SLAC TRANS - 80

SUMMARY DATA ON SMALL-ANGLE p - d AND p - d SCATTERING AND THE REAL PART OF THE p - n SCATTERING AMPLITUDE IN THE 1-10 GeV ENERGY RANGE

by

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(Submitted to Yadernaya Fizika)

Translated by Robert Addis (March 1968)
from the Russian Itogovye dannye po p - p i p - d rasseyaniyu na malye ugly i veshchestvennaya chast' amplitudy p - n rasseyaniya v intervale energii 1 - 10 Gev
JINR Preprint No. P 1-3641, Dubna 1967

TRANSLATED FOR
STANFORD LINEAR ACCELERATOR CENTER

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SUMMARY DATA ON SMALL-ANGLE p - p AND p - d SCATTERING AND THE REAL PART OF THE p - n SCATTERING AMPLITUDE IN THE 1-10 GeV ENERGY RANGE

Tables are given for the differential cross-sections of elastic p - p and p - d scattering in the 1-10 GeV energy range, also refined data on the magnitude of the real part of the amplitude of p - n scattering in the 1-10 GeV energy range after an increase of statistics. The magnitude of the real part of the p - n scattering amplitude is calculated on the basis of the Glauber deuteron model.

The experimental results are compared with predictions following from the dispersion relations and with relations for the scattering-amplitude derivatives for the point $t = 0$ flowing from the general principles of quantum field theory. The real part of the p - n scattering amplitude obtained in the reported experiment is compared with n - p charge-exchange data.

In this paper we report the results of a study of proton-deuteron elastic scattering at energies of 1, 2, 4, 6, 8 and 10 GeV in the $/t/$ range from 0.003 to 0.2 $(\text{GeV}/c)^2$. The differential cross-sections were measured in the internal beam of the JINR synchrophasotron with a thin target ($< 1\ \mu$) of ordinary or deuterated polyethylene and the apparatus that we had used earlier to measure the differential cross-section of elastic p - p and p - d scattering.[1,2,3] Recoil particles were recorded. Elastic p - d scattering events were reliably distinguished from instances of quasi-elastic scattering wherein the deuteron dissociated into individual nucleons.

The differential cross-section was measured with a statistical error of ≈ 3%, while the absolute accuracy was 7%. Tables 1 and 2 (at the end of the text) give the differential cross-sections of elastic p - p and p - d scattering. The region of small scattering angles, where interference of the Coulomb and nuclear scatterings plays the most important role, affords the most information for determining the value of α_{pd}, the ratio of the real part of the nuclear amplitude of p - d scattering to its imaginary part. Analysis of the elastic p - d scattering data obtained has enabled us to calculate that

$$\alpha_{pd} = \frac{\text{Re } A_{pd}(0)}{\text{Im } A_{pd}(0)} .$$

As was done in our analysis of the elastic p - p scattering data, the differential cross-section is approximated with the expression:

$$\left(\frac{d\sigma(t)}{dt}\right)_{CM} = \left| i\,\mathrm{Im}\,A_{pd}(t)\sqrt{1+\beta} + \mathrm{Re}\,A_{pd}(t) + A_c(t)\right|^2 , \qquad (1)$$

where A_{pd} and A_c are the nuclear and Coulomb amplitudes of the p - d scattering, and β is a coefficient describing the overshoot of the differential cross-section, near 0°, above the optical point, not due to the presence of the real part in the p - d scattering amplitude or to the Coulomb amplitude. For the amplitudes we adopted the following analytical representation:

a) $\mathrm{Im}\ \mathrm{Apd}(t) = \sqrt{\left(\frac{d\sigma}{dt}\right)_0} \exp\left[\tfrac{1}{2}(b_i t + c_i t^2)\right]$ a)

b) $\mathrm{Re}\ \mathrm{Apd}(t) = \sqrt{\left(\frac{d\sigma}{dt}\right)_0}\ \alpha \exp\left[\tfrac{1}{2}(b_r t + c_r t^2)\right]$ б)

c) $Ac(t) = -\frac{2n\,F(t)}{t} e^{-i\eta}$; $\eta = 2n\ln\frac{\phi}{\theta}$ в) (2)

d) $2n = \frac{z_1 z_2}{137\beta_{\text{лаб}}}$; $\left(\frac{d\sigma}{dt}\right)_0 = \frac{\sigma^2}{16\pi\hbar^2}$ г)

e) $F(t) = \exp\left[\tfrac{1}{2}(b_i t + c_i t^2)\right]$ д)

f) $t = -2 p^2_{\text{сцм}} (1 - \cos\theta)$; $k = \frac{p_{\text{сцм}}}{\hbar}$. е)

Translator's Note: Russian abbreviation in (2d) is "lab." (for "laboratory").

We shall give some explanation of these formulae. The exponential dependence of the amplitudes on the square of the transferred momentum t both follows from the optical model (for small values of t) and is amply confirmed by the many experiments carried out hitherto on elastic scattering of particles. The square term in the exponent of expressions (2a) and (2b) is needed to describe p - d scattering in the range

$0.003 \leq /t/ \leq 0.2\ (\mathrm{GeV}/c)^2$. But in this range the differential cross-section of elastic p - p scattering is satisfactorily approximated with expressions in which the square term with t^2 is dropped. The normalization factor in the amplitudes $\sqrt{\left(\frac{d\sigma}{dt}\right)_0}$ $\left[\left(\frac{d\sigma}{dt}\right)_0\right.$ is the optical point$\left.\right]$ is selected for dimensional reasons, and automatically assures fulfillment of the optical theorem (2d). The function $F(t)$ in (2e) plays the role of deuteron electromagnetic form factor. We note that in the region of small scattering angles, in which we are mainly interested, $F(t) \approx 1$, whence our adopted approximation is fully justified.

The amplitude of the Coulomb scattering of strongly interacting particles (2c) has both a real and an imaginary part. The real part is much larger than the imaginary one. The latter is determined by the phase η . Theoretically, calculation of the phase η consists in taking into account the radiative corrections for the strong interactions. This problem is solved solely on the basis of certain model approximations. Taking a quasi-classical nonrelativistic approximation, Bethe has made an analysis[4], finding for Φ [see (2c)] the value $\Phi = 1.06/ak$, where a is the radius of the strong interaction.

L.D. Solov'ev[5] has solved the same problem with the methods of relativistic quantum electrodynamics. He got the value $\Phi = 2$. Here the optical theorem has to be written in the form

$$\mathrm{Im}\, A\,(0) = \frac{k}{4\pi}\,[\sigma(>\theta\ \mathrm{min}) - \sigma_c\,(>\theta\ \mathrm{min})] + + 2n\,\mathrm{Re}\, A\,(\cdot 0)\,\ell n\,(2/\theta\ \mathrm{min}) \qquad (3)$$

where A is the nuclear scattering amplitude. In this expression $\sigma\ (>\theta\ \mathrm{min})$ is the total cross-section, wherein its elastic part is integrated, starting from a certain small angle θ min. That angle is defined by the experimental possibilities afforded by the method of measuring the total cross-section σ . The $\sigma_c\ (>\theta\ \mathrm{min})$ has the

Translator's Note: The subscript here is believed to be c but is not very legible in the Russian.

same sense for the Coulomb cross-section. In other words, writing the optical theorem in this way explicitly allows for the effect of interference of the nuclear and electromagnetic interactions and the influence thereof on the total cross-section of the elastic scattering.

The indeterminacy of the phase η exerts little influence on the parameter

$$\alpha = \frac{\text{Re } A_{pd}(0)}{\text{Im } A_{pd}(0)} .$$

Within the limits of accuracy of our experiments η can be considered determinate.

We know that the differential cross-section of the scattering of particles having spins may, with $t = 0$, exceed the optical limit because of the contribution of the spin-dependent terms to the scattering amplitude. We allow for this fact with the parameter β in expression (1). Here we assume that the scattering amplitudes in the different spin states (singlet or triplet in the case of p - d scattering, doublet and quartet in that of p - d scattering*) do not differ in the form of their dependence on t. In terms of our parameterization [(2a) and (2b)] this means that the quantities b_j, b_r, c_j, c_r are not dependent on the spin state of the system of interacting particles. Since

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* Translator's Note: Sic! p - p scattering?

the parameter b_j is directly tied to the interaction radius, with respect to b_j this assumption seems reasonable, for the maximum strong-interaction radius is determined by the mass of the lightest hadron (π-meson) and cannot greatly exceed $\approx \frac{T}{m_\pi}$. This matter has been dealt with in detail by I.I. Levintov.[6] The author proposes a special parameterization of the differential cross-section such that the quantities α and β acquire a self-evident form.

Using the experimental data, we calculate the total cross-section of the elastic p - d scattering σ_e^* and the parameters α_{pd}, b_j, b_r, c_j, c_r and β by the method of least squares. The results are given in Table 3. We did not refine the values of α_{pd} for 2.78 and 4.85 GeV/c, taken from ref. 3. In Figure 1 the experimental results are compared with the predictions following from the dispersion relations. The solid-line curve was calculated by Carter and Bugg[8], and the broken lines show the error corridor of those calculations. The data on neutron-proton charge exchange gained from the experiments of Palevsky[9] and Manning[10]

* Translator's Note: Above subscript illegible in the Russian.

enable us to obtain two solutions for the α_{pn} values. One of them obviously is in better agreement with the dispersion relations, while the other largely contradicts them. As seen from Figure 1, the data obtained by us are in harmony with the dispersion relations and agree better with the Palevsky-Manning solution for α_{pn}, which gives a smaller value.

In recent years a number of works have appeared in which, from the general principles of quantum field theory, the authors have arrived at some limitations on the behavior of the elastic-scattering amplitude at high energies. McDowell and Martin[11], for instance, have come up with the inequality:

$$\left[\frac{d}{dt} \ln A(S,t)\right]_{t=0} > \frac{\sigma^2}{36\pi\sigma_e} - \frac{1}{9k^2}, \qquad (4)$$

where σ is the total cross-section, σ_e the elastic-scattering cross-section.

Popov and Mur[12] have derived the following inequality for values of the n-th derivative of the elastic-scattering amplitude for $t = 0$:

$$\frac{1}{A(S,0)}\left[\frac{d^{n}A(S,t)}{dt^{n}}\right]_{t=0} > \frac{1}{(2n+1)\,n!}\left[\left(1+\frac{1}{2n+1}\right)\frac{\sigma^{2}}{16\pi\,\sigma_{e}}\right]^{n} . \qquad (5)$$

Nonfulfillment of even one of the n inequalities would indicate violation of the unitarity and analyticity. Having experimental data on the magnitude and behavior of the elastic p - p and p - d scattering amplitude in the region $/t/ < 0.2\ (\mathrm{GeV}/c)^2$, we tried to verify the fulfillability of the above Popov-Mur inequalities. [When (5) is fulfillable, (4) is fulfilled all the more.] As the calculation shows, the Popov-Mur inequality for the first and second derivatives of the p - p and p - d elastic-scattering amplitudes is fulfilled in the 1-10 GeV energy range. To illustrate the fulfillability of the Popov-Mur inequalities we give Table 4 for p - p and p - d scattering at 10 GeV.

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Manuscript submitted to
Publishing Section
27 December 1967.

Таблица 1

Дифференциальное сечение упругого p – p-рассеяния

Table 1: Differential cross-section of elastic p - p scattering.

PC	2,78 Гэв/с (a)		4,85 Гэв/с		6,87 Гэв/с	
$\left(\frac{d\sigma}{d\omega}\right)_0$	(30.7±0.7) мбн/стерад (b)		(53.3±1.8) мбн/стерад		(78.9±1.9) мбн/стерад	
№	θ^0 сцм (c)	$\frac{d\sigma}{d\omega}$ мбн/стерад	θ^0 сцм	$\frac{d\sigma}{d\omega}$ мбн/стерад	θ^0 сцм	$\frac{d\sigma}{d\omega}$ мбн/стер.
I	3.37	38.2 ± 2.I	2.67	85.8 ± 7	I.95	I32.9±8.4
2	3.89	36.4 ± I.9	3.I4	73.2 ± 6	2.42	I04.I±6.0
3	4.40	36.7 ± I.8	3.45	7I.8 ± 4	2.9I	96.7±3.0
4	4.79	33.2 ± I.7	3.85	63.I ± 3	3.39	90.7±2.4
5	5.I5	3I.2 ± I.6	5.25	52.4 ± 2	3.85	82.4±I.9
6	6.36	28.7 ± I.I	5.86	5I.5 ± 2	5.30	73.5±I.7
7	7.27	28.6 ± I.I	6.58	47.2 ± 2	5.35	73.I± I.6
8	9.42	26.3 ± I.I	7.25	44.2 ± 2	6.I3	63.3±I.4
9	I0.9	24.I ± I.0	7.72	43.7 ± 2	6.I5	64.8±I.0
I0	I5.2	20.3 ± I.6	9.68	39.4 ± I.5	7.67	52.7±3.I
II	I6.7	I6.4 ± 0.7	II.I	34.6 ± I.5	9.06	49.I±I.9
I2	20.5	I2.7 ± 0.5	II.2	34.9 ± I.6	9.75	42,3±I.9
			II.3	3I.7 ± I.3	II.2	32.3±I.2
			I4.4	23.7 ± I.2	I2.0	26.8±I.I
					I2.8	26.3±I.3
					I5.0	I9.I±I.0

a) GeV/c

b) mb/sterad

c) center-of-mass

T a b l e 1 (continued): Differential cross-section of elastic p - p scattering.

Таблица 1 (продолжение)

Дифференциальное сечение упругого p − p - рассеяния

PC	8,89 Гэв/с [a]		10,9 Гэв/с	
$\left(\frac{d\sigma}{d\omega}\right)_0$	(102.0±4.0) мбарн/стерад. [b]		(121.9±1.9) мбн/стерад	
№	θ^0 сцм [c]	$d\sigma/d\omega$ мбн/стерад	θ^0 сцм	$\frac{d\sigma}{d\omega}$ мбн/стерад.
I	I.22	258 ± 46	I.39	2I0 ±I0
2	I.7I	I73 ± I6	I.48	I90 ±I0
3	I.99	I36 ± 6.7	I.72	I70 ±7
4	2.22	I33 ± 8.7	I.99	I49 ±6.3
5	2.60	I26 ± 5.0	2.22	I42 ±6.3
6	2.76	II9 ± 4.5	2.62	I36 ± 5.5
7	2.99	II3.5±3.5	3.I7	I22.9±4.4
8	3.42	I00.6±3.7	4.I6	II2.0±3.7
9	4.52	87.4±I.9	4.83	92.6±3.0
I0	4.94	90.5±2.I	6.27	80.8±2.6
II	5.43	84.6±2.0	7.47	62.I±2.5
I2	8.I5	56.8±2.8	8.85	47.I±2.3
I3	8.34	54.6±I.8	9.95	37.6±2.3
I4	9.75	37.I± I.5		
I5	I0.5	35.4± I.4		
I6	II.6	25.5±I.2		

a) GeV/c

b) mb/sterad

c) center-of-mass

T a b l e 2 : Differential cross-section of elastic p - d scattering.

Таблица II
Дифференциальное сечение упругого p - d-рассеяния

PC (Гэв) лаб a	1.70		2.78		4.85	
$\left(\frac{d\sigma}{d\omega}\right)_0$	(97.8±0.5) мбн/стерад b		(202.4±1.0) мбн/стерад		(373±2) мбн/стерад	
	θ^0 сцм c	$\frac{d\sigma}{d\omega}$ $\frac{мбн}{стерад}$ b	θ^0 сцм	$\frac{d\sigma}{d\omega}$ $\frac{мбн}{стерад}$	θ^0 сцм	$\frac{d\sigma}{d\omega}$ $\frac{мбн}{стерад}$
I	4.07	98.2±4.I	3.07	I72±7	2.4I	302±II
2	4.I2	99.8±4.I	3.I7	I60±6.2	2.44	307±I3
3	4.23	95.4±4.0	3.29	I6I±6.0	2.48	3I3±I0
4	4.23	95.0±4.0	3.37	I57±8.5	2.57	287±I3
5	4.29	85.8±3.5	3.40	I58±5.5	2.65	287±I3
6	4.50	82.3±2.4	3.40	I63±8.5	2.68	277±I2
7	4.50	85.3±3.4	3.40	I58±5.3	2.70	292±I0
8	4.8I	82.I±2.2	3.45	I57±6.5	2.76	272±I2
9	5.I3	80.6±2.0	3.52	I47±6.0	2.88	260±8
I0	5.44	75.I±I.9	3.72	I42±8.0	3.02	276±I5
II	5.75	72.2±2.5	3.73	I5I±4.5	3.I4	26I±8
I2	6.07	72.6±I.8	3.89	I44±5.0	3.20	259±I0
I3	6.68	65.9±I.5	3.98	I54±4.5	3.33	230±8
I4	7.I6	6I.4±I.4	4.I3	I43±5.0	3.68	204±I0
I5	8.93	47.3±I.3	4.46	I38±4.0	3.75	206±6
I6	I5.65	I2.7±0.5	4.54	I32±4.5	3.77	2I2±I4
I7			4.89	I26±3.5	3.78	208±7
I8			4.90	II8±4.0	3.82	202±I0
I9			5.I9	I2I±3.5	3.84	20I±I0
20			5.30	II6±8.0	3.94	206±6
2I			5.57	II2.6±3.0	4.06	I86±6
22			5.66	I06.5±3.0	4.I0	I77±8
23			5.99	I03.0±3.0	4.37	I66±6
24			6.56	92.2±3.0	4.6I	I52±5.0
25			7.30	70.7±2.5	4.74	I45±5.0
26			8.46	54.5±2.0	5.3I	I24±4.2
27			I0.8	28.2±I.5	5.4I	I27±7.0
28			II.2	23.6±I.0	5.47	II7±5.0
29			I3.6	II.3±0.5	6.49	74±2.7
30			I4.6	8.5±0.5	6.57	7I.8±3.0
3I			I5.6	5.7±0.5	6.79	68.0±2.5
32					7.76	45.0±3.0
33					8.03	35.9±I.5
34					9.3I	I8.2±I.0
35						
36						
37						

a) (GeV) lab b) mb/sterad c) center-of-mass

T a b l e   2 (continued) : Differential cross-section of elastic p - d scattering.

Таблица II (продолжение)

Дифференциальное сечение упругого p – d-рассеяния

		a				
PC (Гэв) лаб	6.87		8.89		10.9	
$\left(\frac{d\sigma}{d\omega}\right)_0$	(547+3) мбн/стерад b		(711+19) мбн/стерад		(857+32) мбн/стерад	
№	$\theta^0_{\text{сцм}}$ c	$d\sigma/d\omega$ мбн/стерад	$\theta^0_{\text{сцм}}$	$d\sigma/d\omega$ мбн/стер b	$\theta^0_{\text{сцм}}$	$d\sigma/d\omega$ мбн/стерад
I	I.45	673 ± I42	I.36	8I7 ± 53	I.I6	940±42
2	I.49	604 ± 50	I.48	7I4 ± 28	I.20	964± 45
3	I.67	5I7± 2I	I.64	67I ± 20	I.30	944± 45
4	I.7I	488± 22	I.76	637 ± 20	I.35	886± 40
5	I.9I	53I± I8	I.94	563 ± 30	I.42	839± 30
6	I.93	469 ± I3	2.I3	570 ± I7	I.58	8I0± 30
7	2.95	465 ± I2	2.I6	556 ± I7	I.58	756± 22
8	2.32	479± I3	2.33	537 ± I4	I.74	726± 25
9	2.37	44I ± I0	2.37	490 ± I5	I.74	734± 22
I0	2.54	397 ± I3	2.63	463 ± I3	I.96	650± 22
II	2.76	399 ± I0	2.65	44I ± I3	I.96	633± 20
I2	2.92	347 ± 8	2.99	388 ± II	2.I2	594± 20
I3	3.26	3I4 ± 9	3.08	377 ± II	2.I2	574± 25
I4	3.33	285 ± 8	3.20	360 ± I0	2.33	533± 20
I5	3.76	249 ± 5	3.5I	3I6 ± I2	2.5I	509± I4
I6	4.66	I6I ± 6	3.80	244 ± I0	2.5I	489± 20
I7	4.74	I59 ± 4	4.3I	I70 ± I0	2.79	423± I5
I8	6.07	74.0±2	5.37	86 ± 2.3	2.82	445± I3
I9	6.62	54 ± I.5	5.42	78.2± 5	3.I9	338± II
20	7.65	26,8± I	6.32	42.4± I.4	3.2I	339± I3
2I	8.35	I6.4± I	7.08	20.4± I	3.79	233± 8
22	9.78	5.4 ± 0.5	7.62	I4.2± I	3.83	24I±I2
23	9.83	5.6 ± 0.5	8I88	3.85± 0.6	5.08	88.7±2.5
24	9.83	6.0 ± 0.5			5.87	46.I±I.6
25	I0.37	4.4 ± 0.5			6.32	30.8±I.2
26	II.67	I.27± 0.23			6.42	26.2±I.0
27	I2.64	I.03± 0.23			8.I6	4.45±0.7
					8.22	4.36±0.54

a) (GeV) lab b) mb/sterad c) center-of-mass

Значени параме

$E_{\text{кин}}$ (гэв)

I
2
4
6
8
I0

Значе

p – p
p – d

Таблица III

Значения полных сечений упругого p − d -рассеяния и параметров α, b и c для упругого p − d-рассеяния в интервале энергий 1-10 Гэв

$E_{кин}$ (гэв) E_{kin} (GeV)	σ_e (мбн) (mb)	$b_j \equiv b_r$ (Гэв/с)$^{-2}$ (GeV/c)	$c_j \equiv c$ (Гэв/с)$^{-4}$	α
I	I0,7±0,7	33,7±I	42±I0	−0,I4±0,08
2	I0,2±0,7	37,5±I,5	83±I2	
4	9,5±0,7	37,8±I,4	72±I4	
6	9,6±0,7	36,0±0,8	45± 6	− 0,30±0,09
8	9,3±0,7	36,5±I,0	40± 7	− 0,26±0,09
I0	9,0±0,6	34,3±0,9	34± 6	− 0,39±0,08

Table 3: Values for the total cross-sections of elastic p - d scattering and the parameters α, b and c for elastic p - d scattering in the 1-10 GeV energy range.

Таблица IV

Значения неравенств П.М. для p − p и p − d-рассеяния при I0 Гэв

	n = 1 в ед (Гэв/с)$^{-2}$	n = 2 в ед (Гэв/с)$^{-4}$
p − p	4,35±0,35 > 3,65±0,I5	I7±6 > I0±0,5
p − d	I7 ±0,5 > I3,5 ±I	3I9±I0 > I50±24
	in units of (GeV/c)$^{-2}$	in units of (GeV/c)$^{-4}$

Table 4:

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Values for the Popov-Mur inequalities for p - p and p - d scattering at 10 GeV.

16.9

мбн/стерад

	dσ/dω мбн/стерад
I6	940±42
20	964±45
30	944±45
35	886±40
42	839±30
58	810±30
58	756±22
74	726±25
74	734±22
[illegible]	650±22
[illegible]	633±20
I2	594±20
I2	574±25
33	533±20
5I	509±I4
5I	489±20
79	423±I5
82	445±I3
I9	338±II
2I	339±I3
79	233± 8
83	241±I2
08	88.7±2.5
67	46.I±I.6
32	30.8±I.2
42	26.2±I.0
I6	4.45±0.7
22	4.36±0.54

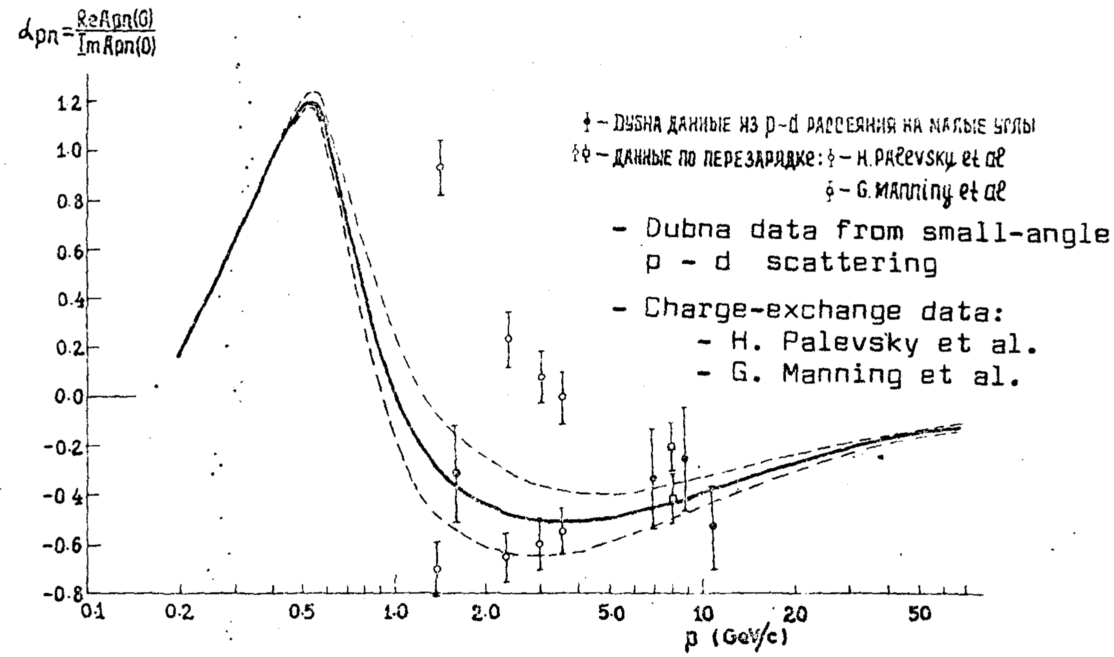

Рис.1.

Figure 1