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Parabolic Behavior of Total Cross-Sections of Proton-Proton And Proton-Antiproton Interactions

Dr. J. P. GUPTA
Associate Professor
Department of Physics
D.S. College Aligarh (UP) India

ABSTRACT

The analysis of proton-proton and proton-antiproton total cross-sections (σ_{tot}), the difference in p-p and p-p̄ total cross-sections ($\Delta\sigma_{tot}$) and the ratio ρ of the real to imaginary parts of the nuclear amplitude are of crucial importance to understand the hadron-nucleus interactions. It seems likely that proton-proton and proton-antiproton interactions will be different, even at CERN collider and TeV energies and is quite feasible that they will remain different forever. This is contrary to the widely held belief that annihilation channel, which are largely responsible for the huge difference in p-p and p-p̄ total cross-sections at low energies, should become less and less effective at higher energy. In the present work, an attempt has been made to parameterize the total cross-sections for proton-proton and proton-antiproton interactions. The energy dependence of (σ_{tot}) has also been studied and analyzed. A new approach to parameterize the σ_{tot}, is used to calculate the difference in total cross-sections ($\Delta\sigma_{tot}$), for proton-proton and proton-antiproton interactions and also the ratio ρ of the real to imaginary parts of the nuclear amplitude is calculated as a function of incident energy. An asymptotic ln^2 s behavior appears, for both the p-p and p-p̄ total cross-sections. The results of the present parameterization show a batter agreement experimental data.

Key words : *p-p interaction, p-p̄ interaction, h-h interaction, total cross-section, scattering cross-section*

INTRODUCTION :

The total cross-section (σ_{tot}) is one of the basic parameters of scattering processes in the sum of several cross-sections (i.e. various types of inelastic cross-sections and elastic cross-sections) of all accessible final states. Hadron-hadron scattering cross-sections are often used as standards in hadron-nucleus and nucleus-nucleus collisions, and in the same time comparisons with theoretical models provide information on nucleon-nucleon nuclear potential. The measurement and analysis of the p-p and p-p̄ total cross-sections and the ratio of real to imaginary part of the nuclear amplitude at high energies (Abreu, P. et al., 2012 and other references), during last five decades or so, have opened a new era in high energy physics. Earlier, the σ_{tot} is obtained from the measurement of differential elastic scattering cross-section by the application of optical theorem (Amaldi, U. et al., 1977). The total cross-sections were believed to approach a finite limit with increasing energy, but some hints of a growth were present in cosmic ray data at very high energies.

A number of theorems and bounds can be derived, which constrain the asymptotic behavior of the total cross-sections with limit to a ln^2s growth at maximum. It seems likely that p-p and p-p̄ interactions will be different even at CERN Collider and TeV energies (Amos, N. et al., 1990 etc.) and it is quite feasible that they will remain different forever.

This is contrary to widely held belief that annihilation channel, which are largely responsible for the huge difference in p-p and p-p̄ total cross-sections at low energies, should become less and less effective at higher energy.

In the present work, an attempt has been made to parameterize the total cross-sections for proton-proton and proton-antiproton interactions. The energy dependence of (σ_{tot}) has also been studied and analyzed. A new approach to parameterize the σ_{tot}, is used to calculate the difference in total cross-sections ($\Delta\sigma_{tot}$), for proton-proton and proton-antiproton interactions and also the ratio ρ of the real to imaginary parts of the nuclear amplitude is calculated as a function of incident energy. An asymptotic ln^2s behavior appears, for both the p-p and p-p̄ total cross-sections. The results of the present parameterization show a batter agreement experimental data.

FITTINGS OF TOTAL CROSS-SECTION :

The increasing behavior of the total cross-sections of proton-proton and proton-antiproton interactions has been analyzed (Castaldi, R. 1985, etc.) and several fittings (Landshoff, P.V. 2008 etc.) for the experimental data have been proposed by different authors. Some data have been fitted by a linear increase with *ln* s, where, s is the square of c.m. energy, while some other fittings have predicted the ln^2 s behavior of σ_{tot} (Amalds, V. et al. 1978 etc.). For example the commonly used fittings are,

$$\sigma_{tot(pp)} = 4.91\, ln\,[(p+541)/0.3] + (11.1 / p^{0.58}) \qquad \text{------------- (1)}$$

and $$\sigma_{tot(pp)} = 38.4 + 0.49\, ln^2\, s \qquad \text{------------- (2)}$$

where,'s' is the squared c.m. energy (GeV^2) and 'p' is the laboratory momentum (GeV/c). The total cross-section is expressed in milibarns. In similar manner, $\sigma_{tot(p\bar{p})}$ for proton-antiproton interactions might be fitted. The expression for the fitting could not be available. The ln^2 s behavior of σ_{tot} is incapable of explaining the variation of σ_{tot} at lower energies (up to about 250 GeV). With the consideration of ln^2 s behavior, the variation of σ_{tot} should have the same form for proton-proton and proton-antiproton interactions, which is not in consistent with experimental data. Also the fittings given in Eqn. (1) and (2) are not in agreement with experimental data at high energies (above about 200 GeV.). There is, therefore, a need of a new or a modified form of the parameterization of σ_{tot} for proton-proton and proton-antiproton interactions, which might predict the entire experimental data.

The difference between the total cross-sections of proton-proton and proton-antiproton interactions is an important parameter for the comparative study of p-p and p-p̄ interactions. The energy dependence of the differences of particle-particle and particle-antiparticle interactions has been considered to follow the Regge behavior (Carboni, G. et al., 1985), which was expected from the analysis of the lower energy scattering. The energy dependence of total cross-section difference $\Delta\sigma_{tot} = \sigma_{tot(p\bar{p})} - \sigma_{tot(pp)}$, exhibits a Regge behavior of kind $s^{-\alpha}$, with $\alpha = -1/2$, which makes it tends to zero rather rapidly.

PRESENT WORK :

The present work is done to calculate the total cross-sections $\sigma_{tot(p\bar{p})}$ and $\sigma_{tot(pp)}$, the difference in total cross-sections $\Delta\sigma_{tot}$ and the ratio ρ of the real to imaginary part of the scattering amplitude. From the behavior of the variation of σ_{tot} for proton-proton and proton-antiproton interactions, we find that the variation is of parabolic shape. The axis of the parabola, in both the cases, is found inclined towards the axis of c.m. energy. The angle of inclination, in the tow cases turn out to be different. In the case of p-p interaction, this angle is found to be 82.9^o, while in the case of p-p̄ interaction, its value is 80.8^o. In other words the entire symmetry of parabola is rotated by 7.1^o in the case of p-p and 9.2^o in the case of p-p̄, from the axis representing the σ_{tot} and the c.m. energy. With these findings we have tried to give a new parameterization of σ_{tot} for p-p and p-p̄ interactions, as following,

(i) For p-p interactions, $\sigma_{tot(pp)} = A[ln\, s - B\{ln\, s + C\}^{1/2} + D]$ ......(3)

where, A, B, C and D are parameters having values, 20.86, 6.22, 4.92 and 16.43 respectively.

(ii) For p-p̄ interactions, $\sigma_{tot(p\bar{p})} = A'[ln\, s - B'\{ln\, s - C'\}^{1/2} + D']$ ......(4)

with parameters A', B', C' and D' having values, 15.936, 4.47, 1.13 and 6.47 respectively.

Equ. (3) and (4) are, simply, the equations of parabola and the values of parameters A, B, C, D, A', B', C' and D' are obtained from the two parabola, passing through the experimental data of $\sigma_{tot(pp)}$ and $\sigma_{tot(p\bar{p})}$. The parabolic shape is considered from the Ref. (Castaldi, R. 1985). The total cross-sections for proton-proton and proton-antiproton interactions are calculated on the basis of present parameterization. The predictions are presented in the Table-1.

Using the Eqn. (3) and (4), a direct parameterization of the total cross-section difference $\Delta\sigma_{\text{tot}}$ as a function of c.m. energy is obtained as following,

$$\Delta\sigma_{\text{tot}} = \sigma_{tot(p\bar{p})} - \sigma_{tot(pp)}$$

$$\Delta\sigma_{\text{tot}} = [\ln s - B'\{\ln s - C'\}^{1/2} + D'] - A[\ln s - B\{\ln s + C\}^{1/2} + D]$$

$$\Delta\sigma_{\text{tot}} = 4.92[14.42\ \{1.82(\ln s - B'\{\ln s - 4.92)^{1/2} - (\ln s - 1.13)^{1/2} - \ln s\} + C\}^{1/2} - 48.6] \quad \ldots\ (5)$$

The prediction of the present parameterization of $\Delta\sigma_{\text{tot}}$ are compared with the experimental data and a fair agreement in each case is obtained (Fig.2 and Table-2)

The present parameterization have been used to calculate the ratio 'ρ' of the real to imaginary part of the scattering amplitude in the case of proton-proton interactions, as following,

$$\rho = \left(\frac{\pi}{2\sigma_{\text{tot}}}\right)\left[\frac{d\sigma_{\text{tot}}}{d\ln s}\right] = (\pi A / 2\sigma_{\text{tot}})\ [1-\{B / 2(\ln s + C)^{1/2}] \quad \text{-----------}\ (6)$$

RESULTS AND DISCUSSION :

The results of the present parameterization of the total cross-sections $\sigma_{tot(p\bar{p})}$ and $\sigma_{tot(pp)}$ for p-p and p-p̄ interactions are shown in Fig.1. The values of the total cross-sections $\sigma_{tot(p\bar{p})}$ and $\sigma_{tot(pp)}$ for c.m. energies from 5 GeV. to 2000 GeV. are presented in Table-1. It is noteworthy that the entire data taken for analysis follow the pattern suggested by the expressions (3) and (4). The present results show a fair agreement with the experimental data. The values of σ_{tot} decreases, with c.m. energy, up to 10 GeV. in the case of p-p interactions and up to 22 GeV in the case of p-p̄ interactions, then increases with c.m. energy, giving the parabolic shape to the variation of σ_{tot} with c.m. energy. The predictions of the present parameterization follow the Pomeranchuk theorem (Pomeranchuk, I. 1958), i.e., $\sigma_{tot(p\bar{p})}/\sigma_{tot(pp)} \rightarrow 1$, for $s \rightarrow \infty$. An asymptotic $\ln^2 s$ behavior appears as favored when looking for a common asymptomatic trend for both the p-p and p-p̄ total cross-sections

Table-1 : Total Cross-sections σ_{tot}(pp) and σ_{tot}(pp̄) for 5.00 GeV < ($\sqrt{s}$) < 2000 GeV

S.No.	C.M. Energy ($\sqrt{s}$) GeV	Proton-Proton Interaction Cross-section		Proton-Antiproton Interaction Cross-section	
		σ_{tot}(pp) mb Calculated	σ_{tot}(pp) mb Experimental	σ_{tot}(pp̄) mb Calculated	σ_{tot}(pp̄) mb Experimental
1.	5.00	39.66	.....	51.47	...
2.	5.43	39.38	39.2 ± 0.2	50.20	51.0 ± 0.8
3.	6.24	38.96	39.0 ± 0.2	48.15	48.2 ± 0.5
4.	6.61	38.82	39.6 ± 0.8	47.43	47.3 ± 0.2
5.	6.93	38.72	38.7 ± 0.2	46.88	46.9 ± 0.2
6.	7.30	....	....	46.32	46.2 ± 0.3
7.	7.59	38.55	38.4 ± 0.3	45.93	45.9 ± 0.3
8.	8.05	38.47	38.3 ± 0.2	45.38	45.1 ± 0.3
9.	8.21	38.44	38.3 ± 0.2	45.20	45.4 ± 0.2
10.	8.54	38.40	38.3 ± 0.2	44.87	44.6 ± 0.3
11.	8.69	38.36	38.4 ± 0.3	...	....
12.	8.89	38.35	....	44.55	44.9 ± 0.2
13.	9.32	38.33	38.3 ± 0.2	44.20	44.0 ± 0.5
14.	9.69	38.31	38.3 ± 0.2	43.93	43.1 ± 1.1
15.	9.81	38.30	38.3 ± 0.3	43.85	43.8 ± 0.2
16.	11.57	38.27	......	42.91	47.1 ± 0.2
17.	13.43	38.38	38.5 ± 0.3	...	...
18.	13.70	....	.....	42.23	42.0 ± 0.3
19.	15.12	38.53	38.6 ± 0.3	41.94	41.6 ± 0.2
20.	16.55	38.67	38.6 ± 0.2	....	....

21.	16.81	…	..	41.72	41.7 ± 0.2
22.	18.05	38.84	38.9 ± 0.3	41.62	41.6 ± 0.2
23.	19.15	……	….	41.57	41.0 ± 0.2
24.	19.53	39.01	39.0 ± 0.3		
25.	21.13	…	…	41.53	41.9 ± 0.3
26.	21.82	39.27	39.1 ± 0.3	…….	….
27.	23.04	39.45	39.5 ± 0.4	41.54	42.0 ± 0.4
28.	23.31	39.48	39.3 ± 0.8	………	…….
29.	23.50	39.51	39.1 ± 0.4	……	…….
30.	23.77	39.54	39.6 ± 0.3	……	…….
31.	24.73	39.67	39.7 ± 0.3	……	……
32.	25.72	39.80	39.8 ± 0.4	…..	…….
33.	30.10	40.36	40.0 ± 0.3	……	……..
34.	30.46	40.41	39.1 ± 0.2	41.88	42.0 ± 0.8
35.	30.60	40.43	40.5 ± 0.5	…….	….
36.	30.82	…..	………	41.93	42.7 ± 0.3
37.	31.81	40.57	40.1 ± 0.3	…….	……
38.	44.63	42.11	41.9 ± 0.4	……..	………
39.	53.27	43.05	43.0 ± 0.4	43.79	44.6 ± 0.5
40.	63.00	44.08	43.3 ± 0.3	44.64	45.05 ± 0.5
41.	80.00	45.53	……	45.96	……
42.	100.00	47.08	…..	47.41	…….
43.	200.00	52.64	…..	52.81	……..
44.	400.00	59.21	…….	59.40	…….
45.	500.00	61.53	…..	61.74	…….
46.	520.00	61.94	61.7 ± 3.2	62.16	……..
47.	546.00	….	…….	62.69	62.2 ± 1.5
48.	600.00	63.48	…….	63.72	……….
49.	800.00	66.69	……	66.96	………
50.	890.00	……	……	68.19	65.2 ± 4.3
51.	1000.00	69.27	……..	69.57	………
52.	1800.00	76.44	72.1 ± 4.3	76.82	78.3 ± 5.9
53.	2000.00	77.78	……	78.16	…

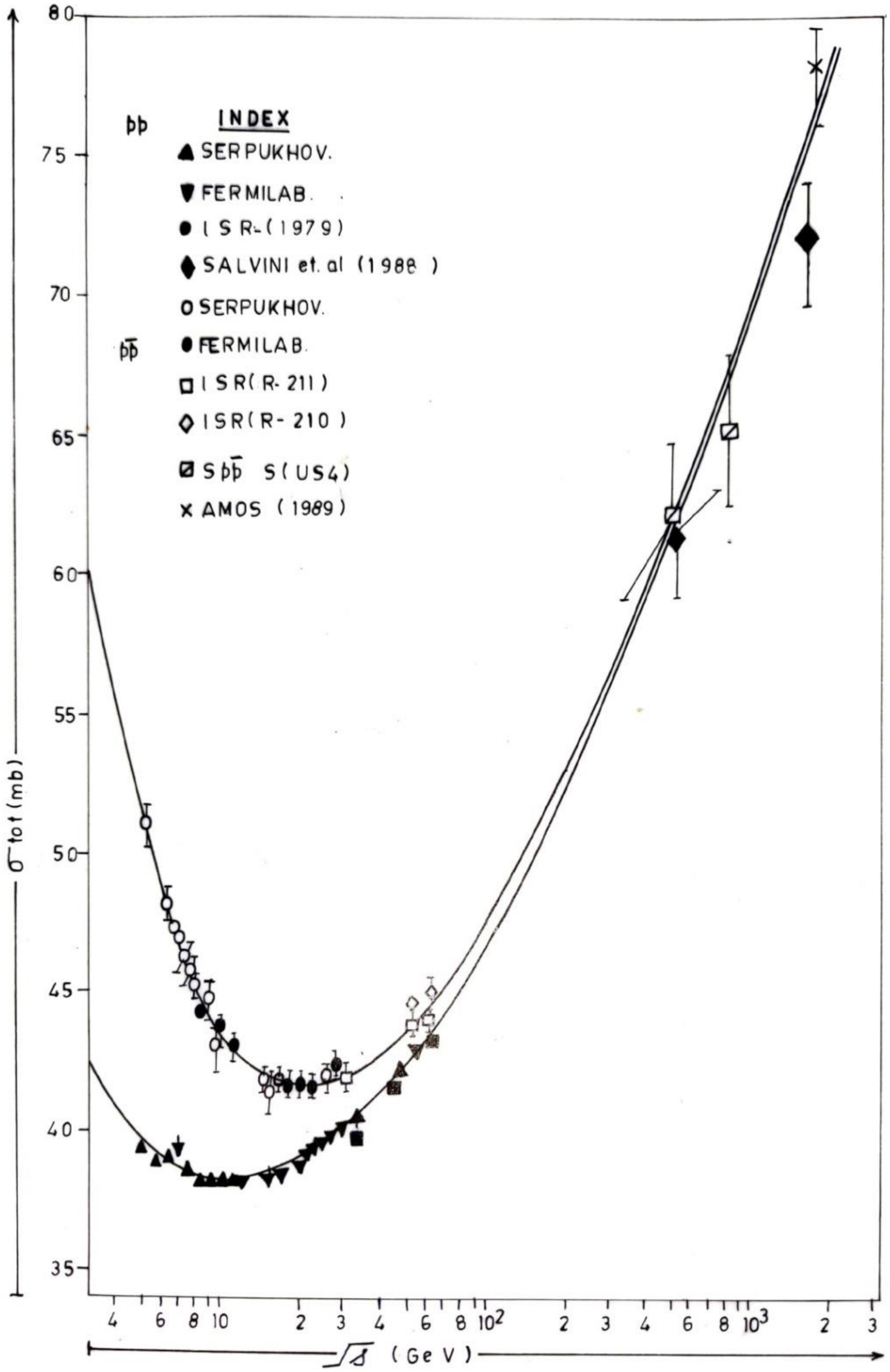

Fig.1: Total cross-sections (σ_{tot}) at different c.m. energies for p-p and p- $\bar{p}$ interactions.

The parabolic behavior of σ_{tot} can be explained by the internal structures of protons and antiprotons. At lower energies the projectile beam has larger wavelength which decreases on increasing the beam energy. Consequently, the σ_{tot} decreases with the increase of energy. But above about 10 GeV, the quark-quark interactions begin to show its influence in place of p-p or p- $\bar{p}$ interactions. In other words, the spatial distribution of quarks goes on spreading with the increase in c.m. energy. Consequently, the rising

Table-2: Total cross-section difference $\Delta\sigma_{tot}$ and the ratio ρ, for 5.00 GeV < ($\sqrt{s}$) < 2000 GeV

S.No.	c.m. Energy (GeV)	$\Delta\sigma_{tot}$ (mb) Calculated	$\Delta\sigma_{tot}$ (mb) Experimental	ρ (pp) Calculated	ρ (pp) Experimental
1.	5.00	11.81	.....	0.250	0.280 $\pm$ 0.02
2.	5.43	10.82	10.80 $\pm$ 1.0	0.239	0.270 $\pm$ 0.02
3.	6.24	9.19	9.20 $\pm$ 0.7	0.216	0.202 $\pm$ 0.02
4.	6.93	8.16	8.20 $\pm$ 0.4	0.197	0.162 $\pm$ 0.04
5.	7.30	7.71	…	0.196	0.168 $\pm$ 0.03
6.	7.59	7.38	7.38 $\pm$ 0.5	0.175	…
7.	8.05	6.91	6.8 $\pm$ 0.5	…	…
8.	8.21	6.76	7.1 $\pm$ 0.4	…	…
9.	8.54	6.47	6.3 $\pm$ 0.5	…	…
10.	8.79	6.19	6.1 $\pm$ 0.5	0.163	0.180 $\pm$ 0.04
11.	9.33	5.87	5.7 $\pm$ 1.2	…	….
12.	9.69	5.62	4.8 $\pm$ 1.2	…	…
13.	9.81	5.55	5.5 $\pm$ 0.6	0.144	0.168 $\pm$ 0.03
14.	13.70	3.85	3.5 $\pm$ 0.6	0.094	0.095$\pm$ 0.03
15.	15.12	3.41	3.0 $\pm$ 0.5	….	…
16.	16.81	3.05	3.1 $\pm$ 0.5	…	…
17.	18.05	2.78	2.8 $\pm$ 0.5	0.058	0.049 $\pm$ 0.03
18.	19.15	2.57	2.5 $\pm$ 0.6	…	…
19.	19.53	…	…	0.044	0.039 $\pm$ 0.03
20.	21.13	2.23	2.3 $\pm$ 0.3	…	…
21.	21.82	…	…	0.035	0.019 $\pm$ 0.03
22.	23.04	2.09	2.5 $\pm$0.8	0.026	…
23.	23.77	….	…	0.023	0.022 $\pm$ 0.01
24.	25.72	…	…	0.017	0.018 $\pm$ 0.01
25.	29.57	…	…	0.000	….
26.	30.10	1.50	2.6 $\pm$ 0.8	0.0015	0.019 $\pm$ 0.02
27.	30.46	1.44	1.85 $\pm$ 1.1	…	…
28.	43.20	…	…	0.035	0.054 $\pm$ 0.03
29.	53.87	0.74	1.6 $\pm$ o.9	0.054	0.062 $\pm$ 0.03
30.	63.00	0.56	1.4 $\pm$ 1.1	0.065	0.062 $\pm$ 0.03
31.	100.00	0.33	…	0.096	…
32.	200.00	0.17	…	0.125	…
33.	400.00	0.19	…	0.142	…
34.	520.00	0.22	1.5 $\pm$ 4.7	0.145	…
35.	600.00	…	…	0.150	…
36.	1000.00	…	…	0.152	…
37.	1800.00	0.38	0.68 $\pm$ 10.2	0.153	…
38.	2000.00	0.38	…	0.153	…

interaction radius causes σ_{tot} to rise.The results of the present parameterization of $\sigma_{tot(pp)}$ and $\sigma_{tot(p\bar{p})}$ show a batter agreement for all GeV and TeV energies.

The energy dependence of the total cross-section difference $\Delta\sigma_{tot}$ between $\sigma_{tot(pp)}$ and $\sigma_{tot(p\bar{p})}$ is shown in Fig.2 and the its values are presented in Table-2. On increasing the energy, the values of $\Delta\sigma_{tot}$ decreases and go to vanish towards $s \to \infty$. The energy dependence of $\Delta\sigma_{tot}$ for p-p̄ and p-p follows the Regge behavior (Giacomelli, G. and Jacob, M. 1979), as expected from the analysis of the lower energy scattering data. The Regge behavior makes the $\Delta\sigma_{tot}$ tends to zero rather rapidly and follow $\sigma_{tot(p\bar{p})}/\ \sigma_{tot(pp)} \to 1$ as required by the Pomeranchuk theorem (Pomeranchuk, I., 1958). This difference in the

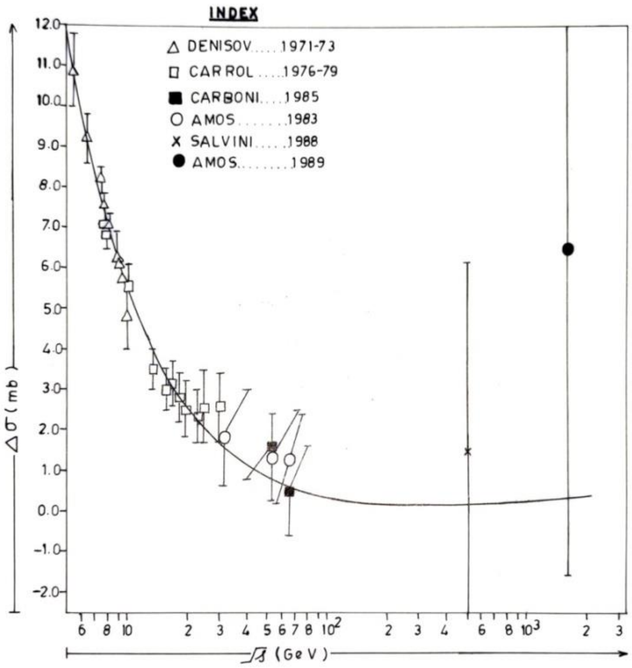

Fig.2: Total cross-section difference $\Delta\sigma_{tot} = \sigma_{tot(p\bar{p})} - \sigma_{tot(pp)}$ *as a function of c.m. energy*

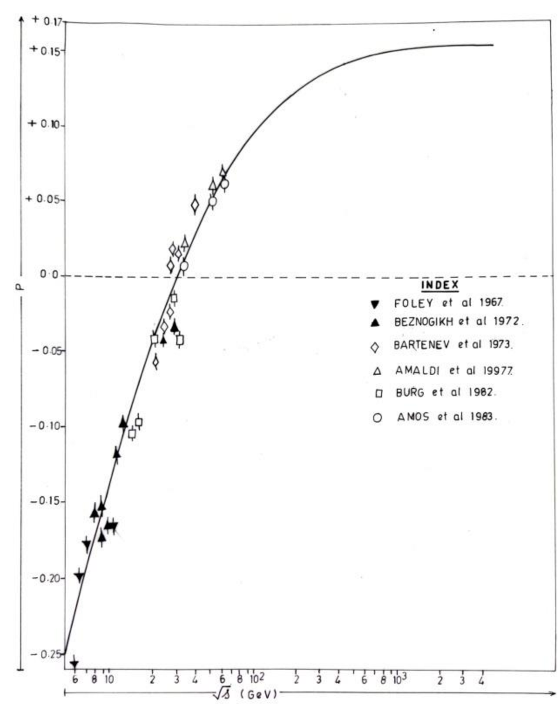

Fig.3: Variation of the ratio ρ of real to imaginary part of the scattering amplitude for the forward p-p interaction, as a function of c.m. energy

total cross-sections for p-p̄ and p-p interactions is mainly due to the opposite nature of Coulomb effect in p-p̄ and p-p cases. The Coulomb effect becomes less and less important towards higher energies. The results of present parameterization of $\Delta\sigma_{tot}$ are compared with the experimental data and are found to be in fair agreement with the data.

The ratio 'ρ' of the real to imaginary part of the scattering amplitude in the case of proton-proton interactions has been calculated in this work for different c.m. energies between 5.0 GeV and 2000 GeV and are presented in the Table-2. The variation of 'ρ' as a function of c.m. energy is presented in Fig.3. When the coulomb and nuclear amplitudes are of the same order, a non-negligible interference effect takes place, if the hadronic amplitude is not purely imaginary. A sizeable destructive interference is observed in the ISR p-p data (Amaldi, U. et al., 1977), which becomes more and more pronounced as energy increases. The results of the present parameterization are compared with the experimental data and are found to be in fair agreement with the data.

CONCLUSIONS :

1. A modified parameterization for $\sigma_{tot(p\bar{p})}$, $\sigma_{tot(pp)}$, $\Delta\sigma_{\text{tot}}$ and the ratio 'ρ' of the real to imaginary part of the scattering amplitude is proposed in the present work.
2. The variations of $\sigma_{tot(p\bar{p})}$ and $\sigma_{tot(pp)}$ for p-p and p-$\bar{p}$ interactions as a function of c.m. energy follow the parabolic behavior in GeV as well as in TeV energy ranges.
3. The parameterization of $\Delta\sigma_{\text{tot}}$ is obtained from the parameterizations of $\sigma_{tot(p\bar{p})}$ and $\sigma_{tot(pp)}$ and are found to be in fair agreement with the experimental data.
4. The calculated values of the ratio 'ρ' of the real to imaginary part of the scattering amplitude follow the theoretical concepts and experimental data.

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