PHENOMENOLOGICAL ANALYSIS OF pp INTERACTION AT 657 MeV. I

L. S. AZHGIREĬ, N. P. KLEPIKOV, Yu. P. KUMEKIN, M. G. MESCHERYAKOV, S. B. NURUSHEV, and G. D. STOLETOV

Joint Institute for Nuclear Research

Submitted to JETP editor April 24, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **45**, 1174-1182 (October, 1963)

A phase shift analysis is made of the available data on pp interaction near 660 MeV, including the results of measurements of the inelastic scattering, polarization, and depolarization differential cross sections, the triple scattering parameters R and A, the spin correlation parameters C_{KP} and C_{nn}, the total pp-interaction cross section, and also the total cross sections for the reactions $pp \rightarrow \pi^+ pn$, $pp \rightarrow \pi^+ d$ and $pp \rightarrow \pi^0 pp$. The statistically best set is obtained for the real parts of the phase shifts and absorption coefficients (solution 1 in Table II). The real parts of the phase shifts thus found can be smoothly connected with the corresponding YLAM solution[2,4] and solution 1 in [3]. It is found that, in accordance with the peripheral model of inelastic processes, ^3F-states significantly contribute to π-meson production.

1. INTRODUCTION

DATA on pp scattering at energies $E \leq 310$ MeV were subjected to a phase shift analysis in many investigations, a review of which is given, for example, in [1]. The greatest accomplishment of recent years in this field is the representation of the entire aggregate of available experimental data on pp scattering in terms of the phase shift[2-5]. It was possible in this way to overcome, to a considerable degree, the ambiguity of the phase-shift solutions, arising in the analysis of results obtained for one value of the energy, and to establish the energy dependence of the phase shifts of states with $l \leq 4$ in the interval from 9.7 to 345 MeV.

The performance of the major part of the pp-interaction research with the six-meter synchrocyclotron in Dubna has uncovered the possibility of carrying out a phase shift analysis in an energy region where pion production processes must be taken into account. Recently Hoshizaki and Machida[6], who estimated the imaginary parts of the phase shifts of the ^3P-, $^1D_2$-, and ^3F states on the basis of the resonance model for the production of pions in nucleon-nucleon collisions developed by Mandelstam[7], have carried out a phase shift analysis of the differential elastic pp-scattering cross sections, polarization, and depolarization at 660 MeV without an account of Coulomb interaction effects and the contribution of one-meson exchange. At the same energy, an analysis of pp scattering was carried out on the basis of all the available data in Dubna by Zulkarneev and Silin[6], with an account of the Coulomb interaction and the contribution of the one-meson exchange, but without an account of pion production in ^3F states of the pp system. In a subsequent paper by the same authors[9], the phase shifts were calculated with an account of the relativistic correction, with the experimental values of the parameter R included in the analysis. They also corrected an error made in [8] in the calculation of the contribution of the one-meson diagram, something which did not lead to an essential change in the phase shifts of the most probable solution, but decreased the number of solutions.

In the present investigation we made a phase-shift analysis of pp scattering on a broader base, including the results of recent measurements of the parameter A (90°) and the total cross sections of all the elastic processes. This analysis was based on the following premises:

1) With increasing energy, an ever-increasing role is assumed by peripheral inelastic processes, so that it cannot be assumed, as was done in [8,9], that there is no absorption at 660 MeV in the $^3F_{2,3}$ states, which according to the resonance model for pion production can contribute to the inelastic processes.

2) Elastic scattering in states with $l \geq 5$ can be represented only by the contribution of one-meson exchange in accordance with [10-12].

Table I

Observed quantity	θ_{cms}, deg	Experimental value	Reference	Observed quantity	θ_{cms}, deg	Experimental value	Reference
$\sigma(\theta)$ mb/sr	5	18.9±1,1	[13]	D	54	0.99±0.25	[15]
660 MeV*	10	11.0±0.7		635 MeV	72	0.69±0.20	
	15	8,67±0.53			90	0.93±0,17	[16]
	20	7.75±0,48			108	0.28±0.16	[15]
	25	6,56±0.40			126	0.57±0.20	
657 MeV	30	5.58±0,15	[14]	R	54	0,450±0,084	[17]
	40	4,78±0.26		635 MeV	72	0,493±0,077	
	50	3.99±0,20			90	0.264±0,070	
	60	3,41±0,13			108	0,325±0,056	
	70	2,94±0.12			126	0,489±0,121	
	80	2,20±0.05		A	90	0,195±0,061	this paper
	90	2.07±0.03		608 MeV			
P	11.6	– 0,022±0,095	[12]	C_{KP}	90	0,22±0,18	[18]
635 MeV	16.2	0.197±0,046		660 MeV			
	20.8	0.276±0.039		C_{nn}	54	0.57±0,14	[19]
	27.6	0.384±0,049		640 MeV	72	0,65±0.15	
	27.6	0,402±0.033			90	0.93±0.21	
	34,4	0,400±0,030		σ_t, mb		41,4±0,6	[20]
	41,2	0,424±0.029		660 MeV			
	47,9	0.378±0,027		$\sigma(\pi^+pn)$, mb		10,9±1,1	[21]
	54.5	0.357±0,023		657 MeV			
	61,0	0.307±0.021		$\sigma(\pi^+d)$, mb		3,1±0,2	[22]
	67,5	0.279±0,027		657 MeV			
	73,8	0,195±0,028		$\sigma(\pi^0pp)$, mb		3,22±0,17	[23]
	80,1	0,167±0.026		660 MeV			
	86,3	0.084±0.040					
	90,3	–0,016±0.025					

*The energy at which the observed quantity is measured is indicated below the quantity.

2. EXPERIMENTAL DATA

The experimental data used in the analysis [12–23] are gathered in Table I. The table does not include the results of the measurements by Selektor et al [24–25] of the differential cross sections of elastic pp scattering at 660 MeV. A comparison of these results with those of Bogachev and Vzorov [13,14] has shown that they are not compatible, and the ratio $\overline{\chi^2}/\chi^2$ of the sum of the weighted squares of the deviations of the points from a smooth curve to the number of degrees of freedom, calculated from the data of [24,25], exceeds 1.7, which is much larger than the ratio $\chi^2/\overline{\chi^2}$ corresponding to the data of [13,14].

We have also included in the analysis the result of recent measurements of the parameter A (90°). In these measurements a longitudinally-polarized proton beam with energy 612 MeV was used [26], and the experimental setup employed was specially intended for the observation of triple scattering [27]. A detailed description of this experiment will be presented separately.

As is well known [28], in the energy region 600—660 MeV the differential cross sections for elastic pp scattering are sensitive to changes in the energy, and therefore the phase shift analysis is referred to an energy of 657 MeV, at which the angular dependence $\sigma(\theta)$ was measured. In addition, we kept in mind the fact that $\sigma(\theta)$ was measured with maximum relative accuracy. With respect to the other observed quantities used in the analysis, it was assumed that they do not experience essential changes over the energy interval under consideration.

3. REPRESENTATION OF THE OBSERVABLE QUANTITIES

The elastic pp scattering matrix is written in the form (see, for example, [29]

$$
\begin{aligned}
M(\theta) = {} & \tfrac{1}{2} a(\theta)[1 + (\sigma_1\mathbf{n})(\sigma_2\mathbf{n})] + \tfrac{1}{2} b(\theta)[1 - (\sigma_1\mathbf{n})(\sigma_2\mathbf{n})] \\
& + \tfrac{1}{2} c(\theta)[(\sigma_1\mathbf{m})(\sigma_2\mathbf{m}) + (\sigma_1\mathbf{l})(\sigma_2\mathbf{l})] \\
& + \tfrac{1}{2} d(\theta)[(\sigma_1\mathbf{m})(\sigma_2\mathbf{m}) \\
& - (\sigma_1\mathbf{l})(\sigma_2\mathbf{l})] + \tfrac{1}{2} e(\theta)[(\sigma_1\mathbf{n}) + (\sigma_2\mathbf{n})].
\end{aligned} \tag{1}
$$

Here σ_1 and σ_2 are the spin operators of the first and second protons,*

$$
\mathbf{n} = \frac{[\mathbf{k}\mathbf{k}']}{|[\mathbf{k}\mathbf{k}']|}, \quad \mathbf{l} = \frac{\mathbf{k}+\mathbf{k}'}{|\mathbf{k}+\mathbf{k}'|}, \quad \mathbf{m} = \frac{\mathbf{k}-\mathbf{k}'}{|\mathbf{k}-\mathbf{k}'|},
$$

$\mathbf{k}$ and $\mathbf{k}'$ are the initial and final momenta of the scattered proton in the c.m.s.

*$[\mathbf{k}\mathbf{k}'] = \mathbf{k} \times \mathbf{k}'$.

The scattering amplitudes a, b, c, d, and e are functions of the energy and of the c.m.s. scattering angle θ. The observed quantities in pp scattering are connected with these amplitudes by the relations

$$\begin{aligned}
&\sigma(\theta) = \tfrac{1}{2}(|a|^2 + |b|^2 + |c|^2 + |d|^2 + |e|^2), \qquad \sigma(\theta)P(\theta) = \mathrm{Re}\, ae^*,\\
&\sigma(\theta)[1 - D(\theta)] = |c|^2 + |d|^2,\\
&\sigma(\theta)R(\theta) = \mathrm{Re}\, ab^*\cos(\theta - \theta_{\mathrm{lab}}) + \mathrm{Re}\, ieb^*\sin(\theta - \theta_{\mathrm{lab}}) + \mathrm{Re}\, cd^*\cos\theta_{\mathrm{lab}},\\
&\sigma(\theta)A(\theta) = -\mathrm{Re}\, ab^*\sin(\theta - \theta_{\mathrm{lab}}) + \mathrm{Re}\, ieb^*\cos(\theta - \theta_{\mathrm{lab}}) - \mathrm{Re}\, cd^*\sin\theta_{\mathrm{lab}},\\
&\sigma(\theta)C_{KP}(\theta) = \mathrm{Re}\, ide^*\cos(\alpha' - \alpha) - \mathrm{Re}\, bc^*\sin(\alpha' + \alpha) - \mathrm{Re}\, ad^*\sin(\alpha' - \alpha)\\
&\sigma(\theta)[1 - C_{nn}(\theta)] = |b|^2 + |d|^2, \quad \sigma_t = 2\pi k^{-1}\,\mathrm{Im}\,[a(0) + b(0)]. \qquad (2)
\end{aligned}$$

Relations (2) are written with an account of the relativistic effects [30,31]; here $\alpha = \theta/2 - \theta_{\mathrm{lab}}$, $\alpha' = \Phi/2 - \Phi_{\mathrm{lab}}$, θ and Φ are the scattering and recoil angles in the c.m.s., while θ_{lab} and Φ_{lab} are the same in the laboratory frame. By $\sigma(\theta)$ are denoted the differential scattering cross sections of the unpolarized beam and by σ_t the total scattering cross section. The last relation in (2) is the optical theorem, which relates the total cross section of pure nuclear scattering to the amplitudes $a(\theta)$ and $b(\theta)$ for $\theta = 0$ in the expressions for which Coulomb additions are eliminated.

Under the assumption that the interaction in states with large angular momenta ($l > l_{\max}$) can be described in the one-meson approximation, $M(\theta)$ is of the form

$$M(\theta) = M(\Delta) - M^{PS} + M^{P} + M^{C} + M^{PC}, \quad (3)$$

where $M(\Delta)$ is the part of the amplitude describing the observed quantities with the aid of the phenomenological phase shift [32], M^{PS} —the contribution of the one-meson exchange in the states with angular momenta $l \le l_{\max}$, M^{P} —total contribution of the one-meson exchange to the scattering amplitude [33–35], and M^{C} —contribution of the Coulomb interaction. The term M^{PC} pertains to partial waves with $l > l_{\max}$ and is a result of the fact that only the scattering phase shifts are expressed in terms of the sums of the phase shifts corresponding to different forms of interactions. The calculation of M^{PC} has shown that the contribution of this term to $M(\theta)$ does not exceed 1% of the contribution of the remaining terms, and therefore the term M^{PC} is disregarded at the present stage of the analysis. The Coulomb interaction was calculated using the nonrelativistic formulas.

4. ACCOUNT OF INELASTIC PROCESSES

The matrix $M(\Delta)$ was parametrized in terms of the barred phase shifts (see formula (3.15) in [36]), but these phase shifts were assumed to be complex: $\Delta = \delta + i\gamma$. The imaginary part of the phase shifts γ is connected with the absorption coefficient by the relation

$$e^{-2\gamma} = r. \quad (4)$$

Absorption in the states $^3P_{0,1,2}$ and $^3F_{2,3}$ was described respectively by the average coefficients r_1 and r_3, introduced in the same manner as used by Hoshizaki and Machida [6], but with the misprints contained in Eq. (8) of their paper corrected. In this formula, the squares of the absorption coefficients r_1 and r_3 should be expressed in terms of the squares of the absorption coefficients corresponding to different j. The coefficient r_2 describes absorption in the state $^1D_2$. In accordance with the resonance model, and assuming that the pion production occurs only with S and P scattering of the isobar and of the second nucleon, it has been assumed that no absorption takes place in the remaining states.

The total cross sections for the meson production reactions were expressed in terms of the absorption coefficients in the following manner:

$$\begin{aligned}
&\sigma(\pi^+ d) + \sigma(\pi^+(pn)_S) = (5\pi/2k^2)(1 - r_2^2),\\
&\sigma(\pi^+(pn)_P) + \sigma(\pi^0 pp) = (\pi/2k^2)[9(1 - r_1^2) + 12(1 - r_3^2)]. \qquad (5)
\end{aligned}$$

The breakdown of the cross section $\sigma(\pi^+ pn)$ obtained in [21] into the parts $\sigma(\pi^+(pn)_S)$ and $\sigma(\pi^+(pn)_P)$, corresponding to the production of mesons in the reaction $pp \to \pi^+ pn$ with S and P scattering, was initially made in accordance with the results of the calculations of [37], but then the ratio $\sigma(\pi^+(pn)_S)/\sigma(\pi^+ pn)$ was varied in such a way as to ensure statistically the best description of all the observed quantities.

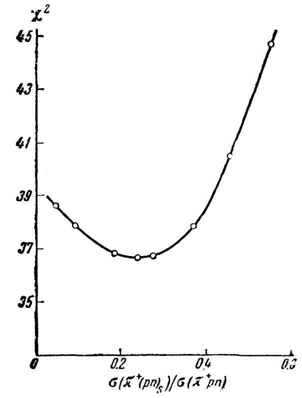
5. METHOD AND CALCULATION RESULTS

In the analysis we used 45 values of the observable quantities [three total cross sections $\sigma(\pi^+ d)$, $\sigma(\pi^+ pn)$, and $\sigma(\pi^0 pp)$ were introduced

Table II

Phase shifts and absorption coefficients	Solution 1 $\chi^2=36.7$	Solution 2 $\chi^2=60.1$
$\delta\,(^1S_0)$	-31.5 ± 4.0	-7.6 ± 3.1
$\delta\,(^3P_0)$	-52 ± 10	-18.0 ± 4.8
$\delta\,(^3P_1)$	-36.9 ± 3.7	-5.7 ± 1.8
$\delta\,(^3P_2)$	18.8 ± 1.2	-43.1 ± 1.5
$\delta\,(^1D_2)$	11.7 ± 2.2	7.8 ± 2.5
$\delta\,(^3F_2)$	-4.2 ± 1.8	0 ± 1.1
$\delta\,(^3F_3)$	-0.2 ± 1.4	3.0 ± 1.2
$\delta\,(^3F_4)$	1.6 ± 0.7	12.2 ± 0.6
$\delta\,(^1G_4)$	7.9 ± 0.7	6.5 ± 1.1
r_1	0.954 ± 0.019	0.819 ± 0.024
r_2	0.668 ± 0.038	0.558 ± 0.034
r_3	0.781 ± 0.020	0.912 ± 0.016
$\chi^2/\overline{\chi^2}$	1.11	1.82

FIG. 1. Dependence of χ^2 on the ratio $\sigma(\pi^+(pn)_S)/\sigma(\pi^+pn)$ for solution 1.



into the calculation as two quantities combined in accordance with (5)]. A total of 12 parameters were determined—nine phase shifts of waves up to $l = 4$ inclusive, and three absorption coefficients in the ^3P, $^1D_2$, and ^3F states. The mixing parameter ϵ_2 was first assumed equal to 0. The phase shifts of the waves with $l \geq 5$ were taken into account in the one-meson approximation. The pion-nucleon coupling constant f^2 was assumed equal to 0.08, the pion mass was assumed equal to $m(\pi^0)$. The phase shifts and the absorption coefficients were determined by least squares using the electronic computer of the Joint Institute for Nuclear Research. A search for the minima of the functional χ^2 was made with random initial values of the parameters by the linearization method [38]. As a result of 70 searches, two solutions were obtained with values $\chi^2 < 3\overline{\chi^2}$ ($\overline{\chi^2} = 33$). The obtained sets of phase shifts (in degrees) and of the absorption coefficients are listed in Table II.

The probability that $\chi^2 \geq 36.7$ for $\overline{\chi^2} = 33$ is 31%. For the second of the solutions obtained $\chi^2 = 60.1$, and the corresponding probability is approximately 0.2%. On this basis, solution 2 is disregarded henceforth. It must be noted that the solutions obtained in [6,9] do not coincide with the solutions obtained, and in accordance with the χ^2 criterion, describe the available experimental data with considerably lesser relability than the solution 1 of Table II. Figure 1 shows the obtained dependence of χ^2 on the ratio $\sigma(\pi^+(pn)S)/\sigma(\pi^+ pn)$ for the best solution. The minimum is attained in the case when this ratio is 0.24.

In order to check on the stability of solution 1, the previously fixed parameters were varied. In varying the mixing parameter ϵ_2 and the pion-nucleon interaction coupling constant f^2, we found that $\epsilon_2 = -1.6° \pm 1.8°$ and $f^2 = 0.064 \pm 0.024$, whereas the remaining parameters remain practically unchanged. Replacement of the phenomenological phase shift $\delta(^1G_4)$ for its value calculated in the one-meson approximation has led to an increase in the ratio $\chi^2/\overline{\chi^2}$ from 1.1 to 2.3. By including in the analysis, in addition to ϵ_2, also ϵ_4 and the phase shift $\delta(^3H_4)$ the ratio $\chi^2/\overline{\chi^2}$ decreased from 1.1 to 1.0, but the values of all the remaining varied parameters changed insignificantly, except that their errors increased. The obtained values of ϵ_4 and $\delta(^3H_4)$ did not differ noticeably from the corresponding values calculated in the one-meson approximation. From the foregoing analysis it follows that the experimental information used on the pp interaction near 660 MeV need not be included in the phenomenological analysis of the states with $l \geq 5$. Since the existing data on inelastic pp interaction are satisfactorily described in the framework of the Mandelstam resonance model by three independent parameters, at the present stage it is not justified to introduce a larger number of varied parameters in order to take separately into account the absorption in the states $^3P_0$, $^3P_1$ and $^3P_2$, as well as $^3F_2$ and $^3F_3$.

The angular dependences of the observed quantities, calculated from the obtained phase shifts, as well as their experimental values used in the analysis, are shown in Figs. 2—4. It must be noted that for solution 1 the value of χ^2 is uniformly distributed over the data of the different experiments.

6. DISCUSSION OF RESULTS

The analysis has shown that the existing experimental data on elastic pp scattering near 660 MeV can be represented with statistical reliability by means of the $^1S_0$, $^3P_{0,1,2}$, $^1D_2$, and $^3F_{2,3,4}$ and $^1G_4$ phase shifts, provided only that we assume that, in addition to the ^3P and $^1D_2$ states, the $^3F_{2,3}$ states also participate effectively in the pion production. In this connection it should be noted that for somewhat larger energies, the energy spectrum of the neutrons and the Q-value distribution of the π^+p system in the reaction $p + p \rightarrow \pi^+ + p$

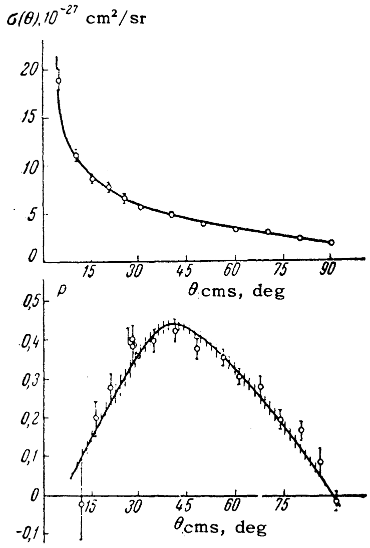


FIG. 2

FIG. 2. Angular dependence of the differential cross section and of the polarization in elastic pp scattering. The vertical bars denote the error corridor of the curves calculated from the phase shifts of solution 1. The experimental data used are indicated.

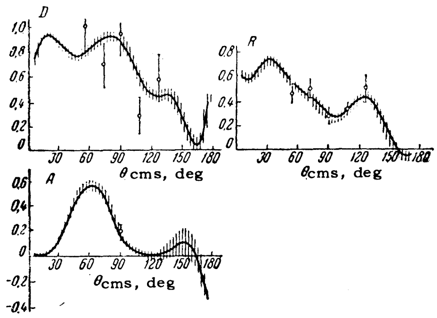


FIG. 3

FIG. 3. Angular dependence of the parameters of triple scattering. The experimental data used are indicated.

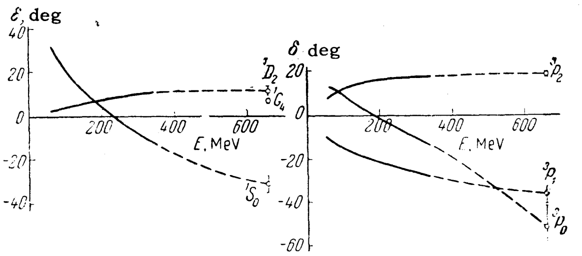


FIG. 5. Energy dependence of the singlet $^1S_0$, $^1D_2$, and $^1G_4$ and triplet $^3P_0$, $^3P_1$, and $^3P_2$ phase shifts. The solid curves for energies up to 345 MeV represent the YLAM solution[2,4]. The phase shifts of solution 1 of the present work are indicated for 657 MeV. The dashed curves are drawn free hand.

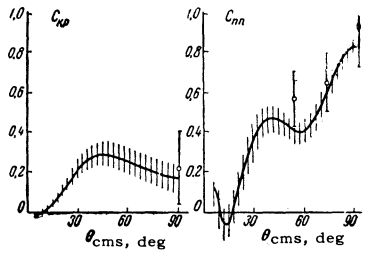


FIG. 4. Angular dependence of the spin correlation coefficients. The experimental data used are indicated.

+ n is well described by the peripheral model of inelastic processes[39,40].

A characteristic feature of the phase shifts obtained is that, as shown in Fig. 5, they can be connected by means of smooth curves with the corresponding phase shifts of the YLAM solution[2,4], which represent pp scattering in the energy range from 9.7 to 345 MeV, and also with solution 1 from [3]. It can be thought that these smooth curves reflect to some degree the main features of the energy dependence of the phase shifts of the lower pp-system states between 310 and 660 MeV. If this is so, they offer evidence that over the considered energy interval the same states play an essential role in pp interaction, the properties of which do not experience, in this case, noticeable changes, since neither the singlet $^1S_0$, $^1D_2$, and $^1G_4$ phase shifts nor the triplet $^3P_0$, $^3P_1$, $^3P_2$ phase shifts reverse sign. The fact that at 660 MeV the same phase shifts are relatively as large as at 310 MeV is apparently due to the influence exerted on the elastic scattering by the inelastic processing occurring only in the ^3P, $^1D_2$, and $^3F_{2,3}$ states owing to the resonant nature of the pion-nucleon interaction.

It is remarkable that at 660 MeV, as at 310 MeV, the $^3P_2$ phase shift is positive, which is characteristic of **LS** forces which are attractive when the spin is parallel to the orbital momentum. The indication that at high energies the **LS** forces play a large role in pp scattering follows directly also from the fact that at 660 MeV the value of the depolarization parameter for 90° is close to unity in the c.m.s.[16] As to the $^2F_{2,3,4}$ phase shifts, they are small.

Worthy of special consideration is the behavior of the $^1S_0$ phase shift, which decreases monotonically with increasing energy, although not as strongly as in the solution obtained by Hoshizaki and Machida. More surprising is the fact that up to 660 MeV the form of the energy dependence of this phase shift can be reproduced satisfactorily by using the parameters obtained by Noyes[41] for the expansion of the function $k \cot[\delta(^1S_0) + kr]$ in the effective-radius approximation. The value of the $^1S_0$ phase shift predicted in this way is $-34.5°$, whereas its phenomenological value is $-31.5 \pm 4.0°$. This apparently signifies that up to 660 MeV the behavior of the $^1S_0$ phase shift can qualitatively be described on the basis of the potential model of the nucleus with a solid repelling core.

The authors express their gratitude to S. M. Bilen'kiĭ, Yu. M. Kazarinov, R. M. Ryndin, and Ya. A. Smorodinskiĭ for useful discussions.

---

[1] MacGregor, Moravcsik, and Stapp, Ann. Rev. Nucl. Sci. 10, 291 (1960).

[2] Breit, Hull, Lassila, and Pyatt, Phys. Rev. **120**, 2227 (1960).

[3] Yu. M. Kazarinov and I. N. Silin, JETP **43**, 692 and 1385 (1962), Soviet Phys. JETP **16**, 491 and 983 (1963).

[4] Breit, Hull, Lassila, Pyatt, and Ruppel, Phys. Rev. **128** 826 (1962).

[5] Stapp, Noyes, and Moravcsik, Proc. of 1962 Int. Conf. on High-energy Phys. at CERN, Geneva (1962), p. 131.

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

[7] S. Mandelstam, Proc. Roy. Soc. **A244**, 491 (1958).

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

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

[10] L. B. Okun' and I. Ya. Pomeranchuk, JETP **36**, 300 (1959), Soviet Phys. JETP **9**, 207 (1959).

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

[12] Meshcheryakov, Nurushev, and Stoletov, JETP **33**, 37 (1957), Soviet Phys. JETP **6**, 28 (1958).

[13] N. P. Bogachev, DAN SSSR **108**, 806 (1956), Soviet Phys. Doklady **1**, 361 (1957).

[14] N. P. Bogachev and I. K. Vzorov, DAN SSSR **99**, 931 (1951).

[15] Kumekin, Meshcheryakov, Nurushev, and Stoletov, JETP **38**, 1451 (1960), Soviet Phys. JETP **11**, 1049 (1960).

[16] Kumekin, Meshcheryakov, Nurushev, and Stoletov, JETP **35**, 1398 (1958), Soviet Phys. JETP 8, 977 (1959).

[17] Kumekin, Meshcheryakov, Nurushev, and Stoletov, JETP **43**, 1665 (1962), Soviet Phys. JETP **16**, 1175 (1963).

[18] Nikanorov, Peter, Pisarev, and Poze, JETP **42**, 1209 (1962), Soviet Phys. JETP **15**, 837 (1962).

[19] Golovin, Dzhelepov, Zul'karneev, and Tsui, JETP **44**, 142 (1963), Soviet Phys. JETP **17**, 98 (1963).

[20] Dzhelepov, Moskalev, and Med'ved', DAN SSSR **104**, 380 (1955).

[21] B. S. Neganov and O. V. Savchenko, JETP **32**, 1265 (1957), Soviet Phys. JETP **5**, 1033 (1957).

[22] M. G. Meshcheryakov and B. S. Neganov, DAN SSSR **100**, 677 (1955),

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

[24] Bogomolov, Zombkovskii, Nikitin, and Selektor, Symposium, CERN, II, 129, 1956.

[25] Selektor, Nikitin, Bogomolov, and Zombkovskiĭ, DAN SSSR **99**, 967 (1954).

[26] Meshcheryakov, Kumekin, Nurushev, and Stoletov, Atomnaya énergiya **14**, 38 (1963).

[27] Biktimirov, Kumekin, Nurushev, and Stoletov, PTÉ, in press.

[28] Meshcheryakov, Neganov, Soroko, and Vzorov, DAN SSSR **99**, 959 (1954).

[29] Puzikov, Ryndin, and Smorodinskiĭ, JETP **32**, 592 (1957), Soviet Phys. JETP **5**, 489 (1957).

[30] H. P. Stapp, Phys. Rev. **103**, 425 (1956).

[31] D. W. L. Sprung, Phys. Rev. **121**, 925 (1961).

[32] S. C. Wright, Phys. Rev. **99**, 996 (1955).

[33] A. F. Grashin, JETP **36**, 1717 (1959), Soviet Phys. JETP **9**, 1223 (1959).

[34] Cziffra, MacGregor, Moravcsik, and Stapp, Phys. Rev. **114**, 880 (1959).

[35] G. Breit, Revs. Modern Phys. **34**, 766 (1962).

[36] Stapp, Ypsilantis, and Metropolis, Phys. Rev. **105**, 302 (1957).

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

[38] S. N. Sokolov and I. N. Silin, Preprint Joint Inst. Nuc. Res. D-810, 1961.

[39] Barnes, Bugg, Dodd, Kinson, and Riddiford, Phys. Rev. Lett. **7**, 288 (1961).

[40] E. Ferrari and F. Selleri, Suppl. Nuovo cimento **24**, 453 (1962).

[41] H. P. Noyes, Proc. Int. Conf. of Nucl. Forces, Vol. I. London, (1960), p. 39.

Translated by J. G. Adashko
192