New data on the interactions of elementary particles (from materials of the Eighteenth International Conference on High Energy Physics, Tbilisi, July 15–21, 1976)

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The Eighteenth International Conference on High Energy Physics, which took place in Tbilisi during the period July 15–21, 1976 and brought together over 800 participants, summarized the results of investigations of the strong, electromagnetic, and weak interactions of elementary particles that have been undertaken in the past two years in laboratories throughout the world. The character and trend of these investigations have been greatly influenced by the discovery in November 1974 of new elementary configurations—the J/ψ particles—a discovery which led to a succession of diverse conjectures and hypotheses and which brought about a series of new experimental arrangements. The programs of research in most scientific centers were revised and reoriented to a great extent towards the study of the properties of the new particles, the characteristics of their production in various interactions, and tests of the consequences of the various interpretations of the nature of the J/ψ particles. It is not surprising that an appreciable fraction of the papers presented at the Tbilisi Conference were concerned in some way with the new particles and that this subject was at the center of attention of the participants at the conference.

There was also great interest in recent studies of processes involving weak interactions of elementary particles, particularly neutrino processes and, specifically, processes induced by neutral currents and deep inelastic electromagnetic processes. New data on strong-interaction processes at high energies which revealed certain unexpected characteristics of these processes were reported at the conference.

We shall discuss here the principal new results pertaining to the above-mentioned types of interactions.[1)] With regret and due apologies, the authors are obliged to state that some of the data reported at the conference must inevitably remain outside the scope of this discussion.

1. NEW PARTICLES

One of the central events of the Tbilisi Conference was a report on the observation of the first specimens of the family of "charmed" particles, i.e., particles which carry the new quantum number "charm." The discovery of charmed particles has created a new field of research in elementary-particle physics—the study of the properties and decay characteristics of these particles.

The discovery of the new particles (barring any unforeseen disappointment) was an indisputable success of the theory. It is well known that the original quark model of Gell-Mann and Zweig, which was based on three quarks q (u, d, s) and enjoyed great success in describing the basic properties of the hadrons, encountered major difficulties in describing the weak interactions, since it led, for example, to appreicable strangeness-changing neutral currents. It was shown by Glashow, Iliopoulos, and Maiani that this difficulty is automatically eliminated if one introduces a fourth (charmed) quark c. The introduction of this new quark led directly to the conclusion that there exists a new family of elementary particles: charmed particles (mesons of the type $(c\bar{q})$ and baryons of the type (cqq), (ccq), or (ccc)) and particles with hidden charm (mesons of the type $(c\bar{c})$). Recent data confirm that this conclusion is correct. In order to give a better appraisal and systematization of the current experimental situation, we shall present a more detailed account of the consequences of the four-quark model.

A. $c\bar{c}$ spectroscopy (charmonium spectroscopy)

It is expected that there exists a family of SU_3-singlet neutral mesons with quantum numbers $P=(-1)^{L+1}$ and $C=(-1)^{L+s}$, where L and s are the orbital angular momentum and spin of the $c\bar{c}$ pair. The ψ (3095) meson which was discovered two years ago must then be interpreted as an ortho-state of a $c\bar{c}$ pair with $J^{PC}=1^{--}$, and the ψ' (3684) must be interpreted as a radial excitation of the ψ. The masses of the ψ mesons enable us to estimate the mass of the c quark as $m_c \approx 1.5$ GeV, which is much greater than the masses of the q quarks.

B. Spectroscopy of charmed particles

It is predicted that there exist long-lived ($\tau \approx 10^{-12}$–10^{-13} sec) pseudoscalar mesons $D^0=(c\bar{u})$ and $D^+=(c\bar{d})$, vector mesons D^* and F^*, and baryons B_c: (cqq),

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TABLE I.

m_χ	3415	3450	3500	3550
J^P	0^+	0^-	1^+	2^+

(ccq), and (ccc). The new particles are expected to have masses in the region of 2 GeV (on the basis of the c-quark mass), and we must evidently have $m(D) < m(F) < m(B_c)$.

C. Decays and selection rules

Since the strong and electromagnetic interactions conserve charm, it is the weak interaction that is responsible for the decays of charmed particles. In the framework of the simplest quark scheme, these decays are primarily due to the transitions $c \to u\bar{d}s$ and $c \to sl^+\nu_l$ $(l = e, \mu)$. Most of the decays of D mesons should therefore involve kaon emission (and the decays of the baryons (cqq) should involve the emission of kaons or $\Lambda(\Sigma)$ hyperons). A characteristic prediction of this model is that K^- mesons should be emitted in D^+ decays into $K(n\pi)$, while K^+-meson emission is forbidden. These qualitative predictions are confirmed experimentally.

The experimental data on the new hadrons were reviewed in the rapporteur talks by R. Schwitters (U.S.A.) and B. Wiik (West Germany) and by S. P. Denisov (U.S.S.R.), while the theoretical situation was reviewed in a paper by A. De Rujula (U.S.A.).

1) *$c\bar{c}$ spectroscopy*. Reports were presented at the conference on data obtained by various groups at the SPEAR and DORIS accelerators, favoring the existence of four C-even states: $\chi(3415)$, $\chi(3450)$, $\chi(3500)$, and $\chi(3550)$ (the uncertainties in the masses are less than or of order 10 MeV). These states were studied in the radiative decays $\psi' \to \gamma + \chi$. Their most probable J^P values on the basis of the existing data are given in Table I.

The branching ratio for the decays $\psi' \to \gamma\chi$ among all the ψ' decay modes has now been determined more accurately to be $\approx 20\%$, a value which appears to resolve the problem of the missing ψ' decays that has been a source of concern for over a year.

The decays $\psi \to \gamma X \to 3\gamma$ have been studied at the DORIS accelerator. Apart from the observation of the known η and η' particles in these decays, a peak of 3.3 standard deviations was seen in the mass region 2.8 GeV $< m(X) < 2.9$ GeV. The relative probability of a transition into this state is given by $B(\psi \to \gamma X)B(X \to 2\gamma) = 1.6 \times 10^{-4}$. However, an analysis of the decay $\psi \to p\bar{p}\gamma$ carried out at SPEAR revealed no state of mass 2.8 GeV in the $p\bar{p}$ system. The experimental limit is $B(\psi \to \gamma X)B(X \to p\bar{p}) < 4 \times 10^{-5}$. From the point of view of testing the predictions of the quark model, it is of great importance to ascertain whether there exists a state that has a natural interpretation as a pseudoscalar meson constructed from a c and $\bar{c}$ quark (η_c) and to determine its mass, but this problem has not yet been fully resolved.

2) *Charmed particles*. The SLAC-LBL group presented a paper at the conference in which they reported the observation of narrow peaks in the $K(n\pi)$ systems and in their associated missing-mass spectra. The measurements were made in the energy range 3.9–4.6 GeV, in which, on the one hand, the production of new particles is energetically possible and, on the other hand, the sharp growth and characteristic structure of the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ indicate that new physical phenomena occur in this region. Peaks of mass 1865 ± 15 MeV and width $\Gamma < 40$ MeV, corresponding to the experimental resolution, were seen in the $K^\pm\pi^\mp$ and $K^\pm\pi^\mp\pi^+\pi^-$ systems. Studies of the missing-mass spectra of the $K\pi$ and $K3\pi$ systems showed that these systems are produced in association with heavier states.

The numbers of events in the $K^\pm\pi^\mp$ and $K^\pm\pi^\mp\pi^+\pi^-$ systems in the resonance region correspond to a product of the cross section and the relative decay probability (σB) equal to 0.52 ± 0.05 nb and 0.72 ± 0.18 nb, respectively. The value of σB falls off slowly with increasing energy.

Peaks have also been seen in the charged-meson combinations $K^\pm\pi^\mp\pi^\mp$, corresponding to exotic states ($Q = \pm 1$, $S = \mp 1$) of mass 1876 ± 15 MeV and $\Gamma < 40$ MeV, in an analysis of multi-track events in the energy range 4.0–4.16 MeV. The spectrum of recoil masses has a peak near 2.01 GeV. The quantity σB for this resonance is equal to 0.27 ± 0.05 nb at 4.03 GeV.

A very important circumstance is that no statistically reliable peaks have been found in the mass spectrum of the non-exotic $K^\pm\pi^\pm\pi^\mp$ system. In addition, no peaks have been seen in the $K^\pm\pi^\pm$, $\pi^+\pi^-$, and $\pi^+\pi^+\pi^-$ systems.

These facts are in good agreement with the theoretical expectations described above, and they can be interpreted most naturally as the discovery of a doublet of D mesons. If we attempt to interpret these peaks as hadronic resonances, we must assume that there exist at least two resonances with very similar masses and identical quantum numbers. This possibility seems rather unnatural. In this case, there is no convincing explanation of the spectrum of recoil masses. We note, however, that the observation of semi-leptonic decays of the new particles would provide a reliable confirmation of the existence of the quantum number "charm" (see below).

Searches for charmed-particle production in hadron-hadron collisions have so far not led to such definitive results as in the case of e^+e^- annihilation. Yields have been observed in the effective-mass spectra of various combinations of particles near 2 GeV in a number of cases, but the statistical reliability of these yields is so far inadequate. Considering the existing data on D^0, it would be of interest to observe the $K^0\pi^0$ system with mass ~ 1.87 GeV at Serpukhov. The JINR group working at Serpukhov observed a peak in the mass spectrum of the $\Lambda\pi^+\pi^-$ system (containing 14 events) at 2.09 GeV, which can be taken as evidence for the existence of a charmed baryon having this mass.

After the conference, there appeared a paper reporting the observation of photoproduction of a charmed antibaryon of mass 2.26 GeV and $\Gamma < 75$ MeV in the $\bar{\Lambda}\pi^-\pi^-\pi^+$ system, using the high-energy photon beam at FNAL.

No peak was found in the $\bar{\Lambda}\pi^+\pi^+\pi^-$ system, in accordance with what is expected in the scheme involving charm. There is evidence for the existence of the cascade.

$$\bar{\Lambda}(4\pi)^0 (m \approx 2.5 \text{GeV}) \rightarrow \bar{\Lambda}(3\pi)^- (m \approx 2.26 \text{GeV}) + \pi^+.$$

3) *μe events and direct leptons*. It appears that charmed-particle production is intimately related to the observation of so-called μe events in a number of processes, i.e., events in which an electron and a muon seem to originate in the same interaction event within the existing experimental space-time resolution. One of the possible origins of μe events is the rapid ($\tau \lesssim 10^{-12}$ sec) semi-leptonic decays of charmed particles produced in the interaction process responsible for the emission of the electron or the muon, or (in the case of associated production) both particles at the same time, from practically the point of interaction. This same mechanism should also be responsible to some extent for "direct" (i.e., non-decay) leptons in hadron-hadron collisions.

Most of the μe events have been observed in neutrino processes. Groups working on the FNAL and CERN accelerators presented papers at the conference reporting bubble-chamber data on neutrino-induced events of the type

$$\nu_\mu + N \rightarrow \mu^- + e^+ + \text{anything} .$$

A total of 15 such events were detected at FNAL, and 12 at CERN. Of the 15 $\mu^- e^+$ events detected at FNAL, 11 were accompanied by a V^0 particle (i.e., K^0_S or Λ). At CERN, V^0 particles were observed in three events. The presence of strange particles among the final products of the reaction constitutes further evidence that these events involve the decays of charmed particles. Since μ^- production in neutrino processes is due to ν_μ charge exchange, we must assume that single production of charmed particles and their subsequent semi-leptonic decay have been observed in these events (the e^+ charge has precisely the expected sign in this case). The yield of $\mu^- e^+$ events is at the level of $\sim 1\%$ of all the single-muon events.

The CERN group obtained preliminary data suggesting the existence of μe events in proton-proton collisions in the storage rings (ISR). These events are presumably also due to the decays of charmed particles. In addition, μe events and "direct" leptons have been observed in e^+e^- annihilation processes. In this case, there are evidently two different mechanisms that lead to μe events and "direct" leptons.

Papers were presented at the conference reporting a large quantity of data obtained at DORIS and SPEAR on the processes

$$e^+e^- \rightarrow e^\mp + \mu^\pm + \text{missing energy} , \quad (1)$$
$$e^+e^- \rightarrow e(\mu) + X. \quad (2)$$

Correlations between the yields of "direct" $e^\pm$ and $K^\pm, K^0_S$ mesons have also been studied.

These events were found in the same energy region as the new hadrons. The energy dependence of the production cross section for μe events and "direct" leptons has a pronounced threshold behavior. It would be most natural to interpret these events as the result of the production and subsequent multi-particle decay of a pair of charmed particles. However, the "direct" leptons might also originate from the decays of hypothetical heavy leptons with mass in the region of 2 GeV. The scheme involving a charmed quark does not necessarily imply the existence of heavy leptons; however, various experimental data on e^+e^- annihilation, particularly the value of R above 5 GeV and certain characteristics of the μe events, apparently cannot be satisfactorily described in terms of charmed particles alone.

The principal differences between the hadronic decays of heavy leptons and the semi-leptonic decays of charmed mesons are as follows: 1) the momentum distribution of charged leptons in the case of D-meson decays is concentrated within a region of lower momenta than in the case of heavy-lepton decays; 2) the charged and neutral tracks accompanying "direct" leptons should have a much larger multiplicity in the case of the D meson than in the case of the heavy lepton, where the multiplicity is of order 2–3; 3) in contrast with heavy-lepton decay, there should be significant Ke correlations in the case of D-meson decay.

The DASP spectrometer has been used to measure the inclusive spectra of "direct" $e^\pm$ in the energy regions 3.60–3.68 GeV, 4.0–4.2 GeV, and 4.4 GeV. In the energy region 3.60–3.68 GeV the signal did not exceed the background, while at energies 4.0–4.2 GeV a distinct signal was observed, with an $e^\pm$ spectrum that falls off sharply for $p > 0.7$ GeV and an accompanying multiplicity of charged and neutral tracks equal to 5–6. At 4.4 GeV the statistics are smaller, but there is still a signal with approximately the same properties. The characteristics of these events exclude the possibility of explaining them by means of the decay of a heavy lepton, and it appears that they must be explained by the semi-leptonic decays of a new hadron H with $m(H) \approx 2$ GeV. The yield of leptons corresponds to a cross section $\sigma(e^+e^- \rightarrow H^+H^-) \cdot 2B(H \rightarrow eX) > 1$ nb at 4.1 GeV and $\sigma(e^+e^- \rightarrow H^+H^-) \cdot 2B(H \rightarrow eX) > 0.44$ nb at 4.4 GeV.

The observation by the DASP group of events containing charged kaons in coincidence with "direct" electrons constitutes strong evidence that the hadron H has a new quantum number—charm. Measurements were made in the energy regions <3.8 GeV, 4.0–4.3 GeV, and 4.3–4.5 GeV. A definite correlation was found only in the range 4.0–4.3 GeV. A qualitatively similar situation occurs in measurements of $K^0_S e$ correlations carried out by the PLUTO group.

The μe events observed at SPEAR have been a subject of lively discussion for about a year. So far, 139 such events (with an expected background of 34) have been detected in the energy range 3.8–7.8 GeV. The experiments involved the selection of those events containing a non-collinear electron and muon (with momentum greater than 0.65 GeV) in which no other charged particles or photons were detected. The yield of these events exhibits a pronounced threshold behavior, and the distributions with respect to the angles of noncollinearity and the lepton momenta indicate that they origi-

TABLE II. Searches for new narrow resonances.

Mass range, GeV	Laboratory	Limit on the lepton width
0.78–1.34	Novosibirsk	$\Gamma_{ee} < 200$ eV
2.5–3.0	Frascati	$\Gamma_{ee} < 500$ eV
3.2–7.4	SLAC	$\Gamma_{ee} < 500$ eV
5.7–6.4	SLAC	$\Gamma_{ee} < 100$ eV
7.0–7.4	SLAC	$\Gamma_{ee} < 60$ eV

nate from multi-particle decays of pairs of particles with masses in the range 1.6–2.0 GeV (the latest reports indicate that the mass may be somewhat greater).

We note that the existence of μe events was confirmed at SPEAR using a special muon detector (a muon tower), in which 12 such events were observed against a background of one event.

Evidence against an explanation of these events in terms of the decays of charmed particles is provided by the fact that they involve no additional hadrons or photons, as well as by the shape of the distribution with respect to the lepton momenta and the absence of any correlations between the production cross section for μe pairs and the structure of the quantity R. All the available data on μe events can be reconciled with the assumption that these events originate from the decays of new heavy leptons with a new lepton number analogous to muonic charge. The relative probability for decay into the lepton channel is $B=0.17^{+0.06}_{-0.03}$. This interpretation is also supported by measurements at SPEAR of "direct" high-energy muons (with momentum greater than 1.05 GeV) at 4.8 GeV.

The observation of μe events using the PLUTO detector at DORIS was reported. Although a symbol has already been reserved for the new heavy leptons (τ, as proposed by Perl), the situation is not completely clear at the present time and requires further experimental study.

4) *Searches for new narrow resonances in e^+e^- annihilation.* Extensive data on the search for narrow resonances ($\Gamma < 10$ MeV) in the direct channel of e^+e^- annihilation into hadrons were presented at the conference. The search for such particles, which would be analogous to the ψ mesons, is of special interest from the point of view of investigating the possible existence of other quarks (apart from the u, d, s, and c quarks) in the various multi-quark schemes.

No new narrow resonances in e^+e^- annihilation have been found. The experimental limits on their leptonic widths obtained by various groups are given in Table II.

In particular, the SLAC results do not confirm the existence of the resonance Υ, whose discovery had been claimed by the FNAL group ($m(\Upsilon) \simeq 6$ GeV).

The conference also heard a report on the observation at DESY of the photoproduction on the proton of a new narrow resonance of mass 1.1 GeV, which decays into e^+e^-. However, the existence of this resonance is in conflict with the results of a search for narrow resonances in e^+e^- annihilation at Novosibirsk, and it would be highly desirable to carry out further investigations in this energy region.

Thus all the experimental data on new particles discussed above are in qualitative agreement with the predictions of the four-quark model. Of course, it has not yet been irrefutably proved that the new hadrons decay as a result of the weak interaction (i.e., there are large lifetimes and appreciable semi-leptonic decays, nonconservation of parity is observed, etc.), and grounds for skepticism remain. However, it is difficult at the present time to imagine another model that might explain the existing data in a natural way.

If it turns out that the μe events in the e^+e^- annihilation process actually involve the production and subsequent decay of heavy leptons, this would be theoretical evidence of the need to revise the simple 4-quark scheme.

A necessary condition for the construction of a unified theory of electromagnetic and weak interactions with no Adler anomalies is that $\sum_i Q_i = 0$, where the sum is taken over all the leptons and quarks. This condition is satisfied for the electron, muon, and four quarks. The existence of heavy leptons requires the introduction of additional quarks. Moreover, as we have already mentioned, the value of R above 5 GeV ($R=5.5\pm0.5$) is too large in comparison with what might be expected in the 4-quark model ($R=\frac{4}{3}$) even if allowance is made for a contribution from heavy-lepton decays (effectively $\Delta R \approx 0.7$); i.e., the total value would be $R=3.3+0.7=4$, although it must of course be borne in mind that this value of R refers to asymptotic energies.

A number of papers presented at the conference discussed the results of experiments on e^+e^- annihilation in the framework of models in which the number of valence quarks is $n=5$ or 6. Taking into account the contribution to R from heavy leptons, it was found that the experimental data are best described on the basis of five quarks, with $Q_5=-\frac{1}{3}$. Nevertheless, the extent to which it is necessary to go beyond the framework of the 4-quark model to describe the experimental data remains an open question. Further investigations are required to answer this question.

2. WEAK INTERACTIONS AND NEUTRINO PROCESSES

The rapporteur talks of the Soviet delegates S. S. Gershteĭn and B. A. Arbuzov were devoted to problems in weak-interaction physics. An important aspect of weak-interaction physics during the period between the 17th and 18th Conferences on High Energy Physics has been the study of the properties of neutral currents, whose discovery was reported at the preceding 17th Conference in London. The question of whether parity is conserved in processes induced by neutral currents was of the greatest interest in this connection. This interest was connected largely with theoretical constructions using 6-quark models which predict a purely vec-

TABLE III.

$\sigma^{\bar{\nu}}_{NC}/\sigma^{\nu}_{NC}$	Group
0.52 ± 0.16	CERN
0.81 ± 0.25	Harvard, Pennsylvania, and Wisconsin Universities and Fermi National Accelerator Laboratory
0.75 ± 0.14	California Institute of Technology

tor character for the neutral currents (and hence the conservation of parity in the corresponding transitions).

Several papers presented at the conference gave definitive evidence that parity is violated in processes induced by the neutral currents. Of these papers, special mention should be made of a study of elastic scattering of neutrinos (and antineutrinos) by protons at BNL. In this experiment, 30 events of the reaction $\nu_\mu p \to \nu_\mu p$ and 22 events of the reaction $\bar{\nu}_\mu p \to \bar{\nu}_\mu p$ were detected. On the basis of these data, the quantity $\sigma(\bar{\nu}p \to \bar{\nu})/\sigma(\nu p \to \nu p)$ was found to have the value 0.35 ± 0.2, while for a purely vector current this quantity has the value 1.

Similar conclusions regarding the nature of the neutral current were obtained by the Aachen–Padua collaboration from a study of scattering of the muonic neutrino (antineutrino) by the electron. This group found 13 events for the reaction $\nu_\mu + e^- \to \nu_\mu + e^-$ and 16 events for the reaction $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$. These data lead to a value

$$\frac{\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{\sigma(\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-)} = 0.44 \pm 0.26,$$

which is very different from both the value 1 (for a pure V or A variant) and the value 3 predicted by the $V-A$ variant.

The data on $\nu_\mu p$ scattering and $\nu_\mu e^-$ scattering can be described by the Weinberg–Salam model, and the two values obtained for the quantity $\sin^2\theta_W$ are not very different: $\sin^2\theta_W = 0.3^{+0.05}_{-0.1}$ in the first case, and $0.4 \leq \sin^2\theta_W \leq 0.7$ in the second case.

The same conclusions regarding the properties of the neutral current follow from an analysis of the inclusive process of antineutrino-nucleon scattering, $\bar{\nu}_\mu + N \to \bar{\nu}_\mu + X$, in particular from a study of the y-distribution.

More accurate values of the total cross sections for the interactions of neutrinos and antineutrinos with nucleons induced by neutral currents also indicate that the neutral current does not have a purely vector character. Various groups have obtained the values shown in Table III for the ratio of total cross sections $\sigma^{\bar{\nu}}_{NC}/\sigma^{\nu}_{NC}$, while the purely vector variant predicts that $\sigma^{\bar{\nu}}_{NC}/\sigma^{\nu}_{NC} = 1$.

It should also be mentioned that a detailed study of the ratio of the numbers of neutral and charged pions produced in the process $\nu_\mu + N \to \nu_\mu + N + \pi$ at CERN has made it possible to reject the purely isoscalar variant of the weak neutral hadron current and suggested that this current also contains an isovector component.

Of the other work on weak interactions discussed at the Tbilisi Conference, the first results on the study of the process $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$ using reactor antineutrinos attracted attention. After lengthy efforts, it was possible to separate the effect from the background and obtain information about the magnitude of the cross section for this process:

$$\sigma_{\bar{\nu}e} = (0.86 \pm 0.25)\,\sigma_{V-A} \quad \text{for} \quad 1.5 \leqslant E_{\bar{\nu}} \leqslant 3 \text{ MeV},$$
$$\sigma_{\bar{\nu}e} = (1.7 \pm 0.44)\,\sigma_{V-A} \quad \text{for} \quad 3 \leqslant E_{\bar{\nu}} \leqslant 4.5 \text{ MeV}.$$

Both charged and neutral currents contribute to the scattering process $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$. Assuming that these currents are described by the Weinberg–Salam model, $\sin^2\theta_W$ is found to have the value $\sin^2\theta_W = 0.29 \pm 0.05$.

Recent work has revealed a number of interesting properties of neutrino processes induced by charged currents, i.e., processes of the type

$$\nu_\mu + N \to \mu^- + X,$$
$$\bar{\nu}_\mu + N \to \mu^+ + X.$$

It was claimed at the conference with greater certainty than before that there exists a y-anomaly in the $\bar{\nu}_\mu$ interaction cross section at energies $E_{\bar{\nu}} > 50$ GeV, i.e., an excess of events with $y \approx 1$ and a deviation from the simple dependence $d\sigma^{\bar{\nu}}/dy \sim (1-y)^2$. At the same time, evidence has been found for a growth of the quantity $\sigma^{\bar{\nu}}_{cc}/\sigma^{\nu}_{cc}$ with increasing neutrino energy from a value $\sim \frac{1}{3}$ at low energies (<10 GeV) to a value ~ 0.6 at $E_\nu \simeq 200$ GeV. These two circumstances may be related to one another and suggest that more and more quarks from the "sea" take part in the neutrino process with increasing neutrino energy. The contribution of the quarks from the sea can then affect the behavior of neutrino and antineutrino processes differently, leading to violations of charge symmetry. However, we cannot exclude an alternative interpretation of the observed properties of neutrino processes, according to which it is assumed that there exist $V+A$ charged currents and additional quarks (other than the u, d, s, and c considered above). In this respect, further investigations are necessary.

There has been interest in data on the growth of the yield of strange particles in neutrino processes with increasing neutrino (or antineutrino) energy. At ~100 GeV this yield is 15–20% of the total number of events, while at energies below 10 GeV it is only ~3%.

It should also be mentioned that the ITEP group has obtained a new upper limit of 35 eV on the mass of the electronic neutrino.

3. THE PARTON MODEL AND EXPERIMENTAL DATA

In recent international conferences on high-energy physics, it has become traditional to consider how well the predictions of the parton model agree with experiment. The parton model, in which hadrons are represented in the form of point-like constituents known as partons, provides a qualitatively successful description of deep inelastic lepton-hadron scattering, hadron scattering with large transverse momenta, and e^+e^- annihilation at high energies. These subjects were discussed at the conference in the rapporteur talks by V. I. Zakharov

(U.S.S.R.), P. Darriulet (CERN), and R. Schwitters (U.S.A.), respectively.

Although the parton model cannot at the present time be derived as a consequence of a consistent theory, there have been promising attempts to understand the parton picture in terms of an asymptotically free quantum field theory—the so-called quantum chromodynamics. In this scheme, the quark-quark interaction is due to gauge fields associated with a non-Abelian symmetry group and vanishes at small inter-quark distances. Unlike the naive parton model, quantum chromodynamics leads to a specific violation of gauge invariance of the structure functions, a growth in the average transverse momentum p_T of the hadrons with increasing Q^2 (where Q^2 is the momentum transferred by the lepton), and a number of other predictions.

Some new experimental results which are of great significance as tests of the parton model were presented at the conference. The main results are as follows:

a) Data obtained at FNAL on muon-proton scattering confirm that the ratio of cross sections σ_L/σ_T for the interactions of longitudinally and transversely polarized photons is small. This quantity is close to zero (with an error of 0.3). In the naive parton model $\sigma_L/\sigma_T \sim 1/Q^2$, while in quantum chromodynamics $\sigma_L/\sigma_T \sim g/\ln Q^2$, where g is the gluon interaction constant.

b) The data on neutrino reactions and deep inelastic electroproduction seem to indicate that the magnitude of p_T is limited and independent (or weakly dependent) on Q^2 ($Q^2 \leqslant 60$ GeV^2 for neutrino-induced reactions and $Q^2 \leqslant 17$ GeV^2 for muon-induced reactions).

c) The data from neutrino experiments indicate that the admixture of antiquarks in the nucleon is small at moderate energies: $\alpha = \int \bar{q}\,dx / \int (q+\bar{q})dx = 0.05 \pm 0.02$ (CERN), where q ($\bar{q}$) is the distribution function for quarks (antiquarks) in the nucleon; but it appears that α rises to 15–20% at FNAL energies (see above).

d) There was great interest in a reported observation of deviations from the scale-invariant behavior of the structure function $F_2(x)$ for deep inelastic electroproduction. These deviations are in qualitative agreement with those expected from an asymptotically free theory, in which increasing Q^2 should lead to a growth of F_2 in the small-x region and a fall-off for x close to 1. However, the observed growth with Q^2 at small x seems too rapid. It is possible that the effects at small x are due to the production of new particles.

The parton model provides a good qualitative description of the properties of processes involving the production of hadrons with large p_T. There is a vast quantity of experimental data on the properties of hadronic jets in these processes.

The data on e^+e^- annihilation into hadrons in the energy range 2.4 GeV $< \sqrt{s} <$ 8 GeV also confirm a number of important predictions of the parton model. We cite the following facts:

a) The most important result is the observation of hadronic jets for $\sqrt{s} > 5$ GeV with hadrons having an average p_T with respect to the jet axis of order 300 MeV/c and an angular distribution of the jet axis given by $1+\cos^2\theta$, as expected in the parton model. A preliminary analysis also indicates universal properties of the jets in e^+e^- annihilation, νp and ep scattering, and processes involving the production of hadrons with large p_T.

b) A scale-invariant behavior of the inclusive hadron spectra

$$s\frac{d\sigma}{dx} = f(x) \quad \left(x = \frac{2p}{\sqrt{s}}\right)$$

holds (to an accuracy of order 20%) for $x > 0.4$ over the entire energy range and for $x > 0.2$ when $\sqrt{s} > 5$ GeV.

c) The ratio of the cross sections for e^+e^- annihilation into hadrons and into muon pairs has the value $R \simeq 2.5$ and is practically independent of energy for 2.5 GeV $< \sqrt{s} <$ 4 GeV, in accordance with the predictions of the model of colored q quarks ($R_q = 2$). As we have already pointed out, the theoretical situation regarding the explanation of the value $R \approx 5$ for 5 GeV $< \sqrt{s} <$ 8 GeV is unsatisfactory.

d) The energy dependence of the average multiplicity of charged particles is consistent with a logarithmic law.

We note also that the so-called "energy crisis," i.e., the fact that the fraction of the energy carried away by the charged particles in e^+e^- annihilation is less than $\frac{2}{3}$ and is decreasing as a function of energy, cannot be explained in the framework of the parton picture and may be connected with the properties of charmed-particle decays.

In general, the experimental comparison of the results of the naive parton model and of quantum chromodynamics requires further experimental investigation over as wide as possible a range of values of Q^2.

It appears that we can make only the following statements regarding the current situation:

a) The naive parton model provides a good description of a large set of experimental data on various processes.

b) It is possible that the first experimental data favoring asymptotically free theories have appeared.

4. STRONG INTERACTIONS

Various theoretical and experimental aspects of strong-interaction physics at high energies were discussed at the conference in the rapporteur talks by V. A. Matveev (JINR), A. B. Kaĭdalov (U.S.S.R.), P. V. Shlyapnikov (U.S.S.R.), and I. M. Dremin (U.S.S.R.), and problems related to hadron spectroscopy were discussed in the talks by K. Lanius (JINR) and A. T. Filippov (JINR).

A general review of the existing approaches to the theory of the strong interactions included the results of recent work on the derivation of rigorous bounds on scattering amplitudes from the fundamental principles of quantum field theory. There were discussions of the phenomenological description of interaction processes, the Regge approach, and the quark-model description, with special attention to the model in which the cross section has an asymptotic behavior of the form $\sigma \sim \ln^2 s$, as well as three-component duality. There were discussions of the extent to which the Regge description can be derived from models of quantum field theory and the use of the density matrix as a means of studying multiparticle processes.

Processes involving large momentum transfers are well described by power laws governed by the internal structure of the hadrons. There were detailed discussions of the existence of power laws and their application to the description of the angular dependences and absolute values of differential cross sections and polarizations. Interesting results regarding the problem of an elementary length in particle physics were also reported. A new scheme for introducing an elementary length leads to a number of well-defined predictions about small-distance behavior, including in particular a violation of parity in the strong interactions.

New data on meson and baryon resonances, as before, are in good agreement with the idea that their quark structures are given by $(q\bar{q})$ and (qqq), respectively. There is still no evidence for the existence of exotic states, which would correspond to more complex quark configurations. All the states which have been studied can be adequately classified according to the representations of the group $SU(6) \otimes O(3)$. Experiments have revealed two more mesons with the quantum numbers $J^P = 3^-$ (ω^* (1675) and K^* (1780)), corresponding to orbital angular momentum $L = 2$ for the system $(q\bar{q})$, as well as a meson h (2040) (Serpukhov-CERN-Vienna-Karlsruhe-Pisa collaboration) with $J^P = 4^+$ and $I = 0$, corresponding to $L = 3$.

Quantitative calculations of the characteristics of bound quantum systems still entail many difficulties, owing to insufficient knowledge of the dynamics of quark systems and the resultant diversity of approaches (the oscillator model, "bags," etc.).

One of the principal sources of information about the mechanisms of hadronic interactions at high energies is the study of binary and few-body processes. Several years ago, the existing experimental data on elastic scattering provided grounds for regarding the differential cross section for elastic hadron-hadron scattering at high energies and small momentum transfers as a simple structureless exponential function of the square of the momentum transfer t. From the point of view of the "geometric" picture of the scattering, such a dependence corresponds to a Gaussian fall-off of the scattering amplitude with increasing impact distance. Measurements carried out in 1972 with the CERN colliding beams at an equivalent laboratory momentum $\sim 10^3$ GeV/c revealed a "break" in the differential cross section for elastic scattering at $t \approx -0.15$ (GeV/c)^2. The existence of this break indicates that the amplitude falls off more slowly than the Gaussian law at large impact distances ρ.

Recent measurements have shown that this break is not merely a feature of high energies, but that it shows up in experiments carried out at Batavia ($p \sim 10^2$ GeV/c) and at Stanford ($p \sim 10$ GeV/c). Moreover, it has been found that the structure of the forward peak is much more complex than just a single break. Thus, it was found at Batavia that there is a decrease in the slope of the differential cross section for pp scattering with decreasing $|t|$ in the region of very small momentum transfers ($|t| \lesssim 0.1$ (GeV/c)^2)—an effect observed for the first time in proton-proton scattering.

These results are evidently closely related to another phenomenon observed in experiments on elastic pp scattering at 60 GeV/c using the Serpukhov accelerator. These experiments showed that, in relation to its average value corresponding to a peak with a break, the experimental differential cross section oscillates with a period $\Delta t \sim 0.4$ (GeV/c)^2. The same structure is present in data obtained at FNAL. The possible existence of such a small-scale oscillatory structure was previously predicted theoretically. It can be explained from the "geometric" point of view by the presence of contributions to the amplitude from processes that take place mainly at the periphery of a hadron at distances of order 1 F. The most suitable candidates for these processes are inelastic diffraction processes, whose peripheral character has recently become more and more apparent.

A similar small-scale oscillatory structure was found in the scattering of relativistic nuclei, which has been studied at the JINR.

A number of interesting results have been obtained from the study of elastic scattering at large momentum transfers.

A comparison of data on pp and pn scattering suggested a discrepancy between them for $|t| \gtrsim 1$ (GeV/c)^2. If these results are confirmed, they will modify the usual idea that the behavior of $d\sigma(NN)/dt$ in this region is determined entirely by the t-channel exchange with zero isotopic spin.

The CERN colliding beams at $\sqrt{s} = 53$ GeV were used to measure the differential cross section for elastic pp scattering up to $|t| = 9$ (GeV/c)^2. After the first diffraction minimum at $t = -(1.34 \pm 0.02)$ (GeV/c)^2, the cross section exhibits a smooth exponential fall-off with slope (1.81 ± 0.02) (GeV/c)^2, with no sign of a change in the slope or a second minimum, at least up to $-t = 6.5$ (GeV/c)^2. None of the theoretical models proposed so far for the description of large-angle elastic scattering has predicted a simple exponential fall-off of the cross section with such a small slope over such a wide range of t.

Measurements of pp scattering in various spin states at ANL using a polarized proton beam of energy up to 12 GeV revealed that spin effects play a major role at large momentum transfers. It is important to note that spin effects were found to increase with energy for $|t| > 1$ (GeV/c)^2, whereas at small $|t|$ they die away with increasing energy. This interesting phenomenon has not yet been explained theoretically.

In the theory of diffraction scattering, considerable attention has been given to the problem of the "bare" pomeron, whose trajectory at $t=0$ lies above unity: $\alpha_P(0)=1+\Delta>1$.

It is well known that calculations in a theory with $\alpha_P(0)=1$ lead to a growth of the total cross sections (due to the decreasing negative cut contribution) at a rate $d\ln\sigma(s)/d\ln s$ of about 2–3%, which is not high enough to reproduce the rate of growth of 6–7% found experimentally at Batavia and CERN. New experimental cosmic-ray data suggest that such a growth continues up to energies $\sim 10^5$ GeV. These facts have stimulated interest in schemes with $\alpha_P(0)>1$. Such a model leads to interesting consequences, such as a violation of Feynman scaling and, under certain conditions, geometric scaling, i.e., a dependence of the amplitude on the ratio $\rho/R(s)$. This results in a picture of the scattering which is very similar to geometric models of diffraction scattering.

Geometric models which assume saturation of the Froissart bound on the rate of growth of the total cross sections have been successfully used for the phenomenological description of high-energy processes and make it possible to correlate a wide range of experimental data on total cross sections, angular distributions, and polarizations in hadronic reactions.

However, it should be pointed out that since the calculations in the theory with $\alpha_P(0)=1$ were performed on the basis of asymptotic formulas, allowance for the requirements of energy and momentum conservation can lead to a "threshold" character for the region of "accelerator" energies, and many conclusions based on the asymptotic formulas must be reconsidered.

The Regge model with allowance for absorptive effects has also been quite successful in describing non-diffractive mechanisms due to the exchange of quantum numbers in the t-channel. In general, we can say that approaches based on Regge theory with allowance for direct-channel unitarity provide an understanding of the main features of two-body and quasi-two-body processes. At the same time, a number of new experimental results presented at the conference have not yet been explained theoretically in the framework of these approaches.

With increasing energy, the fraction of few-particle processes falls off and multi-hadron production processes begin to play a major role. An enormous quantity of experimental data has now been accumulated on multi-particle production processes, and analyses have been made of a large number of theoretical models (the hydrodynamic model, the multiperipheral model, the quark model, etc.) that describe the main characteristics of these processes.

There has been great interest in experimental data on the growth of the inclusive cross sections for secondary particles in the central region of the spectrum over the energy range $\sqrt{s}=23-63$ GeV (for pions the growth amounts to about 40%). This strong growth poses interesting problems. It can be explained directly in the hydrodynamic model of multi-particle production; in the framework of the other models, however, it can be attributed to an anomalously large contribution from the secondary Regge trajectories or to strong threshold effects.

Another acute problem which was widely discussed at the conference concerns the fraction of produced resonances and the production of secondary particles from heavy clusters that do not lead to resonances. Opinions about this problem differ at the present time. The correlations among the secondary particles apparently cannot be explained without invoking clusters.

Finally, cosmic-ray data at ultra-high energies were considered. These data yield evidence of a change in the character of the strong interactions at energies of order 10^{14} eV.

Special attention was devoted at the conference to those characteristics of inelastic processes which are most sensitive to the basic assumptions of the various models and which can therefore help to discriminate between these models. The need for a complete quantitative comparison of all the predictions of the models with experiment was also stressed. This generally requires complicated numerical calculations, but it is of decisive importance for a further assessment of the models in a number of cases.

In addition to the traditional methods, a new approach which has been developed in recent years is the study of the space-time picture for multi-particle production processes. A number of papers were presented at the conference on the experimental determination of the effective dimensions of the interaction region on the basis of the interference effect between secondary identical particles (pions). Experiments yielded values close to 1 F, although the interpretation of these data is ambiguous. These investigations are of great interest in connection with the concept of important contributions from large longitudinal distances, which grow with increasing energy. Experimental confirmation of these ideas would have far-reaching consequences for strong-interaction physics as a whole. The best prospects here are connected with the study of production processes on nuclei and the further development of experimental techniques for the direct measurement of the dimensions of the interaction region.

On the whole, the Tbilisi Conference reflected the ever-increasing rate of development of research in high-energy physics, which offers hope of a deeper understanding of the fundamental interactions of elementary particles in the near future.

[1] The roles of the authors in reviewing the subject matter of the conference were divided as follows: I. V. Andreev and V. A. Tsarev—strong interactions; A. D. Dolgov and V. A. Khoze—new particles in e^+e^- annihilation and parton models; A. A. Komar and V. A. Kuz'min—weak interactions and new particles. The general editor was A. A. Komar.

Translated by N. M. Queen