Hadron-hadron and hadron-nuclei collisions at high energies

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Abstract

A brief review is made of the present situation of hadron-hadron and hadron-nuclei total, elastic and inelastic cross sections at high energies.

1 Introduction

In the 1960’s-1980’s high quality secondary beams became available at proton synchrotrons of increasing energies (PS, AGS, IHEP, FNAL, SPS). The secondary charged hadron beams contained the six stable or quasi stable charged particles $\pi^\pm, K^\pm, p, \bar{p}$. The main experimental lines of research were: i) total hadron–hadron ($hh$) cross section measurements at high energies ($p_{lab} > 20$ GeV/c); ii) elastic $hh$ scattering measurements; iii) measurements of absorption cross sections of hadrons in nuclei (as byproducts of $hh$ total cross section measurements); iv) hadron production at forward angles in $p – nuclei$ collisions, and v) inelastic $hh$ collisions [1-5]. In some high intensity beams many particle searches were made, which also lead to the study of $d$, $t$ and $^{3}He$ production [6].

In order to reach higher energies it became necessary to build hadron colliders. The first was the ISR $pp$ and $\bar{p}p$ collider at CERN, which allowed to reach c.m. energies between 22 and 63 GeV; then the $Sp\bar{p}S$ collider at CERN allowed $p\bar{p}$ collisions from 600 to 900 GeV; finally the Fermilab Tevatron collider allowed $p\bar{p}$ collisions up to 1.8 TeV.

The first experiments performed at the ISR were relatively simple dedicated experiments, like those for total cross section and elastic scattering measurements, and single arm spectrometers for the study of inelastic collisions [7-8]. Then followed general purpose detectors: the SFM at the ISR [9], the general purpose detectors UA1 and UA2 and experiment UA4 at the $Sp\bar{p}S$ collider, and finally the general purpose detectors CDF, D0 and the specialized experiments E710, F8 at Fermilab [10].

The highest energies were and are still obtainable only with Cosmic Rays. We shall discuss total cross sections at high energies, the high energy low $- p_{t}$ parameters and some features of inelastic collisions [11, 12].

2 Hadron-hadron total cross-sections

At fixed target accelerators (AGS, IHEP, FNAL) the total cross sections were measured with the transmission method, with relative precisions smaller than 1% and systematic scale errors of about 2%. The measurements of the total cross sections at the $pp$ and $\bar{p}p$ colliders required the development of new experimental techniques: the scattering of particles was measured at very small angles, with detectors positioned in reentrant containers (“Roman pots”) located very close to the circulating beams. The combination of statistical and systematic uncertainties are $\geq 10\%$. Fig 1 summarizes the present status of high energy total cross section measurements: for $E_{cm} = \sqrt{s} > 3.4$ GeV all total $hh$ cross sections decrease, reach a minimum and then increase with increasing energy (the $K^+p$ total cross section was
already increasing at Serpukhov energies \[1\]). Moreover the differences between the cross sections \(\pi p\) and \(xp\) decrease with increasing energy \[5\].

There is not a unique interpretation for this rise, though in many QCD inspired models it seems to be connected with the increase of the number of minijets and thus to semi-hard gluon interactions.

Most of the high energy elastic and total cross section data have been usually interpreted in terms of Regge Poles, and thus in terms of Pomeron exchange. Even if the Pomeron was introduced long time ago we do not have a consensus on its exact definition and on its detailed substructure. Some authors view it as a "gluon ladder".

Future experiments on hadron-hadron total cross sections remain centered at the Fermilab Collider (for \(pp\)). The near future will rely on the BNL-RICH Collider, and later, on the LHC proton-proton and heavy ion Collider at CERN. Large area cosmic ray experiments may be able to improve the data in the ultra high energy region \[12\].

![Figure 1](image1.png)

**Figure 1**: Compilation of total cross-sections (a) for high-energy \(hh\) scattering and (b) for higher energy \(\bar{p}p\) and \(pp\), including cosmic ray measurements; the solid line is a fit; the uncertainty region is delimited by dashed lines.

## 3 Hadron-hadron elastic scattering

The differential cross section for the elastic scattering of unpolarized particles from unpolarized targets has a simple structure in the high energy region. It depends on two variables: the energy and an angular variable, which is usually chosen to be the square of the four momentum transfer \(t\). The energy dependence is of the \(\ln s\) type. The angular distribution may be divided in four regions: i) The Coulomb region for \(|t| < 0.001\) (GeV/c)\(^2\); ii) The Coulomb-nuclear interference region for \(0.001 < |t| < 0.01\) (GeV/c)\(^2\); measurements in this region yield information on the ratio \(\rho\) of the real to the imaginary part of the forward scattering amplitude. iii) The nuclear diffraction region proper for \(0.01 < |t| < 0.5\) (GeV/c)\(^2\); here the most important parameter is the slope \(B\), or the slopes \(b_i\), of the diffraction pattern. iv) The large angle region for \(|t| > 0.5\) (GeV/c)\(^2\); for \(E_{cm} \leq 100\) GeV it is characterized by a dip-bump structure which resembles that from diffraction from an opaque disc. Most of these features are observed in the \(pp\) and \(\bar{p}p\) elastic scattering angular distributions at \(E_{cm} = 53, 546\) and 1400 GeV, see Fig. 2.

One usually defines the following high energy scattering parameters: i) the total cross section, \(\sigma_t\); ii) the slope \(B\) of the differential elastic nuclear cross section \(d\sigma/dt = Ae^{Bt}\), at \(|t| \approx 0.1\) (GeV/c)\(^2\); iii) the ratio \(\rho = (ReA/ImA)_{t=0}\); iv) the opacity \(O = 2\sigma_{el}/\sigma_t\). At very high energies \(\sigma_t, B\) and \(O\) rise with
energy, while $\rho$ is slightly positive. From the behaviour of these parameters emerges the picture of a proton which becomes bigger (larger $B$) and more opaque (larger $O$) as the energy increases. At the highest energy $O \simeq 0.48$, which is still smaller than the black disk value of 1.

4 Hadron-hadron inelastic processes

Fig. 3 shows pictorially various inelastic processes at low $p_t$: single and double diffraction dissociation and inelastic processes; these are the dominant processes with the largest cross sections, concentrated in particular in the very forward angular region: this is the region which is most important for cosmic ray experiments.

At high energies the total $pp$ cross section may be written as

$$\sigma_t = \sigma_{el} + \sigma_{incl} = \sigma_{el} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$  

(1)

where $\sigma_{el}$ is the elastic cross section, $\sigma_{sd}$ is the single diffractive cross section when the incoming proton fragments into a number of particles, $\sigma_{dd}$ is the single diffractive cross section for the fragmentation of the antiproton (at high energies $\sigma_{sd} = \sigma_{dd}$), $\sigma_{dd}$ is the double diffractive cross section, $\sigma_{nd}$ is the non-diffractive part of the inelastic cross section (Fig. 3). The elastic, single diffractive and double diffractive processes give rise to low multiplicity events with particles emitted in the very forward region in the c.m. system. The non-diffractive cross section is the main part of the inelastic cross section; it gives rise to
high multiplicity events and to particles emitted at all angles. Most of the non-diffractive cross section concerns particles emitted with low transverse momentum (low $p_t$ physics) with properties which change slowly with c.m. energy ($ln s$ physics). A small part of the non-diffractive cross section is due to central collisions among the colliding particles and gives rise to high $p_t$ jets of particles emitted at relatively large angles (large $p_t$ physics). The contribution of jet physics increases with c.m. energy.

In Fig. 4a are shown, vs $\sqrt{s}$, the average charged multiplicities in $pp$ and $\bar{p}p$ collisions. The data may be fitted to a power law of $ln s$:

$$n = A + B \ln s + C \ln^2 s \simeq 3.6 - 0.45 \ln s + 0.20 \ln^2 s$$

At $\sqrt{s} = 1.8$ TeV are produced on average 40 charged and 20 neutral particles. Fig. 4b shows the average number of $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ produced in $pp$ collisions up to $\sqrt{s} \simeq 100$ GeV. Pions are the dominantly produced hadrons. Hadrons are mainly produced at low transverse momenta. The average $p_t$ increases slowly with $\sqrt{s}$: it is $\langle p_t \rangle \simeq 0.36$ GeV/c in $20 < \sqrt{s} < 100$ GeV; then it increases slowly up to $\simeq 0.46$ GeV/c at $\sqrt{s} = 1.8$ TeV. The simplest interpretation of these features is in terms of thermodynamic models: hadrons are emitted from a region with a temperature $T \simeq 130 - 200$ MeV. QCD, at present cannot be used to calculate the data at low $p_t$, because the strong coupling constant is large and perturbative methods cannot be used. Therefore one has to use models. Hard collisions can instead be calculated by perturbative QCD.

5 Hadron-nucleus and nucleus-nucleus collisions

Usually, as byproducts of $hh$ total cross section measurements, the absorption cross sections of $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ on various nuclei (Li, C, Al, Cu, Sn, and Pb) were measured at incident lab momenta up to 280 GeV/c [2, 4, 11]. Most absorption cross sections decrease slowly for $p_{lab}$ up to $\simeq 50$ GeV/c; for higher $p_{lab}$, they are almost constant.

The data at each energy were fitted to the simple expression

$$\sigma_a(A) = \sigma_0 A^\alpha$$

where $A$ is the atomic weight of the target nucleus. Examples are shown in Fig. 5a at three lab momenta for three different incoming hadrons. For all incident particles except antiprotons, the value of $\sigma_0$ increases by up to 10% as the incident $p_{lab}$ increases from 60 to 280 GeV/c, with the largest increase for $K^+$. For $\bar{p}$, $\sigma_0$ decreases with increasing $p_{lab}$. Fig. 5b shows the parameters $\sigma_0$ and $\alpha$ vs the corresponding $hp$
total cross section: $\sigma_0$ rises monotonically with $\sigma_{hp}$; the values of $\alpha$ are consistent with $\alpha$ approaching 0.67 for large values of $\sigma_{hp}$ as would be expected for an opaque nucleus.

Figure 5: (a) Absorption cross sections vs atomic weight; the solid lines are fits to Eq. 3. (b) The parameters $\sigma_0$ and $\alpha$ vs the corresponding $hp$ total cross sections, $\sigma_{hp}$.

The fragmentation cross sections of various nuclei were measured at many energies using nuclear track detectors, which yield high resolution measurements of the restricted energy loss. This arises from the relatively low energy required to break the polymeric bonds of the detectors and because fluctuations due to energetic $\delta$-electrons do not contribute to the latent track formation. The radiation damage along the path of an incoming nucleus may be developed to microscope-visible cones by chemical etching. Fig. 6a shows the charge distribution obtained with 200 GeV/nucleon S$^{16+}$ ions and their fragments produced in a Cu target [13]: notice the good charge resolution and the absence of nuclei with fractional charges. The cross sections in Fig. 6b are relative to fragments of 158 GeV/nucleon Pb$^{82+}$ ions in a target with $\bar{A} = 11.5$ with a variation of atomic number $\Delta Z = 1 - 7$ with respect to the $Z = 82$ of the incoming ions.

Figure 6: (a) Charge distribution of 200 GeV/nucleon S$^{16+}$ ions and their fragments [13]. (b) Cross sections in a target $\bar{A} = 11.5$ of 168 GeV/nucleon Pb$^{82+}$ ions into nuclear fragments for $\Delta Z$ ranging from 1 to 7; the open and black points refer to two different computing methods.
6 Conclusions. Perspectives

A wealth of experimental information has been obtained since the early 1960’s on high-energy hadron-hadron and hadron-nucleus cross sections, starting with simple equipments and proceeding to more complex apparata and better beams.

The higher energy data coming from collider experiments have large systematic uncertainties, mainly connected to the poor knowledge of the collider luminosity, the difficulty of measuring with some precision the single and double diffraction cross sections, etc.

Most of the information on hadron-hadron collisions was interpreted in terms of phenomenological models. Much more work is needed to interpret and systemize the available data, since only the small part of the cross section corresponding to large transverse momenta may be interpreted in terms of QCD.

Few and not too precise data are available at very low \( p_t \) and very small angles, which is the region where more interest lies for cosmic rays. The information is here codified in Monte Carlos, which are becoming progressively more complicated. The Monte Carlos include hadron-nucleus collisions [for which the data are much less abundant than for \( hh \) collisions]; hadron-nucleus effects are mainly interpreted in the context of the Glauber model [14].

Nucleus-nucleus data are even less abundant, and the Monte Carlos have extra complications coming from the used models [14].

In the near future the RICH collider at BNL should provide data on nucleus-nucleus collisions. In the future the different experiments at the LHC collider should provide data on \( hh \), hadron-nuclei and nuclei-nuclei collisions at much higher energies.

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7 References

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