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Statement of the Problem

The following assumptions were made when carrying out the phase-shift analysis:

1. A single-meson approximation is valid for the description of a pp interaction at 1 GeV in states with an orbital moment $\ell > 6$.

2. Mesons are mainly produced from initial $^3P_{0,1,2}$, $^1D_2$ and $^3F_{2,3,4}$ states.

3. The energy dependence of the experimental data used can be ignored and they can be related to 1 GeV within the limits of error (viz. table 1).

The applicability limit for a single-meson approximation is estimated on the basis of the results of the phase-shift analysis at 630 MeV /3/, allowing for variation in the impact parameter during the transition to 1 GeV.

The assumption concerning the nature of the meson production processes was based on the fact that the angular distributions of the π- mesons produced in pp collisions at 1 GeV as well as at 650-660 MeV contain no terms higher than $\cos^4 \theta$ (θ is the π-meson's emission angle). It is also known that, for an adequate description of the experiment during phase-shift analysis at 630 MeV, it is sufficient to allow for phase complexity only in $P_{0,1,2}$, $^1D_2$ and $^3F_{2,3,4}$ states.

The experimental data used for the phase-shift analysis are shown in table 2. In order to eliminate the possibility of systematic errors in the results obtained by the various authors, the data were processed first. The differential cross-sections for elastic pp scattering measured in /6-9/ were renormalized to the total cross-section for elastic scattering $\sigma^{elas.}_{tot.} = 24.8 \pm 0.9$ /15/.

The normalization factors are shown in the fourth column of table 2. To obtain corrected values for the differential cross-sections of the quantity $d\sigma/d\Omega$, shown in the papers listed (table 1), it is essential to divide them into the appropriate norms. The interaction's total cross-sections measured in papers /12/ and /13/ at 1.03 GeV and 1.075 GeV were averaged out. The error in measuring the polarization of the primary beam ($\approx$ 5%) is added quadratically to the results of the polarization measurements/12/. The data on differential cross-sections and polarization for angles $\theta > 90^\circ$ were reduced to the range $0^\circ \leq \theta \leq 90^\circ$ in terms of the known relations.

It is easy to work out that $3\ell_{max} + 1$ free parameters can be determined from the data in table 2 ($\sigma_{tot} + 1$; $\frac{d\sigma}{d\Omega} - \ell_{max} + 1$; $P(\theta) + \ell_{max} - 1$; $C_{nn} + \ell_{max} + 1$; $\sigma^{inelas.}_{total.} + 1$ (or 21 parameters at $\ell_{max} = 6$). The number of phase-shifts to be determined at $\ell_{max} = 6$, if meson production from P, D and F states is taken into account, is 22. The single-meson approximation used to describe a pp interaction in states with high orbital momenta provides the missing equations and the problem seems to be solved. However, there will clearly be a large number of solutions ($\approx 2^m$, where m is the required number of parameters/5/). In order to obtain some overdetermination, as is required with nonlinear problems solved by the maximum-likelihood method, the experimental data also included four points obtained by extrapolating the energy dependence of the depolarization factor D_{pp} measured in the lower energy region (400 - 630 MeV). The errors in the values extrapolated were such that this parameter was positively determined with 0,99 probability.

The solutions were found from the functional minimum condition

$$\chi^2 = \sum_{i=1}^{n} \left[F_{exp} - F(\delta) \right]_i^2 \cdot w_i ,$$

where F_{exp} is the value obtained by experiment, $F(\delta)$ is the calculated value of the quantity measured, W_i is the weight and n is the total number of experimental points used for the phase-shift analysis. The procedure used to search for solutions is described in detail in /19/.

Results

The attempt to find a solution from random initial values and thus to verify that the solution to the problem was single-valued did not meet with success. It turned out that the errors in the parameters found by this method were so great (100% or more) that no distinction could be made between the solutions within the limits of error. It was therefore decided to obtain a set of phase-shifts describing the experimental data at 1 GeV by extrapolating the solution found at 630 MeV /3/. For this purpose, the phase shift values found in /3/ were taken as initial values and were determined more accurately in terms of the experimental data shown in table 2. During this process, measures were taken to ensure that the energy dependences of δ (E) were sufficiently smooth right up to 1 GeV.

The solution obtained is shown in table 3. The table also shows the results of phase-shift analyses at 630 MeV /3/ and 1000 MeV /4/. A comparison of the set of phase-shifts thus obtained with the solution found previously at 630 MeV /3/ indicates that the experimental data at 1 GeV may be adequately described by assuming that there is a smooth dependence of phase-shifts on energy. There is no need to make any assumption about noticeable meson production from an initial $^1S_0$ state, as the authors of paper /4/ had to do at 1000 MeV.

The angular dependences of the values observed were calculated in terms of the set of phase-shifts obtained and are shown in figs. 1-6. The hatched areas in figs. 1-3 are the error margins of the curves. The error margin of the curves in figs. 4-6 for the angular dependences of the Wolfenstein parameters is 100%. It clearly follows from this that at present the most useful information for determining the pp-scattering amplitude can be obtained only from experiments on triple scattering.

After this paper had been finished, fresh results concerning the measurement of differential cross-sections, polarization and depolarization were published (viz. table 1). Firstly, the D_{pp} depolarization at 90° (c.m.s.), measured at 984 MeV, unfortunately features an error of almost 100% and has virtually nothing new to offer in the way of information. The differential cross-sections and polarization measured in the 30° - 90° range correspond to previous data.

In conclusion, the authors wish to thank S.I. Bilen'kaya for her help with this paper.

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Table 1.

Experimental data on elastic pp scattering close to 1 GeV.

E, MeV	θ° c.m.s.	f	Δf	source	E, MeV	θ° c.m.s.	f	Δf	source
PP	total cross-section σ_{tot} (mb)				PP	total cross-section $\sigma_{n.}^{H.}$ (mb)			
968		47,553	0,058	/I8/^{x}	970		22,48	0,8	/I5/
970		47,3	I,0	/I5/					
I030		46,5	2,0	/I2/					
I073		47,49	0,046	/I3/					
I075		48,3	I,6	/I8/^{x}					
PP	differential cross-section $d\sigma/d\Omega$ (mb/ster.)								
950	35,90	6,7I	0,56	/I7/^{x}	I000	36,5	5,66	0,I0	/8/
	38,73	6,30	0,5I	/		4I,3	4,54	0,I0	
	43,I2	4,76	0,25			53,7	2,44	0,07	
	49,45	3,5I	0,23			64,0	I,33	0,05	
	54,55	2,58	0,I7			77,0	0,79	0,05	
	58,67	2,26	0,I8			90,0	0,62	0,05	
	62,62	I,65	0,II		I0I0	I8,5	II,80	0,26	/7/
	67,05	I,45	0,I2			24,6	I0,40	0,33	
	70,I2	I,08	0,09			30,7	7,89	0,I8	
	73,74	I,00	0,08			36,7	5,76	0,09	
	77,88	0,99	0,08			4I,5	4,II	0,09	
	8I,95	0,65	0,05			48,5	2,7I8	0,05I	
	86,55	0,73	0,06			60,0	I,546	0,04I	
	89,43	0,78	0,I0			7I,I	0,922	0,029	
970	I2,30	I9,600	I,200	/6/		79,8	0,739	0,037	
	48,30	3,506	0,088			90,0	0,608	0,030	
	59,73	2,037	0,070		I040	37,82	5,97	0,34	/I7/^{x}
	70,83	I,I85	0,040			44,77	4,38	0,22	
	8I,55	0,898	0,024			50,95	3,04	0,20	
99I	I4,5	I8,620	0,80I	/9/		55,25	2,20	0,I5	
	I9,0	I4,280	0,366			60,00	I,94	0,I6	
	23,0	I2,460	0,280			63,90	I,56	0,I0	
	30,5	I0,334	0,274			68,28	I,I7	0,I0	
	40,0	5,430	0,II7			7I,93	0,95	0,08	
	50,0	3,200	0,089			76,70	0,85	0,06	
	59,5	I,860	0,085			80,80	0,66	0,06	
	70,0	I,04I	0,085			84,27	0,65	0,05	
	80,25	0,690	0,036			88,28	0,65	0,06	

* not used in the search for solutions

Table 1 (Continued)

E, MeV	θ° c.m.s.	f	Δf	source	E, MeV	θ° c.m.s.	f	Δf	source
PP	polarization P								
950	29,55	0,4I	0,03	/I7/x		5I,20	0,330	0,020	
	35,90	0,437	0,04			55,40	0,330	0,020	
	38,73	0,53	0,05			60,00	0,285	0,020	
	43,I2	0,44	0,03			64,60	0,265	0,030	
	49,45	0,47	0,04			67,20	0,287	0,050	
	54,55	0,40	0,04			68,70	0,2I0	0,060	
	58,67	0,37	0,05			7I,60	0,2I0	0,020	
	62,62	0,36	0,05			75,60	0,080	0,035	
	67,05	0,25	0,07			79,40	0,092	0,0I3	
	70,I2	0,20	0,08			83,20	0,090	0,020	
	73,74	0,24	0,08			87,00	-0,0I7	0,047	
	77,88	0,04	0,08		I030	39,88	0,4I9	0,037	/I2/
	8I,95	0,I7	0,08			42,47	0,464	0,046	
	86,55	-0,09	0,09			53,60	0,48I	0,033	
	89,43	-0,I8	0,I3			57,8I	0,4I7	0,043	
970	I2,30	0,237	0,I55	/I0/		6I,62	0,325	0,037	
	22,I0	0,I83	0,079			65,32	0,258	0,074	
	24,50	0,223	0,06I			68,52	0,245	0,035	
	26,90	0,3I2	0,068			7I,37	0,265	0,039	
	29,40	0,237	0,082			77,25	0,095	0,029	
	30,50	0,229	0,056			88,25	-0,02I	0,034	
	36,50	0,297	0,067		I040	30,68	0,4I	0,02	/I7/x
	48,30	0,386	0,070			37,82	0,47	0,03	
	59,70	0,334	0,083			44,77	0,38	0,02	
	70,80	0,I69	0,067			50,95	0,46	0,04	
	8I,60	0,063	0,066			55,25	0,32	0,04	
I029	25,90	0,345	0,040			60,00	0,28	0,05	
	30,90	0,355	0,020			63,90	0,28	0,05	
	35,60	0,370	0,030			68,28	0,32	0,06	
	40,60	0,385	0,030			7I,93	0,2I	0,07	
	42,00	0,405	0,027			76,70	0,22	0,06	
	45,40	0,370	0,020			80,80	-0,0I	0,08	
	46,60	0,360	0,025			84,27	0,II	0,08	
	50,00	0,345	0,02I			88,28	0,0I	0,08	
PP	polarization correlation C_{nn}				PP	depolarization D			
978	42,0	0,70	0,I9	/II/	984	90,0	0,65	0,56	/I6/x
	46,7	0,72	0,I5						
	5I,2	0,6I	0,I6						
	55,6	0,62	0,20						
	60,0	0,46	0,26						
	64,3	0,44	0,27						
	68,6	0,7I	0,47						
	70,0	0,39	0,27						
	73,4	0,69	0,I6						
	77,4	0,79	0,I7						

* not used in the search for solutions

Table 2.

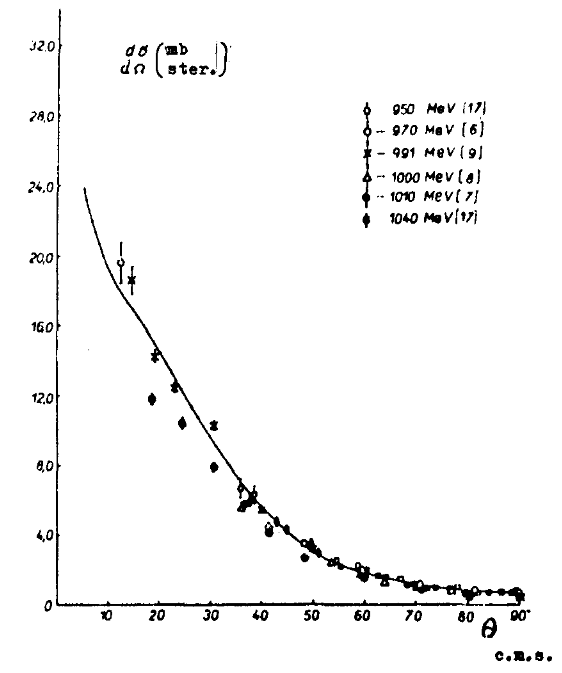
Experimental data processed.

exp. value	E, MeV	no. of points	norm	χ^2	source	remarks
σ^{pp}_{tot}	970	I		0,003	/15/	averaged
	1030	I		0,054	/14/	
	1075	I			/13/	
$\sigma^{inelas.}_{total}$	970	I			/15/	
$(d\sigma/d\Omega)_{pp}$	970	4	I,I09 ± 0,044	4,8	/6/	renormalized to total inelastic cross-section (24,8 ± 0,9 mb)
	991	8	0,990 ± 0,038	20,I	/9/	
	1000	5	0,870 ± 0,034	7,6	/8/	
	IOIO	9	0,835 ± 0,03I	I3,0	/7/	
P_{pp}	970	II		9,8	/10/	
	1029	I7		16,3	/II/	
	1030	10		15,6	/12/	
C_{nn}	978	10		0,82	/II/	
D_{pp}		4				extrapolation

Table 3.

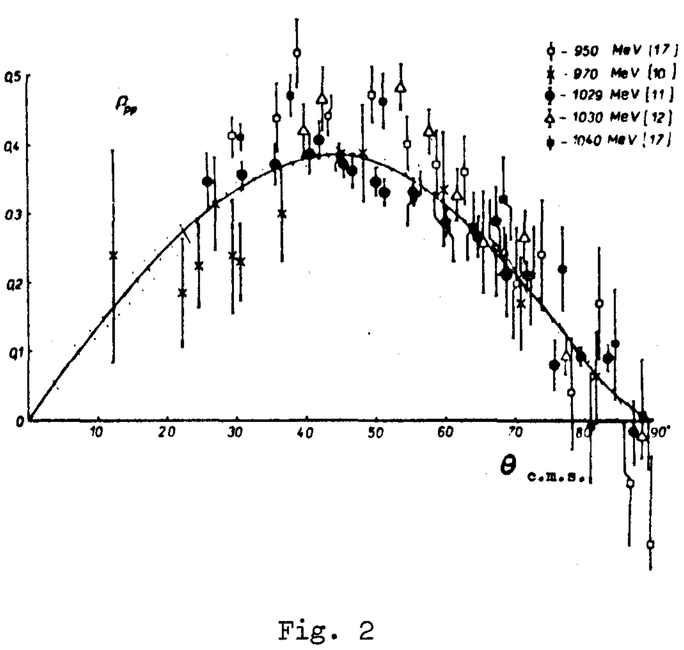
Phase-shifts in degrees (Stapp match [20])

	630 MeV [3]	1 GeV (this paper)	1 GeV [4]
f^2	0,076 ± 0,005	0,07	0,08
${}^1S_0$	-19,4 ± 3,4	-5,0	-30,0
${}^3P_0$	-20,7 ± 2,4	-4I,I	-37,5
${}^3P_1$	-29,9 ± 2,2	-17,6	-71,5
${}^3P_2$	34,7 ± I,8	55,0	I6,9
${}^1D_2$	9,6 ± I,6	II,8	II,3
ε_2	2,9 ± 0,9	3,8	43,5
${}^3F_2$	-4,I ± 0,6	-6,6	-I3,7
${}^3F_3$	0,7 ± 0,8	-0,3	(-7,73)
${}^3F_4$	3,8 ± 0,8	4,7	(6,50)
${}^1G_4$	5,6 ± 0,7	6,4	(4,50)
ε_4	0,7 ± 0,8	-2,5	
${}^3H_4$	-2,3 ± 0,6	-3,5I	(I,I0)
${}^3H_5$	-3,2 ± 0,8	+I,5	(-2,00)
${}^3H_6$	-2,8 ± 0,5	-3,7	(2,40)
I_6	single-meson	-3,2	(0,669)
	imaginary parts of phase shifts		
${}^1S_0$	-	-	40,0
${}^3P_0$	-	2,0	9,0
${}^3P_1$	-	30,2	0,0
${}^3P_2$	5,I ± I,5	5,4	I6,0
${}^1D_2$	I0,9 ± 2,6	6,8	I3,2
${}^3F_2$	0,7 ± I,I	4,9	I9,0
${}^3F_3$	2,4 ± I,5	9,4	I8,0
${}^3F_4$	4,0 ± 0,7	I6,5	3,0
χ^2		88	52
n		82	62



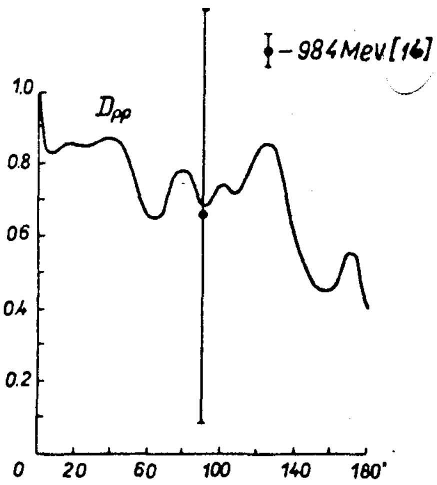
$\frac{d\sigma}{d\Omega}\left(\frac{mb}{ster.}\right)$
950 MeV [17]
970 MeV [6]
991 MeV [9]
1000 MeV [8]
1010 MeV [7]
1040 MeV [17]
θ c.m.s.

Fig. 1



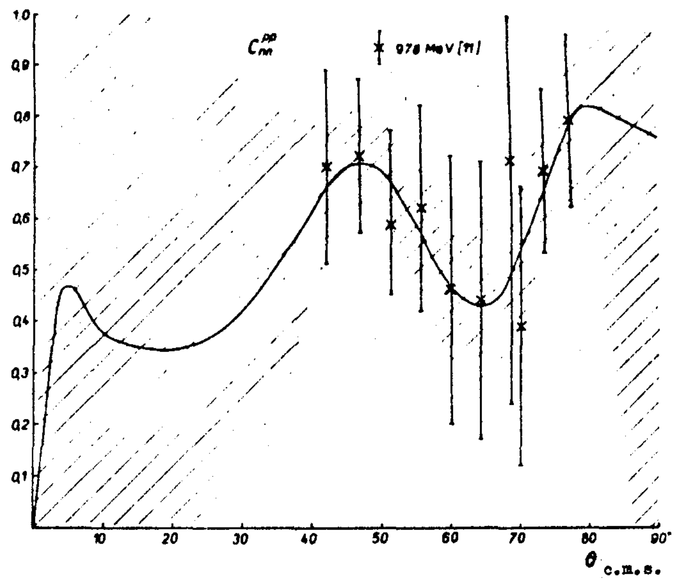
P_{pp}
950 MeV [17]
970 MeV [10]
1029 MeV [11]
1030 MeV [12]
1040 MeV [17]
θ c.m.s.

Fig. 2



- 984 MeV [16]
D_{pp}
1.0
0.8
0.6
0.4
0.2
0
20
60
100
140
180°

Fig. 3



C_{nn}^{pp}
978 MeV [11]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10
20
30
40
50
60
70
80
90°
θ c.m.s.

Fig. 4

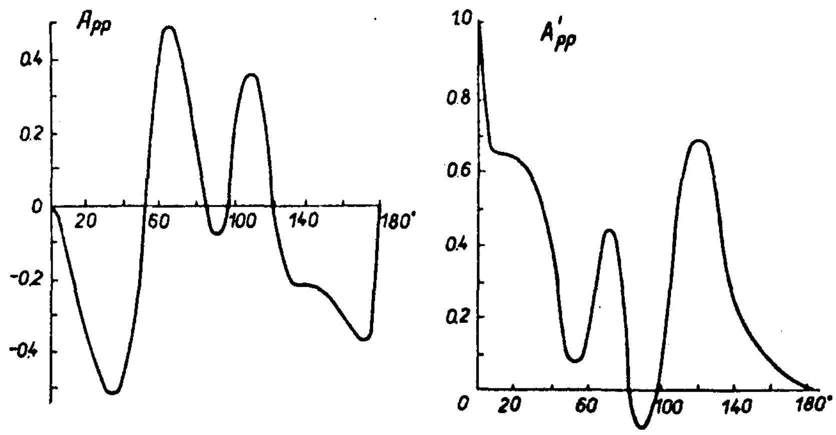

A_{pp}
0.4
0.2
0
-0.2
-0.4
20
60
100
140
180°
A'_{pp}
1.0
0.8
0.6
0.4
0.2
0
20
60
100
140
180°

Fig. 5

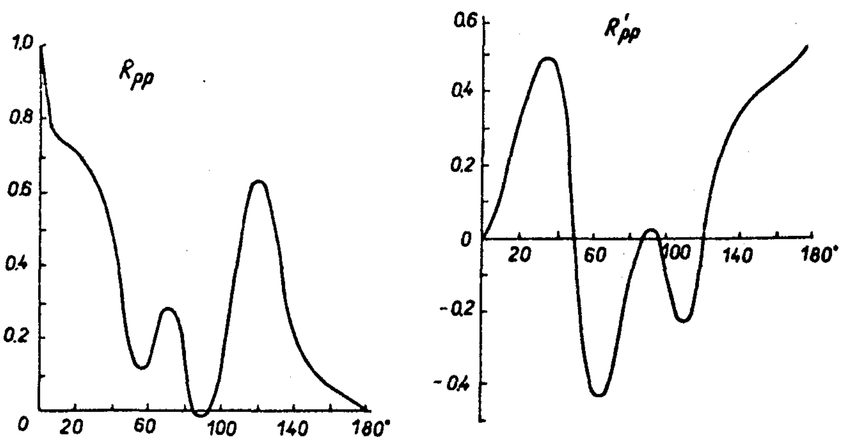

1.0
R_{pp}
0.8
0.6
0.4
0.2
0
20
60
100
140
180°
0.6
R'_{pp}
0.4
0.2
0
-0.2
-0.4
20
60
100
140
180°

Fig. 6