Interaction of protons at the highest accelerator energies

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The highest collision energies of particles accelerated under laboratory conditions have been achieved at CERN in the colliding-beam accelerators—the ISR and SPS colliders. The maximum energies in the center-of-mass system are respectively 63 and 540 GeV, which corresponds to energies in the rest system of one of the colliding particles about 2 TeV and 150 TeV. In the ISR collider the proton beam can collide with opposing proton or antiproton beams, while in the SPS collider only antiprotons travel in the direction opposite to the protons.

We shall consider the results obtained in both colliders, since, although the SPS collider significantly exceeds the ISR in energy, study of the difference in proton-proton and proton-antiproton collisions can be accomplished only up to ISR energies. In addition, comparison of data in these two energy ranges permits observation of general tendencies in the behavior of the basic characteristics of the interactions of hadrons at very high energies.

A detailed discussion of the physics of particles at accelerator-collider energies has already been given in Uspekhi Fizicheskikh Nauk (see the article by Horgan and Jacob: Physics at Collider Energy, CERN, Geneva, 1981. Russian translation in Usp. Fiz. Nauk **136**, 219 (1982)). In the present note we shall present data of experiments carried out in the colliders in 1982–1983 investigating the basic characteristics of interactions of protons with protons an antiprotons, i.e., measuring the total cross sections, the real part of the forward scattering amplitude, and the differential cross sections for elastic scattering and for inelastic processes at large and small momentum transfers. The data presented have been published in the form of CERN preprints, in individual articles in various journals, (most frequently in Physics Letters, where beginning at the end of 1981 practically every issue has contained articles with data from the colliders), and in conference proceedings: XIII Multiparticle Dynamics, Volendam, Holland, 1982, and Proton-Antiproton Interactions, La Plan, France, 1983.[1)]

1. TOTAL CROSS SECTIONS

Already at the energies of the Serpukhov accelerator (up to 70 GeV in the laboratory system) it was noted that the total cross section for interaction of protons with protons stops falling off with increase of energy (the so-called Serpukhov effect). After startup of the ISR collider in 1971 it was observed that the cross sections for interaction of particles begin to increase appreciably with increase of the energy. This tendency still exists at the SPS collider energy. From Serpukhov energies to SPS collider energies the cross sections rise by more than one and one half times, as can be seen from Fig. 1. The data on the total cross sections at $\sqrt{s} = 540$ GeV (the three highest-energy points in the figure) are as follows: $66 \pm 7 \pm 3$ mb (UA4, 1982), $71 \pm 7 \pm 3$ mb (UA4, 1983), and $64.5 \pm 9.3 \pm 4$ mg (UA1, 1983)[2)].

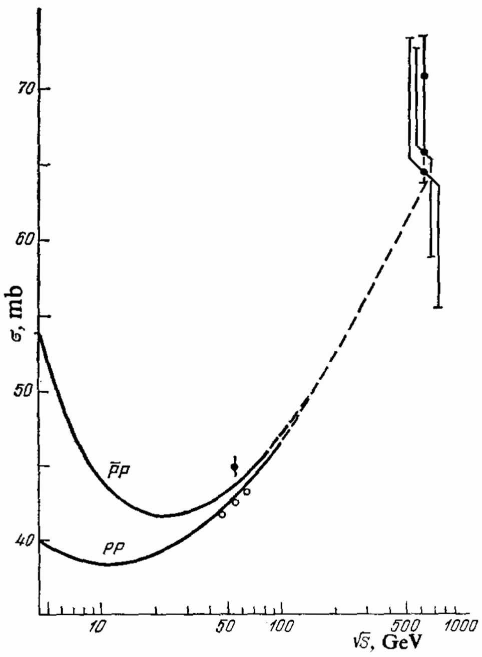

FIG. 1. Behavior of total cross sections for interaction of protons with protons (hollow circles) and with antiprotons (solid circles), as a function of energy.

[1)]I will not mention data on intermediate bosons. See the preceding article in this issue.

[2)]In parentheses we give the experimental group reporting the result and the year of its publication. The first number after the main one is the statistical error, and the second one is the systematic error. In connection with the data of the UA4 group it must be kept in mind that they may contain an additional systematic exaggeration by 1–2 mb due to the fact that in this experiment one actually obtains not σ_{tot} but the value of the product $(1+\rho^2)\sigma_{tot}$, where ρ is the ratio of the real and imaginary parts of the forward elastic-scattering amplitude, which according to estimates based on dispersion relations can lie in the range from 0.1 to 0.2 at this energy (see below). The appearance of this combination is due to the fact that by use of the optical theorem it is possible to exclude the uncertainty in the measurements due to poor knowledge of the accelerator luminosity, expressing $(1+\rho^2)\sigma_{tot}$ only in terms of measured quantities—the fraction of elastic processes and the slope of the diffraction peak. The UA1 group measures $(1+\rho^2)^{1/2}\sigma_{tot}$, i.e., the correction to their data is approximately a factor of two smaller. At the European Conference on High Energy Physics at Brighton (July 1983) this group also reported a number $67.6 \pm 5.9 \pm 2.7$ mb. If we use the theoretically predicted value $\rho \approx 0.15$, averaging of all data will give a total-cross-section value $\sigma_{tot} = 67 \pm 4 \pm 2$ mb.

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Unfortunately three numbers with large errors do not replace the long awaited single number with small errors. Increase of the luminosity of the accelerator will solve this problem. At higher energies there is only an indirect estimate based on recalculation of data obtained in cosmic rays in the "Fly's Eye" installation. It was given in papers by G. B. Yodh at the conferences mentioned:

$\frac{\sigma_{el}}{\sigma_{tot}} = 17,6 \pm 0,4 \pm 0.3\%$

at ISR and $20 \pm 2\%$ at SPS.

For comparison we give a table of data at ISR energies. The rise of the cross sctions is readily evident. It is interesting to note that the difference of the cross sections continues to drop with increase of the energy. Over a rather wide range (at energies above 10 GeV) this difference can be well fitted by the following phenomenological dependence: $\Delta\sigma \approx 78.2 s^{-0.57}$, from which on substitution of s in GeV^2 one obtains the difference of the cross sections in millibarns. This dependence corresponds to our notions of secondary Regge trajectories.

The functional dependence of the cross sections on energy is consistent with the bound of the type $\ln^2 s$ imposed by the Froissart theorem. It is true that numerically the cross sections are still considerably lower than the Froissart limiting values. A theoretical understanding of this rise of the cross sections will require knowledge of the nature of the leading Regge singularity, the pomeron, which should be supercritical, i.e., should lie above 1. This singularity could be obtained in multiperipheral cluster theory. With increase of energy one usually takes into account rescatterings, i.e., multi-pomeron exchanges.

2. ELASTIC PROCESSES

The fraction of elastic processes in the total cross section changes only slightly (if it changes at all) in transition from the ISR to the SPS collider:

σ_{pp} ($\sqrt{s} \sim 15$ TeV) ~ 120 mb.

The ratio of the real and imaginary parts of the forward elastic scattering amplitude has been measured only up to ISR energies. As is well known, it is close to zero at $\sqrt{s} \sim 20$–30 GeV (i.e., at a laboratory energy about 300 GeV), negative at lower energies, and positive at higher energies, rising from 0.029 ± 0.10 at $\sqrt{s} = 30.6$ GeV (R211, 1982) to 0.10 ± 0.02 at $\sqrt{s} = 62.5$ GeV (R211, 1982) in proton-proton interactions. The data on proton-antiproton interactions are less accurate but are consistent with the expectations $\rho^{\bar{p}p} = 0.14 \pm 0.13$ at $\sqrt{s} = 62.5$ GeV with $\Delta\rho = \rho^{p\bar{p}} - \rho^{pp} = 0.04 \pm 0.04$ (R211, 1982). At SPS-collider energies there are no direct data on this ratio. Theoretical estimates give a range of values from 0.1 to 0.2, depending on the form of extrapolation of the cross sections at higher energies. The most reasonable numbers are close to 0.14 ± 0.03.

Energy $\sqrt{s}$, GeV	σ_{tot}^{pp}, mb (group, year)	$\sigma_{tot}^{\bar{p}p}$, mb (group, year)	$\Delta\sigma$, mb (group, year)
30.6	—	40,26±0.2 (R 211, 1982)	—
52,8	44,70±0,40±0,13 (R 210, 1982)	43,26±0,20±0,13 (R 210, 1982)	1,44±0.45 (R 210, 1982) 0,96±0,30±0,13 (R 211, 1982)
62.3	45,25±0,3 (R 210, 1983)	44,68±0,22 (R 210, 1983)	0,57±0.30 (R 210, 1983)
62.5	44,33±0,29 (R 211, 1983)	43,93±0,27 (R 211, 1983)	0,40±0,32 (R 211, 1983)

The differential cross sections for elastic scattering (Fig. 2) fall off exponentially with increase of the square of the momentum transfer $|t|$ at small values of t, and in the region $|t| < 0.2$ GeV^2 the slope of the diffraction peak is appreciably greater than in the region $|t| > 0.2$ GeV^2. In the region $0.8 < |t| < 1.4$ GeV^2 at SPS energies there is a broad shoulder and the dip observed at low energies is not appreciable. In general $d\sigma/dt$ drops by six orders of magnitude on change of $|t|$ from 0.03 to 1.5 GeV^2. The values of the slope of the diffraction peak $b_{\bar{p}p}$ ($d\sigma/dt \sim \exp(b_{\bar{p}p} t)$) in the region $|t| < 0.2$ GeV^2 at $\sqrt{s} = 540$ GeV are as follows: 17.2 ± 1.0 GeV^{-2} (UA4, 1982), 17.6 ± 1.0 GeV^{-2} (UA4, 1983), 17.1 ± 1.0 GeV^{-2} (UA1, 1983), and in the region $|t| > 0.2$ GeV^2 the slope of the peak is 13.6 ± 0.2 GeV^{-2} (UA4, 1983), 13.7 ± 0.2 GeV^{-2} (UA1, 1983). For comparison we give corresponding numbers for the ISR energy $\sqrt{s} = 52.8$ GeV (R210, 1982):

$$|t| < 0.2\ \text{GeV}^2:\quad b_{\bar{p}p} = 13.92 \pm 0.37 \pm 0.22\ \text{GeV}^{-2},\quad b_{pp} = 13.09 \pm 0.37 \pm 0.23\ \text{GeV}^{-2},$$

$$|t| > 0.2\ \text{GeV}^2:\quad b_{\bar{p}p} = 10.68 \pm 0.20\ \text{GeV}^{-2},\quad b_{pp} = 10.34 \pm 0.30\ \text{GeV}^{-2}.$$

It is evident that the diffraction peak becomes steadily narrower with increase of the energy. In the ISR region the proton-antiproton cross sections are somewhat steeper than the proton-proton cross sections. The nature of the variation of the cross section (smooth or with a break) in the region $|t| = 0.2$ GeV^2 is still unknown and will be studied specially.

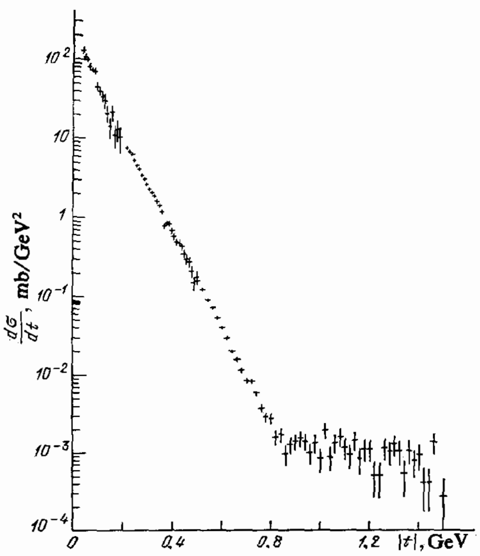

FIG. 2. Differential cross section for proton-antiproton elastic scattering at energy $\sqrt{s} = 540$ GeV.

3. INELASTIC PROCESSES

a) Region of small momentum transfers

As at lower energies, in the SPS collider in inelastic processes mostly particles with small transverse momentum relative to the collision axis are produced. For example, the differential cross section for production of particles with transverse momentum of 0.3 GeV/c is seven orders of magnitude greater than the cross section at transverse momentum of 10 GeV/c. Therefore the average characteristics of inelastic processes are determined practically completely by particles with small transverse momentum.

The average multiplicity of charged particles in the SPS collider has risen substantially in comparison with the ISR. The following values are given for inclusive processes: 27.4 ± 2 (UA5, 1982) and 26.5 ± 1.0 (UA5, 1983). For comparison at ISR energies the corresponding number was about 15 (R210, 1982). In processes where there are no single diffraction excitations of a nucleon, the average multiplicity is higher: 28.9 ± 0.4 (UA5, 1983). In a limited region of comparatively small pseudorapidities η the average multiplicity of charged particles in an event is lower: 21.1 ± 1.0 at $|\eta| < 3.5$, where $\eta = -\log\tan(\theta/2)$ and θ is the emission angle of the particle (UA1, 1983). The law of rise of the average multiplicity with energy is close to $\ln^2 s$.

In the first approximation the distribution of particles in multiplicity is well described by the usually quoted Koba-Nilsson-Olesen scaling curves, although some differences are noted—a narrower maximum for small multiplicities and an increase of the role of processes with multiplicity appreciably exceeding the average value.

The inclusive distribution of secondary particles in pseudorapidity has the same shape (a hat shape or a bell with a slightly depressed center) as at ISR energies, but the height of the hat and its width have increased appreciably (one half of it is shown in Fig. 3). The increase of the height of the distribution appreciably exceeds the increase of the cross section, which can be seen from the value of the cross section at zero rapidity $\left|\frac{1}{\sigma}\frac{d\sigma}{d\eta}\right|_{\eta=0}$, which was approximately 2 at ISR energies (Fig. 3) but has become about one and one half times larger at SPS energy: 3.3 ± 0.2 (UA1, 1982, 1983), 2.7 ± 0.15 (UA5, 1982, 1983)—for the inclusive distributions, and 3.1 ± 0.1 (UA5, 1982, 1983)—for events without single diffraction excitation of a nucleon. Although the half-width of the distribution also has risen from 3.25 up to about 4, this rise is appreciably less than the broadening of the possible range (permitted by the conservation laws) of rapidities in the transition from ISR to SPS.

With increase of multiplicity, the semi-inclusive distribution (for a given number of particles) in rapidity becomes narrower and the maximum appears more and more distinctly.

As at ISR energies, in the SPS collider strong close correlations of two particles in rapidity (with $\Delta y \approx 2$) are observed. At the same time long-range correlations have become more noticeable. For example, the average number of particles emitted in the backward hemisphere rises linearly with increase of the number of particles in the forward hemisphere: $\langle n_B \rangle = a + bn_F$ (where $b \approx 0.5$ and increases slightly with energy). We note that in e^+e^- annihilation there is no similar correlation (there $\langle n_B \rangle$ does not depend on n_F).

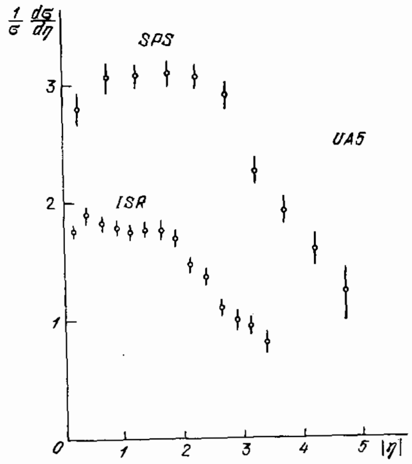

FIG. 3. Distribution in pseudorapidity of secondary particles produced in inelastic proton-antiproton interactions at ISR energies (lower points) and SPS-collider energies (upper points).

One also notes a rise of the average transverse momentum of the particles produced. For example, for charged pions it has risen to 440 MeV/c (UA1, 1982, 1983) in comparison with 360 MeV/c at ISR energy. The rise of the average transverse momentum of heavy particles is still more noticeable: from a value about 400 MeV/c at ISR energy it has risen to 700 ± 120 MeV/c in the case of K mesons and up to 670 ± 200 MeV/c in the case of Λ hyperons (UA5, 1982). It is interesting to note here also that the fraction of protons relative to the sum of kaons and pions has remained approximatley the same as in the ISR, while the fraction of kaons relative to pions has risen by 40% in the range of transverse momenta from 0.4 to 1.4 GeV (UA2, 1983).

It is interesting that in the region $E_T \sim 25$–30 GeV there is a noticeable change in the nature of the process. Whereas at lower E_T there is a practically linear dependence of E_T on the number of particles in jets, on the other hand at large E_T a rise of the momentum of these particles is observed with an extremely weak dependence of the number of the particles on E_T.

Characteristic features are observed also for γ rays at SPS energy. The average number γ rays rises linearly with increase of the number of charged particles with a slope $d\langle n_\gamma \rangle / dn_{ch} = 0.90 \pm 0.08$ as one should expect if they are obtained from decays of neutral pions. In this case the average multiplicities of charged pions and γ rays should coincide (two each per neutral pion). However, the measured value $\langle n_\gamma \rangle = 34 \pm 2$ appreciably exceeds the value of $\langle n_{ch} \rangle$ given above. This difference can be explained if we assume that an appreciable number of η mesons are produced (their fraction relative to neutral pions is estimated as 0.32 (UA5, 1982, 1983) or even 0.55 (UA2, 1982)). The principal excess of the number of γ rays over charged pions is concentrated in the region of small pseudorapidities—in the region where in Fig. 3 a plateau is formed with a small dip at $|\eta| < 2$. The corresponding distribution for γ rays drops smoothly from a value about 0.5 at $\eta = 0$ to 3 at $|\eta| = 2$, and for alrge $|\eta|$ it practically coincides with what is shown in Fig. 3.

The properties of the average characteristics of the inclusive and semi-inclusive distributions of charged particles are rather well described by theoretical schemes which contain as a nucleus a supercritical Pomeron and which take into account scattering effects.

b. Region of large transverse momenta

Although processes with production of particles with large transverse momenta comprise a small fraction of all inelastic processes, they provide great hopes for clarification of the parton structure of hadrons. The exponential falloff of the differential cross section at small transverse momenta is replaced by a power-law drop of the inclusive distributions of particles with large transverse momentum. However, it has not yet been possible to observe the pure p_T^{-4} law which would be expected for dominance of quark diagrams with one-gluon exchange. Furthermore, there have been repeated discussions in the literature as to whether quark (or gluon) jets are observed at all in hadron interactions with large transverse momenta. The diversity of opinion has been due to the different experimental setups (triggers or 4π calorimeters). Apparently it can now be stated that an answer has been obtained for this question: jets actually exist and reliable identification of them is possible at sufficiently large combined transverse energy of an event, $E_T > 30$ GeV $\left(E_T = \sum_i E_i \sin\theta_i\right)$.

This conclusion was drawn initially from the results of experiments R807 and R110 (1983) at the ISR, and subsequently jets appeared distinctly in the SPS collider. Such characteristics were investigated as the circularness of an event, defined as $C = 2\sum_i q_{T_i}^2 / \sum_i p_{T_i}^2$, where q_{T_i} and p_{T_i} are respectively the momenta transverse to the jet axis and to the collision axis. This quantity is equal to unity for spherically symmetric events and to zero for events drawn out along a single axis (the jet axis). It has turned out that the inclusive distribution at $\sqrt{s} = 30$ GeV is described by a smooth curve with a maximum at $C \approx 0.6$ and is close to that given by the ordinary cylindrical phase space. At $\sqrt{s} = 45$ GeV, by separating events with $25 < E_T < 30$ GeV, experimenters have observed in the their distribution in circularness a new peak at small values $C \approx 0.2$. And when at $\sqrt{s} = 63$ GeV/c events were selected with $35 < E_T < 40$ GeV, then the entire distribution had only one sharp maximum at $C \approx 0.05$, which indicated an explicitly jet nature of the events.

Similar conclusions could be drawn also from the dependence of C on E_T. For $E_T \lesssim 30$ GeV/c we have $C \approx 0.6$, and for higher E_T it drops rapidly to zero. The fraction of jet events rises with increase of E_T from 1 or 2% at $E_T = 20$ GeV up to 80% at 40 GeV.

According to the results of the same group in this interval of transverse momenta the falloff of the differential cross sections with increase of transverse momentum has a power-law nature and not an exponential one as occurred at ISR energies.

An interesting and unusual behavior was observed in the exclusion reaction $pp \to pp\pi^+\pi^-$ at $s^{1/2} = 63$ GeV. The differential cross section for this process as a function of the pion pair mass, after passing through a maximum and a smooth drop, reveals a sharp drop at $M_{\pi\pi} \sim 1$ GeV and then a plateau up to mass ~ 1.4 GeV which is replaced by a gradual falloff and then again by a sharp jump downward and a second plateau at masses ~ 1.6 GeV. If the formation of a pion pair occurs as the result of the interaction of two gluons (from the parton composition of the hadrons), then these "anomalies" in the behavior of the cross section could be related to the problem of existence of glueballs.

Distinct jets have been observed in the SPS collider. The high initial energy permits detection of jets with very large E_T. For example, there are two events with $E_T = 186$ and 161 GeV, respectively; several tens of jets have been observed with total mass (energy in the jet c.m.s.) greater than 50 GeV. Two examples of the most typical jets are shown in Fig. 4. The distribution in the production angle of the jets in the center-of-mass system of the colliding partons is broad and has a maximum at an angle of the order 60°, which sometimes is interpreted as one-gluon exchange between the colliding gluon-partons of the initial hadrons.[3)]

It is interesting to note also that in 20% of the jets with transverse momentum above 12 GeV, production of charmed particles was observed (these were identified on the basis of the maxima in the mass distributions of the $K\pi$ and $K\pi\pi$ systems which should be observed in production and decay of D and D* mesons.

Thus, the observation of jets has been clear confirmation of the correctness of the ideas regarding the parton

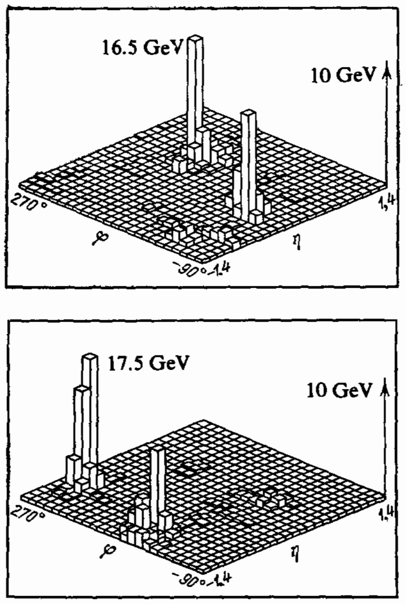

FIG. 4. Two characteristic examples of appearance of jets in proton-antiproton collisions in the SPS collider. The axes represent the pseudorapidity η, the azimuthal angle φ, and the transverse energy E_T.

[3)]We recall that at the SPS collider energy gluons become the most "active" partons of hadrons (for more details see the review of R. Horgan and M. Jacob cited above).

structure of hadrons. So far in such processes no deviations from the qualitative predictions of quantum chromodynamics have been found.

4. EXOTIC EVENTS

In the SPS collider a search has also been undertaken for such exotic events as Centaurs, indications of which have appeared in cosmic rays at somewhat higher energies (events with a large number of secondary charged particles and an anomalously small number of neutral particles). Such events have not been found either by the UA5 group (1982) or by the UA1 group (1983). For example, in statistics of 48 000 events an upper limit $\sigma_{prod} < 1$ μb was obtained for the Centaur production cross section. Possible explanations are as follows: 1) the energy of the SPS collider is small in comparison with the energies at which Centaurs have been observed in cosmic rays; 2) in cosmic rays there is some exotic component; 3) Centaurs are explained by extremely rare fluctuations.

Summarizing, we can say that studies in the SPS collider have already contributed much new information on the properties of hadrons and their interactions at high energies. Unquestionably an increase of the experimental statistics will help not only to provide more precise information on the general characteristics described above, but also to discover the finer details of the phenomenon.

Translated by C. S. Robinson