AN ANALYSIS OF 640-MeV pp SCATTERING INCLUDING CONSIDERATION OF TOTAL CROSS SECTIONS AND PION ANGULAR DISTRIBUTIONS

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Our phase shift analysis of 640-MeV pp collisions, unlike earlier work, includes consideration of the $\pi^{+,0}$ angular distributions. Four solutions of approximately equal probability are obtained. More precise experimental data on elastic pp scattering will be needed to make the analysis less ambiguous.

1. Phase shift analyses of pp scattering in the 600—660-MeV region, where meson production processes complicate considerably our interpretation of NN interactions, have been performed repeatedly with ambiguous results. At an early stage[1,2] it seemed that the problem had been solved uniquely. However new and more accurate experimental information about the parameters $P(\theta)$, $D(\theta)$, and $C_{nn}(\theta)$[2] made it possible, by properly classifying the experimental data in the narrow 635—650-MeV region, to analyze pp scattering more rigorously, devoting special attention to the question of obtaining unique solutions and to procedures for taking pion-emission transitions into account. These analyses[3,4] firmly established the existence of several approximately equally probable solutions.[1)]

The ambiguities clearly result from the incompleteness of the experimental data and the need for further experimental investigations. However, the performance of new experiments and the revision of old results, while extremely desirable for the purposes of future analyses, are often not quickly realized in practice. It is therefore desirable to utilize the now available knowledge regarding meson production as a source of additional and independent information for NN scattering analyses. A combined analysis of elastic and inelastic scattering is also desirable for another reason. In previous analyses, as we know, the two processes have been related only by the optical theorem (through the total scattering cross section). It can therefore be understood why the phase shifts that are responsible for pion emission are very uncertain. More ample data could establish additional relations for the phase shifts and reduce the uncertainties.

In the present work elastic proton-proton scattering at 640 MeV is analyzed taking into consideration the total cross sections and $\pi^{+,0}$ angular distributions. The calculations were based on the resonance model of meson production.[5]

2. Our analysis was based on the elastic scattering data that had been used in[3] and experimental data on meson production in pp collisions at 650—660 MeV[6]:

$$\sigma(\pi^+pn),\quad \sigma(\pi^+d),\quad \sigma(\pi^0pp),\quad \frac{d\sigma(\pi^+pn)}{d\Omega},\quad \frac{d\sigma(\pi^0pp)}{d\Omega}.$$

We considered 110 experimental points, as shown in Table I.

Table I. Distribution of experimental contributions in χ^2

Quantity	Number of experimental points	Solution I	Solution II	Solution III	Solution IV
$\sigma_{elast}(\theta)$	37	30	30	25	30
$P(\theta)$	23	8	12	13	13
$D(\theta)$	8	7	7	8	7
$R(\theta)$	5	10	17	14	15
$A(\theta)$	5	1	3	4	3
$C_{nn,\,\kappa p}(\theta)$	14	8	9	10	9
$\sigma_{inelast}$	18	11	12	17	14
Total	110	75	90	91	91

Table II. Phase shifts (l = 5, $\overline{\chi^2}$ = 90)

States of the pp system	Solution I		Solution II		Solution III		Solution IV	
	δ	$\pm\Delta\delta$	δ	$\pm\Delta\delta$	δ	$\pm\Delta\delta$	δ	$\pm\Delta\delta$
	Real parts of the phase shifts, deg							
$^1S_0$	—23,3	3,9	—28,5	5,2	—37,0	5,3	—33,2	5,3
$^1P_0$	—59,0	6,7	— 8,4	4,7	—16,7	2,5	—16,8	8,3
$^3P_1$	—35,8	4,5	—25,3	4,1	—34,0	2,7	—21,7	5,4
$^3P_2$	20,5	2,5	41,0	3,0	34,3	3,2	40,2	3,5
$^1D_2$	11,2	3,1	8,0	3,2	3,7	2,2	6,1	3,0
ε_2	—3,7	2,1	1,3	3,4	—0,6	3,4	—3,0	2,2
$^3F_2$	—5,4	2,2	—3,4	1,7	—8,4	1,0	—5,0	2,2
$^3F_3$	4,6	2,3	8,8	2,0	4,5	3,2	8,7	1,5
$^3F_4$	2,3	0,8	4,0	1,5	—2,2	1,6	1,2	2,5
$^1G_4$	5,2	1,3	3,7	1,7	2,2	1,2	3,2	1,5
ε_4	—2,9	1,1	—1,5	1,0	—1,5	1,2	—2,9	0,8
$^3H_4$	1,5	1,3	—0,7	0,6	—2,4	0,9	—1,4	1,0
$^3H_5$	1,3	0,9	1,0	1,0	—1,4	1,5	0,0	1,2
$^3H_6$	1,9	0,5	0,6	0,8	—2,0	1,0	0,9	1,2
	Imaginary parts of the phase shifts, deg							
$^3P_0$	0,7	4,9	6,0	5,6	—7,1	5,0	5,2	8,0
$^3P_1$	6,8	4,5	6,1	4,5	6,6	4,1	6,7	3,2
$^3P_2$	2,4	2,0	8,6	3,4	11,2	3,9	6,5	2,7
$^1D_2$	7,3	0,6	7,3	0,6	7,5	0,6	7,3	0,6
$^3F_2$	7,2	2,0	2,9	1,5	1,8	1,6	2,3	1,5
$^3F_3$	5,6	1,7	6,2	1,6	6,1	1,5	5,3	1,3
χ^2	75		90		91		91	

The meson production amplitudes and elastic scattering parameters are related as follows[7]:

$$\sigma(pp\to\pi^+pn)=4\pi\sum_{J=0}^{3}\sum_{l=1}^{3}|\beta_{Jl}|^2A_{Jl}^{+},\tag{1}$$

$$\sigma(pp\to\pi^+d)=4\pi|\beta_{22}|^2A_{22}^{d},\tag{2}$$

$$\sigma(pp\to\pi^0pp)=4\pi\sum_{l=1}^{3}\sum_{J=0}^{3}|\beta_{Jl}|^2A_{Jl}^{0},\tag{3}$$

$$\frac{d\sigma}{d\Omega}(pp\to\pi^+pn)=\frac{\sigma(\pi^+pn)}{4\pi}+P_2(\theta)\sum_{J=0}^{3}\sum_{l=1}^{3}|\beta_{Jl}|^2B_{Jl}^{+},\tag{4}$$

[1)]Some of these were already known from [1,2].

$$\frac{d\sigma}{d\Omega}(pp \to \pi^0 pp) = \frac{\sigma(\pi^0 pp)}{4\pi} + P_2(\theta)\sum_{J=0}^{3}\sum_{l=1}^{3}|\beta_{Jl}|^2 B_{Jl}^0. \quad (5)$$

In these expressions the β_{Jl}, which are the partial amplitudes for pion production by protons having initial total angular momentum J and orbital angular momentum l, are model parameters. The A_{Jl} and B_{Jl} coefficients were calculated on the resonance model; total angular momentum, parity, and isotopic spin were conserved. We allowed for pion-nucleon (3/2, 3/2) resonant interaction and the final nucleon-nucleon interaction. $P_2(\theta)$ is the second Legendre polynomial and θ is the emission angle in the center-of-mass system.

The relationship between β_{Jl} and the elements S_{Jl} of the elastic scattering matrix[1] is given by the expressions[7]

$$\frac{8k^2}{2J+1}(A_{Jl}^0 + A_{Jl}^+)\,|\beta_{Jl}|^2 = 1 - |S_{Jl}|^2 \quad \text{for } l, J \neq 2, \quad (6)$$

$$\frac{8k^2}{5}(A_{22}^0 + A_{22}^d + A_{22}^+)\,|\beta_{22}|^2 = 1 - |S_{22}|^2 \quad \text{for } J, l = 2. \quad (7)$$

Here k is the c.m.s. wave vector of the colliding protons.

In accordance with the conventional procedure, meson creation has been introduced only in "resonance" states: $^3P_{0,1,2}$, $^1D_2$, and $^3F_{2,3}$. Real mixing parameters have been assumed. The method of analysis did not differ in other respects from that used in[1-4].

3. In view of the recent[3] quite thorough search for the minima of the functional χ^2 on the basis of different hypotheses regarding the mechanism of meson creation, and also assuming that additional experimental data on meson creation would not essentially change the number of lowest-lying minima of χ^2, we considered it permissible to omit a search for solutions from random phase shifts. Instead, we limited ourselves to revising the eight solutions obtained in[3]. Four solutions finally remained, with χ^2 = 75, 90, 91, and 91, respectively, and $\overline{\chi^2}$ = 90 (Table II). The solution with χ^2 = 75 is analogous to that obtained previously in[2,8]. The phase shifts in the other three solutions are close to those obtained in[1,3,4,8]. The solutions are completely independent.

The existence of several solutions indicates that the utilized information about inelastic interaction processes does not have the same weight as the available information about elastic pp scattering. For this reason our procedure for taking inelastic processes into account has not been very effective as a method of removing the ambiguity of the analysis.

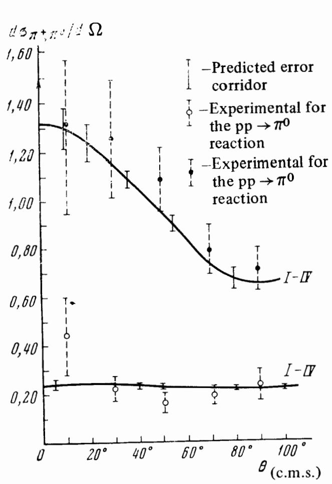

FIG. 1. Angular dependences of the cross sections (mb/sr) for π^+ and π^0 production in pp → π^+np and pp → π^0pp. The curves were predicted by the phase shift analysis; the experimental points were taken from [6].

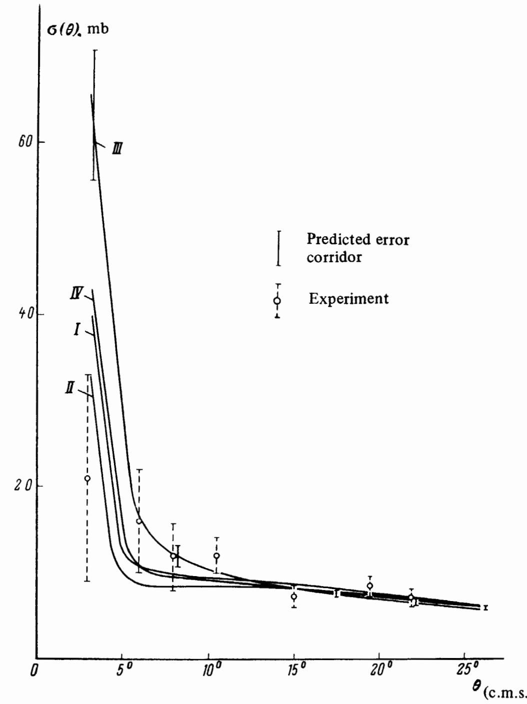

FIG. 2. pp scattering cross sections in the c.m.s. angular range 0° – 26°.

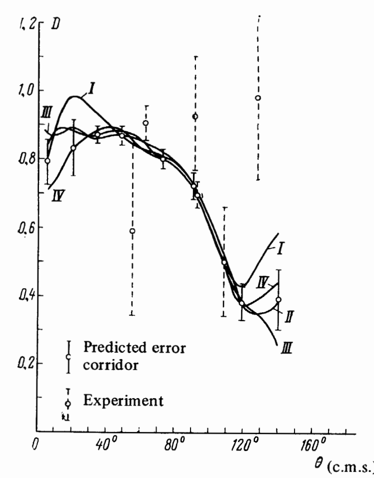

FIG. 3. Angular dependence of the D parameter.

Table II shows that there are especially great differences between the solutions in triplet states. The imaginary parts of the phase shifts are more determinate and are practically unique, with errors reduced about one-half although still quite large (2°–4°). We may expect that in future analyses the utilization of pion spectra will enable us to determine more accurately the roles of the $^3P_1$, $^3P_2$, and $^3F_2$ states in meson creation and to reduce the errors in the imaginary parts of the phase shifts.

The $\pi^{+,0}$ angular distributions are well described by all the sets of phase shifts and are predicted very accurately (Fig. 2 and Table II). The elastic scattering cross sections and the R parameter are described less accurately; the contribution in χ^2 reaches 30.

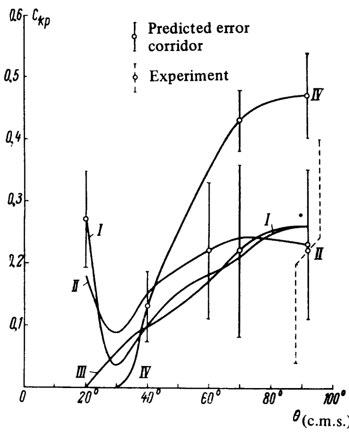

FIG. 4. Angular dependence of the C_{kp} coefficient.

To obtain further improved and still less ambiguous results it would be desirable to perform precision measurements of differential cross sections $d\sigma/d\Omega$ in the range 3°—20° and to extend the measurements of the D parameter to larger angles. The angular dependence of the C_{kp} coefficient should be investigated in the c.m.s. range 10°—80°. It can be seen from Figs. 1, 3, and 4 that all these measurements could be of great assistance toward achieving a unique analysis.

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