ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

ЛАБОРАТОРИЯ ЯДЕРНЫХ ПРОБЛЕМ

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p-p – PHASE SHIFTS AT 660 MEV

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А н н о т а ц и я

1. Приведены все экспериментальные данные о pp -взаимодействии при $\approx$ 660 Мэв., включая результаты измерений дифференциального сечения упругого рассеяния, поляризации, параметров тройного рассеяния D , R и A , коэффициентов спиновой корреляции C_{KP} и C_{nn} , а также полных сечений pp -взаимодействия и реакций

$$pp \to \pi^+ pn\,, \quad pp \to \pi^+ d\,; \quad pp \to \pi^0 pp\,.$$

Произведен фазовый анализ pp -рассеяния при 657 Мэв. Найдено, что экспериментальные данные могут быть статистически надежно представлены следующим набором реальных частей фазовых сдвигов: $\delta(^1S_0) = -32{,}0 \pm 5{,}5$; $\delta(^3P_0) = -58{,}7 \pm 8{,}4$; $\delta(^3P_1) = -34{,}1 \pm 4{,}3$; $\delta(^3P_2) = 19{,}3 \pm 3{,}4$; $\delta(^1D_2) = 8{,}7 \pm 4{,}9$; $\delta(^3F_2) = -5{,}0 \pm 1{,}3$; $\delta(^3F_3) = 2{,}0 \pm 1{,}9$; $\delta(^3F_4) = 1{,}8 \pm 0{,}7$; $\delta(^1G_4) = 6{,}7 \pm 1{,}4$; $\delta(^3H_4) = 0{,}4 \pm 0{,}7$; параметров смешивания $\epsilon_2 = -3{,}6 \pm 2{,}8$; $\epsilon_4 = -5{,}4 \pm 1{,}4$ /в градусах/ и усредненных по j коэффициентов поглощения $r(^3P_{0,1,2}) = 0{,}936 \pm 0{,}022$; $r(^1D_2) = 0{,}678 \pm 0{,}037$; $r(^3F_{2,3}) = 0{,}795 \pm 0{,}020$.

Реальные части найденных фазовых сдвигов могут быть плавно связаны с соответствующими кривыми, представляющими энергетическую зависимость фаз pp -рассеяния при меньших энергиях.

Abstract

All the experimental data on pp – interaction at about 660 MeV are given. Included are the results of measurements of the differential elastic scattering cross sections, polarization, triple scattering parameters D, R, and A, spin correlation coefficients C_{KP} and C_{nn} , and of the total pp interaction cross sections and the total cross sections for the reactions $pp \to \pi^+ pn$, $pp \to \pi^+ d$, $pp \to \pi^0 pp$.

The pp scattering phase analysis has been performed at 657 MeV.

It has been found that the experimental data may be described statistically safely by the following set of the real parts of the phase shifts : $\delta(^1S_0) = -32.0 \pm 5.5$; $\delta(^3P_0) = -58.7 \pm 8.4$; $\delta(^3P_1) = -34.1 \pm 4.3$; $\delta(^3P_2) = 19.3 \pm 3.4$; $\delta(^1D_2) = 8.7 \pm 4.9$; $\delta(^3F_2) = -5.0 \pm 1.3$; $\delta(^3F_3) = 2.0 \pm 1.9$; $\delta(^3F_4) = 1.8 \pm 0.7$; $\delta(^1G_4) = 6.7 \pm 1.4$; $\delta(^3H_4) = 0.4 \pm 0.7$, of the mixing parameters : $\epsilon_2 = -3.6 \pm 2.8$, $\epsilon_4 = -5.4 \pm 1.4$ (in degrees), and of the absorption coefficients averaged over j : $r(^3P_{0,1,2}) = 0.936 \pm 0.022$; $r(^1D_2) = 0.678 \pm 0.037$; $r(^3F_{2,3}) = 0.795 \pm 0.020$. The real parts of the found phase shifts may be smoothly connected with the corresponding curves showing the energy dependence of the pp scattering phase shifts at lower energies.

The accomplishment at Dubna of the major part of the programme of the investigation of p-p -interaction near 660 MeV allowed to perform a phase shift analysis of the p-p -scattering above the threshold of pion production[1-4]. The most essential difference between the solution found in[1-3] manifested itself in the prediction of the angular dependence of the triple scattering parameter A. Recently the measurements of the parameter A in the angular region of $54^{\circ} - 126^{\circ}$[5] have been completed. It turned out that the experimental values agreed best with the angular dependence computed by the phase shifts found in[3] *. New data on the parameter A allow to investigate further the phase shift solution obtained in[3]. In this article we present the results of the phase shift analysis of all available data on p-p -scattering which are given in Table 1. The phase shift analysis was attributed to the energy of 657 MeV at which the differential scattering cross section was measured. It was supposed that the other observables relatively slower depend on the energy in the interval between 608 and 660 MeV.

According to the resonance model of pion production in nucleon-nucleon collisions[18] it was supposed that pion production takes place in $^3P_{0,1,2}$, $^1D_2$, $^3F_{2,3}$ states. The production of pions in $^3P_{0,1,2}$ and in $^3F_{2,3}$ states was described by means of absorption coefficients averaged over j which were introduced in[1]. The ratio of the cross sections $\sigma(\pi^+(pn)_S)$ and $\sigma(\pi^+(pn)_P)$ corresponding to S -state and P -state pion production in the reaction $pp\to\pi^+ pn$ was chosen so that to give the statistically best phase shift description of all observables. This was attained at $\sigma(\pi^+(pn)_S)/\sigma(\pi^+ pn) = 0,24$.

The scattering matrix $M(\theta)$ was parametrized in terms of bar phase shifts. The parameters R, A and C_{KP} were taken into account with relativistic corrections[19,20]. The Coulomb interaction was treated nonrelativistically.

The most probable solution of[3] was taken as the starting point of the computation. The real parts of $^1S_0$, $^3P_{0,1,2}$, $^1D_2$, $^3F_{2,3,4}$, and $^1G_4$ phase shifts, as well as the absorption coefficients $r(^3P_{0,1,2})$, $r(^1D_2)$ and $r(^3F_{2,3})$ were determined phenomenologically; the mixing parameter ϵ_2 was put equal to zero; the phase shifts with $\ell > 4$ were computed in the one-pion-exchange approximation ($f^2 = 0.08$, $m = m(\pi^{\circ})$). The further specification of this solution consisted in successive inclusion into the analysis of the mixing parameters ϵ_2 and ϵ_4 and the real parts of the $^3H_4$, $^3H_5$, $^3H_6$ phase shifts. As it is seen from Table 2, such an augmentation of the number of the parameters varied does not lead to any essential change in the real parts of the $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$ and $^1D_2$ phase shifts and the absorption coefficients.

From the values of $\chi^2/\overline{\chi}^2$ for different versions of computation it is seen that in an analysis of the considered experimental data on p-p -scattering at 660 MeV all waves with $j \leq 4$ should be accounted phenomenologically. In order to check the stability of the obtained solution, the absorption coefficients of the $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, $^3F_2$, $^3F_3$ states were varied separately. In this case the real parts of the phase shifts and the absorption coefficients were changed within their error limits. Therefore, at this stage of the analysis it seems unnecessary to introduce a greater number of parameters in order to describe the absorption in the $^3P_0$, $^3P_1$, $^3P_2$ as well as in the $^3F_2$, $^3F_3$ states separately.

Thus, the available data on the elastic p-p -scattering near 660 MeV may be statistically safely described by $^1S_0$, $^3P_{0,1,2}$, $^1D_2$, $^3F_{2,3,4}$, $^1G_4$, $^3H_4$ phase shifts and mixing parameters ϵ_2 and ϵ_4 if pion production is admitted to take place only in resonance transitions from $^3P_{0,1,2}$, $^1D_2$, $^3F_{2,3}$ states.

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* The most probable solution of[4] is analogous to that found in[3].

Table 1

Data used in the phase shift analysis. The energy at which the quantities were measured are indicated below the corresponding observables

Observable	c.m. angle in degr.	Experimental value	Ref.	Observable	c.m. angle in degr.	Experimental value	Ref.
$\sigma(\theta)$, mb/ster	5	18.9 ± 1.1	(6)	D	54	0.99 ± 0.25	(9)
660MeV	10	11.0 ± 0.7		635MeV	72	0.69 ± 0.20	
	15	8.67 ± 0.53			90	0.93 ± 0.17	(10)
	20	7.75 ± 0.48			108	0.28 ± 0.16	(9)
	25	6.56 ± 0.40			126	0.57 ± 0.20	
657MeV	30	5.58 ± 0.15	(7)	R	54	0.450 ± 0.084	(11)
	40	4.78 ± 0.26		635MeV	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	54	0.477 ± 0.091	(5)
	90	2.07 ± 0.03		608MeV	72	0.464 ± 0.094	
P	11.6	−0.022 ± 0.095	(8)		90	0.195 ± 0.061	
635MeV	16.2	0.197 ± 0.046			108	−0.083 ± 0.085	
	20.8	0.276 ± 0.039			126	−0.201 ± 0.139	
	27.6	0.384 ± 0.049		C_{KP}	90	0.22 ± 0.18	(12)
	27.6	0.402 ± 0.033		660 MeV			
	34.4	0.400 ± 0.030					
	41.2	0.424 ± 0.029		C_{nn}	54	0.57 ± 0.14	(13)
	47.9	0.378 ± 0.027		640MeV	72	0.65 ± 0.15	
	54.5	0.357 ± 0.023			90	0.93 ± 0.21	
	61.0	0.307 ± 0.021		σ_t, mb 660MeV		41.4 ± 0.6	(14)
	67.5	0.279 ± 0.027					
	73.8	0.195 ± 0.028		$\sigma(\pi^+ pn)$, mb 657MeV		10.9 ± 1.1	(15)
	80.1	0.167 ± 0.026					
	86.3	0.084 ± 0.040		$\sigma(\pi^+ d)$, mb 657MeV		3.1 ± 0.2	(16)
	90.3	−0.016 ± 0.025		$\sigma(\pi^0 pp)$, mb 660MeV		3.22 ± 0.17	(17)

T a b l e 2

Values of the real parts of phase shifts (in degrees) and absorption coefficients for different numbers of parameters varied. OPEC values are bracketed

	I	2	3	4	5	6
χ^2	42.9	40.7	35.4	30.5	29.7	28.1
$\delta(^1S_0)$	-29.7±3.2	-29.9±3.4	-33.5±4.1	-32.0±5.5	-32.1±6.1	-31.0±6.2
$\delta(^3P_0)$	-55.2±7.8	-53.5±8.6	-62.8±7.4	-58.7±8.4	-58.3±8.4	-56.9±8.6
$\delta(^3P_1)$	-37.5±3.1	-38.1±3.4	-36.6±2.7	-34.1±4.3	-35.0±4.4	-34.7±4.3
$\delta(^3P_2)$	18.1±1.0	18.6±1.2	16.8±1.4	19.3±3.4	19.0±3.3	19.0±3.3
ϵ_2	0	- 2.3±1.7	- 1.9±1.8	- 3.6±2.8	- 3.8±2.8	- 3.9±2.9
$\delta(^1D_2)$	12.3±2.1	11.4±2.3	10.0±2.4	8.7±4.9	8.0±6.2	8.5±6.2
$\delta(^3F_2)$	- 3.8±1.6	- 4.4±1.6	- 5.0±1.6	- 5.0±1.3	-5.4± 1.5	- 6.2±1.7
$\delta(^3F_3)$	0.1±1.2	0.5±1.3	1.6±1.5	2.0±1.9	2.8±2.6	2.7±2.6
$\delta(^3F_4)$	1.7±0.6	1.7±0.6	1.3±0.6	1.8±0.7	1.8±0.7	1.6±0.7
ϵ_4	(-2.811)	(-2.811)	(-2.811)	- 5.4±1.4	-5.6±1.3	-5.4±1.4
$\delta(^1G_4)$	7.9±0.7	7.9±0.7	8.2±0.7	6.7±1.4	6.0±2.0	6.3±2.0
$\delta(^3H_4)$	(1.291)	(1.291)	0.1±0.6	0.4±0.7	0.3±0.7	0.6±0.8
$\delta(^3H_5)$	(-2.670)	(-2.670)	(-2.670)	(-2.670)	-1.8±1.3	-2.0±1.3
$\delta(^3H_6)$	(0.621)	(0.621)	(0.621)	(0.621)	(0.621)	1.0±0.4
$r(^3P_{0,1,2})$	0.947± 0.020	0.937± 0.022	0.929± 0.024	0.936± 0.022	0.936± 0.022	0.945± 0.023
$r(^1D_2)$	0.671± 0.037	0.672± 0.037	0.686± 0.036	0.678± 0.037	0.675± 0.037	0.679± 0.038
$r(^3F_{2,3})$	0.785± 0.021	0.792± 0.022	0.797± 0.022	0.795± 0.020	0.796± 0.021	0.787± 0.022
$\chi^2/\ \overline{\chi^2}$	1.16	1.13	1.01	0.90	0.90	0.88

The absorption in 'peripheric' $^3F_{2,3}$ states turned out to be even greater than in the $^3P_{0,1,2}$ states.

The angular distribution of the observables computed from the specified set of the phase shifts and absorption coefficients, which are presented in column 4 of Table 2, are given in Fig. 1 and 2 together with the corresponding experimental values.

It is characteristic of the real parts of the phase shifts of the specified set that, as it is shown in Fig. 3, they may be connected by smooth curves with the corresponding phase shifts which have been found at lower energies /21-25/. It seems that these smooth curves reflect to a certain extent the gross behaviour of the ^1S , ^3I and ^1D phase shifts between 310 and 660 MeV. If it is so, they point to the fact that within this energy interval the same states play an essential role in p-p -interaction and the properties of this interaction do not change substantially, since both singlet $^1S_0$, $^1D_2$, $^1G_4$ and triplet $^3P_0$, $^3P_1$, $^3P_2$ phase shifts do not change their signs. It is noteworthy that both at 660 MeV and 310 MeV the $^3P_2$ phase shifts are positive what is characteristic of LS -forces.

The behaviour of the $^1S_0$ phase shift, monotonically decreasing with energy, deserved special attention. It is striking that up to 660 MeV the form of the energy dependence of $\delta(^1S_0)$ may be satisfactorily predicted, using the parameters A , B and $\bar{r}$ of the effective range expansion $k\, ctg[\delta(^1S_0) + k\bar{r}] = A + B\bar{r}^3 k^4 + O(k^6)$ found by Noyes /26/. The value of $\delta(^1S_0)$ computed in this way is -34.5^0 at 660 MeV. This may mean that up to 660 MeV the behaviour of $\delta(^1S_0)$ may be qualitatively represented on the basis of a potential model of the nucleon having a hard repulsive core.

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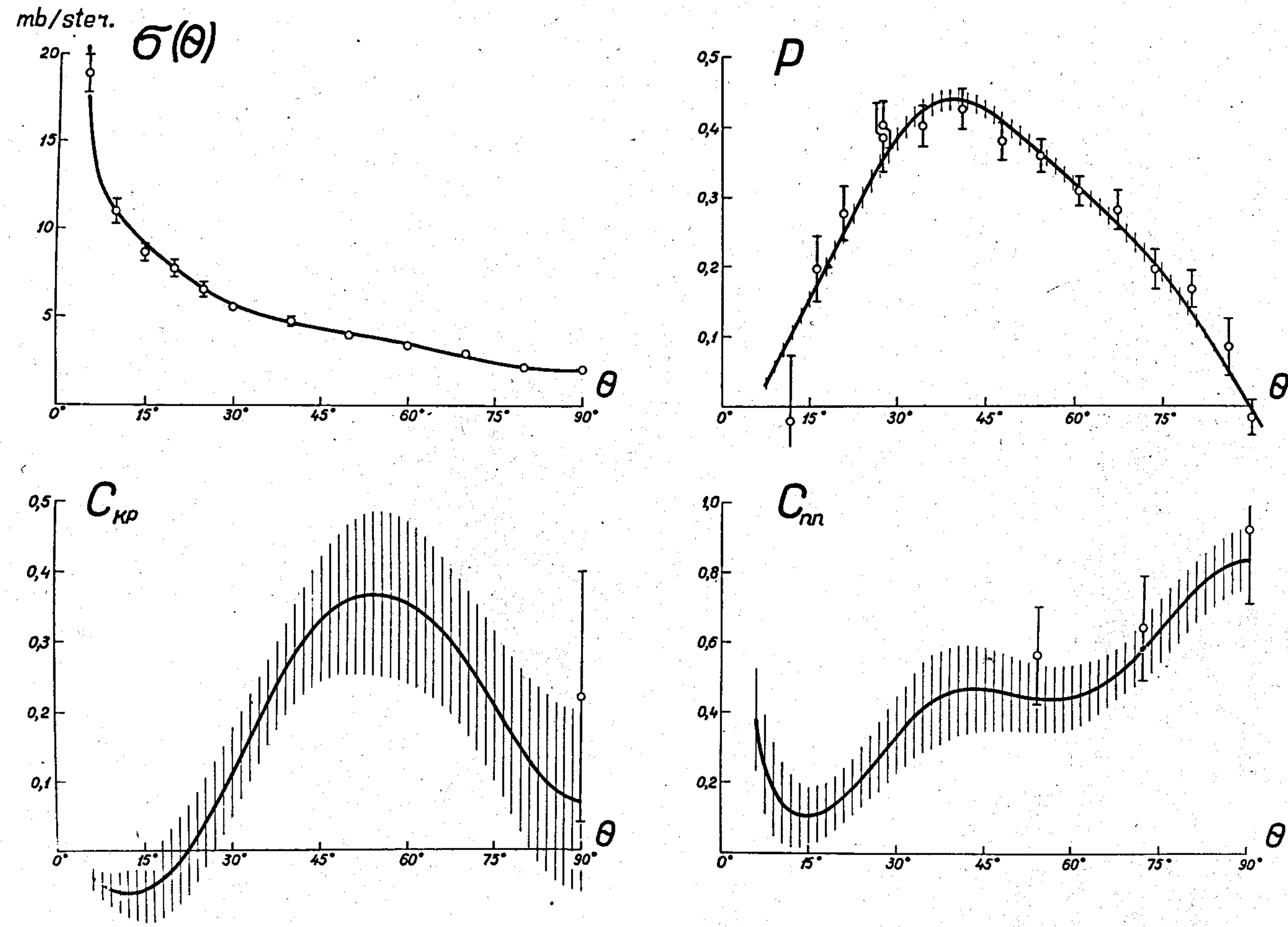
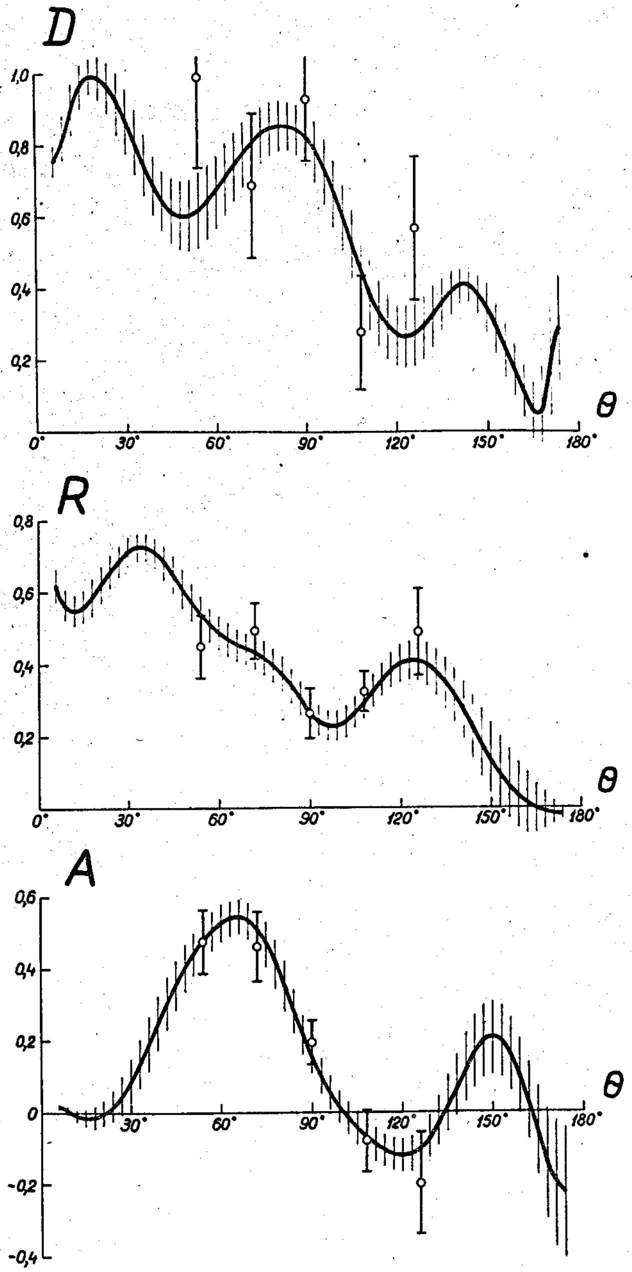


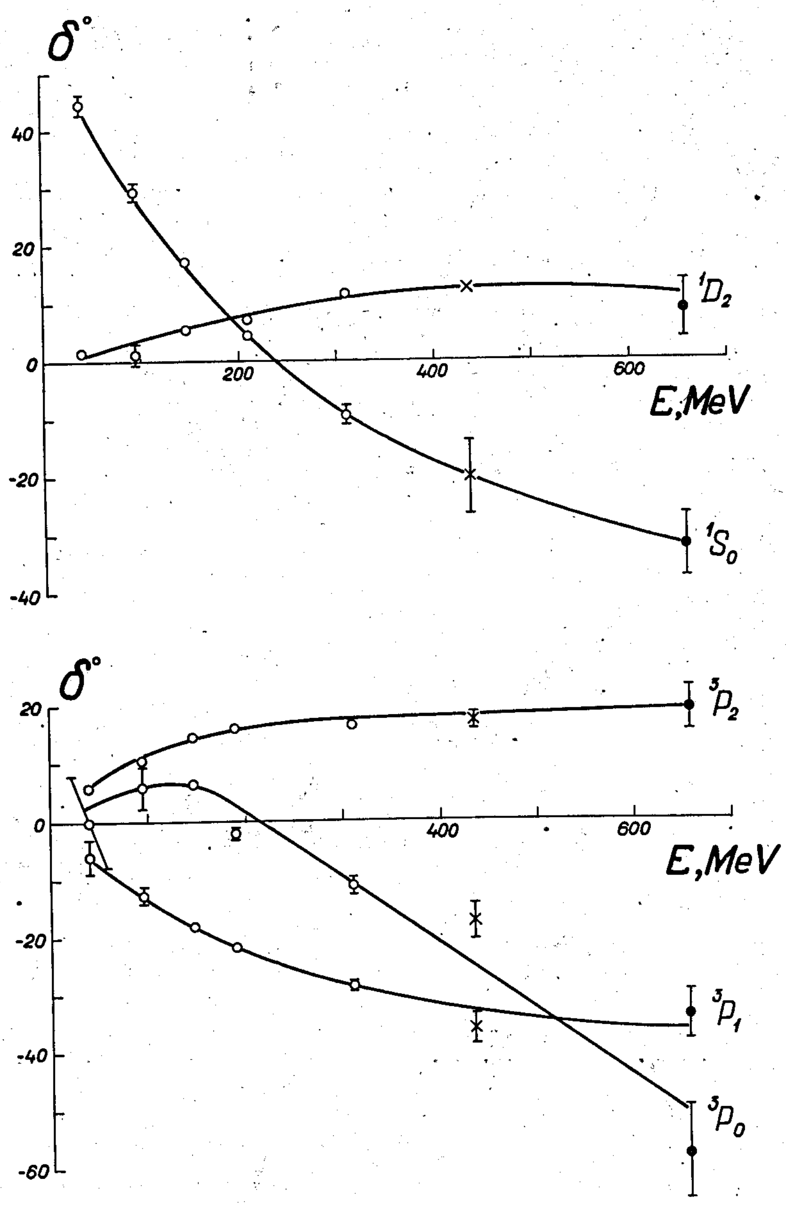
F i g. 1.

Angular dependence of the differential cross section, polarization and the coefficients C_{KP} *and* C_{nn} *at 657 MeV according to the set of phase shifts presented in column 4 of Table 2. Vertical dashes show the error corridor. The used experimental data are indicated.*



F i g. 2.

Angular dependence of the parameters **D** , **R** *and* **A** . *The used experimental data are indicated.*



F i g. 3.

Energy dependence of the phase shifts of the pp -scattering. ⧲ - (22,23); ⧱ -(25); ⧳ - *the present paper. The solid curves are drawn visually. Below 345 MeV they fit with the YLAM-solution*/24/.