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# QUASIPOTENTIAL APPROACH AND BACKWARD $\pi N$ SCATTERING AT HIGH ENERGY

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In the present paper we continue a study of $\pi N$ scattering at high energies in the quasipotential approach. Here we consider backward scattering phenomena. We do not describe here the basic ideas of the Logunov-Tavkhelidze quasipotential approach [1] and refer the reader to the appropriate review papers [2-6].

The quasipotential equation for the case of two-particle system with spins 0 and 1/2 looks as follows [5,7]*

$$[E\gamma_0 - \omega(-i\vec{\nabla}) - W(-i\vec{\nabla})]\psi(\vec{r}) = \frac{-1}{\omega(-i\vec{\nabla})} V(E;\vec{r})\,\psi(\vec{r}) \,. \quad (1)$$

Here $E$ is the total energy of two particles in the c.m.s., $\gamma$ is the Dirac matrix, $\omega(-i\vec{\nabla}) = \sqrt{\mu^2 - \vec{\nabla}^2}$, $W(-i\vec{\nabla}) = \sqrt{M^2 - \vec{\nabla}^2}$, $\mu$ and $M$ are the masses of the scalar and spinor particles, respectively.

We represent the quasipotential $V(E;\vec{r})$ in the form :

$$V(E;\vec{r}) = \begin{pmatrix} V_{11}, & 0 \\ 0, & V_{22} \end{pmatrix} , \quad (2)$$

where $V_{11}$ and $V_{22}$ are 2x2 matrices. In what follows only $V_{11}$ term of the quasipotential is of interest.

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* Corresponding equation in the finite-difference formulation of the quasipotential approach [8] can be found in Ref. [9].

We omit the indices of $V_{11}$ and write it in the form:

$$V(E;\vec{r}) = V_d(E;\vec{r}) + V_e(E;\vec{r})\hat{P}, \tag{3}$$

where $\hat{P}$ is the coordinate exchange operator; $V_d$ and $V_e$ are the direct and the exchange parts of the quasipotential, respectively; $V_d$ and $V_e$ are chosen in the form:

$$V_{d,e}(E;\vec{r}) = V^{(+)}_{d,e}(E;\vec{r}) + \frac{1}{2ip} V^{(-)}_{d,e}(E;\vec{r})(\vec{\sigma}\vec{L}),$$

$$\vec{L} = -i[\vec{r}\times\vec{\nabla}], \tag{4}$$

$V_d^{(\pm)}$ and $V_e^{(\pm)}$ are assumed to be the energy dependent smooth functions of $r^2$.

The scattering amplitude corresponding to the quasipotential (3) looks as follows:

$$T(\vec{p},\vec{k}) = T_d(\vec{p},\vec{k}) + T_e(\vec{p},\vec{k}), \tag{5}$$

where $T_d$ contributes mainly to the region of small $t$ and decreases exponentially in the region of small $u$, $T_e$ differs from zero essentially in the region of small $u$ only. We are interested here only in

$$T_e(\vec{p},\vec{k}) = \chi^{+}_{1/2,m_z'}(\vec{k})[T^{(+)}_e(\vec{p},\vec{k}) + i\sigma_y T^{(-)}_e(\vec{p},\vec{k})]\chi_{1/2,m_z}(\vec{p}), \tag{6}$$

$T^{(+)}_e$ and $T^{(-)}_e$ are expressed in terms of the initial quasipotential in the following way

$$T^{(+)}_e(\vec{p},\vec{k}) = -ip[\int_0^\infty \rho\, d\rho\, J_0(\rho\Delta_u)\, e^{\chi^{(+)}_d(E;\rho)}\chi^{(+)}_e(E;\rho) + O(\frac{V_e}{p})], \tag{7a}$$

$$T^{(-)}_e(\vec{p},\vec{k}) = p[\int_0^\infty \rho\, d\rho\, J_1(\rho\Delta)\, e^{\chi^{(+)}_d(E;\rho)}\chi^{(-)}_e(E;\rho) + O(\frac{V_e}{p})]$$

$$\Lambda_u = [ (\sqrt{\vec{p}^2 + \mu^2} - \sqrt{\vec{p}^2 + M^2})^2 - u ]^{1/2}, \tag{7b}$$

where

$$\chi_d^{(+)}(E;\rho) = \frac{-1}{2ip} \int_{-\infty}^{\infty} V_d^{(+)}(E,\vec{r})\, dz, \tag{8a}$$

$$\chi_e^{(+)}(E;\rho) = \frac{-1}{2ip} \int_{-\infty}^{\infty} V_e^{(+)}(E;\vec{r})\, dz, \tag{8b}$$

$$\chi_e^{(-)}(E;\rho) = \frac{-1}{2ip} \frac{\rho}{2} \int_{-\infty}^{\infty} V_e^{(-)}(E;\vec{r})\, dz. \tag{8c}$$

Experimentally observable quantities, differential cross section and polarization parameter, are expressed in terms of $T_e^{(+)}$ and $T_e^{(-)}$:

$$d\sigma/du = \frac{\pi}{p^2} [\, |T_e^{(+)}|^2 + |T_e^{(-)}|^2 \,], \tag{9a}$$

$$P = 2\,\mathrm{Jm}\,(T_e^{(+)} T_e^{(-)*}) / [\, |T_e^{(+)}|^2 + |T_e^{(-)}|^2 \,]. \tag{9b}$$

In order to associate our considerations with physical processes in $\pi N$ system it is necessary to consider the structure of the quasipotential in the isotopic spin space. We will consider in what follows quasipotentials and all the quantities connected with it with definite isospin in the s -channel. We choose $V_e^{(I,\pm)}$ as the following smooth functions of $r^2$:

$$V_e^{(I,+)}(E;\vec{r}) = \frac{h_1^{(I,+)} + h_2^{(I,+)} r^2}{(p/\sqrt{s_0})^{a(I,+)}}\, e^{-r^2/4b^{(I,+)}},$$

$$V_e^{(I,-)}(E;\vec{r}) = \frac{h_1^{(I,-)} + h_2^{(I,-)} r^2}{(p/\sqrt{s_0})^{a(I,-)}}\, e^{-r^2/4b^{(I,-)}},$$

The quasipotential $V_d^{(I,+)}$ is taken in the form which has been given in Ref. /11/.Since we are dealing with the first approximation in the small parameter $1/p$ ( $p$ is the relative momentum of two particles in the c.m.s.) only the leading term of

$$V_d^{(I,+)}(E;\vec{r}) = 2ipg_{I,0}a_1^{-3/2} e^{-r^2/4a_1} \tag{10}$$

gives the main contribution.

The eikonal functions $\chi_d^{(I,+)}$, $\chi_e^{(I,+)}$ and $\chi_e^{(I,-)}$ are of the form:

$$\chi_d^{(I,+)}(E;\rho) = -h\, e^{-\rho^2/4a_1}, \tag{11a}$$

$$\chi_e^{(I,+)}(E;\rho) = \frac{-1}{2ip} \frac{f_1^{(I,+)} + f_2^{(I,+)}\rho^2}{(p/\sqrt{s_0})^{\alpha(I,+)}} e^{-\rho^2/4b^{(I,+)}} \tag{11b}$$

$$\chi_e^{(I,-)}(E;\rho) = -\frac{\rho}{2} \frac{1}{2ip} \frac{f_1^{(I,-)} + f_2^{(I,-)}\rho^2}{(p/\sqrt{s_0})^{\alpha(I,-)}} e^{-\rho^2/4b^{(I,-)}}. \tag{11c}$$

Expanding $e^{\chi_d^{(I,+)}}$ in formulas (7a) and (7b) in power series in $\chi_d^{(I,+)}$ and integrating over $\rho$ one obtains the following expressions for the amplitudes $T^{(I,\pm)}$:

$$T^{(I,+)} = \frac{f_1^{(I,+)}}{(p/\sqrt{s})^{\alpha(I,+)}} \sum_{n=0}^{\infty} \frac{(-h)^n}{n!} B_n(b^{(I,+)}) \times$$

$$\times e^{-B_n(b^{(I,+)})\Delta_u^2} + \frac{4f_2^{(I,;)}}{(p/\sqrt{s_0})^{\alpha(I,+)}} \sum_{n=0}^{\infty} \frac{(-h)^n}{n!} \times$$

$$\times [B_n(b^{(I,+)})]^2 [1 - B_n(b^{(I,+)})\Delta_u^2] e^{-B_n(b^{(I,+)})\Delta_u^2},$$

$$T^{(I,-)} = \frac{-if_1^{(I,-)}\Delta_u}{(p/\sqrt{s_0})^{\alpha(I,-)}} \sum_{n=0}^{\infty} \frac{(-h)^n}{n!} [B_n(b^{(I,-)})]^2 \times$$

$$\times e^{-B_n(b^{(I,-)})\Delta_u^2} - \frac{8if_2^{(I,-)}\Delta_u}{(p/\sqrt{s_0})^{\alpha(I,-)}} \sum_{n=0}^{\infty} \frac{(-h)^n}{n!} \times$$

$$\times [B_n(b^{(I,-)})]^3 [1 - \frac{B_n(b^{(I,-)})}{2}\Delta_u^2] e^{-B_n(b^{(I,-)})\Delta_u^2},$$

where

$$f_1^{(I,\pm)} = 2\sqrt{\pi b^{(I,\pm)}} (h_1^{(I,\pm)} + 2h_2^{(I,\pm)} b^{(I,\pm)}), \quad (12a)$$

$$f_2^{(I,\pm)} = 2\sqrt{\pi b^{(I,\pm)}} h_2^{(I,\pm)}, \quad (12b)$$

$$B_n(b^{(I,\pm)}) = \frac{a_1 b^{(I,\pm)}}{a_1 + n b^{(I,\pm)}}, \quad (12c)$$

$$h = \frac{2\sqrt{\pi}\, g_{1,0}}{a_1}. \quad (12d)$$

Note, that in numerical calculations 6-9 terms of the series (11a) and (11b) give a noticeable contribution.

We have performed an analysis of the known experimental data on differential cross sections of backward $\pi\ p$ scattering, charge exchange reaction $\pi^- p \to \pi^0 n$ for $-2.86\ (GeV/c)^2 \leq u \leq 0.06\ (GeV/c)^2$ and $p_L \geq 7.8$ GeV/c, and polarization parameter in backward scattering

Table 1

| Reaction | Quantity measured | $p_L$ GeV/c | Number of points | Number of excluded points | Systematic error indicated by the authors % | Norm | Reference |
|---|---|---|---|---|---|---|---|
| $\pi^-p$ | $\frac{d\sigma}{du}$ | 9.85 | 20 | - | 5 | 0.92±0.03 | Owen, 1969 (12) |
| | | 16.25 | 3 | - | 5 | 1.28±0.27 | -"- |
| | | 13.73 | 6 | - | 5 | 1.07±0.07 | -"- |
| | | 8.0 | 11 | - | 20 | 1.23±0.08 | Anderson,1968 (13) |
| | | 16.0 | 8 | - | 20 | 1.80±0.16 | -"- |
| | | 7.8 | 6 | - | 10 | 1.48±0.43 | Brody, 1966 (14) |
| | $P$ | 6.0 | 12 | - | 5 | 1 (fixed) | Dick, 1973 (15) |
| $\pi^+p$ $(\pi^-n)$ | $\frac{d\sigma}{du}$ | 9.85 | 19 | - | 5 | 1.5 ±0.05 | Owen, 1969 (12) |
| | | 13.73 | 13 | - | 5 | 0.77±0.06 | -"- |
| | | 17.07 | 2 | - | 5 | 1.01±0.44 | -"- |
| | | 23.0 | 5 | - | 20 | 0.92±0.14 | Babaev, 1972 (16) |
| | | 40.0 | 8 | - | 5 | 1.72±0.21 | -"- |
| | | 7.8 | 7 | - | 10 | 0.74±0.06 | Brody, 1966 (14) |
| | $P$ | 6.0 | 20 | - | 5 | 1 (fixed) | Dick, 1972 (17) |
| $\pi^-p\to\pi^0n$ | $\frac{d\sigma}{du}$ | 10.1 | 14 | - | 15 | 1.08±0.07 | Boright, 1970 (18) |
| | | 13.8 | 13 | - | 20 | 0.71±0.07 | -"- |
| | | 8.0 | 8 | - | 30 | 1.40±0.11 | Schneider,1969(19) |
| | | 11.0 | 7 | - | 40 | 1.66±0.21 | -"- |

at $\pi^{\pm}p$ 6 GeV/c * (see Table 1). A rather complete review of experimental data on $\pi N$ scattering can be found in Ref. /20/.

The parameters entering the definition of the quasipotentials $V_c^{(I,\pm)}$ have been found by minimization of the functional:

$$\chi^2 = \sum_{k,i} \frac{[F_i^k - M_k F_i^k(x_n)]^2}{(\sigma_i^k)^2}, \qquad (13)$$

where $F_i^k$ is the quantity which has been measured at the $i$ -th point of the $k$ -th experiment, $F_i^k(x_n)$ - the value of the quantity $F_i^k$ calculated by means of the parameters $x$, which we are searching for, $\sigma_i^k$ - experimental error of the quantity $F_i^k$, $M_k$ - the norm of the $k$ -th experiment. The parameter $M_k$ allows one to take into account a systematic error of the $k$ -th experiment.

The values of the parameters $g_{1,0}$ and $a_1$ entering the definition of $V_d^{(I,+)}$ have been taken from Ref. /11/, where an analysis of the experimental data on small angle $\pi N$ scattering at high energies has been performed.

In Figs. 1-6 the calculated curves of the differential cross sections (norms have been taken into account) and polarization together with the existing data are shown. The eikonal functions $\chi_e^{(I,\pm)}$ and the corresponding amplitudes for $\pi^{\pm}p$ scattering at $p_L = 9.85$ GeV/c are drawn in Figs. 7-10 and 11-14, respectively. In Figs. 15-20 some predictions for higher values of $P_L$ are plotted. The predictions are accompanied by their uncertainties, which are caused by uncertainties in the parameters. We note, that the polarization parameter $p(\pi^- p \to \pi^\circ n)$ is the ratio of two very small quantities and small variation of the parameters may cause large variation of the result of calculation.

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* There are no data on polarization parameter at higher values of $P_L$.

Table 2

$$b^{(3/2,+)} = \left[1.4866 \pm 0.0277 + (0.4281 \pm 0.0554)\left(\ln\frac{s}{s_0} - \frac{i\pi}{2}\right)\right](GeV/c)^{-2}$$

$$b^{(3/2,-)} = \left[-4.0947 \pm 0.0466 + (2.0347 \pm 0.0118)\left(\ln\frac{s}{s_0} - \frac{i\pi}{2}\right)\right](GeV/c)^{-2}$$

$$b^{(1/2,+)} = \left[1.9133 \pm 0.0950 + (0.4993 \pm 0.0737)\left(\ln\frac{s}{s_0} - \frac{i\pi}{2}\right)\right](GeV/c)^{-2}$$

$$b^{(1/2,-)} = \left[1.0939 \pm 0.0246 + (0.4756 \pm 0.0492)\left(\ln\frac{s}{s_0} - \frac{i\pi}{2}\right)\right](GeV/c)^{-2}$$

$$h_1^{(3/2,+)} = (-0.0717 \pm 0.0088) \quad (GeV/c)^2$$

$$h_2^{(3/2,+)} = (0.0071 \pm 0.0008) \quad (GeV/c)^4$$

$$h_1^{(3/2,-)} = (0.0055 \pm 0.0029) \quad (GeV/c)^3$$

$$h_2^{(3/2,-)} = \left[-(8.5 \pm 5.1).10^{-5} - i(3.4 \pm 2.1).10^{-5}\right] \quad (GeV/c)^5$$

$$h_1^{(1/2,+)} = -i(0.0408 \pm 0.0121) \quad (GeV/c)^2$$

$$h_2^{(1/2,+)} = i(0.0028 \pm 0.0009) \quad (GeV/c)^4$$

$$h_1^{(1/2,-)} = \left[-0.1251 \pm 0.0270 - i(0.0216 \pm 0.0074)\right] \quad (GeV/c)^3$$

$$h_2^{(1/2,-)} = (0.0113 \pm 0.0023)(GeV/c)^5$$

$$\alpha^{(3/2,+)} = (2.1467 \pm 0.1303)$$

$$\alpha^{(3/2,-)} = 1.2542 \pm 0.5732$$

$$\alpha^{(1/2,+)} = 2.0269 \pm 0.3530$$

$$\alpha^{(1/2,-)} = 3.2940 \pm 0.2274$$

$$s_0 = 1 \ (GeV/c)^2$$

The obtained value of $\chi^2 = 151$ (the number of experimental points is 182, the number of parameters is 22) shows that a statistically satisfactory fit to the data is obtained. It is worthwhile noting, however, that in the two cases ( $p_L$ = 16 GeV/c in $\pi^- p$ scattering and $p_L$ =40 GeV/c in $\pi^+ p$ scattering) the norms differ from unity by more than three standard errors and deviations are considerably larger than the systematic errors given in Refs. /13,16/. In this connection it would be very desirable to measure the differential cross sections of the backward $\pi p$ scattering in the momentum region $p_L$ = 16 - 40 GeV/c. Also it is very interesting to investigate polarization effects at $p_L > 6$ GeV/c.

Some attempts to describe qualitatively and quantitatively backward scattering are known /21-27/. It seems that in the present paper the best fit to the $\pi N$ backward scattering has been obtained.

We note in conclusion that the amplitudes of $\pi N$ scattering which have been calculated in this paper and in Ref. /11/ can be used for the analysis of $\pi d$ scattering at high energies.

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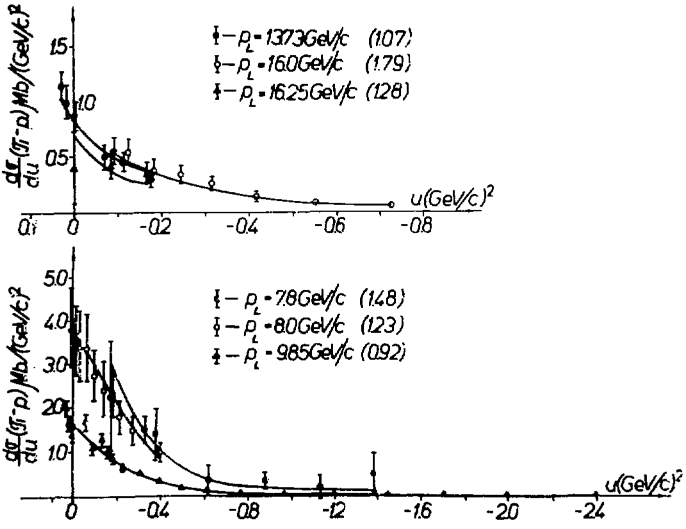



Fig. 1. Differential cross section of $\pi^- p$ scattering at $p_L$ = 13.73, 16.0, 16.25, 7.8, 8.0 and 9.85 GeV/c. (The number in brackets denotes the norm of the corresponding experiment).

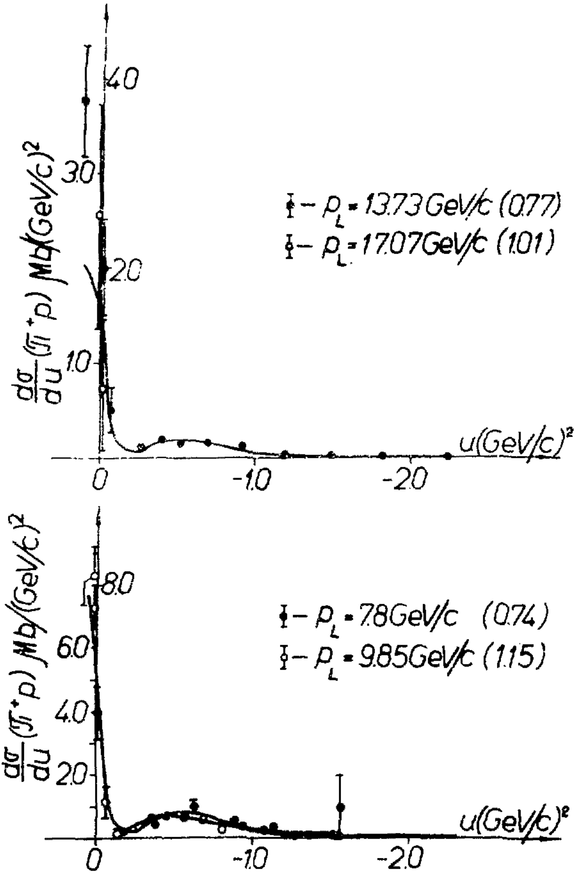



Fig. 2. Differential cross section of $\pi^+p$ scattering at $p_L$ = 13.73, 17.07, 7.8 and 9.85 GeV/c. The data are taken from $\pi^-n$ experiment. (The number in brackets denotes the norm of the corresponding experiment).

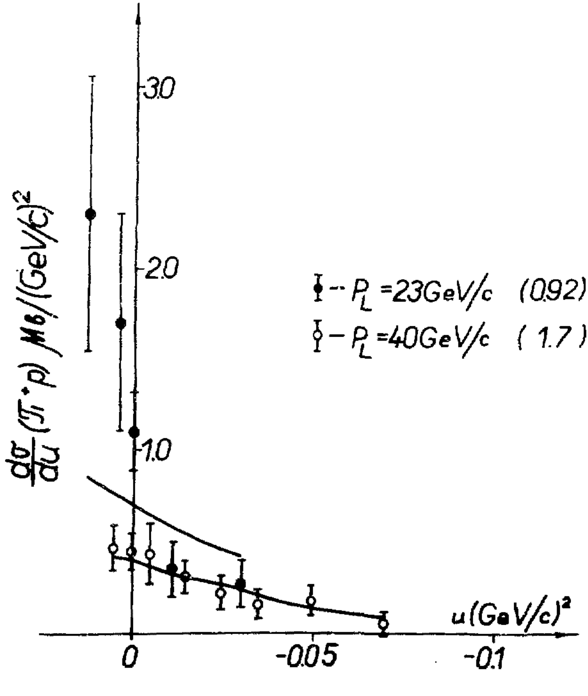



Fig. 3. Differential cross section of $\pi^+ p$ scattering at $p_L$ = 23 and 40 GeV/c. The data are taken from the $\pi^- n$ experiment. (The number in brackets denotes the norm of the corresponding experiment).

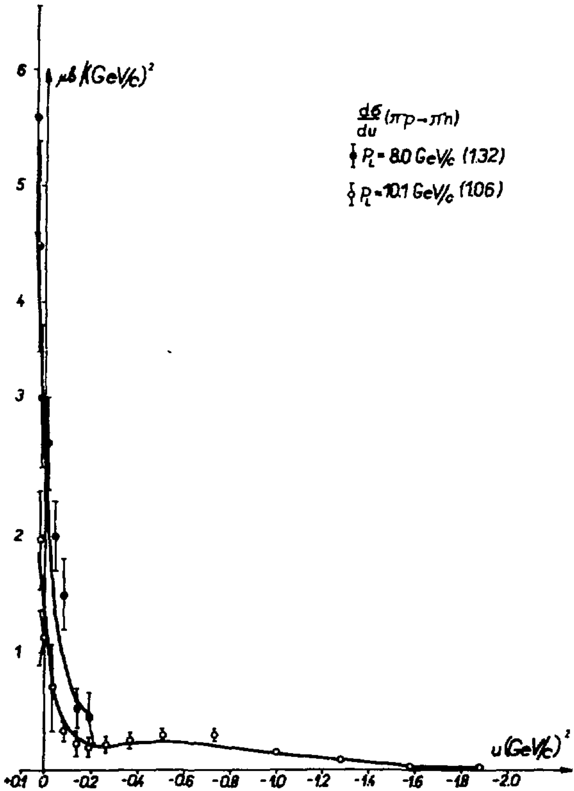



Fig. 4. Differential cross section of the reaction $\pi^- p \to \pi^0 n$ at $p_L$ = 8.0 and 10.1 GeV/c. (The number in brackets denotes the norm of the corresponding experiment).

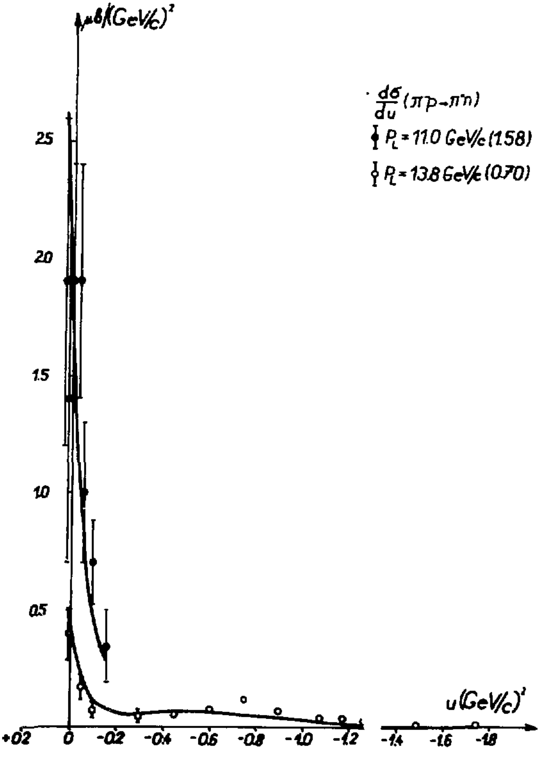



Fig. 5. Differential cross section of the reaction $\pi^- p \to \pi^0 n$ at $p_L$ = 11.0 and 13.8 GeV/c. (The number in brackets denotes the norm of the corresponding experiment).

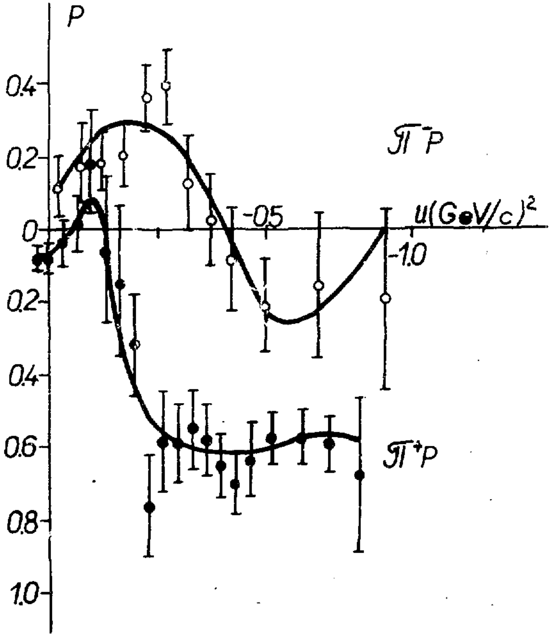



Fig. 6. Polarization parameter in $\pi^{\pm}p$ scattering at $p_L$ = 6 GeV/c. The data are taken from the $\pi^- p$ and $\pi^- n$ experiments.

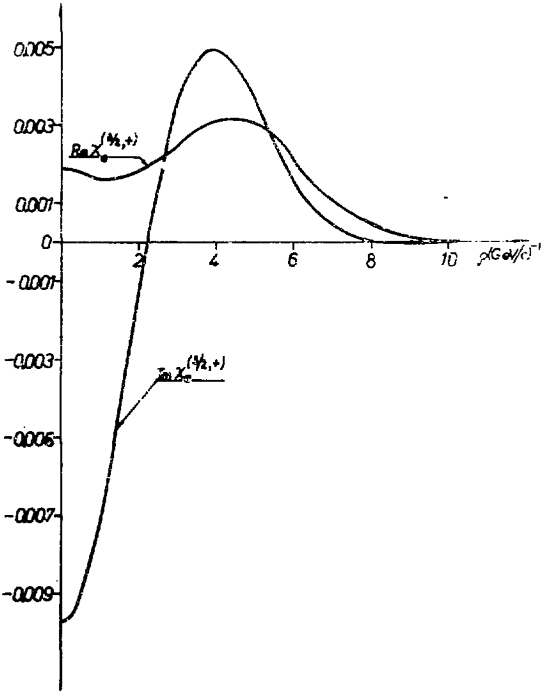
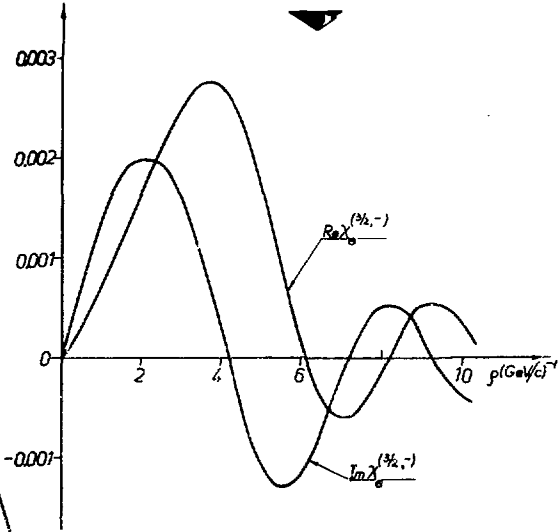



Fig. 7. The functions $\mathrm{Re}\,\chi_e^{(3/2,+)}(E;\rho)$ and $\mathrm{Jm}\,\chi_e^{(3/2,+)}(E;\rho)$ at $p_L$ = 9.85 GeV/c.

Fig. 8. The functions Re $\chi_e^{(3/2,-)}(E;\rho)$ and Im $\chi_e^{(3/2,-)}(E;\rho)$ at $p_L$ = 9.85 GeV/c.



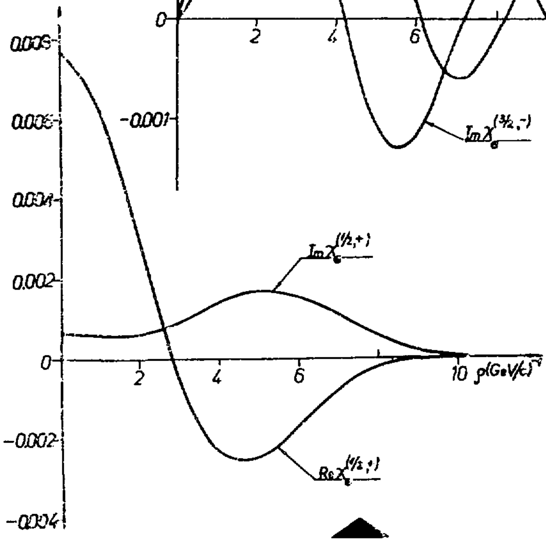
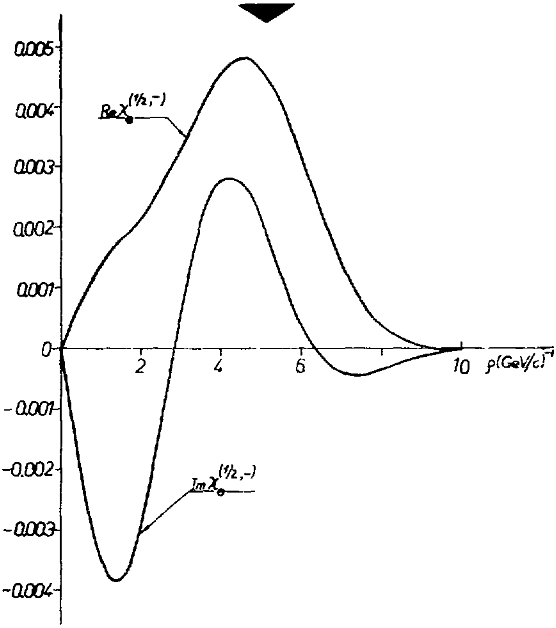




Fig. 9. The functions Re $\chi_e^{(1/2,+)}(E;\rho)$ and Im $\chi_e^{(1/2,+)}(E;\rho)$ at $p_L$ = 9.85 GeV/c.

Fig. 10. The functions $Re\chi_c^{(1/2,-)}(t;p)$ and $Im\chi_c^{(1/2,-)}(t;p)$ at $p_L$ = 9.85 GeV/c.



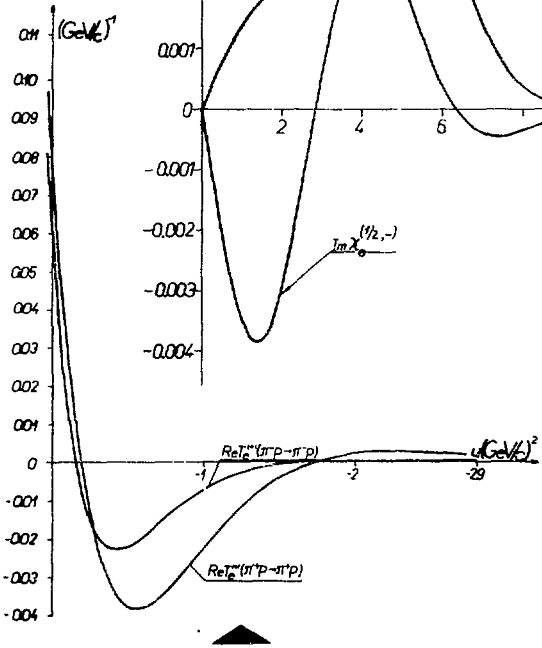
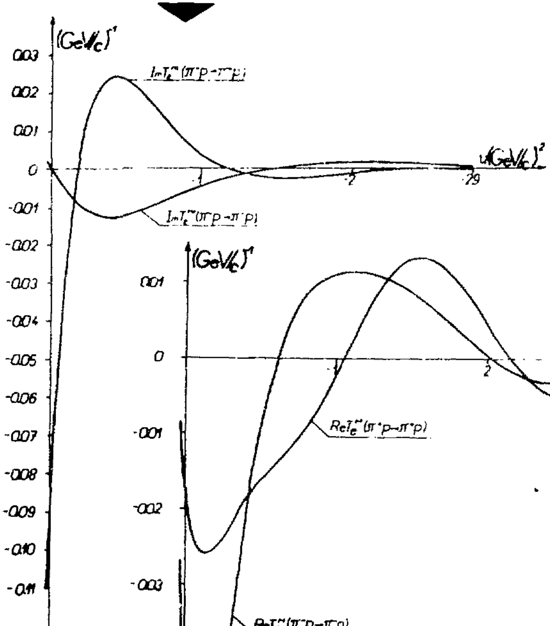




Fig. 11. Real parts of the spin-non-flip amplitudes of $\pi^{\pm}p$ scattering at $p_L$ = 9.85 GeV/c.

Fig. 12. Imaginary parts of the spin-non-flip amplitudes of $\pi^{\pm}p$ scattering at $p_L$ = 9.85 GeV/c.



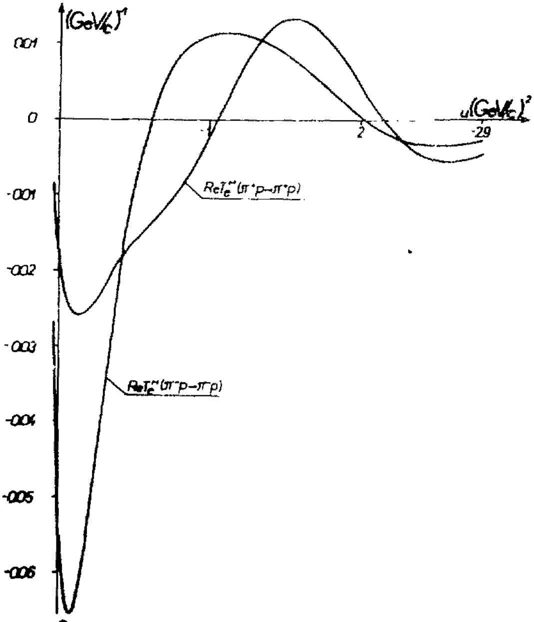




Fig. 13. Real parts of the spin-flip amplitudes of $\pi^{\pm}p$ scattering at $p_L$ = 9.35 GeV/c.

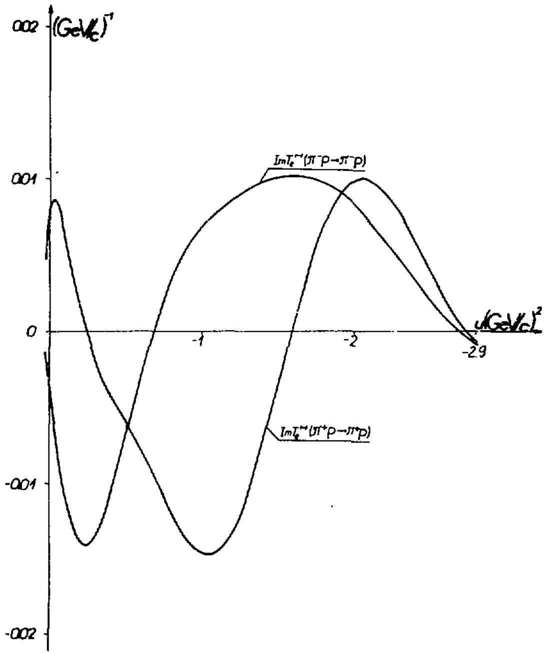



Fig. 14. Imaginary parts of the spin-flip amplitudes of $\pi^{\pm}p$ scattering at $p_L = 9.85$ GeV/c.

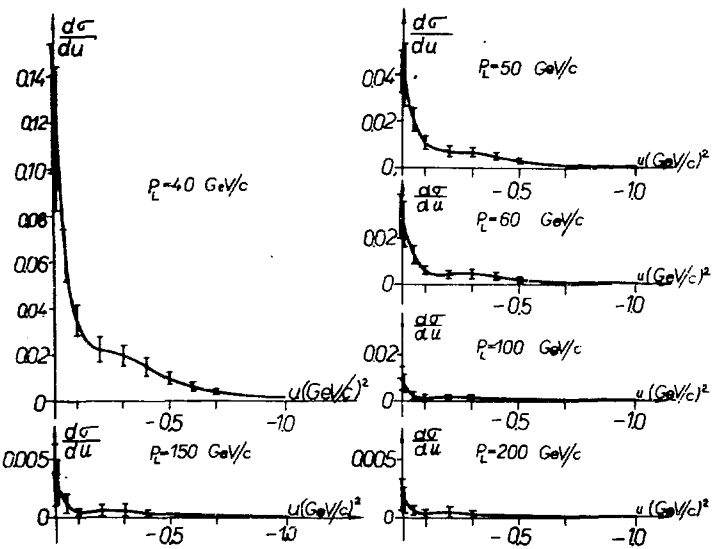



Fig. 15. Predictions for the differential cross section of $\pi^- p$- scattering in $\mu b$ $(GeV/c)^2$ .

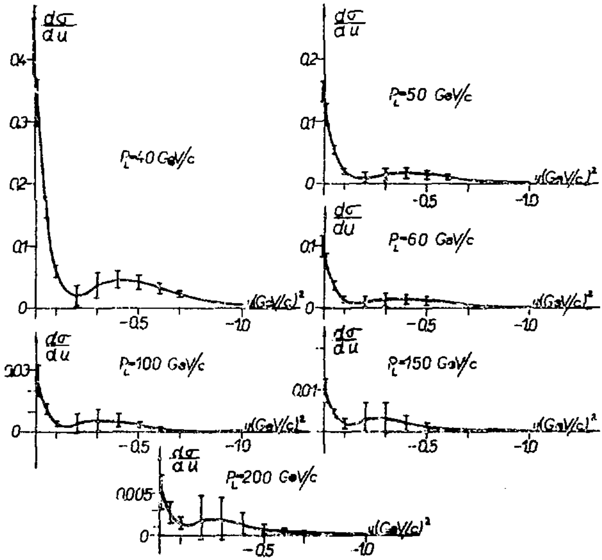



Fig. 16. Predictions for the differential cross sections of $\pi^+ p$ scattering in $\mu b\ (GeV/c)^2$

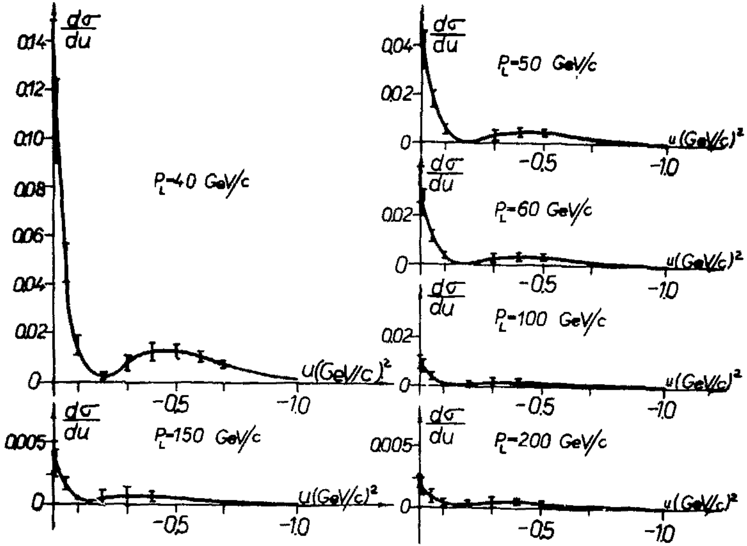



Fig. 17. Predictions for the differential cross section of the reaction $\pi^- p \to \pi n$ in $\mu b$ $(GeV/c)^2$

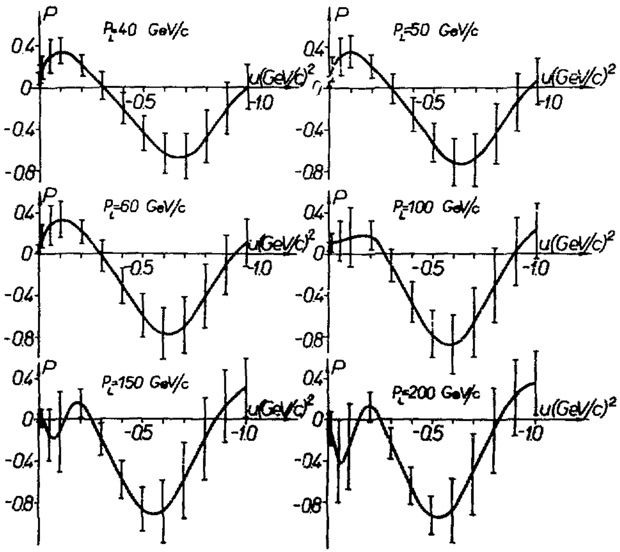



Fig. 18. Predictions for the polarization parameter in $\pi^- p$ scattering.

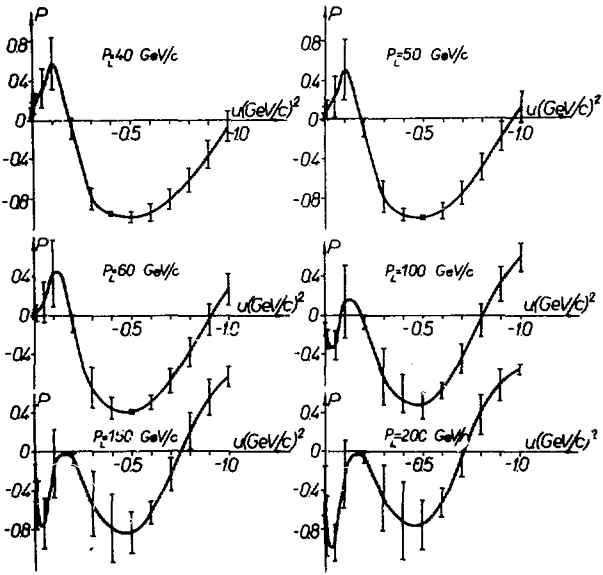



Fig. 19. Predictions for the polarization parameter in $\pi^+ p$ scattering.

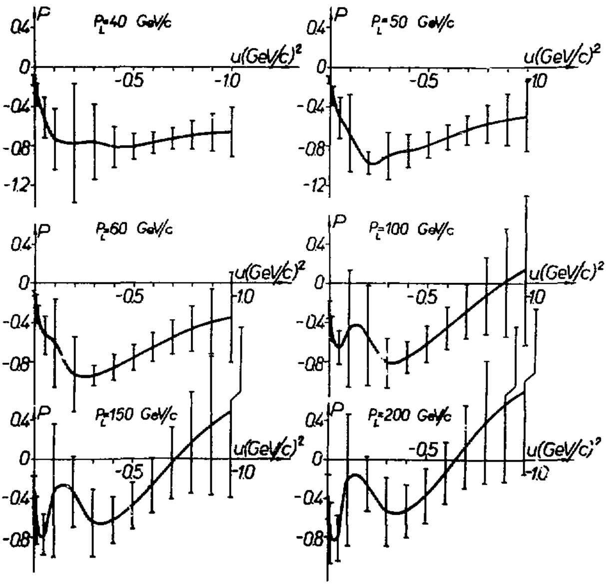



Fig. 20. Predictions for the polarization parameter in the reaction $\pi^- p \to \pi^\circ n$.