CONTRIBUTION OF ^{3}P *AND* ^{3}F *WAVES TO MESON PRODUCTION IN 660-MeV pp-COLLISIONS*

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Submitted to JETP editor April 24, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1169-1173 (October, 1963)

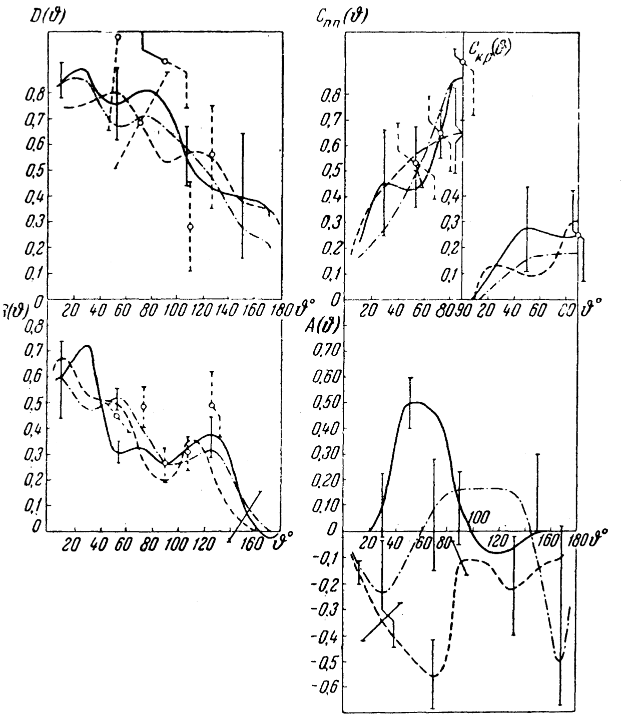
The present status of the analysis of elastic pp-scattering data at 660 MeV is clarified. To this end, a phase shift analysis of pp-scattering at 660 MeV is performed by taking into account meson production from $^3P_{0,1,2}$, $^1D_2$, and $^3F_{2,3,4}$ states of the pp system. Four solutions are obtained without any assumptions being made regarding the relation between the imaginary parts of the phase shifts in the interval $\chi^2 \leq 2\overline{\chi^2}$. Three of the solutions are definitely independent. From the results obtained it can be concluded that if the relationships $\delta(^3P_0) = \delta(^3P_1) = \delta(^3P_2) \neq 0$ and $\delta(^3F_2) = \delta(^3F_3) = \delta(^3F_4) \neq 0$ are correct then the phase-shift analysis problem has practically a single solution (solution I). However, if one assumes that $\delta(^3P_0) \neq \delta(^3P_1) \neq \delta(^3P_2)$ and $\delta(^3F_2) \neq \delta(^3F_3) \neq \delta(^3F_4)$ then solutions II, III, and IV can be distinguished. It is concluded that mesons are predominantly produced in peripheral pp-collisions at 660 MeV. It is mentioned that with increasing energy the role of single-meson exchange in elastic pp scattering with $L \geq 2$ may dominate.

A phase shift analysis of elastic pp scattering at 660 MeV [1,2] was recently carried out in Dubna, and it was shown that relatively little additional experimental material is necessary for a more rigorous formulation. Such a formulation presupposes, in our opinion, at least the variation of all the phase shifts for $L \leq 6-7$. However, as is clear from [2,3], in the modified analysis it is sufficient to obtain only the phase shifts with $L \leq 5$ 1). The question from which states the formation of the pions in pp collisions at 660 MeV proceeds in this case (the imaginary parts of which phase shifts differ from zero) remains open. We can only follow here the indications of a particular interaction model. Therefore, generally speaking, any analysis without an account of meson production for at least one of the states $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, etc., cannot be regarded as sufficiently rigorous.

Certain approximation is inherent also in the analysis [1,2] in which account is taken of meson production for the states $^3P_0$, $^3P_1$, $^3P_2$ and $^1D_2$ in the framework of the Mandelstam theory. Some features of this analysis are: (a) the presence of a unique solution in the interval $\overline{\chi^2} \leq \chi^2 \leq 2\overline{\chi^2}$; b) the clearcut difference of the imaginary parts of the phase shifts $\bar{\delta}^I(^3P_2)$ and $\bar{\delta}^I(^1D_2)$ in the states $^3P_2$ and $^1D_2$ from zero.

It can be thought that (a) is the consequence of the fact that the sufficiently rigid premises of the Mandelstam resonance theory have been introduced in the analysis from the very outset, and this has naturally led to the limitation of the space in which the solutions were sought. The possible limitation of phase space was indicated by us already in [2]. In fact, the fixing of $\bar{\delta}^I(^1D_2)$ and the use of its semi-empirical value obtained on the basis of the Soroko papers [4] leads, within the framework of this model, to a situation wherein variation of $\bar{\delta}(^3P_{0,1,2})$ is subjected to the limitation of the form $\sigma_{tot} - 5.5\lambda\!\!\!^-{}^2 \approx 1.41\lambda\!\!\!^-{}^2[1-r^2(^3P)]$ where $r^2(^3P)$ is a function of $\bar{\delta}^I(^3P_0)$, $\bar{\delta}^I(^3P_1)$, $\bar{\delta}^I(^3P_2)$. This means that when seeking for solutions in [2], only two parameters, characterizing the transitions with emission of a pion in pp collision, were effectively varied. Under these conditions, naturally, the result (b) agrees with the resonance model, in which it is assumed that the transitions from the initial $^3P_{0,1,2}$ and $^1D_2$ states of the pp system are particularly important [5]. Now that the existence of a practically unique solution within the framework of the Mandelstam theory has been established, it is reasonable to dispense with the indications of this model and to carry out further search under less stringent assumptions.

1)In the pp system this is rigorously correct only for odd values of l.



Angular dependence of the quantities C_{nn}, C_{kp}, D, R, and and A, calculated in accordance with solutions I, II, and IV. The vertical solid lines denote the calculated error corridor, the points show the experimental data; the calculated curves are: solid–for $\chi^2 = 22$, solution I; dashed–for $\chi^2 = 23$, solution II; dash dot–for $\chi^2 = 40$, solution III; $\overline{\chi^2} = 23$.

In the present note we give the results of a phase shift analysis carried out under the assumption that the imaginary parts of the phase shifts of the $^3F_{2,3,4}$ waves cannot be neglected. Introducing $\bar{\delta}^I(^3F_{2,3,4})$, we wish to emphasize in particular that, unlike Hoshizaki and Machida [6], we do not imply in the present work the validity of the equalities

$$\bar{\delta}^I(^3F_2) = \bar{\delta}^I(^3F_3),$$

$$\bar{\delta}^I(^3P_0) = \bar{\delta}^I(^3P_1) = \bar{\delta}^I(^3P_2), \quad \varepsilon_2^R = \varepsilon_2^I = 0$$

and of formula (10) of [6], the truth of which cannot be regarded as experimentally confirmed. The premises of the Japanese authors were fully utilized also in the work of Azhgirei et al [7], which was carried out simultaneously with our work. These extremely stringent assumptions greatly limit the class of solutions obtained in the analysis, and therefore lead to an unavoidable loss of some of them during the search.

The search for the solutions was carried out by us on the basis of the method and experimental material used in [1,2], and was done in two stages. In the first stage, $\bar{\delta}^I(^1D_2)$, $\bar{\delta}^I(^3P_{0,1,2})$, $\bar{\delta}^I(^3F_2)$ and the parameter ϵ_2 were assumed imaginary, and the real parts of the phase shifts were varied in the same way as in [1]. After 60 searches we found not a single solution different

Table I

Solution	I	II	III	IV
χ^2	22	23	26	40
$\chi^2/\overline{\chi^2}$	1	1.05	1.18	1.80
$P(\chi^2 > \overline{\chi^2})$, %	40	40	~20	~2

from that previously obtained in the interval $\overline{\chi^2} \le \chi^2 \le 2\overline{\chi^2}$. As before in [2] it was found that $\epsilon_2^I \le 2°$. This fact must be regarded as some indication that the equation $\epsilon_2^I \approx 0$ is correct. Starting from this, a further search for the solutions, with additional variation of $\bar{\delta}^I(^1D_2)$, $\bar{\delta}^I(^3F_{2,3,4})$ and ϵ_2^R, was carried out under the assumption that $\epsilon_2^I = 0$. After 60 attempts, a total of eight solutions was found with χ^2 in the interval $\overline{\chi^2} \le \chi^2 \le 2\overline{\chi^2}$. Four solutions were discarded as leading to negative values of the πN interaction constant and $\bar{\delta}^I(^3P_{0,1})$. The remaining four frequently-repeating solutions have the values of χ^2 listed in Table I. The phase shifts of the solutions are given in Table II. The figure illustrates the angular dependences of several experimental quantities in accordance with the solutions obtained. By virtue of the great generality of our analysis, results already known are obtained for several particular cases. Thus, if in accordance with the resonance model [5] we assume that $\bar{\delta}^I(^3P_0) \neq \bar{\delta}^I(^3P_1) \neq \bar{\delta}^I(^3P_2)$ and $\bar{\delta}^I(^3F_2) = \bar{\delta}^I(^3F_3) = \bar{\delta}^I(^3F_4) \approx 0$, then we obtain solution III. The latter is an analog of the well-known solution No. 1 of [1,2]2).

On the other hand, if we assume, as was done in [7] (without rigorous justification) that $\bar{\delta}^I(^3P_0) = \bar{\delta}^I(^3P_1) = \bar{\delta}^I(^3P_2)$ and $\bar{\delta}^I(^3F_2) = \bar{\delta}^I(^3F_3) = \bar{\delta}^I(^3F_4) \neq 0$, then we must exclude from consideration all the solutions of the present work, except for solution I, which is analogous also to that obtained in [7]. It is appropriate to note in this connection that the use in [7] of formulas (9) and (10) of [6] may actually signify the introduction of only two independent parameters for the description of transitions with pion production, if it turns out that the accuracy with which these formulas are satisfied is much lower than the error in some quantities contained in the formulas. For this reason it is not surprising that a single set of phase shifts was found in [7].

The stability of solution II which we have obtained is subject to doubt. Thus, if we put $\bar{\delta}^I(^3P_0) = \bar{\delta}^I(^3P_1) = 0$ and find χ^2_{min}, then we obtain the analog of solution I with $\chi^2/\overline{\chi^2} = 1$. We see there-

2)Solution No. 1 in [2] was obtained with an account of the relativistic spin flip and for a π N-interaction constant equal to 0.08.

Table II

	Phase shifts in degrees			
	Solution I $\chi^2 = 22$	Solution II $\chi^2 = 23$	Solution III $\chi^2 = 26$	Solution IV $\chi^2 = 40$
$\bar{\delta}^R\,(^1S_0)$	—33,40±6,00	—24,24±8,00	—21,62±8,00	—3.85±5.00
$\bar{\delta}^R\,(^3P_0)$	—61,04±11.00	—20,95±3,00	—40,52±13,00	—6.54±14,00
$\bar{\delta}^R\,(^3P_1)$	—41.10±5,00	—30,75±2.00	—21,11±5.00	—11,22±2,00
$\bar{\delta}^R\,(^3P_2)$	14,23±3,00	6,86±5,00	47,88±8.00	—33,00±1,94
$\bar{\delta}^R\,(^1D_2)$	7,74±4.00	7,80±2,2	7,77±2.00	4,97±4,00
ε_2^R	—3.80	—14.00	—0,63	1,90
$\bar{\delta}^R\,(^3F_2)$	— 9,98±2,00	4,89±2,00	—4,46±2,00	3,80±1,00
$\bar{\delta}^R\,(^3F_3)$	—0,67±3,00	—5,25±3,00	0,83±2,00	—0,78±2,00
$\bar{\delta}^R\,(^3F_4)$	1,21±2,00	6,58±1,00	—4,95±1,00	15,60±1,00
$\bar{\delta}^R\,(^1G_4)$	6,64±1,00	6,55±1.00	7,18±1,00	5,07±1,00
$\bar{\delta}^I\,(^1S_0)$	—	—	—	—
$\bar{\delta}^I\,(^3P_0)$	2,01±6,00	—17,80±4,00	9,94±9,8	27,30±15,00
$\bar{\delta}^I\,(^3P_1)$	4,62±4,00	—4,40±4,00	—2,04±3,00	—1,83±3,00
$\bar{\delta}^I\,(^3P_2)$	—0,64±2,00	29,00±8,00	20,27±7,00	—3,37±2,00
$\bar{\delta}^I\,(^1D_2)$	10.00	10,00	10,00	17,50
$\bar{\delta}^I\,(^3F_2)$	3,65±4,00	5,58±3,00	—0,58±2,00	3,08±2,00
$\bar{\delta}^I\,(^3F_3)$	5,01±5,00	2,69±3,00	—0,36±2,00	2,38±4,00
$\bar{\delta}^I\,(^3F_4)$	2,86±1,00	3,66±1,00	3,06±1,00	2,85±3,00
ε_2^I	—0,64	5,00	—2,00	—2.00

fore that the character of solution II can depend on the method used to make it more precise. Therefore, with the available experimental information, it is apparently premature to speak of a complete number of solutions obtained by varying $\bar{\delta}^I(^3F_{2,3,4})$, etc. However, even now we can draw some interesting conclusions concerning the character of meson production at 660 MeV.

The solutions we obtained can be divided into two groups. One group of solutions (III and IV) leads to meson production from ^{3}P and ^{1}D states. The second group (solutions I and II) is characterized by more intense meson production in the ^{1}D and ^{3}F states. The latter conclusion could signify that pion production occurs only in peripheral collisions between two protons.

A comparison of some of the values of $\bar{\delta}^R$ for solutions I, II, and IV with the corresponding values obtained in the one-pion approximation shows that they do not agree badly. If this is so, then the results of the present analysis and the analysis in the region $E \le 300$ MeV show [8] that the role of exchange of one pion in elastic scattering with $L \ge 2$ can become dominating at higher energies. This fact can be taken into account in the analysis of the available data on pp scattering, for example, at 970 MeV energies.

To confirm the conclusions of the present work we must have more information than is available at present, not only concerning elastic pp scattering, but also concerning the processes $pp \to pp\pi^0$ and $pp \to pn\pi^+$.

The authors are grateful to V. P. Dzhelepov, Yu. M. Kazarinov, L. I. Lapidus, and B. M. Golovin for discussion and advice, and also to I. N. Silin for consultation on mathematical problems.

[1] R. Ya. Zul'karneev and I. N. Silin, Phys. Lett. **3**, 265 (1963).

[2] R. Ya. Zul'karneev and I. N. Silin, Preprint, Joint Inst. Nuc. Res. R-1217, 1963.

[3] Kazarinov, Kiselev, Silin, and Sokolov, JETP **41**, 197 (1961), Soviet Phys. JETP **14**, 143 (1962).

[4] L. M. Soroko, JETP **35**, 276 (1958), Soviet Phys. JETP **8**, 190 (1959).

[5] A. F. Dunaĭtsev and Yu. D. Prokoshkin, JETP **36**, 1656 (1959), Soviet Phys. JETP **9**, 1179 (1959).

[6] N. Hoshizaki and S. Machida, RIFP-21, August (1962).

[7] Azhgireĭ, Klepikov, Kumekin, Meshcheryakov, Nurushev, and Stoletov, JETP **45**, 1174 (1963), this issue, p. 810.

[8] Yu. M. Kazarinov and I. N. Silin, JETP **43**, 1385 (1962), Soviet Phys. JETP **16**, 983 (1963); Hull, Lasila, Ruppel, McDonald, and Breit, Phys. Rev. **123**, 2154 (1961).

Translated by J. G. Adashko
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