are there only strong, electromagnetic, weak and gravitational interactions or is this classification arbitrary and there exists a variety of intermediate interactions, or, lastly, are they only different manifestations of a single interaction encompassing all elementary particles?

3. What symmetry properties correspond to each type of interaction and in what way is their change related to the change in the interaction strength?

It is to be hoped that a future theory will shed some light on all these questions, although most likely these questions will not exhaust its content. It is also to be expected that a mathematical apparatus will be found making it possible to calculate, in principle, dynamic characteristics of micro-processes (cross sections, form factors, coupling constants, etc.). The resolution of the above formulated questions and the construction of the mathematical apparatus are today in their very initial stages. The present stage of elementary particle investigations is characterized mainly by accumulation of copious data and attempts at systematization of this data.

Table I (cont'd)

Symbol	Mass, MeV	$(I)\,J^{PG}$	Lifetime, sec.	Principal decay modes		
				Type	Fraction, %	Q, MeV
				Baryons		
p	938.256 ± 0.005 mass difference -1.2933 ± 0.0001	$(^1/_2)\ ^1/_2{}^+$	Stable			
n	939.550 ± 0.005		$1.01 \cdot 10^3$ ± 0.03	$pe^-\nu$	100	0.78
Λ	1115.40 ± 0.11	$(0)\ ^1/_2{}^+$	$2.62 \cdot 10^{-10}$ ± 0.02	$p\pi^-$	67.7 ± 1.0	37.5
				$n\pi^0$	31.6 ± 2	40.9
				$p\mu\nu$	$<10^{-4}$	71.5
				$pe\nu$	$(0.88 \pm 0.08) \times \times 10^{-3}$	176.6
Σ^+	1189.41 ± 0.14	$(1)\ ^1/_2{}^+$	$0.788 \cdot 10^{-10}$ ± 0.027	$p\pi^0$	5.1 ± 2.4	116.1
				$n\pi^+$	49.0 ± 2.4	110.3
				$n\pi^+\gamma$	$\sim 0.4 \cdot 10^{-4}$	110.3
				$\Lambda e^+\nu$	$\sim 0.2 \cdot 10^{-4}$	73.5
				$p\gamma$	$\sim 3 \cdot 10^{-3}$	251.1
				$n\mu^+\nu$	$<2.3 \cdot 10^{-4}$	144.2
				$ne^+\nu$	$<1.0 \cdot 10^{-4}$	249.3
Σ^0	1192.4 ± 0.3 mass difference 4.44 ± 0.10		$1.0 \cdot 10^{-14}$	$\Lambda\gamma$	100	77.0
Σ^-	1197.08 ± 0.19		$1.58 \cdot 10^{-10}$	$n\pi^-$	100	117.9
				$n\pi^-\gamma$	$\sim 0.1 \cdot 10^{-4}$	117.9
				$n\mu^-\nu$	$(0.66 \pm 0.14) \times \times 10^{-3}$	151.9
				$ne^-\nu$	$(1.4 \pm 0.3) \times \times 10^{-3}$	257.0
				$\Lambda e^-\nu$	$(0.75 \pm 0.28) \times \times 10^{-4}$	81.2
Ξ^0	1314.3 ± 1.0 mass difference 6.5 ± 1.0	$(^1/_2)\ ^1/_2{}^+$	$3.06 \cdot 10^{-10}$ ± 0.40	$\Lambda\pi^0$	~ 100	76.9
				$p\pi^-$	<0.4	249.4
				$pe^-\nu$	<0.4	388.5
				$\Sigma^+e^-\nu$	<0.3	137.4
				$\Sigma^-e^+\nu$	<0.25	129.7
Ξ^-	1320.8 ± 0.2		$1.74 \cdot 10^{-10}$ ± 0.05	$\Lambda\pi^-$	100	65.8
				$\Lambda e^-\nu$	$(3.0 \pm 1.7) \times \times 10^{-3}$	204.9
				$n\pi^-$	$5 \cdot 10^{-3}$	214.7
Ω^-	1675 ± 3	$(0)\ ^3/_2{}^+$? ?	$\sim 0.7 \cdot 10^{-10}$	$\Xi\pi$	?	221
				ΛK	?	66

In most cases the dynamic characteristics of the processes studied are discussed on the basis of particular hypotheses, which are not always related to each other and which often must be changed under the pressure of experimental facts. With their help it is sometimes possible to bring some clarity into the mechanisms of individual processes but their range of applicability is, as a rule, limited. Nevertheless they play an important role serving as bridges, albeit temporary and shaky, into the future theory.

Somewhat isolatedly the axiomatic approach has been developing, at the foundations of which lies the desire to construct a systematic apparatus for the theory on the basis of a minimum of most general postulates. In this method it is most difficult to arrive at consequences that can be checked experimentally and the number of such consequences found so far is not large.

The most interesting peculiarity of high energy physics investigations in recent years, which may turn out to be decisive for its further development, is connected with, of all things, the unexpected increase in the number of elementary particles. While until recently 30 stable and quasistable particles (i.e. particles with long life times on the scale of the nuclear time of 10^{-23} sec) were known to physicists,

Table II.
Resonances

Symbol	Mass, MeV	$(I)J^{PG}$	Width, MeV	Principal decay modes		
				Type	Fraction, %	Q, MeV
			Mesons			
η	548.7 ±0.5	(0) 0^{-+}	<10	see Table I		
ω	782.8 ±0.5	(0) 1^{--}	9.4 ±1.7	$\pi^+\pi^-\pi^0$	86	369
				$\pi^+\pi^-$	<1	504
				neutral $+\pi^0\gamma$	11±1	648
				$\pi^+\pi^-\gamma$	3.2±1	504
				e^+e^-	<0.3	782
				$\mu^+\mu^-$	<0.5	572
$(\eta 2\pi)$	957.5 ±1.5	(0)$0^{-+}, 1^{++}, ..$	<12	$\eta 2\pi$	large	131
				2π	<20	680
				3π	<30	540
				4π	<3	400
				6π	<3	121
				$\pi\pi\gamma$	?	680
φ	1019.5 ±0.3	(0) 1^{--}	3.1 ±0.6	K_1K_2	41±6	23
				K^+K^-	59±6	32
				$\pi\pi$	<8	740
				$\pi\varrho+3\pi$	<10	117
				$\pi^0\gamma$		885
f	1253 ±20	(0) 2^{++}	100 ±25	$\pi\pi$	large	974
				4π	8±6	695
				$\bar{K}K$	?	265
$\pi^\pm$ π^0	139.6 135.0	(1) 0^{--}		see Table I		
ϱ	763 ±4	(1) 1^{-+}	106 ±5	2π	100	483
				4π	small	204
A_1	1080 ±10	⩾(1)	125 ±25	$\varrho\pi$	~100	188
				$\bar{K}K$	<5	
B	1215 ±18	(1) 1^{++}, 2^-	122 ±17	$\omega\pi$	~100	293
				$\pi\pi$	<30	I-forbidden for even l
				$\bar{K}K$	<10	G-forbidden for even l
				4π	<50	
A_2	1310	(1) 2^{+-}	80	$\varrho\pi$	~70	408
				$\bar{K}K$	~30±7	816
				$\eta\pi$	seen	622
$K^\pm$ K^0	493.8 498.0	($^1/_2$) 0^-		see Table I		
$\varkappa$	725			$K\pi$		

at the present moment the total number of discovered particles approaches 200, with a majority of the newly discovered particles being unstable objects—"resonances"—with lifetimes of 10^{-22} – 10^{-23} sec (see Tables I-II). The decay products of the resonances consist of the "usual" quasistable particles: nucleons, hyperons, pions and kaons. It is now clear that the formation of resonances is not an exceptional but rather a general property of strongly interacting systems. Practically all known strongly interacting particles can at an appropriate energy in the center of mass system combine, two or more at a time, to form unstable complexes ("resonances"). The resonances discovered first (the ρ and K* mesons, the Y_1^* hyperons) were two-particle complexes. Thus the ρ meson (a particle of spin 1 and mass of 760 MeV) decays into two pions. The K* meson (a particle of spin 1 and mass of 891 MeV) decays into a kaon and a pion. The Y_1^* hyperon (spin 3/2, mass 1382 MeV) decays into the Λ particle and a pion. Recently more complicated complexes have been discovered: for example the $\eta 2\pi$ meson (spin 0, mass 957 MeV), the $K\bar{K}\pi$ meson (mass 1415 MeV), and others. It turned out that in a number of cases the decay of a "resonance" proceeds in a cascade manner, i.e. the "resonance" decays into another "resonance" of lower mass and some quasistable particle, and that this type of decay is more the rule than an exception. As exam-

Table II. (cont'd)

Symbol	Mass, MeV	$(I)\,J^{PG}$	Width, MeV	Principal decay modes: Type	Fraction, %	Q, MeV
K^*	891	$(^1/_2)\ 1^-$	50	$K\pi$	~ 100	258
	± 1		± 2	$K\pi\pi$	<0.2	118
				$K\pi$	<0.2	27
Baryons						
p	938.2	$(^1/_2)\ ^1/_2^+$		see Table I		
n	939.6					
$N^*_{1/2}$	1518	$(^1/_2)\ ^3/_2^-$	125	πN	~ 80	440
	± 10		± 12	$N\pi\pi$		301
$N^*_{1/2}$	1688	$(^1/_2)\ ^5/_2^+$	100	πN	~ 80	610
				$N\pi\pi$		471
$N^*_{1/2}$	2190	$(^1/_2)\ ^9/_2^+$	~ 200	πN	~ 30	1112
				ΛK		577
$N^*_{3/2}$	1236	$(^3/_2)\ ^3/_2^+$	125	πN	100	160
	± 2					
$N^*_{3/2}$	1924	$(^3/_2)\ ^7/_2^+$	170	πN	34	842
				ΣK		237
$N^*_{3/2}$	2360	$(^3/_2)\ ^{11}/_2^+$	~ 200	πN	~ 10	1282
Λ	1115.4	$(0)\ ^1/_2^+$		see Table I		
Y^*_0	1405	$(0)\ ^1/_2^-$	50	$\Sigma\pi$	100	76
				$\Lambda\pi\pi$	<1	10
Y^*_0	1518.9	$(0)\ ^3/_2^-$	16	$\Sigma\pi$	55 ± 7	190
	± 1.5		± 2	$\bar{K}N$	29 ± 4	87
				$\Lambda\pi\pi$	16 ± 2	124
Y^*_0	1815	$(0)\ ^5/_2^+$	70	$\bar{K}N$	80	875
				$\Sigma\pi$	<10	486
				$\Lambda\pi\pi$	<15	420
				$\Lambda\eta$	?	151
Σ		$(1)\ ^1/_2^+$		see Table I		
Y^*_1	1382	$(1)\ ^3/_2^+$	53	$\Lambda\pi$	96 ± 4	127
	± 0.9		± 2	$\Sigma\pi$	4 ± 4	55
Y^*_1	1660	(1)	44	$\bar{K}N$	~ 5	720
	± 10		± 5	$\Sigma\pi$	~ 31	328
				$\Lambda\pi$	~ 21	405
				$\Sigma\pi\pi$	~ 27	188
				$\Lambda\pi\pi$	~ 16	265
Ξ	1321	$(^1/_2)\ ^1/_2^+$		see Table I		
	1314					
Ξ^*	1529.1	$(^1/_2)\ ^3/_2^+$	7.5	$\Xi\pi$	~ 100	73
	± 1.0		± 1.7			
Ξ^*	1810	$(^1/_2)$	~ 70	$\Xi^*\pi$	~ 45	141
	± 20			$\Lambda\bar{K}$	~ 45	197
				$\Xi\pi$	<10	354
				$\Sigma\bar{K}$	<10	127
Ω^-	1675	$(0)\ ^3/_2^+$		see Table I		
	± 3					

ples we may mention the A_1 meson (mass 1080 MeV), the B meson (mass 1215 MeV), the $N^*_{1/2}$ isobar (mass 1688 MeV), with the following decay schemes:

$$\begin{array}{l} A_1 \to \varrho + \pi, \\ \qquad \searrow \\ \qquad\ \pi + \pi, \\ B \to \omega + \pi, \\ \qquad \searrow \\ \qquad\ \pi + \pi + \pi, \\ N^*_{1/2}\,(1688) \to N^*_{3/2}\,(1236) + \pi, \\ \qquad\qquad\qquad\quad \searrow \\ \qquad\qquad\qquad\quad N + \pi. \end{array}$$

With increasing mass the spins of the resonances invariably increase. While for the first discovered resonances the spin was equal to 1 or 3/2, we now know resonances with spin 2 (f meson, mass 1250 MeV), 5/2, 7/2; yet higher spins are possible. Thus the previously known 30 particles, which only a few years ago could demand exclusive attention, have turned out to be nothing but relatively more stable, lower lying in mass, members of a huge collection of objects. Today it is possible to speak of a kind of spectroscopy of elementary particles. It is clear that the indicated facts require a searching reexamination of the concept of "elementarity", and it is possible that one should no longer attempt to reduce the variety of observed particles to a few elementary entities but rather one should seek a dynamical principle which governs the distribution of the excited levels of a single strongly interacting entity, these levels being what we observe as particles.

The large number of particles that has become known to physicists opened up wide possibilities for their grouping, systematization, and for the discovery and verification of symmetry properties satisfied by the interactions that govern the behavior of these particles. The discovery of one symmetry property or another can not, of course, replace the knowledge of dynamic laws, but it does make possible an ordering of the known facts and the establishing of important connections between apparently unrelated phenomena thus leading to a number of important predictions of both qualitative and quantitative character. In the final analysis the discovery of the symmetry properties of the interactions should serve as a powerful stimulus for the construction of a dynamical theory representing at the same time a critical test of the validity of the theory.

Recent years have seen great advances in precisely this domain of symmetry properties of elementary particle interactions. The discussion of these problems occupied one of the central places at the conference.

2. SYMMETRIES OF THE INTERACTIONS

Symmetry properties and symmetry groups that describe them constitute one of the most important elements of our knowledge of physics. In elementary particle physics one distinguishes external (space-time) symmetries and "internal" symmetries which refer to specific properties of the particles and which, it seemed, were unrelated to their spatial properties. It appears, however, that there is a connection between them (see below).

1) Space-time symmetries. Violation of CP invariance. The importance of the role played by the group of space-time transformations—the inhomogeneous Lorentz group—in the development of all fields of physics, and in particular in the development of quantum field theory, is common knowledge. The fundamental concepts used to describe elementary particles—energy, momentum, mass, spin—arise as a consequence of invariance of physical interactions under this group of transformations. It is also known that in quantum mechanics the Lorentz group is augmented by the group of discrete transformations connected with the operations of space inversion $\mathbf{r} \rightarrow -\mathbf{r}$, time reversal $t \rightarrow -t$, and particle-antiparticle interchange. The operators corresponding to these transformations are denoted by the symbols P, T, C. Given invariance with respect to each of these operations one may introduce quantum numbers for space, time and charge parity, which turn out to be very useful characteristics for the strong and electromagnetic interactions. It is important to emphasize that the basic postulates of quantum mechanics together with the assumption of locality of the theory and its invariance under the inhomogeneous Lorentz group lead to the conclusion that all physical phenomena should be invariant under the product of the three operations C, P, and T (the so called CPT theorem).

Invariance with respect to each of these operations individually may not exist. The discovery of space (and charge) parity nonconservation in weak interactions in 1957 beautifully confirmed this hypothesis. However until recently physicists believed that weak interactions are invariant under the so called "combined" parity operation CP. The point is that if CP invariance is violated then right and left become nonequivalent in empty space, which nonequivalence cannot be reduced, as before, to the diference between particle and antiparticle (left and right screw sense respectively). It is natural that one would like to avoid such a situation. Nevertheless the newest data have shaken this belief. It may be that one of the most important in its future consequences of the papers presented at the conference in Dubna was that of the Princeton (USA) group, which has discovered a process that, apparently, proceeds with violation of CP invariance. The process in question is the decay of the longlived K^0 meson (K_l^0) into a π^+ and a π^-. It turned out that such a decay occurs a fraction of the times equal to 2×10^{-3} of all the other decays. Up til now it was assumed that the K_l^0 meson was the CP-odd superposition of the K^0 and $\bar{K}^0$ states:

$$|K_l^0\rangle = \frac{|K^0\rangle - |\bar{K}^0\rangle}{\sqrt{2}} = |K_2^0\rangle.$$

On the other hand a two-pion system with zero relative orbital angular momentum (the spin of the K_l^0 is zero) is invariant under the CP operation, i.e. is CP-even. Hence the transition between the K_l^0 and the two-pion system is possible only if the K_l^0 contains a certain admixture (rather small) of the CP-even combination of K^0 and $\bar{K}^0$ states $[(|K^0\rangle + |\bar{K}^0\rangle/2) = |K_1^0\rangle]$, or in other words, if the K_l^0 is not an eigenstate of the CP operator, and consequently CP invariance does not hold. If the above result is confirmed by future experiments two different in principle treatments of the decay of the longlived kaon are possible:

1) The decay is due to special causes, specific to the K_l^0 meson, the violation of CP-invariance in it being only apparent.

2) The decay is connected with a true violation of CP-invariance, which is a general property of all (or some) weak interaction processes.

Let us consider some of the explanations belonging to the first alternative.

a) The K_l^0-meson beam arises out of the original K^0 beam as a result of the "dying out" of the shortlived component K_S^0. It is known that starting with some moment the "dying out" law changes from exponential to a power law and in principle, even for very long flight times, there remains a "tail" of shortlived mesons which decay into two pions. It is usually supposed that the exponential decay law of the shortlived mesons remains valid sufficiently long so that for flight times characteristic for the experiment the number of surviving K_S^0 is vanishingly small. If one assumes that this proposition is false and that the exponential decay law is valid only for much shorter times then this could explain the observed effect. A test of the decay law of the K_S^0 meson is one of the important experiments to be carried out in this field of research.*

b) Another possible explanation of the $K_l^0 \to 2\pi$ decay is connected with the available evidence that $m_{K_l^0} > m_{K_S^0}$. In this case the transition $K_l^0 \to \underset{\searrow\, 2\pi}{K_S^0} + v$, where v is a vector particle with negligibly small ($< 10^{-5}$ eV) but finite mass, is allowed. By choosing the constant of interaction between the v-particle and the K^0 mesons it is possible to explain the observed transition probability.

c) A more complicated explanation is based on the assumption of the existence of a long-range vector field with hypercharge as its source. In that case the particles that form our galaxy—the protons and neutrons with hypercharge $Y = +1$—create in the region of the Earth a constant field which acts oppositely on K^0 mesons ($Y = 1$) and $\bar{K}^0$ mesons ($Y = -1$). Since the K_l^0 and K_S^0 states are certain particular superpositions of the K^0 and the $\bar{K}^0$ states, the existence of such an external field will affect this superposition and lead in effect to the decay $K_l^0 \to 2\pi$. In the absence of the external field this decay disappears so that in a true vacuum CP invariance persists.

This list, clearly, does not exhaust all the possibilities. If the decay $K_l^0 \to 2\pi$ is due to a true violation of CP invariance in weak interactions, then the phenomenon should also manifest itself in other processes. Various hypotheses have been advanced for the actual mechanism responsible for the violation of CP invariance in weak interactions, which lead to different conclusions regarding the possibility of its experimental verification. It is important to emphasize that at the moment there are practically no direct experimental tests of CP invariance in weak interactions. In the analysis of the experimental data one usually tests the validity of T invariance and then invokes the CPT theorem to draw conclusions regarding CP invariance. The best of the data in support of T invariance refer to β decay, in particular to the decay of the neutron. All other data are considerably less accurate. It is to be expected that in the near future considerable effort will be expended to test T invariance, as well as to directly test CP invariance, in weak interactions. The most likely possibility is that the violation of CP invariance in weak interaction processes will be accompanied by simultaneous violation of T invariance (i.e. that the CPT theorem is valid). However the possibility can not be excluded that physicists will be faced with the situation in which CP violation is not connected with T violation, i.e., in the final analysis with a violation of the CPT theorem. This latter would mean a collapse of the basic principles on which the modern ideas about the microworld are built; the consequences of such a collapse are hard to estimate today.

2) Symmetries of the strong interactions. Up to now we were considering space-time symmetries. Among internal symmetries the symmetry of isotopic spin is an old and well known characteristic of strong interactions. Invariance under rotations in isospace made possible the grouping of particles with the same value of the isospin I, but with different values of the electric charge, into isotopic multiplets, and established a number of relations between the cross sections for processes involving particles belonging to the same isotopic multiplet. More recent work has led to the conclusion that in fact the strong interactions possess a wider internal symmetry, the so called SU_3 symmetry. In the papers delivered at the conference additional facts were presented confirming the existence of this symmetry.

The term SU_3 symmetry is an abbreviation denoting invariance of the strong interactions under transformations of the SU_3 group (i.e. the group of all unitary matrices of third order with determinant equal to unity*.) This symmetry, by the way, is not exact (see below). The SU_3 group is one of the simplest extensions of the group of isotopic rotations, i.e., of the SU_2 group, which it contains as a subgroup. Invariance under the SU_3 group is closely connected with the existence of two conserved commuting quantities in the strong interactions: the third component of the isotopic spin I_3 and the hypercharge Y.

One of the direct consequences of SU_3 symmetry is the combining into a single supermultiplet of particles with different values of I and Y. Under the transformations of the group the state vectors describing particles belonging to the same supermultiplet are

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*Establishing the existence of deviations from the exponential decay law would be of great interest also for other unstable systems.

*For more details see Ya. A. Smorodinskii, UFN 84, 3 (1964), Soviet Phys. Uspekhi 7, 637 (1965).

linearly expressed in terms of each other. The number of particles entering into a supermultiplet is given by the dimensions of the irreducible representations of the group SU_3. The smallest representations of the group SU_3 have the dimensions 1, 3, 6, 8, 10, 15, etc. The quantum numbers I, I_3, Y of particles in a supermultiplet follow from the formalism of the group. At the moment particles are known filling the supermultiplets 1, 8 and 10. The discovery at the beginning of 1964 of the Ω^- hyperon which closed out the decuplet was an important piece of evidence in favor of the SU_3 group.

The so called mass formulas constitute another important piece of evidence in favor of the SU_3 group. The point is that if the invariance with respect to SU_3 were exact then the masses of all particles belonging to the same supermultiplet should be the same. In fact, as mentioned before, the invariance is not exact. However, if the transformation properties of the term in the Hamiltonian (or in the mass operator) responsible for the violation of the invariance are given, then it is possible to calculate the resultant dependence of the mass on the quantum numbers of the particles in the supermultiplet. The result of this calculation in first order of perturbation theory (assuming that the perturbing term is small) is given by the Gell-Mann-Okubo (GMO) formula:

$$m = m_0 + aY + b\left(I(I+1) - \frac{Y^2}{4}\right), \tag{1}$$

where m_0, a, b are constants for any given supermultiplet. The GMO formula establishes definite relations between the masses of particles belonging to the same supermultiplet, which are well satisfied for the known supermultiplets. In particular the mass of the Ω^- hyperon was predicted with the help of the GMO formula, which was later confirmed with great precision by experiment. In addition the SU_3 symmetry makes it possible to relate amplitudes for processes involving particles belonging to the same supermultiplet. These predictions of SU_3 symmetry are satisfied in not many cases. For example, for the decays of the particles $N^*_{3/2}$, Y^*_1, Ξ^*, belonging to the decuplet, the relations between the decay probabilities following from SU_3 symmetry, are fairly well satisfied:

$$\begin{aligned} &W(N^*_{3/2} \to N + \pi) + 2W(\Xi^* \to \Xi + \pi) \\ &\quad = 3W(Y^*_1 \to \Lambda + \pi) + W(Y^*_1 \to \Sigma + \pi). \end{aligned} \tag{2}$$

At the same time the relations between the squares of the matrix elements for the processes

$$\left.\begin{array}{lr} \pi^- + p \to N^*_{3/2} + \pi^+ & (1') \\ K^- + p \to Y^{*-}_1 + \pi^+ & (2') \\ \pi^- + p \to Y^{*-}_1 + K^+ & (3') \\ K^- + p \to \Xi^{*-} + K^+ & (4') \end{array}\right\}, \tag{3}$$

$$\frac{|M_1|^2}{3} = |M_2|^2 = |M_3|^2 = |M_4|^2, \tag{4}$$

following from SU_3 symmetry, are badly violated. It turns out that

$$|M_2|^2 \approx |M_4|^2 \ll |M_1|^2 \approx |M_3|^2.$$

The reason for such strong deviations is not quite clear; most likely it is due to violation of SU_3 symmetry. Taking into account the symmetry-violating term to first order in perturbation theory removes the discrepancy with experiment. However the problem of taking into account the symmetry violation more exactly has not been solved so far and the complete confrontation of the theory and experiment is a matter for the future.

Along with the obvious successes of the applications of the SU_3 symmetry, certain isolated facts, for which a full explanation within the framework of the SU_3 symmetry is missing, call attention to themselves. Among these one should mention in the first place the preference expressed by the known particles in filling certain representations of the group—those of the dimension 1, 8 and 10. Candidates are missing so far for the representations of smaller dimensions (3, 6). The unfilled representations are in many ways exceptional. If one accepts the Gell-Mann—Nishijima formula for the electric charge

$$Q = I_3 + \frac{Y}{2}, \tag{5}$$

and requires that it be satisfied in all representations of SU_3 (I_3 and Y are definite combinations of the generators of the group), then one finds that for the representations of dimension 3, 6, 15, etc. the electric charge is fractional, a multiple of 1/3. For example for the representation of dimension 3 the particles have the charges 2/3, −1/3, −1/3. Thus the physicists are faced with the following choice:

a) All representations of the SU_3 group are realized in nature; in that case, in addition to particles with integer charge there exist particles with fractional charge which should be discovered.

b) Only certain of the representations of SU_3 (1, 8, 10, 27...), corresponding to integer charges, are realized in nature; in mathematical terms this means that the observed symmetry group is the factor group SU_3/Z_3 (Z_3 is the center of SU_3), and it is necessary to understand the physical reasons responsible for this.

During 1964 intense efforts were made at the large accelerators at Geneva and Brookhaven to discover strongly interacting particles with fractional charge. No such particles with mass up to 4 BeV were found. Of course, it can not be excluded that such particles exist but are heavier. At that it can be shown that for the case of the triplet at least one of these particles will be stable. This means that there may exist in nature an entirely different type of matter from that known to us.

There is, however, an entirely different possibility for avoiding fractional electric charges. To this end it is necessary to extend the group SU_3 and introduce a new quantum number which commutes with I_3 and Y. It is not hard to see that if the Gell-Mann—Nishijima formula is modified into

$$Q=I_3+\frac{Y}{2}+\frac{C}{3}, \tag{6}$$

where for the triplet representation C = 1, we obtain a triplet with integer charges (1, 0, 0). The extension of the SU_3 group is, admittedly, a drastic measure. However a number of facts testify to the usefulness of such a step. Among others these are the facts relating to the existence of nonequivalent unitary supermultiplets with the same spatial quantum numbers: for example for the pseudoscalar particles the supermultiplets 8 and 1, for vector particles the supermultiplets 8 and 1, and for particles of spin 3/2—10 and, perhaps, 8. Such facts, unexplainable within SU_3, are easily interpreted as the result of the decomposition of irreducible representations of groups larger than SU_3 into representations of SU_3.

At the present time the following larger groups are being studied: SU_4, Sp_6 (simplectic group in 6 dimensions), and O_7 (orthogonal group in 7 dimensions). A characteristic feature of all these groups is the appearance of a new quantum number C ("charm"), which appears in Eq. (6). The irreducible representations of these groups contain both usual (C = 0) and unusual (C ≠ 0) particles; also, as a rule, a large number of new particles of both kinds is being predicted. The search for particles with nonzero values of the new quantum number C will be one of the most interesting problems in physics in the next few years.*

Logically the following properties are conceivable for the quantum number C.

a) The quantum number C is absolutely conserved. In that case particles with C ≠ 0 represent a new type of matter (see above) which, perhaps, has something to do with the matter contained in quasars, in galactic nuclei, etc. In the collisions of ordinary particles the particles with C ≠ 0 are produced in pairs only.

b) The quantum number C is not conserved by weak interactions. In that case it is similar in its properties to "strangeness". In the collisions of ordinary particles the particles with C ≠ 0 are produced in pairs and subsequently decay into ordinary particles.

c) The quantum number C is not conserved by interactions of medium strength (approximately 10 to a 100 times weaker than the usual strong interactions); Particles with C ≠ 0 may be produced singly in collisions of ordinary particles, although somewhat less intensely than the known "resonances," and are very similar to them in decaying into ordinary quasistable particles.

Certain of the indicated extensions of the SU_3 group are not directly related to the resolution of the problem of fractional electric charge. To this number belong the groups that are direct products of the groups U_3 or SU_3:

$$U_3\otimes U_3\equiv W_3,\ SU_3\otimes SU_3\equiv (SU_3)^2,\ SU_3\otimes SU_3\otimes SU_3\otimes SU_3\equiv (SU_3)^4.$$

In the group W_3 the mixing of unitary multiplets occurs rather naturally. Thus the representation (3, 3*) reduces from the point of view of the SU_3 group into $8\oplus 1$, (6, 3) into $10\oplus 8$, which may be directly related to the above mentioned existence of unitary multiplets with equal quantum numbers. In particular, within the framework of the W_3 group a formula was obtained for the nine vector mesons

$$m_\varphi^2-m_\rho^2=\frac{4}{3}(m_{K^*}^2-m_\rho^2)(m_\varphi^2+m_\omega^2-2m_{K^*}^2) \tag{7}$$

which is in beautiful agreement with experiment. One of the most interesting consequences of the groups $(SU_3)^2$ and $(SU_3)^4$ is the existence of unitary multiplets conjugate in parity. In the group $(SU_3)^2$, for example, to each octet of mesons 0^-, 1^- there corresponds an octet of mesons 0^+, 1^+, and in the group $(SU_3)^4$ each octet is in addition repeated twice, i.e., 16 mesons 0^-, 1^- are predicted and as many mesons 0^+, 1^+. In the near future experiment should show whether this is the case.

Attempts to enlarge the group SU_3 and find more general "internal" symmetries are closely related to attempts of another kind, whose aim is to find a group which simultaneously describes the space-time and the "internal" symmetries. The most promising from this point of view is, apparently, the group SU_6. This group contains as a subgroup the direct product $SU_3\otimes(SU_2)_q$. The group SU_3 in this case is the already discussed group of "internal" symmetries, and the group $(SU_2)_q$ is the group of spatial rotations corresponding to the conservation of the mechanical spin. The symbol q indicates that the spatial rotations are performed at a given value q of the 4-momentum. Decomposing the irreducible representations of the SU_6 group in terms of the irreducible representations of the direct product $SU_3\otimes(SU_2)_q$ one obtains a set of unitary multiplets of the group SU_3, each of them with a prescribed value of the mechanical spin. Let us recall that previously these quantities were in no way related. It can also be shown that the parity of all the multiplets must be the same.

It is customary to denote an irreducible representation of $SU_3\otimes(SU_2)_q$ by (m, n) where m denotes the dimension of the SU_3 multiplet and n the dimension of the $(SU_2)_q$ multiplet, which is equal to 2s + 1, where s is the mechanical spin. Let us write

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*There is nothing in principle that excludes the existence of other quantum numbers (in addition to C) that might govern strong interaction processes at super-high energies.

out the decomposition of some of the irreducible representations of SU_6 into the irreducible representations of $SU_3 \otimes (SU_2)_q$:

SU_6	$SU_3 \otimes (SU_2)q$
6	(3.2)
15	(3*. 3) ⊕ (6.1)
20	(8.2) ⊕ (1.4)
35	(8.3) ⊕ (8.1) ⊕ (1.3)
56	(10.4) ⊕ (8.2)
70	(10.2) ⊕ (8.4) ⊕ (8.2) ⊕ (1.2)

It is not hard to see that the SU_6 group does not resolve the problem of the fractional electric charge since, for example, the representations 6 and 15 contain the triplet and sextet of SU_3, which have fractional charges. In the given case only the value of the spin of the triplet is determined, which is 1/2 for the sextet. Nevertheless, with the help of SU_6 it is possible to systematize a large number of facts and relate many parameters which previously appeared to be unrelated.

First of all, with the help of this group the representation 56 describes in a unique way the octet of baryons $1/2^+$ (N, Σ, Λ, Ξ) and the decuplet of baryons $3/2^+$ ($N^*_{3/2}$, Y^*_1, Ξ^*, Ω), and the representation 36 describes the meson octet 0^- (π, K, η) and also the meson octet 1^- to which is admixed the singlet 1^- (ρ, K^*, ω, φ). The formalism of the group determines uniquely the mixing parameter.

Further, the SU_6 group determines uniquely the nature of the meson-baryon interaction. In the SU_3 group two types are possible for this interaction conventionally called F- and D-couplings; in the SU_6 group the ratio of F to D is 2/3. At the same time a relation is established between the coupling constants for the interaction of vector and pseudoscalar mesons with baryons. If, for example, one takes the value of the vector constant from experiment then $g^2_{ps}/4\pi$ turns out to be ~ 13, in good agreement with the generally accepted value.

Assuming a definite form for the violation of the symmetry of the SU_6 group we obtain mass formulae for each supermultiplet in which in addition to a dependence on Y and I there also appears a dependence on the spin of the particle. Thus a relation is established between the masses of particles with different spin. In particular, the long ago noticed relation

$$m^2_{K^*} - m^2_{\rho} = m^2_K - m_{\pi}$$

is explained, as well as a number of other curious regularities in the mass distribution.

It will be of exceptional interest to test relations between the cross sections for various processes predicted by the formalism of the SU_6 group. The success of the SU_6 group can be hardly accidental and further developments in investigations in this direction are to be expected.

3) Symmetries of electromagnetic and weak interactions. The electromagnetic and weak interactions do not satisfy the symmetry laws characteristic of the strong interactions. Each of them violates the symmetry in a specific way. However even in this case the application of group-theoretic methods turned out to be most fruitful. The establishing of the actual form of the violation of the symmetry of the strong interactions (as in the case of the derivation of the mass formulae) leads to a number of useful predictions and to definite selection rules for various reactions. A considerable amount of time was also devoted at the conference to the determination of the symmetry properties of electromagnetic and weak interactions.

The electromagnetic interactions violate SU_3 symmetry, as well as isotopic invariance. They conserve, however, a subgroup of SU_3 for which the electric charge Q is an invariant (this is the SU_2 subgroup of the so called U-spin). The utilization of this, apparently trivial, fact already gives rise to a number of interesting relations between the masses of particles entering into the octet and decuplet, which are valid even when the violation of the invariance of the strong interactions with respect to SU_3 is taken into account.

For example,

$$m_n - m_\rho + m_{\Sigma^+} - m_{\Sigma^-} + m_{\Xi^-} - m_{\Xi^0} = 0, \tag{7a}$$

$$m_{N^{*-}_{3/2}} - m_{N^{*0}_{3/2}} + m_{Y^{*0}_1} - m_{Y^{*-}_1} = 0, \tag{7b}$$

$$m_{N^{*0}_{3/2}} - m_{N^{*+}_{3/2}} + m_{Y^{*+}_1} - m_{Y^{*0}_1} = 0. \tag{7c}$$

All these relations are in good agreement with experiment [the best accuracy is achieved in the case of (7a)].

Leaving aside the violation of the SU_3 group by the strong interactions and accepting Eq. (5) for the electric charge, one may obtain a number of additional relations: a) for the magnetic moments of the particles entering the octet:

$$\left.\begin{array}{ll} \mu_\Lambda = \frac{1}{2}\mu_n & \mu_{\Sigma^0} = -\frac{1}{2}\mu_n, \\ \mu_{\Sigma^+} = \mu_p & \mu_{\Xi^0} = \mu_n, \\ \mu_{\Sigma^-} = \mu_{\Xi^-} = -(\mu_p + \mu_n); & \end{array}\right\} \tag{8}$$

b) for the matrix elements of various processes, in particular decay processes

$$\begin{gathered} \langle \eta \mid 2\gamma \rangle = -\frac{1}{\sqrt{3}} \langle \pi^0 \mid 2\gamma \rangle, \\ \langle \varrho^+ \mid \pi^+\gamma \rangle = -\frac{1}{2} \langle K^{*0} \mid K^0\gamma \rangle = \langle K^{*+} \mid K^+\gamma \rangle \end{gathered} \tag{9}$$

and photoproduction processes

$$\begin{gathered} \frac{\langle \gamma p \mid N^{*0}_{3/2}\pi^+ \rangle}{\langle \gamma p \mid Y^{*0}_1 K^+ \rangle} = \frac{\langle \gamma p \mid N^{*0}_{3/2}\varrho^+ \rangle}{\langle \gamma p \mid Y^{*0}_1 K^{*+} \rangle} = -\sqrt{2}, \\ \frac{\langle \gamma n \mid N^{*-}_{3/2}\pi^+ \rangle}{\langle \gamma n \mid Y^{*-}_1 K^+ \rangle} = \frac{\langle \gamma n \mid N^{*-}\varrho^+ \rangle}{\langle \gamma n \mid Y^{*-}_1 K^{*+} \rangle} = -\sqrt{3}. \end{gathered} \tag{10}$$

At the same time a number of processes are forbidden.

For example, the following decays are forbidden:

$$Y_1^{*-} \to \Sigma^- + \gamma, \quad \Xi^{*-} \to \Xi^- + \gamma. \tag{11}$$

It is important to emphasize that in the derivation of these results use was made of Eq. (5). If the quantum number C exists then one should use Eq. (6): $Q = I_3 + Y/2 + C/3$, where C is a unitary scalar. Some of the above mentioned relations will in that case be violated. In particular the equalities $\mu_\Lambda = \frac{1}{2}\mu_n$ and $\mu_n = -(\mu_{\Sigma^+} + \mu_{\Sigma^-})$ are no longer valid. Certain other processes will also be affected, for example the ratio of the decay probabilities

$$\frac{W(\varphi \to \mu^+ + \mu^-)}{W(\omega \to \mu^+ + \mu^-)}.$$

It is however true that at that one must keep in mind the possible complications due to the violation of exact SU_3 symmetry in the strong interactions.

The search for effects due to the existence of the quantum number C in electromagnetic interactions is of considerable interest. It is not out of the question that success will be reached along these lines before the direct production of particles with $C \neq 0$.

The above considerations are based on the properties of electromagnetic interactions with respect to the group SU_3. If the true symmetry of the strong interactions should turn out to be wider than the SU_3 symmetry then the analysis of the electromagnetic interactions must be correspondingly modified. The inclusion of the number C in the formula for the charge in effect simulates such an analysis.

Most recently first attempts were made to analyse the electromagnetic interactions on the basis of the SU_6 group. Equation (5) was accepted for the electric charge. Many of the above results were reproduced* and in addition a number of interesting relations among magnetic moments was obtained. From among these we mention

$$\frac{\mu_n}{\mu_p} = -\frac{2}{3}, \tag{12}$$

which is in brilliant agreement with experiment.

In weak-interactions physics an important role has been played in recent years by the study of selection rules for leptonic and nonleptonic decays. At the moment one can claim with some assurance that in weak decays strangeness S and isotopic spin I change as follows:

for nonleptonic decays

$$|\Delta S| = 1, \quad |\Delta I| = \frac{1}{2}, \tag{13}$$

for leptonic decays

$$\left.\begin{array}{c} |\Delta S| = 1, \\ |\Delta I| = \frac{1}{2}, \\ \Delta S = \Delta Q \end{array}\right\} \tag{14}$$

(in the latter case the indicated differences refer to the strongly interacting particles).

Until recently these empirical selection rules had no satisfactory theoretical explanation. The study of symmetry properties of weak interactions (with respect to the SU_3 group) has led to substantial advances in the understanding of the origin of these rules.

A most important role was played here by three hypotheses.

a) The weak current of the strongly interacting particles J_μ transforms like the octet representation of the SU_3 group.

b) The weak current establishes a preferred direction in the abstract space in which the SU_3 group operates characterized by an angle θ. The current J_μ is written in the form

$$J_\mu = \cos\theta\, J_\mu^{\text{s.c.}} + \sin\theta\, J_\mu^{\text{s.n.c.}}, \tag{15}$$

where $J_\mu^{\text{s.c.}}$ is the strangeness conserving current, and $J_\mu^{\text{s.n.c.}}$ is the strangeness nonconserving current.

Equation (15) is valid for the vector and axial vector currents with the same value of θ.

c) The weak interactions Lagrangian, $\mathcal{L}_W$, describing the nonleptonic decays is a member of an SU_3 octet.

The first and last assumptions are independent. If use is made of more particular assumptions one can, however, find a connection between them (see below).

The strangeness carrying components of the octet have the quantum numbers of the K meson. Since for K mesons $|S| = 1$ and $I = 1/2$, we arrive automatically at the observed selection rules (13) and (14). We recall in addition that for $K^\pm$ mesons $Q = \pm 1$, $S = \pm 1$, i.e., $Q = S$.

Thus, assumptions a) and c) describe quite satisfactorily the existing situations on selection rules.

Further, comparison with experiment shows that the value of the angle $\theta \cong 0.24$ describes surprisingly well the totality of existing data on leptonic decays of strange particles. This then confirms the correctness of the choice of the weak current in the form (15) and resolves the long outstanding problem of suppression of leptonic decays of strange particles. Now for these decays $G_{\text{eff}} = G \sin\theta \cong 0.25\, G$, where G is the usual weak interactions coupling constant. In the same way, apparently, will be resolved the difficulty connected with the difference in the value of the vector weak interaction coupling constant from β decay and μ decay. With (15) taken into account the effective vector constant of β decay is $G \cos\theta \cong 0.97\, G$, i.e., it is somewhat reduced, in qualitative agreement with the data on β decay.

In addition, assumptions a) and c) establish definite relations between the amplitudes of leptonic and nonleptonic decays of the octet of baryons. The existing data on leptonic decays are not as yet sufficiently de-

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*This fact is quite naturally explained by the observation that SU_3 is a subgroup of SU_6.

tailed for a complete test of these relations but, without any doubt, such a test will be carried out in the near future.

From among the relations for nonleptonic decays we mention the following:

$$\langle \Lambda | p\pi^- \rangle + 2\langle \Xi^- | \Lambda\pi^- \rangle = \sqrt{3}\langle \Sigma^+ | p\pi^0 \rangle. \tag{16}$$

It is not hard to see that the Lagrangian corresponding to the strangeness changing nonleptonic decays can be a linear combination of octet members that transform like the K_1^0 and K_2^0 mesons (these are the only neutral, strangeness violating, components). Depending on the choice made ($\mathcal{L}_W \sim K_2^0$ or $\mathcal{L}_W \sim K_1^0$), the relation (16) is valid for the S- or the P-wave part of the amplitudes in question, and in the general case—for their mixture. At the moment the relation (16) has been tested for the full amplitudes and agrees, within the errors, with the experimental data.

The choice $\mathcal{L}_W \sim K_2^0$ is interesting because it forbids the decay $K_1^0 \rightarrow 2\pi$ (to within the accuracy that SU_3 invariance holds for the strong interactions), whereas the decay $K^+ \rightarrow 2\pi$ is allowed. Thus a possibility arises for a theoretical explanation for the ratio of probabilities for these processes, which in the past produced great difficulties.

These examples were chosen to illustrate how the symmetry properties of the weak interactions can be explored to discuss from a single point of view a great variety of phenomena and to bring clarity to a number of involved problems. The study of the symmetry properties of the weak interactions will, without doubt, continue even more intensively. Keeping this perspective in mind it is necessary to make two comments.

In the first place, the above considerations completely ignored the violation of SU_3 symmetry in the strong interactions, which should have a definite effect on the weak processes. In the future a careful analysis of these violations is imperative. Investigations in that direction have already begun.

In the second place, the symmetry properties of weak interactions have been studied with some semblance of completeness only from the point of view of the group SU_3. The enlarging of this group will necessarily lead to a corresponding review of the symmetry properties of the weak interactions and may reveal new interesting possibilities.

We have already mentioned that the establishing of the symmetry properties of the interactions constitutes but a first step in the development of an adequate dynamical theory. Investigations, whose aim is to produce a dynamical basis for the symmetries, are already under way, but successes so far are few. We still don't know the dynamical laws which underlie the appearance in strong interactions of SU_3 or SU_6 symmetry, and what is the mechanism responsible for the violation of these symmetries. We don't know why the weak interactions Lagrangian $\mathcal{L}_W$ belongs to an SU_3 octet. In the widely used version of the weak interactions theory where $\mathcal{L}_W \sim J_\mu J_\mu^+$ (the so called "current × current hypothesis") with J_μ transforming like 8, $\mathcal{L}_W$ could just as well have the transformation properties of the supermultiplets 10 and 27.

There is hope that the problem of obtaining a dynamical basis for the symmetries may be solved by the selfconsistency requirement for a system of integral equations. It is assumed that the selfconsistency requirement (the so called bootstrap mechanism) will automatically select the correct symmetry, but for the moment this assumption has not been convincingly justified. For weak interactions the hypothesis of dynamical enhancement of the octet has been advanced, which could explain point c) in the above listed assumptions. This idea, too, has not been worked out mathematically in all detail.

Certain of the assumptions for justifying the transformation properties of $\mathcal{L}_W$ are connected with the properties of the intermediate boson in weak interactions (in this connection, see below).

Without any doubt, the problem of dynamic justification of the symmetries is one of the most important problems in the physics of elementary particles and it is to be expected that a large number of theorists in all countries will devote their efforts to its solution.

3. DYNAMICAL ASPECTS OF THE THEORY OF ELEMENTARY PARTICLES AND DYNAMIC CHARACTERISTICS OF THE PROCESSES

a) Strong interactions and certain general problems of the theory. It follows from what has been said in Sec. 1 that the theory should be fully specified by the interactions between the particles. This means that the theory should in principle explain all quantitative regularities of processes involving elementary particles. The basic experimental information on elementary particle processes is obtained in the form of differential cross sections describing the result of the collision of two particles. These cross sections, on the other hand, are expressed in accordance with the general principles of quantum mechanics in terms of matrix elements of the scattering matrix (the S matrix). In this way the S matrix constitutes the central link between theory and experiment. Experimenters obtain information about the matrix elements of the S matrix, and the theorists attempt to formulate a theory whose equations produce these matrix elements. The comparison of theory and experiment tests the validity of the basic axioms used to construct the theory. In other words, the main task of elementary particle physics is, in the final analysis, the discovery of axioms starting from which and making use only of the rules of logic and mathematics all of the questions raised in Sec. 1 can be answered.

There exists a school of research in which from the very beginning axioms are formulated which are a natural generalization of quantum mechanics and the theory of relativity. Unfortunately the axiomatic quantum field theory has been developing very slowly. This approach is connected with the development of an abstract complicated mathematical apparatus and requires mathematically rigorous proofs. The authors rarely succeed in relating the starting axioms with the properties of the matrix elements of the S matrix. In this connection great value was attached to the study of the analytic properties of the S matrix as a function of relativistically invariant combinations of 4-momenta of the particles participating in the reaction. These investigations resulted in the proof of dispersion relations—integral relations connecting matrix elements of the S matrix.

The most rigorous axiomatic approach is that of Wightman and his co-workers. The main concept in this approach is that of the quantized Heisenberg field, and the main working apparatus—the vacuum expectation values of products of field operators. The weakest point of this approach consists of not only the practically complete absence of experimentally observable consequences, but also of the absence of a model example which would satisfy all the postulates and result in a nontrivial S matrix. Recently some progress has been achieved in the determination of the S matrix and proof of the dispersion relations in this approach.

In parallel with the work of Wightman investigations proceed in a different direction, in which the main concept is that of the S matrix. The basic postulates in the S-matrix approach are in part analogous to the axioms of Wightman. Of special importance among them is the principle of locality which guarantees the microcausality of the theory. An important role in the development of the S-matrix approach was played by the work of N. N. Bogolyubov and his co-workers. It was using this approach that N. N. Bogolyubov proved in 1956 dispersion relations. Experimental verification of dispersion relations has so far been carried out only for the scattering of pions by nucleons up to energies of ~ 15 BeV, and with very limited accuracy for the photoproduction of pions on nucleons at low energies. The further tests of dispersion relations are one of the most pressing problems of experimental research, since for the time being they represent the only means for testing the basic postulates of the theory and, in particular, the principle of locality.

The study of analyticity properties has resulted in one more possibility for the experimental verifications of the axioms. We have in mind the relations between cross sections for various reactions at asymptotically high energies. The first relation of this kind—the equality of total cross sections for the interaction of a particle and an antiparticle with an arbitrary particle-target—was obtained by I. Ya. Pomeranchuk.

In recent years a number of papers has appeared devoted to a rigorous proof and more precise formulation of this relation. It was clarified that the Pomeranchuk relation is a special case of a whole class of relations, which are subject to experimental verification. Based on one and the same approach relations were obtained between differential cross sections for crossed scattering processes, photoproduction processes, between polarization characteristics, also relations for processes with particle production and for form factors.

The drawback of this method of testing the axioms has to do with the lack of a definition of what energy region may be considered as being asymptotically high. In the energy regions achieved by the accelerators the resultant relations are not in agreement with experiment, however one can, apparently, speak of a clearly defined tendency towards improved agreement with increasing energy. For more reliable conclusions further work is necessary on the experimental verification of the asymptotic relations.

The success of dispersion relations has revived the hope, expressed by Heisenberg already in 1941, that the S matrix should be the basic working tool of quantum field theory. According to this approach the fundamental equations of the theory should involve only the matrix elements of the S matrix. Without any doubt, the study of the analytic properties of the S matrix occupies at this time a central place in the attempts to construct a dynamical theory of elementary particles. If simple integral relations (of the dispersion type) were found for the matrix elements of the S matrix involving an arbitrary number of particles one could hope that these relations and the unitarity conditions of the S matrix are sufficient for a complete determination of the theory.

Since the proof of the analytic properties of the amplitudes has even in the rather simple cases encountered almost unsurmountable difficulties, many theorists have taken the approach of postulating the analytic properties of the matrix elements without worrying about the connection between these properties and the fundamental axioms. Of special interest has been the so called "principle of maximal analyticity." However, explicit investigations of even the simplest cases have shown that the analyticity nature of the matrix elements is considerably more complicated.

In connection with the existence of these limitations as far as the general approaches are concerned some interest is attracted by attempts to construct a theory for certain high energy phenomena by making use of particular hypotheses (such as postulating certain analytic properties for individual matrix elements, assuming the dominance of a certain class of perturbation theory diagrams for certain processes, the resonance or pole approximation, the expansion of the S matrix in a series in the neighborhood of singularities).

These investigations make possible the unification of separate experimental facts by a common explication, the establishing of rather unexpected connections between different processes, the expressing of a group of quantities in terms of a small number of constants.

Thus, for example, it became possible to relate a whole series of strong, electromagnetic and weak interaction processes through the pion-nucleon interaction constant.

This sort of success helps to orient experiments and prepares the ground for a future theory by singling out from the experimental results easily interpretable regularities and indicating what phenomena the theory still must explain.

Among researches along these lines special hopes were raised by the approach based on the complex angular momentum method (Regge). It has now become clear that the value of this method had been greatly overestimated. Experiments did not confirm the hypothesis of dominance of Regge poles in the asymptotic behavior of cross sections. Also theoretically it has been shown that it is inconsistent to hope for the absence of branch points in the complex l plane.

The hypothesis of Regge behavior of cross sections at asymptotically high energies led to careful experimental studies, as a result of which rather precise data were obtained on the elastic (p, p), ($\pi^{\pm}$, p), ($K^{\pm}$, p) and ($\bar{p}$, p) scattering at high energies and especially at small angles. Now, however, we are without a theoretical basis for their discussion. This situation is characteristic of strong interaction physics: intensive accumulation of data on the energy and angular dependence of S-matrix elements is taking place, with rather difficult experiments being stimulated by quite shaky theoretical considerations and the results of the experiments being, as a rule, in poor agreement with these considerations. This of course does not mean that the theorists are misleading the experimenters since the experimental information obtained is needed to test not only the speculation that stimulated the given experiment but also many of the subsequent theories. As an example of this assertion may serve the experimental data on pion-nucleon scattering and pion photoproduction in the low energy region which were used to test the various attempts to construct a theory of strong interactions. One cannot expect to have a quantitative theory if there are no reliably measured quantitative characteristics available to test it. At the same time in the absence of a dynamical theory quantitative measurements seem pointless and do not inspire experimenters. In addition to stimulating experiments theoretical speculations often lead to the discovery of regularities of permanent value. The experimental study of quantitative characteristics of elementary particle interactions occupy an important place in high energy physics. Considerable efforts have been spent to deduce the elastic nucleon-nucleon scattering amplitude from the experimental data. At this time reasonable success has been achieved in carrying out the complete experiment on pp-scattering at energies up to 660 MeV. Analogous studies on np-scattering encounter considerable experimental difficulties. In performing a phase-shift analysis of nucleon-nucleon scattering the high angular momentum states are described by the one-meson Feynman diagram. At that the coupling constant (when it is taken as a free parameter) turns out to be close to the number obtained on the basis of dispersion relations from the data on πN scattering and pion photoproduction near threshold. The one-meson (or, more generally, the one-particle) exchange in elementary particle reactions has found wide generalizations in the analysis of other reactions. The one-pion exchange model is based on the fact that the pion is the lightest of strongly interacting particles and consequently has the longest range of interaction. On the basis of this model the collisions of high energy particles are classified as peripheral and central. The peripheral ones are due to interactions of longest range, i.e. to the one-meson exchange. The one-meson exchange, naturally, plays different roles in the collisions of different particles, which is reflected in the experimentally observed regularities. The sharp prominence of the one-meson exchange even at large momentum transfers is astonishing. However recently understanding of the prominent role of the one-meson exchange has been achieved, and most of the data at superhigh energies are analyzed on this basis. The inelastic interactions of particles at energies of $10^{11} - 10^{12}$ eV are successfully interpreted in terms of a two-center model for particle production (the so called fireball model). The regularities in the appearance of these phenomena have as yet been studied little. Fireballs are produced in approximately half of the collisions at energies of several hundred BeV. The mechanism of double fireballs is particularly clearly apparent at energies above 10,000 BeV. These events belong to cosmic rays physics where statistics are poor.

Most of the quantitative characteristics (principally differential cross sections) obtained experimentally await at this time a theoretical interpretation and it is difficult to state now which of these characteristics will turn out to be most useful for testing of the future theory. One can only suppose that probably the study of limiting cases will be most important, that is to say very small, $q^2 \ll m^2$, and very large, $q^2 \gg m^2$, energies (where q are the momenta and m the masses of the particles participating in the reaction), neighborhoods of resonances and thresholds, and angles close to 0°, 90° and 180°.

Considerable progress in obtaining complete information on the amplitudes of fundamental processes is expected with the beginning of the use of a polarized hydrogen target.

b) Electromagnetic interactions. Approaches based on perturbation theory and model considerations deduced from the resonance or pole approximations, have been particularly valuable in the physics of electromagnetic interactions. The physics of electromagnetic interactions is remarkable first of all in the fact that for a whole class of phenomena there exists a theory—quantum electrodynamics—which gives with amazing precision quantitative characteristics. Electrodynamics serves as the prototype, a model field theory. The electromagnetic interactions of heavy particles at low energies, and in some special cases also at high energies (for example, the electron-proton interaction), are characterized by relative simplicity and in a number of cases permit a simple, easily understandable, interpretation.

When a theory exists with a limited region of applicability, the limits of that region are of greatest interest. The limit of validity of the existing theory of electron-photon, and particularly muon-photon, interactions is of special interest. Quantum electrodynamics has a "natural" limit of applicability when at small distances (or large momentum transfers) the pion vacuum (virtual electromagnetic production of pion pairs) begins to play a significant role in electromagnetic phenomena. Consequently, in that region we shall again be faced with the problem of strong interactions in all its glory. Estimates based on the resonance approximation show that the strong interactions may play a significant role starting from distances of the order of $10^{-15} - 10^{-16}$ cm.

The problem of the limits of applicability of muon electrodynamics is particularly acute: all experiments performed so far have shown no difference between the electromagnetic interactions of the muon and the electron. The problem of the origin of the large mass of the muon continues to be one of the most interesting mysteries if one accepts the hypothesis of a field origin of particle masses. It could be expected that the muon differs from the electron in its interactions with other fields. This should give rise to a specific anomalous magnetic moment and other demonstrations of the existence of an "electromagnetic structure."

Experiments on the test of electrodynamics at small distances (ep and μp scattering, the gyromagnetic ratio of the muon, electron and muon pair production at large angles) have moved the boundary to 10^{-14} cm. So far no deviations from electrodynamics, down to distances of this order, have been discovered.

A new important stage begun in the physics of electromagnetic interactions with the increase of the maximum available under laboratory conditions photon and electron energy to 6 BeV, i.e. five times larger than what was available to experimenters till 1963.

In 1966 the upper limit on the energy is expected to reach 20 BeV when the large linear accelerator in California begins to operate. Studies in the new energy region, in addition to the above mentioned tests of validity of quantum electrodynamics, have led to a number of important results on ep scattering and meson photoproduction. Among these results the following should be mentioned:

a) Data on nucleon form factors up to values of the 4-momentum transfer squared $q^2 = 175 \times 10^{26}$ cm^{-2}; it turned out that the form factors fall off with increasing q like $1/q^2$, which result is sometimes interpreted as indicating an absence of a "nucleon hard core."

b) The amazing ratio of the cross sections for the reactions

$$\gamma + p \rightarrow \begin{cases} \pi^+ + n, & (1) \\ \pi^0 + n, & (2) \\ \eta + n & (3) \end{cases}$$

at energies in the 3 BeV region—$d\sigma^{(1)} : d\sigma^{(2)} : d\sigma^{(3)} \cong 1 : 10 : 100$.

c) A group of preliminary data on the photoproduction cross sections of mesons, resonances and strange particles in a liquid hydrogen bubble chamber.

Quantitative experiments continue in the energy region up to 1 BeV for electrons and photons. Experiments on ep scattering uncovered an interesting regularity in the ratio of the electric G_{Ep} and magnetic G_{Mp} form factors of the nucleons: $G_{Mp} = G_{Ep}\mu_p$, where μ_p is the magnetic moment of the proton. All of the available data up to the highest energies are in agreement with this relation.

The resonance approximation, as applied to electron-nucleon scattering and photoproduction processes, permits one in principle to determine the characteristics of unstable particles (particularly the coupling constant) and even to predict the existence of new particles and resonances. Thus, for example, the existence of the ρ meson was predicted from an analysis of nucleon form factors on the basis of the resonance model. However all of the existing attempts of this sort must be considered as preliminary. The resonance models of the form factors, which were intensively discussed in the past, turned out to be in contradiction with the new data on form factors at high energies and the relation $G_E = G_M$ at $q^2 = -4M^2$. The experimental information on form factors in this region is obtained from the data from the reactions $\tilde{p} + p \rightarrow \begin{cases} e^+ + e^- \\ \mu_0^+ + \mu^- \end{cases}$. At the moment only preliminary data are available on these reactions, which only allow one to assert that in the region of negative values for the square of the momentum transfer the form factors are much less than unity. The comparison of the form factors at large positive and large negative values is of fundamental significance since, according to recent theoretical works, it could serve as a test of the basic assumptions of quantum field theory.

The application of the resonance model to meson photoproduction is also of a preliminary character; in particular the characteristics of the $\gamma - 3\pi$ interaction, important for the understanding of the electromagnetic interactions, as determined from photoproduction of pions near threshold, from pion scattering with the emission of a photon, from peripheral production of ρ mesons, and from neutral pion production by negative pions in the Coulomb field, are in contradiction with each other.

The study of the electromagnetic interactions of the neutron proceeds mainly on the basis of studies of the electromagnetic interactions of few-nucleon systems (d, He^3, H^3). However the level of theoretical interpretation of the interactions of bound nucleons in terms of the properties of free nucleons is at this time already below the level of experimental accuracy.

Among other studies in the physics of electromagnetic interactions one should note the establishing of an upper limit for the electric dipole moment of the electron $d/e < 3.5 \times 10^{-16}$ cm, where e is the electron charge. This experiment verifies invariance with respect to time reversal, and a further lowering of the upper limit on d is of great interest.

c) Weak interactions. One of the central problems of the dynamics of weak interactions is the question what is their primary Lagrangian: four-fermion or a Yukawa type, in which the weak current interacts with the intermediate (vector) boson W (the so called half-weak interaction, $\mathcal{L}_{h.w.} = gJ_\mu W_\mu$). Recently the solution of this question seemed to favor the intermediate boson version (there were preliminary indications from neutrino experiments on direct production of W from nuclei irradiated by a neutrino beam). These indications, however, were not confirmed by the studies reported at the conference. The lower limit on the W mass has now been raised to 1.8 BeV.

The existence of the W meson continues to be a problem for future studies. There remain the difficult experiments with neutrinos for the search of this particle. Should the mass m_W turn out to be very large it will become more convenient to study the electromagnetic (pair) production of W or to search for effects due to its existence in strong interactions, for example the appearance of a resonance in the annihilation reaction

$$n+p \to W^+ \to \mu^+ + \nu_\mu,$$

or the appearance of leptons in the process

$$\begin{array}{l} p+p \to d+W^+ \\ \qquad\qquad\quad \searrow \\ \qquad\qquad\qquad \mu^+ + \nu_\mu . \end{array}$$

It is clear from the foregoing that if the W meson indeed exists then it is quite heavy. In that case a serious difficulty arises in how to explain its mass. The usually ascribed to it half-weak interaction, it would seem, cannot produce a large field mass, if one ignores its nonrenormalizability and the possible contributions from higher orders of perturbation theory. In connection with this difficulty suggestions have been made to the effect that the W meson possesses strong interactions. In order to preserve its role in the weak interactions it was suggested that it has a nonzero value of the C quantum number, which is not conserved by the weak interactions. (In the simplest version the W meson is an SU_3 triplet.) In this scheme the W meson can interact strongly in pairs with nucleons:

$$\mathcal{L} \sim \bar{N}N\bar{W}W.$$

On the other hand when it interacts singly with the weak current $J_\mu W_\mu$ then C is not conserved, hence the interaction is considerably weakened. If this hypothesis is correct the process of pair production of W mesons in nucleon annihilation

$$N+\bar{N} \to W+\bar{W}$$

should proceed with a large cross section. The ascribing to the W meson of definite transformation properties under the SU_3 group is independent of whether or not it possesses strong interactions and has a definite relation to the resolution of the question why $\mathcal{L}_W \in 8$. If $J_\mu \in 8$ and $W_\mu \in 3$, then the product $gJ_\mu W_\mu = \mathcal{L}_{h.w.}$ may transform like 3. If we postulate that $\mathcal{L}_{h.w.}$ always transforms like 3, then $\mathcal{L}_W = \mathcal{L}_{h.w.}\mathcal{L}^+_{h.w.}$ automatically belongs to an SU_3 octet. This introduces considerable clarity into the question of the origin of the transformation properties of $\mathcal{L}_W$ and establishes a possible connection between these properties and the properties of the current J_μ.

The assumption that $W \in 3$ brings into play neutral weak currents of strongly interacting particles, whereas their existence as always remains an unsolved problem. On the contrary, in the case of leptonic currents the existing data definitely point towards the absence of neutral components and this raises certain doubts with regard to the existence of neutral currents for the strongly interacting particles. The idea of dynamical enhancement of the octet in $\mathcal{L}_W$, mentioned in Sec. 2, does not require the existence of neutral currents for the strongly interacting particles. In this connection certain differences arise in the predictions made by the latter version of the theory and the version that makes use of the idea of an SU_3 triplet for the W, which we shall consider now.

The version of the theory with the W meson automatically gives to $\mathcal{L}_W$ the structure of the "current × current" type ($J_\mu J^+_\mu$). On the other hand this form of the interaction Lagrangian with only charged currents may be postulated independently, as is often done, and augmented by the idea of dynamical enhancement of the octet. The Lagrangian of the type $J_\mu J^+_\mu$, when both currents refer to strongly interacting particles, gives rise to a contribution from the weak interactions to the internucleon potential. A group of Soviet authors has reported at the conference the discovery of such an effect. In the observations of the decay of Cd^{114*}, produced by capture of polarized neutrons in Cd^{113}, $n + Cd^{113} \to Cd^{114*} \to Cd^{114} + \gamma$, they succeeded in detecting an asymmetry in the emission of the photons with respect to the spin direction of the neutron. The magnitude of the asymmetry was in good agreement with the value to be expected on the basis of a contribution of $\mathcal{L}_W$ to the strong interactions. The appearance of a contribution of $\mathcal{L}_W$ in nuclear effects was also observed by a group of scientists from the California Institute of Technology, who detected circular polarization of the photons from the chain

$$\begin{tikzcd} \mathrm{Hf}^{181} \arrow[r] & \mathrm{Ta}^{181*}+e^-+\nu_\mu, \arrow[d] \\ & \mathrm{Ta}^{181}+\gamma. \end{tikzcd}$$

These facts, without any doubt, point in favor of a "current × current" structure for the weak interactions Lagrangian.

The above-mentioned difference in the predictions of the theory with the W meson and the theory based on octet enhancement has to do precisely with weak processes involving strongly interacting particles. The theory with the neutral currents predicts approximately equal contributions to weak processes of transitions with $\Delta I = 0$ and $\Delta I = 1$, whereas the theory with the dynamically enhanced octet for the product of charged currents results in a dominance of transitions with $\Delta I = 0$. A test of these predictions is possible in a number of nuclear reactions (for example, in parity forbidden reactions or in reactions in which asymmetries of the above mentioned type appear). The clarification of which version of the theory actually occurs will be of great importance for the dynamics of weak interactions.

The "current × current" hypothesis predicts, among other things, also the existence of direct interactions between leptons: $(\bar{\mu}\nu_\mu)(\bar{\nu}_\mu\nu)$ and $(\bar{e}\nu_e)(\bar{\nu}_e e)$. So far these interactions have not been detected. At the moment various proposals for experiments to discover effects due to these interactions with the help of reactors, cosmic rays and accelerators, are under study. The discovery of these processes would introduce a certain order into the dynamical picture of weak interactions.

As far as some of the details of the weak interactions picture are concerned the latest data (including those reported at the conference) fully confirm the existence of two types of neutrinos; the precision with which the muon lepton number is conserved is established at the level of $10^{-3} - 10^{-4}$ from the absence of $\mu \rightarrow e + \gamma$ and at the level of 10^{-2} from direct neutrino experiments with accelerators. All existing data confirm the V – A version of the weak interactions theory as its main component (the latest data refer to the $K_{\mu 3}$ decay and the beta decay of the Λ hyperon).

A beginning has been made in the study of form factors for various processes for $q \neq 0$. In particular the neutrino experiments show that the axial vector form factor $F_A(q^2) < 1$ and that to a good approximation $F_A(q^2) = F_V(q^2)$. The value of the latter agrees not too badly with values obtained in electromagnetic measurements, in full correspondence with the conserved vector current hypothesis. The most accurate tests of this hypothesis have also yielded positive results.

The new data on muon capture in hydrogen and in nuclei are in the main in agreement with the idea of universality* for strangeness conserving processes. It is true that there are some difficulties with the results on the asymmetry of neutron emission in μ^- capture in heavy nuclei. This asymmetry is much larger than expected, which may be due to the specific dynamics of the given process or to some more basic reasons, possibly connected with violation of CP invariance.

It is important to emphasize that in all the weak interaction processes that have been studied no difference has been observed in the behavior of the muon and the electron, if one does not count the fact that each of them is accompanied by its own type of neutrino and that there are kinematic effects due to the mass difference. This deepens the mystery of the origin of the muon mass, mentioned in the Section on electromagnetic interactions, and transforms it into one of the most acute problems of elementary particle physics.

In conclusion let us mention that from a purely theoretical point of view a serious problem exists in weak interactions—that of justifying calculations usually carried out in first order of perturbation theory, since in fact we are dealing with a strongly divergent theory. This problem has also its practical aspects, since in a number of cases it is important to obtain an estimate of the contributions from higher order approximations. Certain prescriptions have been proposed for the summing of the contributions from the leading terms in each order, which, however, are in need of further justification. The development of the apparatus of dynamics of weak interaction theory has in fact barely begun in this direction and, undoubtedly, will be continued and expanded in the coming years.

In this article we have discussed mainly those studies which "lie in the mainstream." One should, however, keep in mind the oft expressed opinion, that a new theory can arise only as the result of revolutionary changes in the basic principles, in other words, it may happen that the theory will be formulated on the basis of ideas of the type of quantization of space-time, violation of causality at small distances or introduction of nonlinear Lagrangians. Unfortunately little real success has been achieved so far in the application of these ideas to concrete

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*With, as we have seen, the small correction corresponding to the replacement of G by G cos θ for processes with the participation of strongly interacting particles.

problems of elementary particle physics. Therefore a discussion of them has been left out of this review, although they do arouse considerable interest.

We have chosen for discussion those directions of study which at the moment appear to be basic from the point of view of the possibilities of obtaining answers to the questions formulated in Sec. 1. It is not out of the question that some of these will turn out to be incorrectly stated, and some of the discussed directions to produce few results: an estimate of the value of a recently obtained scientific result is almost always largely a matter of guesswork. Nevertheless it is essential to attempt to point out the basic directions and the main results, if for no other reason then for orientation purposes in the huge stream of information, which continues to grow bigger in elementary particle physics. Attempts to look into the future of elementary particle physics are particularly important also because the obtaining here of qualitatively new experimental information requires the creation of gigantic accelerators, the construction of which takes many years. The cost of these constructions often amounts to a significant fraction of national budgets. The development of physics in the last few years has also shown that an effective use of a modern accelerator is only possible if at the same time a complicated detection apparatus is constructed, which makes use of electronic calculating machines. The cost of such a complex turns out to be roughly equal to the cost of the accelerator itself.

Even in those cases when these essential conditions are met (accelerator producing a clean particle beam, and an experimental set-up allowing the detection of the interaction events between the particles), between the time when the problem is posed and the time when experimental results are obtained often many years go by, spent on adapting the experimental set-up to the concrete problem, on collecting of statistics, on control experiments and on the analysis of the experimental data.

To overcome the huge financial, organizational and technical difficulties the greatest physicists of the world spend many years of their lives. And these efforts are not in vain. Step after step we are penetrating into the most fundamental, difficult to get to know, laws of nature, and this, undoubtedly, is one of the highest goals that a scientist can hope to achieve.

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