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Асимптотические угловые зависимости эксклюзивного рассеяния адронов на большие углы

Асимптотические угловые зависимости мезон-нуклонного и нуклон-нуклонного рассеяния на большие углы рассмотрены на основе представления Мандельстама и правил кваркового счета. Полученные формулы использованы для описания $\pi^{\pm}p$-, pp- и pn-рассеяния. Сделаны предсказания относительно $K^{\pm}p$- и $p\bar{p}$-рассеяния.

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Goloskokov S.V., Koudinov A.V., Kuleshov S.P. **E2 - 12627**

Asymptotic Angular Dependences of Exclusive Hadron Large-Angle Scattering

Asymptotic angular dependences of meson-nucleon and nucleon-nucleon large-angle scattering are studied on the basis of Mandelstam representation and quark counting rules. Formulas obtained are used for the descriptions of the $\pi^{\pm}p$, pp and pn scattering. The predictions about $K^{\pm}p$ and $p\bar{p}$ scattering are made.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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INTRODUCTION

In the present paper we shall discuss asymptotic angular dependences of differential cross sections of exclusive high-energy meson-nucleon and nucleon-nucleon scattering with large momentum transfer. This problem is greatly simplified due to the existence of power automodel asymptotics of the two-body large-angle scattering, which have been observed experimentally[1]:

$$\frac{d\sigma}{dt} \cdot \frac{1}{s^{2n}} f(t/s); \quad s,t \to \infty ; \quad t/s = \text{const} \tag{1.1}$$

(s,t, and u are the usual Mandelstam variables). Thus, the energy and angular dependences of differential cross-sections are factorized and the asymptotic behaviour of every process is determined by the single scalar function $f(t/s) = f(\frac{z-1}{2})$, where $z = \cos\theta$ is C.M.S. scattering angle. We stress, that the form of the function $f(t/s)$ is independent of energy.

From theoretical point of view the power automodel asymptotics were originally understood under the assumption of the existence of point-like constituents within hadrons[2,3], the dynamics of large-angle scattering being dominated by their interaction. There, the connection of the exponent n in (1.1) with the total number of elementary constituents of colliding hadrons was obtained too.

The explicit form of the angular distribution functions $f(t/s)$ was investigated, e.g., in the framework of the constituent interchange model[4] and on the basis of the dynamical interpretation of quark diagrams[5]. But apparently, the results of ref.[4,5] are not general enough. In particular, they predict the large value of the cross section for the exchange process $\pi^- p \to \pi^0 n$ as compared to the cross sections of the elastic processes, that is not confirmed experimentally (see, e.g., ref.[6]).

The Logunov-Tavkhelidze quasipotential approach also proved to be very fruitful in the investigation of large-angle scattering /7/. The class of analytic quasipotentials was found, that rendered all the principal features of the hadron scattering, and the spin effects were treated correctly. As well, it provided an efficient calculation scheme for the self-consistent description of deviations from the strict automodelity (1.1) at moderate energies /8/, which are connected with the global hadron structure. At the same time, the amplitudes obtained for different channels of the same reaction do not obey crossing-symmetry relations.

In the present paper we develop an asymptotic approach to the description of large-angle scattering amplitudes based on the analyticity properties and analogous to that of ref. /9,10/. The crossing symmetry, SU(3) symmetry, and spin effects are taken into account as well. As a result, common formulas for a variety of meson-nucleon and nucleon-nucleon processes are obtained. A few free parameters can be found from the fit of the experimental data for one of the reactions under consideration. Then, for the rest of the reactions, we get certain predictions.

2. BASIC ASSUMPTIONS

In the consideration of both meson-nucleon and nucleon-nucleon scattering, the spin of the nucleon is to be taken into account. The complete description of spin effects requires a number of scalar invariant amplitudes for every process. The number of independent amplitudes can be reduced by the requirement of γ_5 -invariance of interaction at high energies and large momentum transfers /11/. The asymptotic behaviour of meson-nucleon scattering is controlled then by one scalar invariant amplitude. As to nucleon-nucleon scattering, there still remain two independent amplitudes, and the spin structure of the process is fixed proceeding from the simplicity arguments and correct description of the experimental data.

As soon as we get a single scalar invariant amplitude for each process, its general form can be found starting from the Mandelstam analyticity and power automodel asymptotics with integer exponents n.

Assuming amplitudes of large-angle scattering to satisfy the unsubtracted Mandelstam representation, we can represent them as /9/:

$$T = \sum \frac{A_i}{s^{\alpha_i} t^{\beta_i}} + \sum \frac{B_i}{s^{\alpha_i} u^{\beta_i}} + \sum \frac{C_i}{t^{\alpha_i} u^{\beta_i}}, \qquad (2.1)$$

where α_i and β_i are integer powers, their sum being larger than n , provided the power automodel asymptotics (1.1) do exist. The coefficients A_i , B_i , and C_i are the corresponding momenta of double spectral functions. As $s+t+u=\Sigma m_i^2$; the last sum in (2.1) can be eliminated. Then, retaining the leading asymptotic terms only, we get:

$$T = \sum_{k=1}^{n-1} \frac{1}{s^{n-k}} \left(\frac{\tilde{A}_k}{t^k} + \frac{\tilde{B}_k}{u^k} \right). \qquad (2.2)$$

The representation (2.2) of invariant amplitudes will be used below for the description of specific reactions.

When considering the scattering amplitudes for mesons and nucleons of the same SU(3) multiplets, it is convenient to express them in terms of amplitudes with definite isospin in t-channel. We assume their matrix elements to be independent of the specific kinds of mesons and nucleons in the initial or final states, provided that they are in the same SU(3) multiplet. In so doing, a certain SU(3)-independence is assumed, that enables us to find the connection between the scattering amplitudes of π and K-mesons. It is worth mentioning that in the case of nucleon-nucleon scattering, where there are no experimental data on the high-energy large-angle scattering of strange baryons, the weaker assumption on charge independence in the framework of isospin symmetry is sufficient.

3. MESON-NUCLEON SCATTERING

As it was mentioned above, the asymptotic amplitude of meson-nucleon scattering is expressed, under the requirement of γ_5-invariance, in terms of one scalar amplitude:

$$F_{MN}(p_1, q_1; p_2, q_2) = \bar{u}(p_2)\hat{Q}\, u(p_1) T(s,t),$$

where p_i and q_i are the momenta of the nucleon and the meson before (i =1) and after (i =2) the collision, $Q = q_1 + q_2$.

In order to describe the scattering of mesons belonging to one SU(3) multiplet on protons, we shall express them in terms of amplitudes with isospin 0 and 1 in t-channel and definite signature of $s \leftrightarrow u$ crossing-symmetry transformation. Under $s \leftrightarrow u$ crossing they transform as follows:

$$\begin{Bmatrix} T_0^{(+)} \\ T_0^{(-)} \\ T_1^{(+)} \\ T_1^{(-)} \end{Bmatrix} \xrightarrow{s \to u} \begin{Bmatrix} -T_0^{(+)} \\ T_0^{(-)} \\ -T_1^{(+)} \\ T_1^{(-)} \end{Bmatrix} \qquad (3.1)$$

Then, taking into consideration the crossing-symmetry relations (3.1), the representation (2.2) of the asymptotic amplitudes, and the prediction of quark counting rules/2/ for the value n (n = 4), we can find the general form of the amplitudes

$$T_I^{(+)} = A_I^{(1)}\left(\frac{1}{s^2t^2} - \frac{2}{st^3} - \frac{1}{2s^2u^2}\right) + A_I^{(2)}\left(\frac{1}{s^3t} - \frac{1}{2s^2u^2} + \frac{1}{s^3u}\right) + A_I^{(3)}\left(\frac{1}{su^3} - \frac{1}{s^3u}\right);$$

$$T_I^{(-)} = a_I^{(1)}\left(\frac{1}{s^2t^2} - \frac{1}{s^3t} - \frac{1}{s^3u}\right) + \frac{a_I^{(2)}}{s^2u^2} + a_I^{(3)}\left(\frac{1}{s^3u} + \frac{1}{su^3}\right). \qquad (3.2)$$

The amplitudes of specific processes are expressed in terms of $T_I^{(\pm)}$ as follows:

$$T_{\pi^+p} = T_0^{(+)} + T_1^{(-)};$$

$$T_{\pi^-p} = T_0^{(+)} - T_1^{(-)};$$

$$T_{\pi^-p \to \pi^0 n} = \sqrt{2}\, T_1^{(-)}; \qquad (3.3)$$

$$T_{K^+p} = T_0^{(+)} + T_0^{(-)} + T_1^{(+)} + T_1^{(-)};$$

$$T_{K^-p} = T_0^{(+)} - T_0^{(-)} + T_1^{(+)} - T_1^{(-)}.$$

Apparently, formulas (3.2) and (3.3) are the most general but they can scarcely be efficiently used in the interpretation of available experimental data because of the great number of free parameters.

The theorem on the asymptotic equality of particle and antiparticle differential cross sections of high-energy scattering with fixed momentum transfers enables us to diminish their number. We shall assume, that this asymptotic equality holds for large-angle scattering near the forward direction, as well.

For the scattering of charged pions this requirement is automatically satisfied provided that $A_0^{(1)} \neq 0$, and it is not anomalously small as compared to the other $A_0^{(i)}$, $a_1^{(i)}$. But it is known, that for these processes the charge independence is approximately valid in the whole range of large angles. It means, that one of the amplitudes $T_0^{(+)}$ or $T_1^{(-)}$ is predominant. The relatively small value of the cross sections of the exchange process $\pi^- p \to \pi^\circ n$ supports the conclusion that the amplitude $T_0^{(+)}$ is large. Assuming the same inequality for the amplitudes with different signatures, we find that the meson-nucleon large-angle scattering is dominated by isospin- 0 amplitudes and get the approximate equations:

$$T_{\pi^+ p} \simeq T_0^{(+)} ;$$

$$T_{\pi^- p} \simeq T_0^{(+)} ;$$

$$T_{\pi^- p \to \pi^\circ n} = \sqrt{2}\, T_1^{(-)} ;$$

$$T_{K^+ p} \simeq T_0^{(+)} + T_0^{(-)} ;$$

$$T_{K^- p} \simeq T_0^{(+)} - T_0^{(-)} .$$

For the scattering of charged kaons, the approximate equality of differential cross sections in forward hemisphere leads to the relations:

$$\tilde{A}_{K^+ p,i} = \pm \tilde{A}_{K^- p,i} \; ; \; i = 1,2,3. \qquad (3.4)$$

($\tilde{A}_i$ are defined in (2.2)).

The reaction of the K^-p elastic scattering is also exotic in u-channel and, consequently, has no peak near the backward direction. It means that:

$$\tilde{B}_{K^-p,i} = 0; \quad i = 1,2,3. \tag{3.5}$$

Thus, under the restrictions (3.4), (3.5), we finally get the following formulas for the amplitudes of $\pi^\pm p$ and $K^\pm p$-scattering, which contain only two free parameters A_1 and A_2:

$$T_{\pi^+p} = T_{\pi^-p} = -\frac{2A_1}{st^3} + \frac{A_1}{s^2t^2} + \frac{A_2}{s^3t} + \frac{A_2}{2su^3} - \frac{A_1+A_2}{2s^2u^2} + \frac{A_2}{2s^3u};$$

$$T_{K^+p} = -\frac{2A_1}{st^3} + \frac{A_1}{s^2t^2} + \frac{A_2}{s^3t} + \frac{A_2}{su^3} - \frac{A_1+A_2}{s^2u^2} - \frac{A_2}{s^3u}; \tag{3.6}$$

$$T_{K^-p} = \frac{2A_1}{st^3} - \frac{A_1}{s^2t^2} - \frac{A_2}{s^3t}.$$

The differential cross sections of four meson-nucleon processes are approximately equal for small t.

The $s \leftrightarrow t$ crossing symmetry enables us to find the amplitudes of annihilation processes $p\bar{p} \to \pi^+\pi^-$ and $p\bar{p} \to K^+K^-$:

$$T_{p\bar{p}\to\pi^+\pi^-} = A_2\left(\frac{1}{st^3} - \frac{1}{su^3}\right) + \frac{A_1-A_2}{2}\left(\frac{1}{s^2t^2} - \frac{1}{s^2u^2}\right) - A_1\left(\frac{1}{s^3t} - \frac{1}{s^3u}\right); \tag{3.7}$$

$$T_{p\bar{p}\to K^+K^-} = \frac{2A_1}{s^3t} - \frac{A_1}{s^2t^2} - \frac{A_2}{st^3}.$$

The differential cross sections of elastic meson-nucleon scattering and annihilation are expressed in terms of invariant amplitudes as:

$$\frac{d\sigma_{MN}}{dt} = (1+z)\,|T_{MN}|^2 ;$$

$$\frac{d\sigma_{N\bar{N}\to M\bar{M}}}{dt} = \frac{1-z^2}{2}\,|T_{N\bar{N}\to M\bar{M}}|^2 . \tag{3.8}$$

It is worth mentioning that if meson-nucleon scattering is dominated by isospin-1 amplitudes, the invariant amplitudes of specific processes will be of the form:

$$T_{\pi^+p} = -T_{\pi^-p} = \frac{1}{\sqrt{2}}T_{\pi^-p\to\pi^0 n} = T_1^{(-)} ;$$

$$T_{K^+p} = T_1^{(+)} + T_1^{(-)}; \tag{3.9}$$

$$T_{K^-p} = T_1^{(+)} - T_1^{(-)};$$

where $T_1^{(\pm)}$, taking into account exoticity of K^-p scattering in u-channel, have the following representations:

$$T_1^{(+)} = B_1\left(\frac{1}{s^2t^2} - \frac{1}{s^3t} - \frac{2}{st^3} - \frac{1}{s^3u}\right) + B_2\left(\frac{4}{st^3} - \frac{2}{s^2t^2} + \frac{1}{s^2u^2}\right) +$$

$$+ B_3\left(\frac{2}{s^2t^2} - \frac{4}{st^3} - \frac{2}{s^3t} - \frac{1}{su^3} - \frac{1}{s^3u}\right); \tag{3.10}$$

$$T_1^{(-)} = B_1\left(\frac{1}{s^2t^2} - \frac{1}{s^3t} - \frac{1}{s^3u}\right) + \frac{B_2}{s^2u^2} - B_3\left(\frac{1}{su^3} + \frac{1}{s^3u}\right).$$

When $B_1 = 2B_2$ and $B_3 = 0$, formulas (3.9), (3.10) are exactly those of ref. /4,5/ for $\alpha=\beta$. This choice of α/β ratio is preferable from the point of view of the experimental data.

4. NUCLEON-NUCLEON SCATTERING

Under the requirement of γ_5-invariance the asymptotic amplitude of the nucleon-nucleon scattering is expressed via two invariant amplitudes, such as vector-vector and axial-axial ones:

$$F_{NN}(p_1,q_1;p_2,q_2) = \bar{u}(p_2)\gamma^{\mu} u(p_1)\bar{u}(q_2)\gamma_{\mu} u(q_1)T_1(s,t) +$$

$$+ \bar{u}(p_2)\gamma_5\gamma^{\mu}u(p_1)\bar{u}(q_2)\gamma_5\gamma_{\mu}u(q_1)T_2(s,t).$$

We shall restrict ourselves to the consideration of the vector-vector amplitude only. The axial-axial amplitude can be analysed independently and analogously. But the vector-vector amplitude proved to be sufficient for the description of the experimental data. The amplitudes of four elastic nucleon-nucleon processes are expressed in terms of the amplitudes with definite isospin in the t-channel as follows:

$$T_{pp} = T_0^{(+)} + T_0^{(-)} + T_1^{(+)} + T_1^{(-)};$$

$$T_{pn} = T_0^{(+)} + T_0^{(-)} - T_1^{(+)} - T_1^{(-)};$$

$$T_{p\bar{p}} = T_0^{(+)} - T_0^{(-)} + T_1^{(+)} - T_1^{(-)};$$

$$T_{\bar{p}n} = T_0^{(+)} - T_0^{(-)} - T_1^{(+)} + T_1^{(-)}.$$

The charge independence of pp and pn scattering shows that again the isospin-0 or isospin-1 amplitudes are predominant. By analogy with the meson-nucleon scattering we assume them to be isospin-0 amplitudes. Consequently:

$$T_{pp} \simeq T_{pn} \simeq T_0^{(+)} + T_0^{(-)};$$

$$T_{p\bar{p}} \simeq T_{\bar{p}n} \simeq T_0^{(+)} - T_0^{(-)}. \qquad (4.1)$$

The general representations of $T_0^{(\pm)}$ in view of (2.2) and the quark counting rule prediction $n=5$, are of the form:

$$T_0^{(+)} = A_1\left(\frac{1}{s^2t^3} - \frac{1}{s^3t^2} - \frac{1}{s^2u^3}\right) + A_2\left(\frac{1}{s^4t} + \frac{1}{s^2u^3} + \frac{1}{s^4u}\right) +$$

$$+ A_3\left(\frac{1}{su^4} + \frac{1}{s^4u}\right) + A_4\left(\frac{1}{s^2u^3} + \frac{1}{s^3u^2}\right);$$

$$T_0^{(-)} = \alpha_1\left(-\frac{4}{st^4} + \frac{2}{s^2t^3} - \frac{1}{s^4t} - \frac{1}{s^4u} + \frac{1}{s^3u^2}\right) +$$

$$+\alpha_2\left(\frac{2}{s^3t^2} - \frac{3}{s^4t} - \frac{3}{su^4} + \frac{1}{s^3u^2}\right) + \alpha_3\left(\frac{1}{s^2u^3} - \frac{1}{s^3u^2}\right) +$$

$$+\alpha_4\left(\frac{1}{s^4u} - \frac{1}{su^4}\right). \qquad (4.2)$$

The elastic $p\bar{p}$-scattering is u-channel exotic; hence we again get the restrictions:

$$\tilde{B}_{p\bar{p},i} = 0; \quad i = 1,2,3,4 . \qquad (4.3)$$

One more restriction can be derived from the fact that in pn elastic scattering the backward peak is damped as compared to the forward peak. This leads to the relations:

$$\tilde{B}_{pn,4} = 0; \quad \tilde{A}_{pn,4} \neq 0. \qquad (4.4)$$

Thus, taking into account (4.1) - (4.4), we get the general representations for the invariant amplitudes of nucleon reactions:

$$T_1 = T_{pp} = T_{pn} = \frac{3A_1 - 3A_2 + A_3}{st^4} + \frac{2A_2 - A_1 - A_3}{s^2t^3} +$$

$$+\frac{A_3 - A_2}{s^3t^2} - \frac{A_3}{s^4t} - \frac{A_1}{s^2u^3} + \frac{A_2}{s^3u^2} - \frac{A_3}{s^4u}; \qquad (4.5)$$

$$T_2 = T_{p\bar{p}} = T_{\bar{p}n} = -\frac{3A_1 - 3A_2 + A_3}{st^4} + \frac{2A_1 - A_2}{s^2t^3} - \frac{A_1}{s^3t^2};$$

Proceeding to the differential cross sections, we obtain

$$\frac{d\sigma_{pp}}{dt} = (1+z)^2 |T_1|^2 + (1-z)^2 |T_1(t \leftrightarrow u)|^2 +$$

$$+ 4 |T_1 + T_1(t \leftrightarrow u)|^2;$$

$$\frac{d\sigma_{pn}}{dt} = [4 + (1+z)^2] |T_1|^2; \qquad (4.6)$$

$$\frac{d\sigma_{p\bar{p}}}{dt} = [4 + (1+z)^2] |T_2|^2.$$

One can easily check that when $t \to 0$ all three differential cross sections grow with approximately the same rate.

$$\frac{d\sigma_{pp}}{dt} \approx \frac{d\sigma_{pn}}{dt} \approx \frac{d\sigma_{p\bar{p}}}{dt}.$$

Thus, near $\theta = 0$ the charge independence is valid for all three nucleon reactions.

5. COMPARISON WITH EXPERIMENT

Formulas (3.6) and (3.8) have been used for the description of the available experimental data on the elastic large-angle $\pi^{\pm} p$-scattering /13,14/. As the energies reached are comparatively low ($p_L \sim 5 \div 10$ (GeV/c)), the deviations from strict automodelity (1.1) are to be taken into account. The simplest way of doing this is to introduce the effective radius which smooths down the angular dependencies:

$$t \to \tilde{t} = t - b;$$
$$u \to \tilde{u} = u - b. \qquad (5.1)$$

The change (5.1) results in the variations of $s^8 \frac{d\sigma}{dt}$ with changing energy. The results of the fit are presented in Table and are illustrated in fig. 1 (the curves in the middle). The majority of the experimental points lie between the curves for $p_L = 8$(GeV/c) and $p_L \to \infty$. Figure 1 shows that the low energy deviations from strict automodelity are taken into account correctly.

Table

Reaction	A_1	A_2	A_3	b	χ^2	$\bar{\chi}^2$	$\chi^2/\bar{\chi}^2$
$\pi^{\pm}p$	11.946 ± 1.229	-23.569 ± 1.851	–	2.50 ± 0.22	102.8	69	1.49
pp&pn	91.408 ± 4.358	240.78 ± 5.23	507.02 ± 8.29	0.937 ± 0.349	357.2	213	1.58

The values of the parameters found from the fit enable us to predict the values of the differential cross-sections for the elastic scattering of kaons and annihilation processes. Figure 1 shows curves for $K^{\pm}p$ scattering (upper and lower curves) and the available experimental points [14,15]. The large interval between the curves for $p_L = 5$(GeV/c) (just this energy is corresponded by the majority of points) and the asymptotic curves is due to the large values of the low-energy deviations from strict automodelity. The self-consistent consideration of these deviations shows that the angular range, in which the asymptotic formulas are correct, becomes more and more narrow with descreasing energy. For $p_L = 5$(GeV/c) the formulas (3.6) - (3.8), even with the change of (5.1), are correct only in the neighbourhood of $\theta = 90°$, where we observe the best agreement with the data.

A few experimentally measured points for the annihilation processes $p\bar{p} \to \pi^+\pi^-$ and $p\bar{p} \to K^+K^-$ are also in qualitative agreement with the predictions of our model.

As to the nucleon reactions, formulas (4.5) and (4.6) have been used for the common fit of the data on pp and pn-scattering [16,17]. The results of fit are shown in the table and fig. 2. There, the predictions for the differential cross

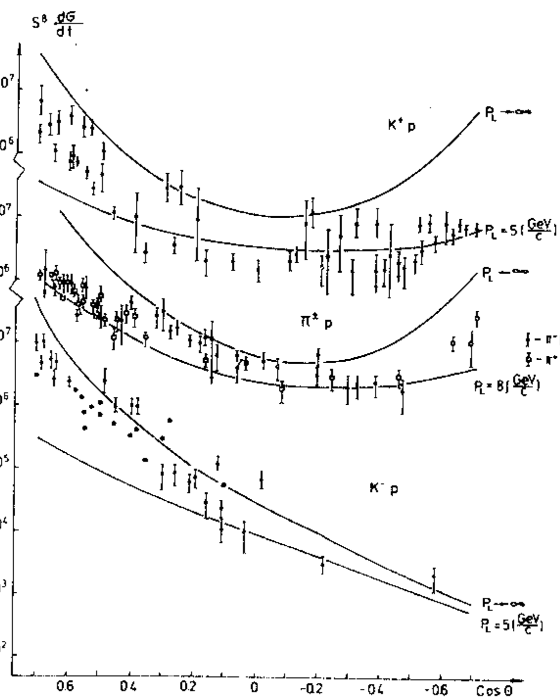

Fig. 1. $s^8 \frac{d\sigma}{dt}$ for meson-nucleon scattering.

section of the $\bar{p}p$-scattering and the available experimental points /15/ are presented, too.

6. CONCLUSION

In conclusion we would like to note that we have considered the simplest variant of the formulas because the amplitudes with isospin $I_t = 1$ have not been taken into account in the elastic processes. The consideration of these amplitudes leads approximately to the 30 per cent violation of the exact charge independence in the case of $\pi^{\pm} p$ -scattering. However, we cannot determine the parameters of the amplitudes $T^{(\pm)}_{MN,1}$ because of the lack of information about high-energy large-angle charge-exchange processes $\pi^- p \to \pi^0 n$ and $\pi^- p \to \eta n$.

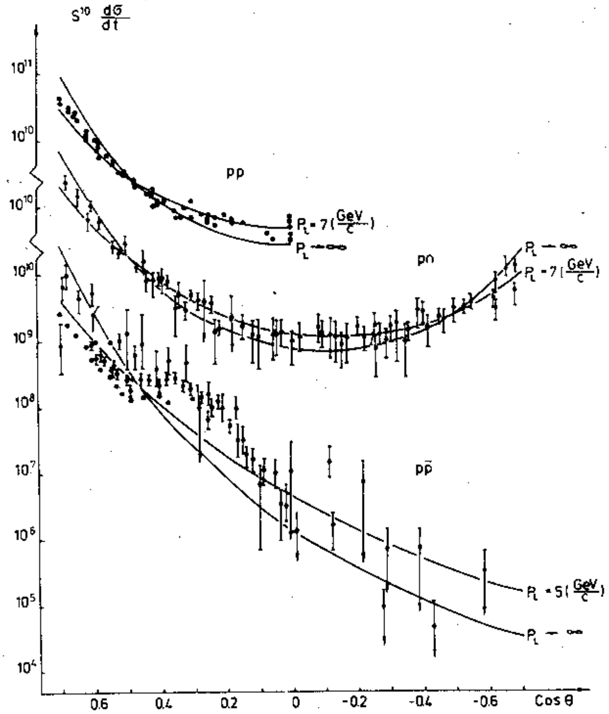

Fig. 2. $s^{10}\frac{d\sigma}{dt}$ for nucleon-nucleon scattering.

There are no reactions analogous to the charge exchange processes in the case of nucleon-nucleon scattering. The consideration of the amplitudes with $I_t = 1$ in this case does not change the analytic form of the amplitudes because the formulas for $T_1^{(\pm)}$ and $T_0^{(\pm)}$ are completely equivalent. However, this results in doubling of the number of free parameters. But this is not needed because the formulas obtained give us a good description of the experimental data. The consideration of additional amplitudes does not violate the charge independence of the elastic processes near $t = 0$.

On the whole the formulas obtained allow a quantitative description of the experimental data for the number of meson-nucleon and nucleon-nucleon reactions. This testifies to adequacy of the approach used.

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