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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

A.A.GRIGORYAN, G.N.KHACHATRYAN

THEORETICAL PREDICTIONS FOR SOME CHARACTERISTICS OF EXOTIC BARYON PRODUCTION IN HADRON PROCESSES

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THEORETICAL PREDICTIONS FOR SOME CHARACTERISTICS OF EXOTIC BARYON PRODUCTION IN HADRON PROCESSES

The properties of exotic baryon resonances whose existence is predicted from the sum rules for the reggeon-particle scattering amplitudes. are given. The theoretical calculations of the cross sections of these resonances production in the processes on π and Σ beams as well as of the angular distributions of their decay products are carried out.

Yerevan Physics Institute

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А.А.ГРИГОРЯН, Г.Н.ХАЧАТРЯН

ТЕОРЕТИЧЕСКИЕ ПРЕДСКАЗАНИЯ НЕКОТОРЫХ ХАРАКТЕРИСТИК РОЖДЕНИЯ ЭКЗОТИЧЕСКИХ БАРИОНОВ В АДРОННЫХ ПРОЦЕССАХ

Приводятся свойства экзотических барионных резонансов, предсказываемых из правил сумм для амплитуд рассеяния реджеонов на частицах. Даются теоретические предсказания сечений рождения этих резонансов в процессах на π и Σ - пучках, а также угловых распределений продуктов их распада.

Ереванский физический институт

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1. Introduction.

The problem of exotic resonances (baryons, which cannot be constructed of 3 valence quarks and mesons, which consist of more than one $q\bar{q}$ -pair of valence quarks) is of particular importance for hadron physics. The existence of such states is predicted in a variety of theoretical models (the strong coupling theory, the bootstrap model, the strings, bags, etc.). An approach to investigation of spin hadrons interactions, which is based on the superconvergent sum rules (SSR) for the reggeon-particle scattering amplitudes (αa -amplitudes), was developed in the works [1-3] . In the framework of this approach the existence of series of exotic baryon resonances with isospins $I \geq 5/2$, spins $\mathcal{J} = I$ and positive parity P was predicted [4-6] . The experiments to search for the baryon resonances with $I = 5/2$ have been carried out now at JINR and ITEP. The results of these experiments look very promising and point out the necessity of the activization of the exotic states investigation efforts. In particular, search for the strange exotic baryons is of great interest. The existence of these baryons is predicted [7] under consideration of SSR for the scattering of reggeons on baryons with nonzero strangeness S . So, in the case of baryons with $S = -1$, two resonances, S_E^* and S_E , with isospin $I = 2$, spins $J_{S_E^*} = 5/2$, $J_{S_E} = 3/2$ and positive parities, are predicted.

The aim of this work is to calculate some characteristics of exotic baryon production. The theoretical calculations can be useful in planning and performing the experiments for the exotic baryons investigations.

In Sect. 2 the properties of E_{55}, S_E^* and S_E, which are predicted from SSR, are given.

Since the processes of the exotic states production have small cross sections, it is very important to choose the optimum reactions and measurement regimes to investigate effectively these states.

As was mentioned in [4,5], the most favourable for the experimental observation of the resonances in the $p\pi^+\pi^+$ $(\Delta^{++}\pi^+)$ - system is the process, where this system is fast flying in the direction of the incident π^+-meson (the so-called backward scattering). Using the predictions of sum rules for $\alpha\alpha$ -amplitudes, one can estimate the E_{55}^{+++} backward production cross section relating it with the $\pi\bar{p}$ -backward cross section which is studied rather well experimentally (see Sect. 3).

The active search for the S_E and S_E^* resonances can be carried out in the Σ -beams experiments. It should be noted that in the Σ -beams experiments the S_E and S_E^* resonances have to be created via different mechanisms. For the S_E production at the energy $\lesssim$ 50 GeV the one-pion exchange mechanism is expected to dominate. The S_E^* -resonance should be produced in the same manner as the E_{55}-baryon in NN-collisions, i.e. through two-pion exchange mechanism [8]. Sects 4 and 5 are devoted to the theoretical calculations of the corresponding cross sections.

To determine the spin and parity of observed resonance, it is necessary to investigate the angular correlations of its decay products. In Sect. 6 we give the calculations of the distribution on the angle θ_{ab}^* between the particles a and b $(J_a^P = 1/2^+ \ ; \ J_b^P = 3/2^+)$ in the rest frame of resonance R decaying as $R \to b\pi \to a\pi\pi$.

2. Properties of E_{55}, S_E^* and S_E -Resonances.

E_{55} -baryon ($I = 5/2$, $J^P = 5/2^+$) is an analog of nucleon and Δ_{33} in the world of states with $I=5/2$. The dominant mode of E_{55}-decay is the cascade process

$$E_{55} \to \Delta_{33} + \pi$$
$$\hookrightarrow N + \pi$$

The width of $E_{55} \to \Delta_{33}\pi$ decay has the following form [6]

$$\Gamma_{E\to\Delta\pi} = \frac{|\vec{p}_\Delta|^3 (E_\Delta + M_\Delta)}{180\pi M_E} \left\{ 6\left(G_1^{E\pi\Delta}\right)^2 + \left[\left(1+\frac{2E_\Delta}{M_\Delta}\right) G_1^{E\pi\Delta} + \frac{2M_E|\vec{p}_\Delta|^2}{M_\Delta} G_2^{E\pi\Delta}\right]^2\right\} \quad (2.1)$$

where $G_1^{E\pi\Delta}$ and $G_2^{E\pi\Delta}$ are the invariant functions entering in the invariant expression for the $E\pi\Delta$ -vertex

$$V_{E\pi\Delta} = \bar{U}_\Delta^\mu \left(G_1^{E\pi\Delta} P_{\Delta_\alpha} g_{\mu\beta} + G_2^{E\pi\Delta} P_{\Delta_\alpha} P_{\Delta_\beta} P_{E_\mu} \right) U_E^{\alpha\beta} \quad (2.2)$$

with U_Δ^μ and $U_E^{\alpha\beta}$ being the wave functions of Δ_{33} and E_{55} .

Sum rules for αa -amplitudes predict the definite value for the coupling $G_1^{E\pi\Delta}$

$$\left(G_1^{E\pi\Delta}\right)^2 = \frac{3}{2S_0} \left(G^{p\pi^0 p}\right)^2 \quad (2.3)$$

where $S_0 = 1\ GeV^{-2}$. As to the function $G_2^{E\pi\Delta}$, its value is not fixed from the considered in [4,5] sum rules. In the approximation of the small decay momenta ($|\vec{p}_\Delta|^2/M_\Delta^2 \ll 1$) one can neglect $G_2^{E\pi\Delta}$ in (2.1) and then

$$\Gamma_{E\to\Delta\pi} = \frac{|\vec{P}_\Delta|^3}{4\pi S_0} \frac{M_\Delta}{M_E} \left(G^{\rho\pi\varphi\rho}\right)^2 \tag{2.4}$$

Table 2.1

M_E (GeV)	1.42	1.44	1.52	1.56	1.60	1.65
$\Gamma_{E\to\Delta\pi}$ (MeV)	21	36	140	215	307	443

In Table 2.1 the values of $\Gamma_{E\to\Delta\pi}$ at different masses of E_{55} are given $\left(\left(G^{\rho\pi\varphi\rho}\right)^2/4\pi = 14.6\right)$

S_E^* (I=2, J^P=5/2$^+$) is the analog of E_{55} with strangeness S=-1. The S_E^* decay scheme is

$$S_E^* \to \Sigma^*(1385) + \pi$$
$$\hookrightarrow \Sigma + \pi$$
$$\hookrightarrow \Lambda + \pi$$

It is seen that the search for S_E^* -baryon should be carried out in the distribution on the effective mass of the system $\Lambda\pi^\pm\pi^\pm$, extracting the $\Sigma^{*\pm}(1385)$-resonance region in the $\Lambda\pi^\pm$ -subsystem.

The $S_E^* \to \Sigma^*\pi$ decay also is described by formulae (2.1) and (2.2). For the small decay momenta

$$\Gamma_{S_E^*\to\Sigma^*\pi} = \frac{|\vec{P}_{\Sigma^*}|}{6\pi} \frac{M_{\Sigma^*}}{M_{S_E^*}} \left(G_1^{S_E^*\pi\Sigma^*}\right) \tag{2.5}$$

The SSR for αq -amplitudes predict the following relation between $G_1^{S_E^*\pi\Sigma^*}$ and the $\Sigma^*(1385) \to \Lambda\pi$ decay coupling $G^{\Sigma^*\pi\Lambda}$

$$\left(G_1^{S_E^* \pi \Sigma^*} / G^{\Sigma^* \pi \Lambda} \right)^2 = 9/5 \tag{2.6}$$

where $\left(G^{\Sigma^* \pi \Lambda} \right)^2$ is fixed from

$$\Gamma_{\Sigma^* \to \Lambda\pi} = \frac{|\vec{P}_\Lambda|^3}{12\pi} \frac{E_\Lambda + M_\Lambda}{M_{\Sigma^*}} \left(G^{\Sigma^* \pi \Lambda} \right)^2 \tag{2.7}$$

$$\left(G^{\Sigma^* \pi \Lambda} \right)^2 / 4\pi = \frac{1}{S_0} 6.6 \tag{2.8}$$

In Table 2.2 the values of $\Gamma_{S_E^* \to \Sigma^* \pi}$ at some $M_{S_E^*}$ are listed.

Table 2.2

$M_{S_E^*}$ (GeV)	1.55	1.60	1.65	1.70	1.75	1.80
$\Gamma_{S_E^* \to \Sigma^* \pi}$ (MeV)	4	24	59	108	172	250

As distinct from S_E^*, the hyperon S_E ($I=2$, $J^P=3/2^+$) is coupled with both $\Sigma^*(1385)\pi$ and $\Sigma\pi$ channels

$$S_E \to \Sigma\pi$$

$$S_E \to \Sigma^* \pi$$

$$\Sigma^* \to \Lambda\pi$$

$$\Sigma^* \to \Sigma\pi$$

The corresponding widths are

$$\Gamma_{S_E \to \Sigma\pi} = \frac{|\vec{P}_\Sigma|^3}{12\pi} \frac{E_\Sigma + M_\Sigma}{M_{S_E}} \left(G^{S_E \pi \Sigma} \right)^2 \tag{2.9}$$

with

$$V_{S_E \pi \Sigma} = \bar{U}_\Sigma P_\Sigma^\mu U_{S_{E\mu}} G^{S_E \pi \Sigma} \tag{2.10}$$

and

$$\Gamma_{S_E \to \Sigma^* \pi} = \frac{|\vec{P}_\Sigma|(E_\Sigma - M_\Sigma)}{8\pi M_{S_E}} \left\{ \left(G_1^{S_E \pi \Sigma^*} \right)^2 + \right. \tag{2.11}$$

$$\left. + \frac{1}{9} \left[G_1^{S_E \pi \Sigma^*} \left(\frac{2E_{\Sigma^*}}{M_{\Sigma^*}} - 1 \right) + G_2^{S_E \pi \Sigma^*} \frac{2|\vec{P}_{\Sigma^*}|^2 M_{S_E}}{M_{\Sigma^*}} \right]^2 \right\}$$

with

$$V_{S_E \pi \Sigma^*} = \bar{U}_{\Sigma^*_\mu} \left(G_1^{S_E \pi \Sigma^*} g_{\mu\alpha} + G_2^{S_E \pi \Sigma^*} P_{S_E}^\mu P_{\Sigma^*}^\alpha \right) \gamma_5 U_{S_{E\alpha}} \tag{2.12}$$

As in the case of vertices $E_{55} \pi \Delta_{33}$ and $S_E^* \pi \Sigma^*$, the constant $G_2^{S_E \pi \Sigma^*}$ does not enter in the sum rules considered in [7]. Therefore we will work in the small energy release approximation, when one can neglect the contribution of $G_2^{S_E \pi \Sigma^*}$ in (2.11), and then

$$\Gamma_{S_E \to \Sigma^* \pi} = \frac{5|\vec{P}_{\Sigma^*}|^3}{72\pi M_{S_E} M_{\Sigma^*}} \left(G_1^{S_E \pi \Sigma^*} \right)^2 \tag{2.13}$$

For the constants $G^{S_E \pi \Sigma}$ and $G_1^{S_E^* \pi \Sigma^*}$ the following values are predicted

$$\left(G^{S_E \pi \Sigma} / G^{\Sigma^* \pi \Lambda} \right) = 3/2 \tag{2.14}$$

$$\left(G_1^{S_E \pi \Sigma^*} / G^{\Sigma^* \pi \Lambda} \right) = \frac{18 S_0}{25} \tag{2.15}$$

The values of widths (2.9) and (2.13) at different M_{S_E} are given in Table 2.3.

Table 2.3

M_{S_E} (GeV)	1.40	1.45	1.50	1.55	1.60	1.65	1.70
$\Gamma_{S_E \to \Sigma\pi}$ (MeV)	17	43	79	127	185	253	332
$\Gamma_{S_E \to \Sigma^*\pi}$ (MeV)					2	5	9

As is seen from Table 2.1, one can effectively search for E_{55}-resonance in the $\Delta^{++}\pi^+$ $(\Delta^-\pi^-)$ system masses region $\lesssim$ 1.55 GeV. At higher masses the separation of the resonance from the background will be difficult because of its large width. The analogous region of the $\Sigma^{*\pm}(1385)\pi^{\pm}$ system masses, where one can search for S_E^* -baryon, is $M(\Sigma^{*\pm}(1385)\pi^{\pm}) \lesssim$ 1.75 GeV. As to the S_E -resonance, it is seen from Table 2.3 that it must be searched in the system $\Sigma^{\pm}\pi^{\pm}$ at masses $\lesssim$ 1.60 GeV. The search for S_E in the mass distribution of $\Sigma^*(1385)\pi$ - system seems to be very ineffective due to the weak coupling of S_E to this system.

3. Production of E_{55} -Baryon in Backward Scattering Processes.

The basic problem arising in the investigation of resonance states in the mass spectra consists in the possibility to discriminate the resonance signal from the background. The question of the resonance signal separation becomes especially important in studying the exotic states which have small production cross sections. The background processes can give a larger contribution, thus making the resonance observation impossible because of too small signal-background ratio. So, it is well known that for the slow-flying system $p\pi^{\pm}\pi^{\pm}$ which is created in the process

$$\pi^+ p \to \pi^- (\pi^+\pi^+ p)_s \tag{3.1}$$

a large contribution into the distribution on the mass $M(p\pi^+\pi^+)$ at small $|t_{\pi^+\pi^-}|$ is given by the background subprocesses

$$\pi^+ p \to V^0(\to \pi^+\pi^-) + \Delta^{++}(\to p\pi^+) \tag{3.2}$$

where $V^0 = \rho, f, \ldots$. Moreover, the (3.2)-type processes may display themselves in the form of kinematical peaks in the distribution on $M(p\pi^+\pi^+)$. E.g., as mentioned in the pioneer work [9] , the peak at $M(p\pi^+\pi^+) \approx 1560$ MeV observed in the reaction (3.1), at p_{lab} = 3.65 GeV, can be explained as a kinematical reflection of the process (3.2) with $V^0 = \rho^0$. Fig. 3.1 presents the diagrams which describe the production of system $p\pi^+\pi^+$ from resonance E_{55} and from the subprocess (3.2).

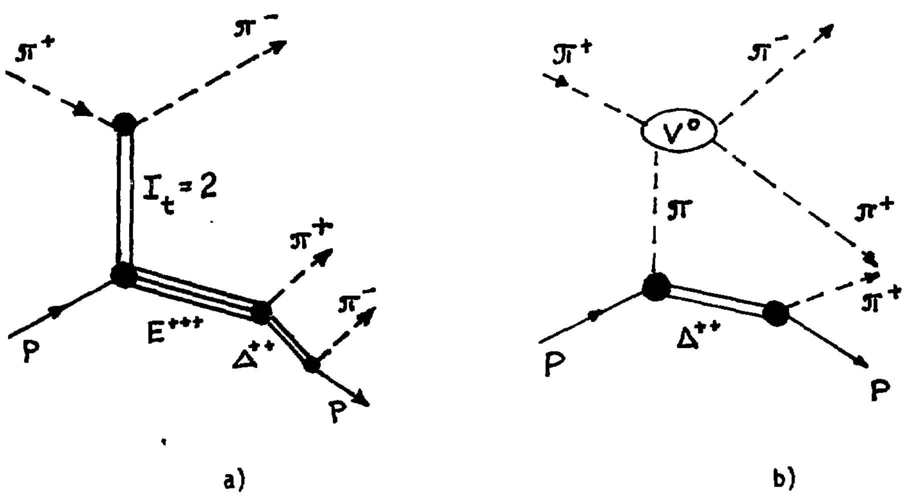

Fig. 3.1

Since the resonance E_{55}^{+++} is produced via the t-channel exchange by the $I_t = 2$ singularity, i.e. with small cross section, then at not too high energies the main contribution into the distribution on $M(p\pi^+\pi^+)$ at $M(p\pi^+\pi^+) \lesssim 2$ GeV is given by the subprocesses (3.2)*).

Consider now the process

$$\pi^+ p \to (p\pi^+\pi^+)_f \pi^- \tag{3.3}$$

where the system $p\pi^+\pi^+$ is fast flying in the lab. frame. Diagram which describes the resonance production of this system is shown in Fig. 3.2a.

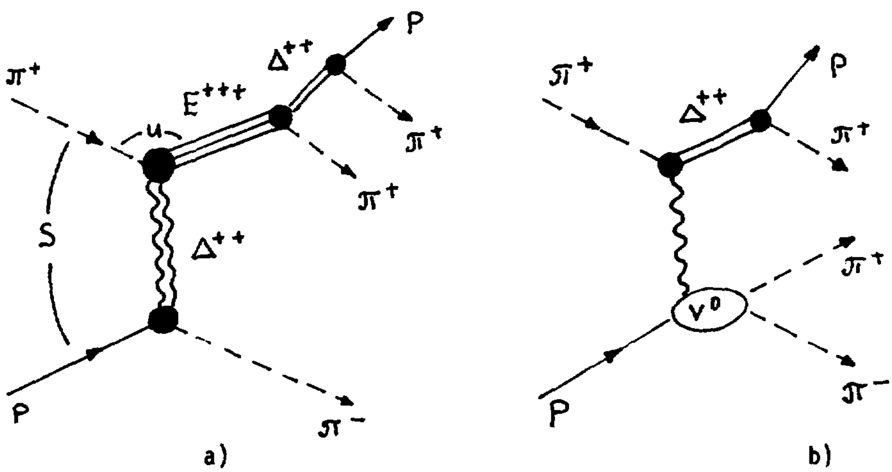

Fig. 3.2

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*) The details omitted, note that at high incident energy one can select the kinematical region where the contribution of background diagrams 3.1b becomes of the same order as that of the resonant production diagram 3.1a.

It is important that in the backward kinematics the (3.2)-type background processes also are determined by the baryon exchange mechanism (see Fig.3.2b), i.e. one can expect that their contribution into the distribution on $M(p\pi^+\pi^+)$ does not prevail so strongly over the resonant one as it is the case with forward production.

Using the prediction of sum rules for $\alpha\alpha$ -amplitudes, one can estimate the cross section of E_{55} backward production process

$$\pi^+ p \to E_{55}^{+++} \pi^- \qquad (3.4)$$

Consider $\pi^- p$ -backward scattering

$$\pi^- p \to p \pi^- \qquad (3.5)$$

which also proceeds via Δ_{33} -Regge trajectory exchange (see Fig. 3.3).

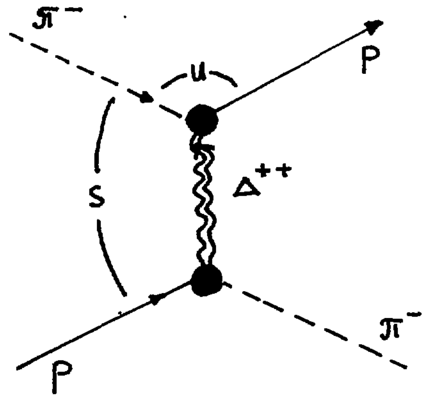


Fig. 3.3

The ratio of the cross sections of the processes (3.4) and (3.5) has the form:

$$\frac{d\sigma}{du}(\pi^+ p \to E_{55}^{+++}\pi^-) \Big/ \frac{d\sigma}{du}(\pi^- p \to p\pi^-) = \Big(\sum_{\lambda_p \lambda_E} \left|A^E_{\lambda_p \to \lambda_E}\right|^2\Big) \Big/ \Big(\sum_{\lambda_p \lambda_{p'}} \left|A^P_{\lambda_p \to \lambda_{p'}}\right|^2\Big)$$

where $A^{\alpha}_{\lambda \to \lambda'}$ are the helicity amplitudes.

To calculate helicity transitions in the vertex $\pi \alpha_\Delta E_{55}$ we will use the invariant expression (2.2) putting the quantity $G_2^{E\pi\Delta}$ (which is not fixed from sum rules) equal to zero. Analogously, the transitions in the vertex $\pi \alpha_\Delta p$ are calculated projecting the invariant expression $G^{N\pi\Delta} \bar{u}_p p_p^{\mu} u_{\Delta\mu}$ on the helicity states.

Assuming that all the helicity amplitudes are reggeized in the same manner, we have

$$A^E_{\lambda_p \to \lambda_E} = G_1^{\pi^+ \alpha_{\Delta^{++}} E^{+++}}(u)\; G^{\pi^- \alpha_{\Delta^{++}} p}(u) \left(\frac{s}{s_0}\right)^{\alpha_\Delta(u) - 1/2} \times$$
$$\times \sum_{\lambda'} M_{\lambda_E \lambda'}(q)\; \bar{u}(\lambda', p_E)\left(f_1^E(u)\,\hat{q} + f_2^E(u)\right) u(\lambda_p, p_p) \tag{3.7}$$

$$A^P_{\lambda_p \to \lambda_{p'}} = \left(G^{\pi^- \alpha_{\Delta^{++}} p}(u)\right)^2 \left(\frac{s}{s_0}\right)^{\alpha_\Delta(u) - 1/2} \times$$
$$\times\; \bar{u}(\lambda_{p'}, p_{p'})\left(f_1^P(u)\,\hat{q} + f_2^P(u)\right) u(\lambda_p, p_p) \tag{3.8}$$

where $u = q^2$.

The explicit expressions for $M_{\lambda_E \lambda'}(q)$ are given in Table 3.1 ($\vec{q}^{\perp}$ is the transverse component of the transferred momentum q).

Table 3.1

λ_E \ λ'	±5/2	3/2	-3/2	1/2	-1/2
1/2	0	$2\sqrt{5}\lvert\vec{q}^{\perp}\rvert$	0	$\frac{M_E^2 - M_\pi^2 - \vec{q}^{\perp 2}}{M_E}$	$-\lvert\vec{q}^{\perp}\rvert$
-1/2	0	0	$-2\sqrt{5}\lvert\vec{q}^{\perp}\rvert$	$\lvert\vec{q}^{\perp}\rvert$	$\frac{M_E^2 - M_\pi^2 - \vec{q}^{\perp 2}}{M_E}$

Sum rules for αa-amplitudes predict the definite relation between $G_{T_1}^{\pi^+\alpha_{\Delta^{++}}E^{+++}}(u)$ and $G^{\pi^-\alpha_{\Delta^{++}}P}(u)$ on the mass shell of E_{55^-}, Δ_{33} and N (i.e. at $u = M_\Delta^2$), namely

$$\left(G_{T_1}^{\pi^+\alpha_{\Delta^{++}}E^{+++}}(u) \Big/ G^{\pi^-\alpha_{\Delta^{++}}P}(u) \right)^2 \Bigg|_{u=M_\Delta^2} = \frac{4}{3} \tag{3.9}$$

Assuming that the formfactor of Δ which describes the off-mass shell effects is the same in the reactions (3.4) and (3.5) (i.e. the relation (3.9) holds at all u and $f_1^P(u) = f_1^E(u)$, $f_2^P(u) = f_2^E(u)$), we get after simple calculations:

$$\frac{d\sigma}{du}(\pi^+ p \to E_{53^-}^{+++}\pi^-) \Big/ \frac{d\sigma}{du}(\pi^- p \to p\pi^-) = \frac{2}{15}\,\varphi(u) \tag{3.10}$$

where

$$\varphi(u) = \left[(M_E^2 - M_\pi^2 + u)^2 - 3M_E^2 u\right] / M_E^4 \tag{3.11}$$

Fig. 3.4 presents the experimental data [10] on $\frac{d\sigma}{du}(\pi^- p \to p\pi^-)\big|_{u=0}$ as a function of initial momentum. The curve represents the parametrization of the experimental data in the form $K\,P_{lab}^{-n}$ with $n = 2.08 \pm 0.06$ [10].

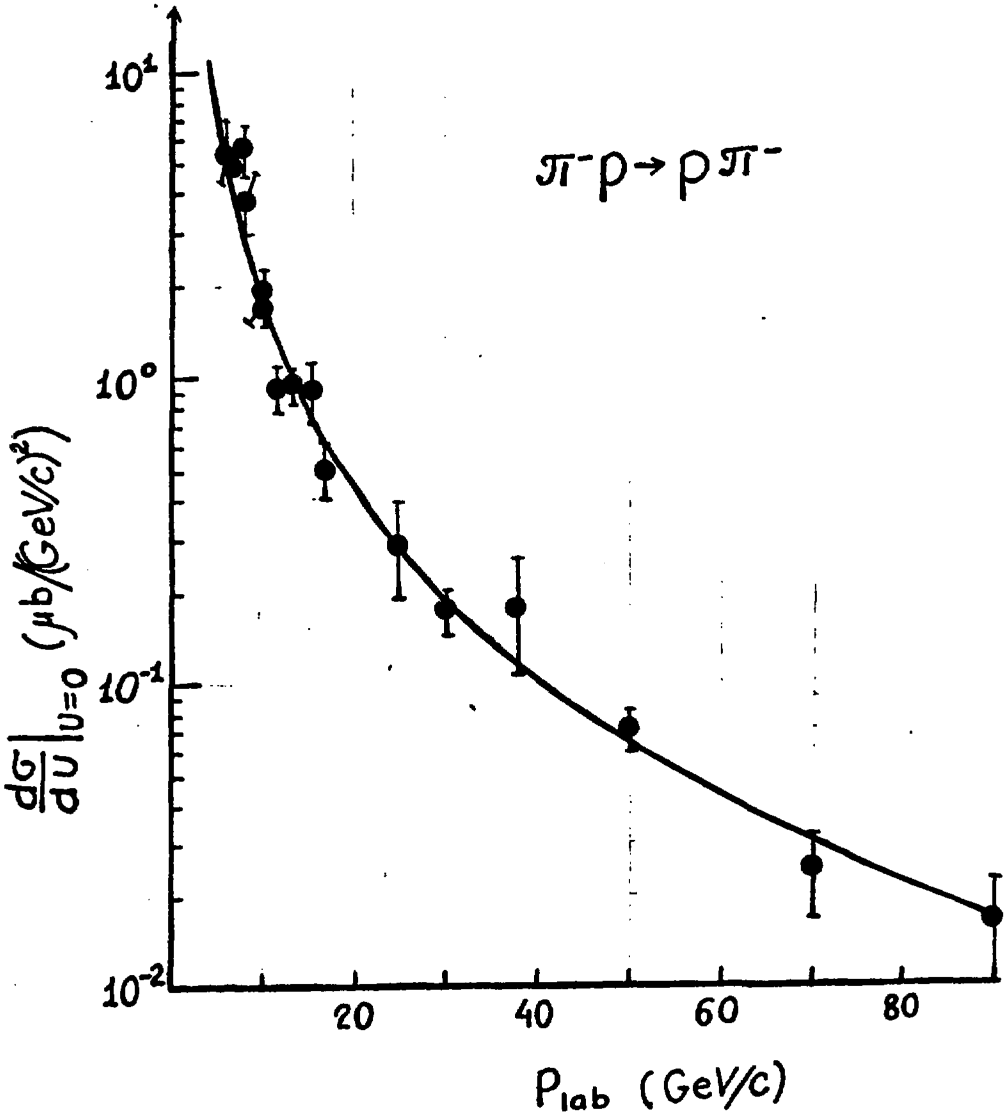


Fig. 3.4

Note that formula (3.10) can be used also to estimate the ratio of the cross sections of the inclusive production of E_{55} and p in the fragmentation region of π^+ and π^- -beams, respectively (see Fig. 3.5 a,b).

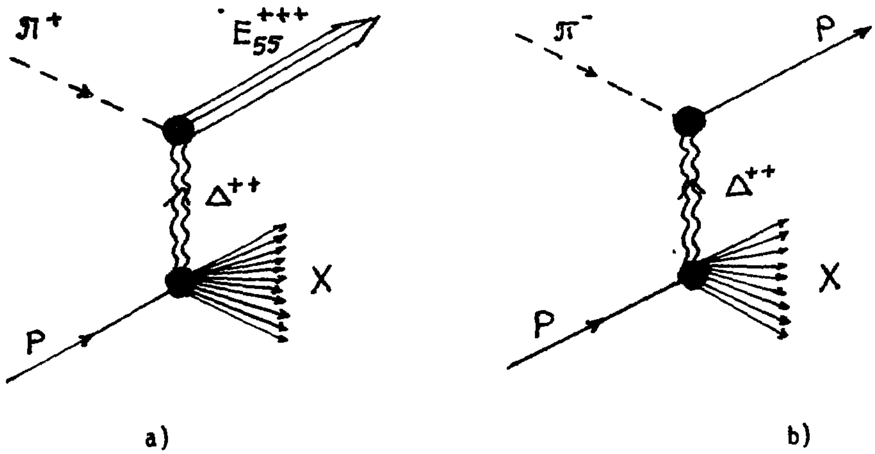


Fig. 3.5

4. Production of S_E -Resonance in Σ -Beam Processes.

Consider the processes

$$\Sigma^- n \to S_E^{--} p \tag{4.1}$$

$$\Sigma^- p \to S_E^{--} \Delta^{++} \tag{4.2}$$

Sum rules for $\alpha\alpha$ -amplitudes predict the strong coupling in the vertices $\Sigma \alpha_i S_E$, where α_i are reggeons with $I = 1$ $-\rho, A_2, \pi$.
This means that the production of S_E in the reactions (4.1) and (4.2) have to proceed via these reggeons exchange (see Fig. 4.1).

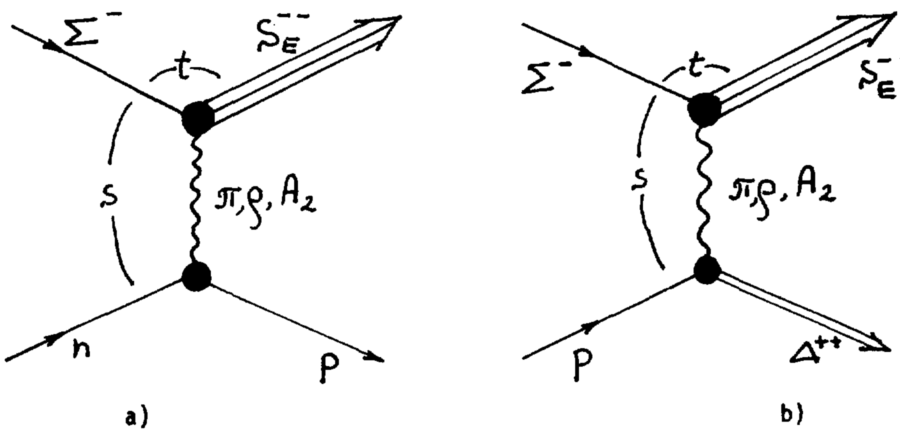


Fig. 4.1

As to the relative size of these reggeons contributions, it is not fixed from the sum rules. We will assume that, as it is the case with the reactions $NN \to N\Delta$, $NN \to \Delta\Delta$, the dominant contribution at $p_{lab} \lessapprox 50$ GeV/c gives π -exchange. The expressions for the differential cross sections, which correspond to the diagrams 4.1a and 4.1b with reggeized π, are

$$\frac{d\sigma}{dt}(\Sigma^- n \to S_E^{--} p) = \frac{\left(G^{\Sigma\pi S_E}\right)^2 \left(G^{p\pi^0 p}\right)^2}{48\pi M_{S_E}^2 \left[s-(M_\Sigma+M_N)^2\right]\left[s-(M_\Sigma-M_N)^2\right]} \times$$

$$\times \left(\frac{s}{s_0}\right)^{2\alpha_\pi(t)} \frac{\left(g_\pi(t)\right)^2}{(t-M_\pi^2)^2}\, t \left[t-(M_{S_E}-M_\Sigma)^2\right]\left[t-(M_{S_E}+M_\Sigma)^2\right]^2 \quad (4.3)$$

$$\frac{d\sigma}{dt}(\Sigma^- p \to S_E^{--}\Delta^{++}) = \frac{\left(G^{\Sigma\pi S_E}\right)^2 \left(G^{N\pi\Delta}\right)^2}{576 M_{S_E}^2 M_\Delta^2 \left[s-(M_\Sigma+M_N)^2\right]\left[s-(M_\Sigma-M_N)^2\right]} \times$$

$$\times \left(\frac{s}{s_0}\right)^{2\alpha_\pi(t)} \frac{\left(g'_\pi(t)\right)^2}{(t-M_\pi^2)^2} \left[t-(M_\Delta-M_N)^2\right]\left[t-(M_\Delta+M_N)^2\right]\left[t-(M_{S_E}-M_\Sigma)^2\right]\left[t-(M_{S_E}+M_\Sigma)^2\right]^2 \quad (4.4)$$

where $g_\pi(t)$ and $g'_\pi(t)$ are formfactors which describe the π -meson off-mass shell effects.

Assume that

$$g'_\pi(t) = g_\pi(t) = (1-at)\exp[R^2(t-M_\pi^2)] \tag{4.5}$$

and fit parameters a and R^2 from the comparison with the experimental data on the processes $NN \to N\Delta_{33}$, $NN \to \Delta_{33}\Delta_{33}$ and $N\bar{N} \to \Delta_{33}\Delta_{33}$ 11-16 , taking the universal form (4.5) of π -meson formfactor in the (4.3) and (4.4)-like formulae for these processes cross sections

$$a = 3\ \text{GeV}^{-2} \ ; \qquad R^2 = 2.2\ \text{GeV}^{-2}$$

The other parameters in (4.3) and (4.4) have the following values:

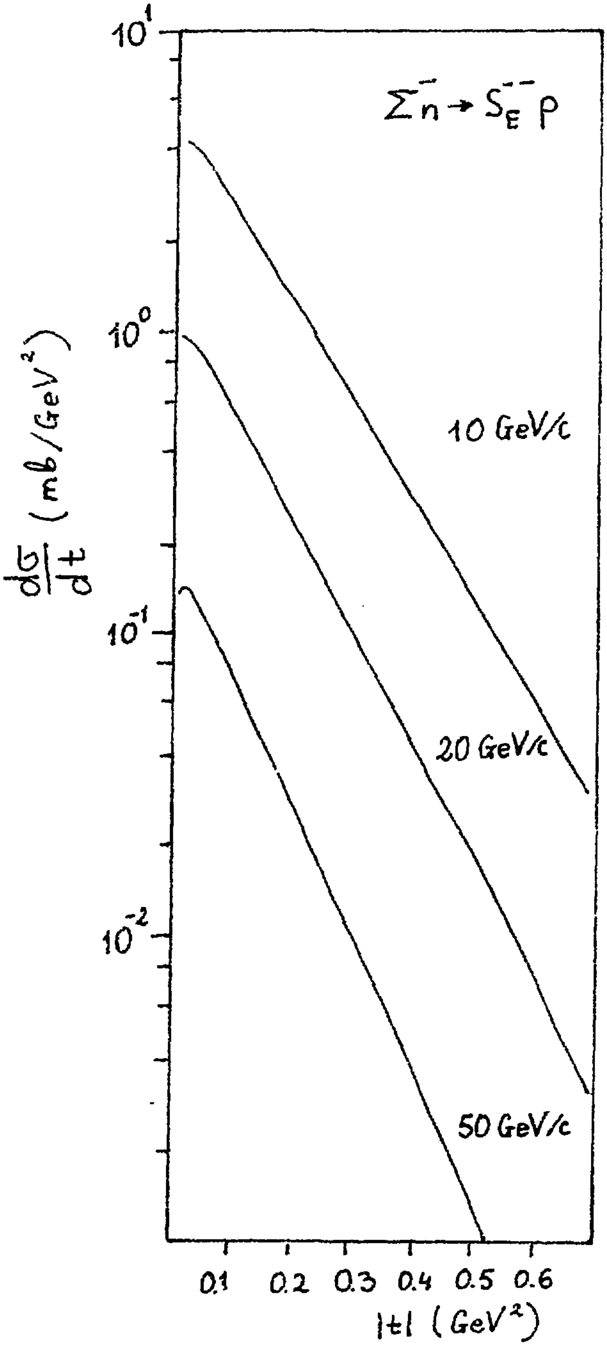
$$\left(G^{\Sigma\pi S_E}/G^{\Sigma^*\pi\Lambda}\right)^2 = \frac{3}{2} \ ; \ \left(G^{N\pi\Delta}/G^{p\pi^0 p}\right)^2 = \frac{1}{S_0}\frac{9}{8}$$

$$\left(G^{\Sigma^*\pi\Lambda}\right)^2/4\pi = \frac{1}{S_0}6.6 \ ; \tag{4.6}$$

$$\alpha_\pi(t) = \alpha'_\pi(t-M_\pi^2) \ ; \qquad \alpha'_\pi = 1\ \text{GeV}^{-2}$$

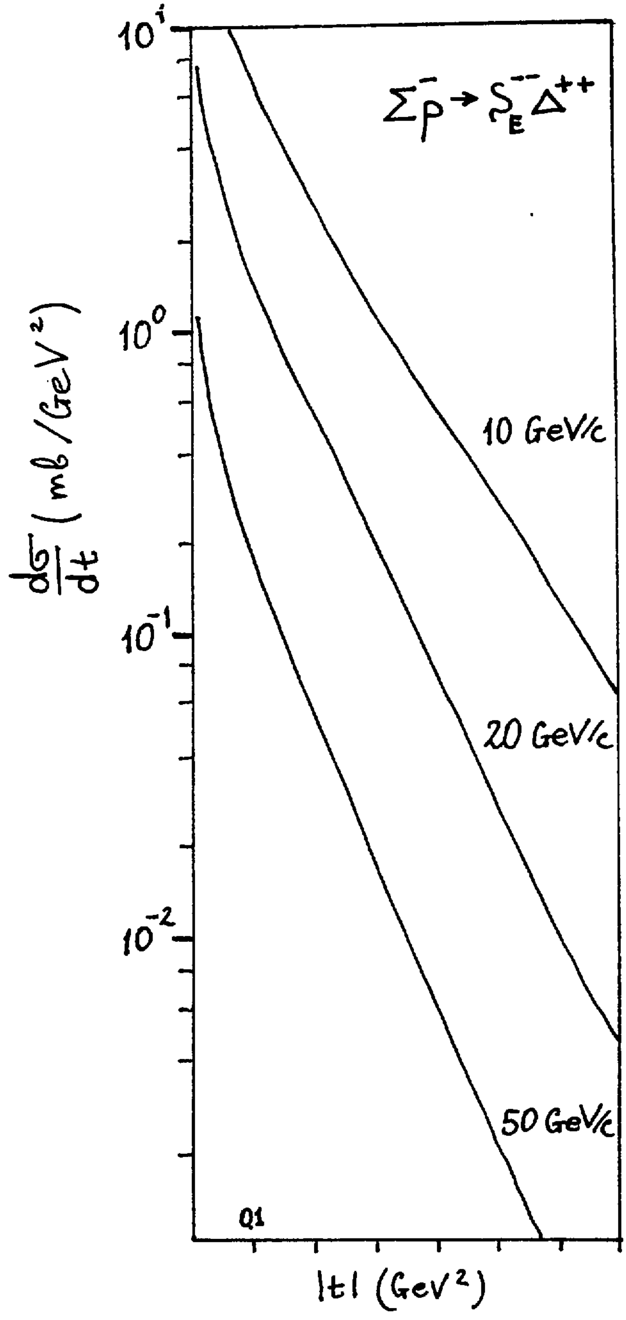
The relations (4.6) are the αa -amplitude sum rules predictions (see (2.3) and [3]).

Fig. 4.2 presents the results of theoretical calculations of the differential cross sections of the process (4.1) at different energies, and Fig. 4.3 - those of the process (4.2). The corresponding integrated cross sections are given in Fig. 4.4. All calculations are made at M_{S_E} = 1.5 GeV. To demonstrate the dependence on M_{S_E} , we give in Fig. 4.3 the cross section of the process (4.2) at M_{S_E} = 1.45 GeV too.



10^1
$\Sigma^- n \to S_E^{--} p$
10^0
$\frac{d\sigma}{dt}$ (mb/GeV²)
10 GeV/c
10^{-1}
20 GeV/c
10^{-2}
50 GeV/c
0.1 0.2 0.3 0.4 0.5 0.6
|t| (GeV²)

Fig. 4.2



10^1
10^0
10^{-1}
10^{-2}
$\frac{d\sigma}{dt}$ (mb/GeV²)
$\Sigma^- p \to S_E^{--} \Delta^{++}$
10 GeV/c
20 GeV/c
50 GeV/c
0.1
|t| (GeV²)

Fig. 4.3

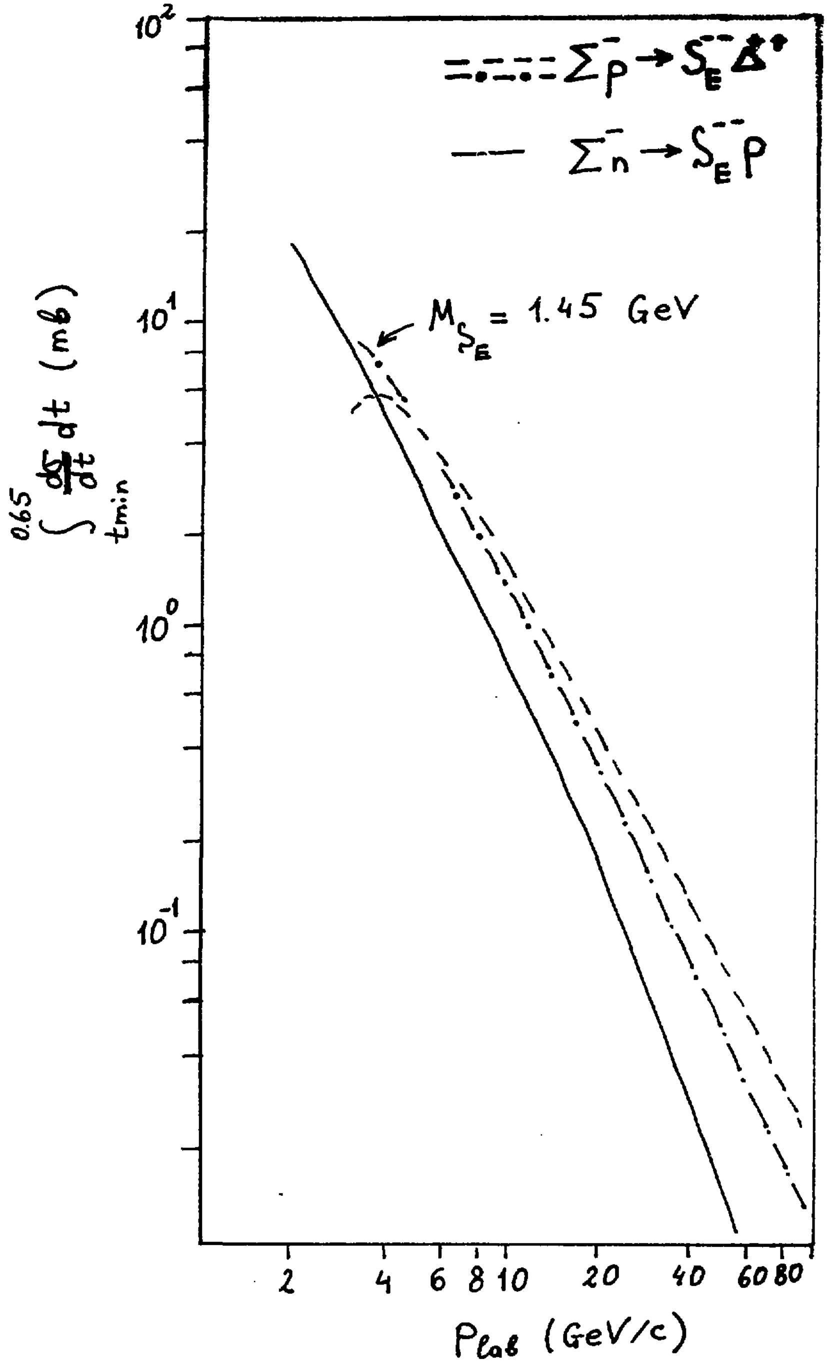
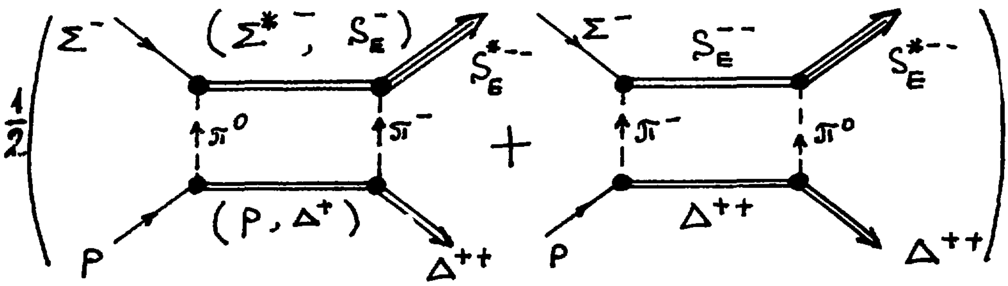

$\Sigma^- p \to S_E^{--} \Delta^{+}$
$\Sigma^- n \to S_E^{--} p$
$M_{S_E} = 1.45$ GeV
10^2
10^1
10^0
10^{-1}
$\int_{t_{min}}^{0.65} \frac{d\sigma}{dt} dt$ (mb)
2
4
6
8
10
20
40
60
80
P_{lab} (GeV/c)

Fig. 4.4

5. Production of S_E^* -Resonance in $\Sigma^- p$ -Collisions.

Unlike the S_E, resonance S_E^* cannot interact immediately with hyperon (the vertices $\Sigma \alpha_i S_E^*$ are predicted to be zero in sum rules). Therefore S_E^* -resonance should be produced in ΣN -collisions through cascade mechanism - just as E_{55} in NN-collisions *).

In this section we calculate the cross section which corresponds to the one of the possible S_E^* -production mechanisms, namely to the two-pion exchange mechanism presented in Fig. 5.1.



a) b)

Fig. 5.1

The detailed description of the model was done in [8], where the reactions $NN \to E_{55}\Delta_{33}$ and $NN \to E_{55} E_{55}$ were considered. Formfactors of π -mesons are taken the same as in [8]. For the couplings in the vertices in Fig. 5.1 SSR predict the following values

---

*) Strictly speaking, the conclusion that the $\Sigma - S_E^*$ coupling is vanishing is closely connected with the condition $M_{S_E^*} - M_\Sigma = 0$, which follows from the neglect of higher states contribution into sum rules. It is possible, in principle, that at $M_{S_E^*} - M_\Sigma \neq 0$ the transitions $S_E^* \to \alpha_i \Sigma$ $(i = \pi, \rho, A_2)$ are nonzero and then in the production of S_E^* on Σ -beams the one-pion exchange mechanism will contribute.

$$G^{\Sigma\pi\Sigma^*} = -\frac{1}{\sqrt{2}} G^{\Sigma^*\pi\Lambda}$$

$$G^{S_E\pi S_E^*} = \frac{1}{\sqrt{S_0}}\frac{1}{\sqrt{5}} G^{\Sigma^*\pi\Lambda}$$

$$G^{\Delta\pi\Delta} = \frac{3\sqrt{3}}{\sqrt{S_0}\sqrt{5}} G^{p\pi^0 p} \tag{5.1}$$

$$\left(G^{N\pi\Delta}\right)^2 = \frac{9}{S_0 8}\left(G^{p\pi^0 p}\right)^2$$

The values of $G^{\Sigma\pi S_E}$, $G^{\Sigma^*\pi S_E^*}$ and $G^{\Delta\pi E}$ are given in (2.14), (2.6) and (2.3).

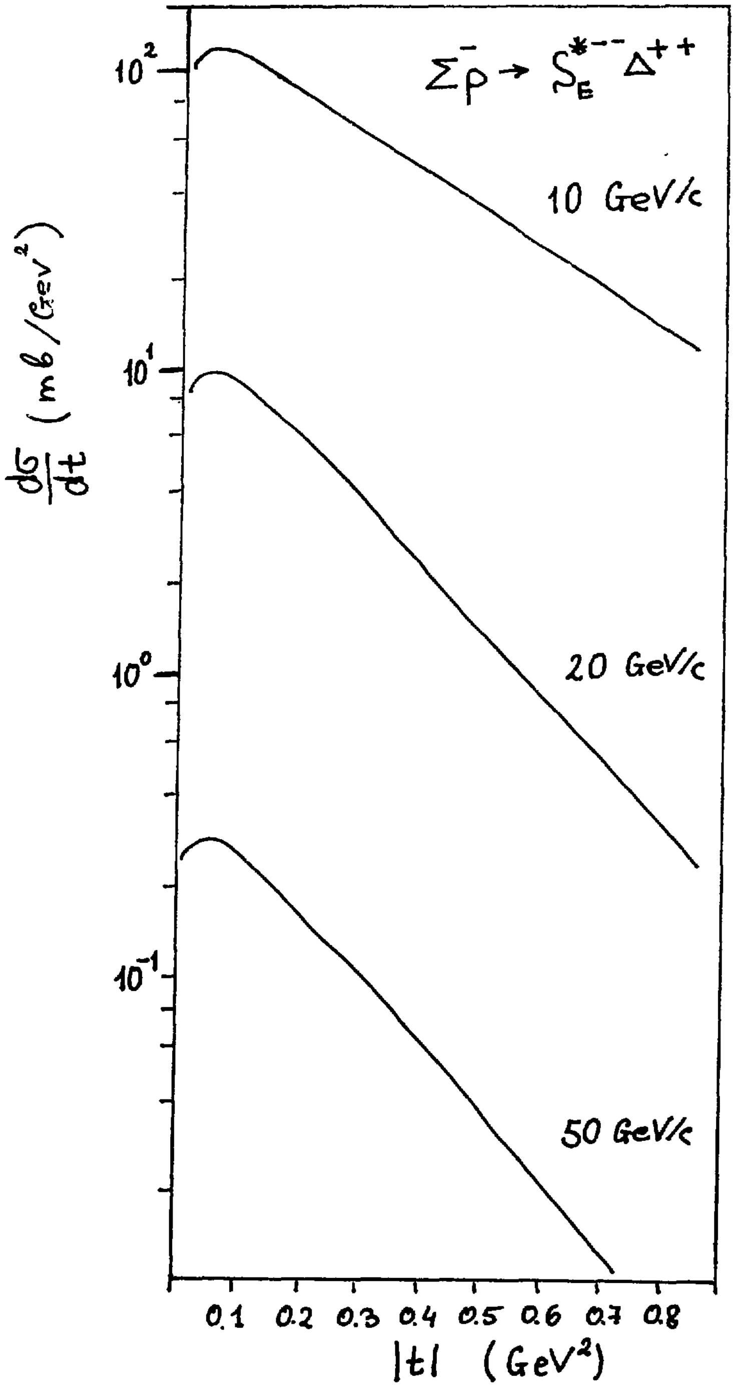
Fig. 5.2 shows the differential cross sections at Σ-hyperon momenta 10, 20, 50 GeV/c, and Fig. 5.3 presents the dependence of the integrated cross section on p_{lab}.

It is worth emphasizing that the cross section which corresponds to the diagrams of Fig. 5.1 turns out to be rather small as compared to the cross section of E_{SS}-production in NN-collisions [8]. This is connected with the relative smallness of vertices which involve strange particles.

Further, in the theoretical calculations the corrections which are due to the experimental cut-off imposed on the masses of systems $\Sigma^*(1385)\pi$ (when selecting S_E^*) and $\Lambda\pi$, $\Sigma\pi$ (when selecting $\Sigma^*(1385)$) are not taken into account. For example, assuming the Breit-Wigner shape distribution for the system $\Sigma^*(1385)\pi$, one must multiply the cross section of S_E^*-production by the coefficient $\left(\alpha(\Gamma_{S_E^*})\right)^2$ with

$$\alpha(\Gamma_{S_E^*}) = \frac{1}{\pi}\left\{\operatorname{arctg}\frac{M_u^2 - M_{S_E^*}^2}{M_{S_E^*}\Gamma_{S_E^*}} + \operatorname{arctg}\frac{M_{S_E^*}^2 - M_d^2}{M_{S_E^*}\Gamma_{S_E^*}}\right\} \tag{5.2}$$

where $M_{S_E^*}$ and $\Gamma_{S_E^*}$ are the mass and width of S_E^*, M_u and M_d are the upper and lower limits of experimental cut-off.


$\Sigma^- p \to S_E^{*--} \Delta^{++}$
10 GeV/c
20 GeV/c
50 GeV/c
10^2
10^1
10^0
10^{-1}
$\frac{d\sigma}{dt}$ (mb/GeV^2)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$|t|$ (GeV^2)
Fig. 5.2

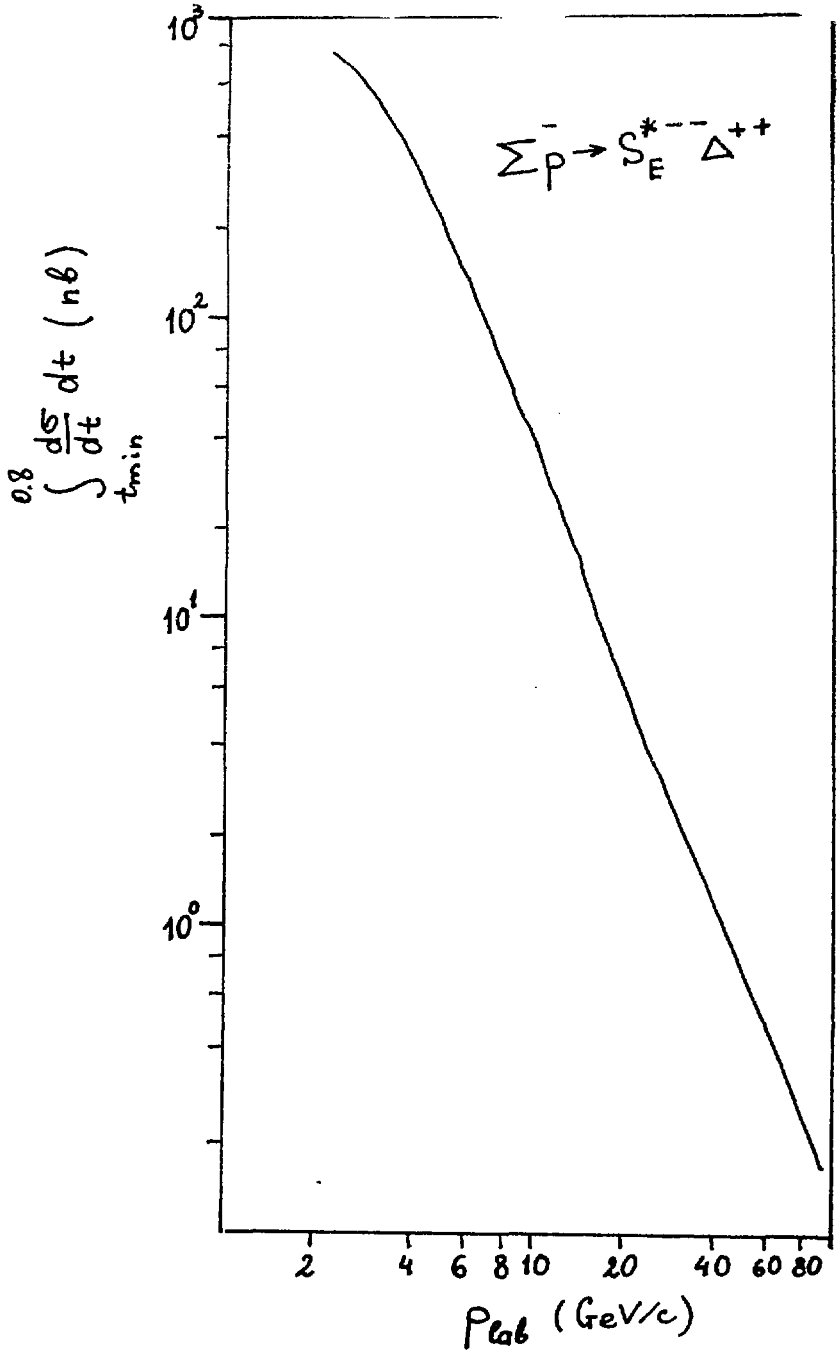

$\Sigma^- p \to S_E^{*--} \Delta^{++}$
$\int_{t_{min}}^{0.8} \frac{d\sigma}{dt} dt$ (nb)
10^3
10^2
10^1
10^0
2 4 6 8 10 20 40 60 80
p_{lab} (GeV/c)

Fig. 5.3

6. Spin and Parity of Resonances. The Angular Distribution of Decay Products.

Under the analysis of the spin and parity of resonance , it is important to study the correlations of the decay products which do not depend on the details of resonance production dynamics. Such a correlation is the distribution $W(\Theta^*_{ab})$ in the angle between particles a and b in the rest frame of resonance R , which decays in the cascade vein:

$R \to b + \pi \to a + \pi + \pi$. The distribution $W(\Theta^*_{ab})$ is determined by the mean value of helicity of particle b which depends on the spin and parity of R . In this section we derive the formula which describes $W(\Theta^*_{ab})$ at different values of $J_R^{P_R}$ in case when $J_b^{P_b} = 3/2^+$ (Δ_{33}, Σ^* -resonances) and $J_a^{P_a} = 1/2^+$ (N, Λ, Σ)

The cross section of the resonance R production with the subsequent decay $R \to b + \pi \to a + \pi + \pi$ (see Fig. 6.1) has the following form:

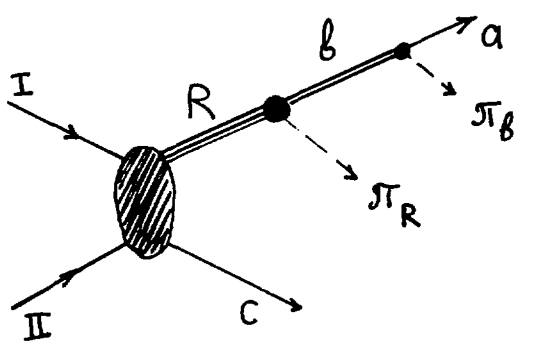


Fig. 6.1

$$\sigma = \frac{1}{(2J_I+1)(2J_{II}+1)} \frac{4\pi^2}{\sqrt{(P_I P_{II})^2-(m_I M_{II})^2}} \int \sum_{\lambda_I \lambda_{II}} \left| A_{\lambda_I \lambda_{II} \to \lambda_a \lambda_c} \right|^2 \times$$

$$\times \delta(p_I + p_{II} - p_c - p_a - p_{\pi_R} - p_{\pi_\ell}) \frac{d^3 p_c}{E_c} \frac{d^3 p_a}{E_a} \frac{d^3 p_{\pi_R}}{E_{\pi_R}} \frac{d^3 p_{\pi_\ell}}{E_{\pi_\ell}} \tag{6.1}$$

where $A_{\lambda_I \lambda_{II} \to \lambda_a \lambda_c}$ are the helicity amplitudes

$$A_{\lambda_I \lambda_{II} \to \lambda_a \lambda_c} = A_{\lambda_I \lambda_{II} \to \lambda_R \lambda_c} \times A_{\lambda_R \to \lambda_a} \times B(M_R^2) \tag{6.2}$$

and

$$A_{\lambda_R \to \lambda_a} = A_{\lambda_R \to \lambda_\ell} \times A_{\lambda_\ell \to \lambda_a} \times B(M_\ell^2) \tag{6.3}$$

In (6.2) and (6.3) $B(M_R^2)$ and $B(M_\ell^2)$ are the propagators of R and ℓ .

Taking into account (6.2) and (6.3) and making the trivial transformations. rewrite the expression (6.1) in the following form

$$\sigma = \int dM_R^2 \, dM_\ell^2 \, |B(M_R^2)|^2 |B(M_\ell^2)|^2 \times \int \rho_{\lambda_R \lambda_R'} \frac{d^3 p_c}{E_c} \frac{d^3 p_R}{E_R} \delta(p_I + p_{II} - p_c - p_R) \times$$

$$\times \int A_{\lambda_R \to \lambda_\ell} A_{\lambda_R' \to \lambda_\ell'} \frac{d^3 p_\ell}{E_\ell} \frac{d^3 p_{\pi R}}{E_{\pi_R}} \delta(p_R - p_\ell - p_{\pi_R}) \times \tag{6.4}$$

$$\times \int A_{\lambda_\ell \to \lambda_a} A^*_{\lambda_\ell' \to \lambda_a} \frac{d^3 p_a}{E_a} \frac{d^3 p_{\pi_\ell}}{E_{\pi_\ell}} \delta(p_\ell - p_a - p_{\pi_\ell})$$

In (6.4) $\rho_{\lambda_R \lambda'_R}$ is the density matrix of resonance R.

Take the z-axis in the direction of momentum of R and turn into the rest frame of R. Then [17]

$$A_{\lambda_R \to \lambda_\ell} = a^{J_R}_{P_R}(\lambda_\ell)\, d^{J_R}_{\lambda_R \lambda_\ell}(\theta^*_\ell)\, e^{i\varphi^*_\ell(\lambda_R - \lambda_\ell)} \tag{6.5}$$

where θ^*_ℓ and φ^*_ℓ are the polar and azimuthal angles of the R-resonance flight, $d^J_{\lambda\mu}$ are the Wigner d-functions (here and in what follows we denote by asterisk the variables in the rest frame of R).

Further, one can show that

$$A_{\lambda_\ell \to \lambda_a} A^*_{\lambda'_\ell \to \lambda_a} = e^{i\varphi^*_\ell(\lambda'_\ell - \lambda_\ell)}\, e^{i\varphi^*(\lambda_\ell - \lambda'_\ell)}\, f_{\lambda_\ell \lambda'_\ell}(\theta^*_{a\ell}) \tag{6.6}$$

where $\theta^*_{a\ell}$ is the angle between $\vec{p}^{\,*}_a$ and $\vec{p}^{\,*}_\ell$, φ^* is the azimuthal angle of $\vec{p}^{\,*}_a$ in the plane which is perpendicular to $\vec{p}^{\,*}_\ell$. The quantities $a^{J_R}_{P_R}(\lambda_\ell)$ and $f_{\lambda_\ell \lambda'_\ell}$ possess the following symmetry properties

$$\begin{aligned} |a^{J_R}_{P_R}(\lambda_\ell)| &= |a^{J_R}_{P_R}(-\lambda_\ell)| \;; \\ f_{\lambda_\ell \lambda'_\ell} &= (-1)^{\lambda_\ell - \lambda'_\ell} f_{-\lambda_\ell\, -\lambda'_\ell} \end{aligned} \tag{6.7}$$

Substitute (6.5) and (6.6) into (6.4). Taking into account (6.7) we get

$$\begin{aligned} \sigma \sim \int & \sigma^{\bar{I}I \to Rc} B(M_R^2) B(M_\ell^2)\, dM_R^2\, dM_\ell^2 \times \\ \times & \frac{|\vec{p}^{\,*}_\ell|}{M_R} \int \Big\{ \sum_{\lambda_\ell > 0} |a^{J_R}_{P_R}(\lambda_\ell)|^2 f_{\lambda_\ell \lambda_\ell}(\theta^*_{a\ell}) \times \frac{|\vec{p}^{\,*}_a|^2\, d\cos\theta^*_{a\ell}}{E^*_\ell |\vec{p}^{\,*}_a| - E^*_a |\vec{p}^{\,*}_\ell| \cos\theta^*_{a\ell}} \end{aligned} \tag{6.8}$$

where $\sigma^{\mathrm{II}\to Rc}$ is the cross section of resonance R production, $|\vec{P}_a^*| = |\vec{P}_a^*(\theta_{a\ell}^*)|$.

It is seen from (6.8) that indeed, the distribution on $\theta_{a\ell}^*$ does not depend on the dynamics of R production and is determined by the ℓ helicity mean value, i.e. the coefficients $|a_{P_R}^{J_R}(\lambda_\ell)|$ depend on λ_ℓ (the kinematical factors in (6.8) are connected to the phase space).

In the case under consideration ($J_\ell^{P_\ell} = 3/2^+$. $J_a^{P_a} = 1/2^+$) the distribution has the form (for the concreteness denote $a \equiv N$, $\ell \equiv \Delta$):

$$W_{P_R}^{J_R}(\theta_{N\Delta}^*) \sim \left\{ f_{3/2\,3/2}(\theta_{N\Delta}^*) + f_{1/2\,1/2}(\theta_{N\Delta}^*)\, \alpha_{P_R}^{J_R} \right\} \cdot \times \frac{|\vec{P}_N^*|^2}{E_\Delta^* |\vec{P}_N^*| - E_N^* |\vec{P}_\Delta^*| \cos\theta_{N\Delta}^*} . \tag{6.9}$$

where

$$\alpha_{P_R}^{J_R} = |a_{P_R}^{J_R}(1/2)|^2 / |a_{P_R}^{J_R}(3/2)|^2 ,$$

$$f_{3/2\,3/2}(\theta_{N\Delta}^*) = |\vec{P}_N^*|^2 \sin^2\theta_{N\Delta}^* ,$$

$$f_{1/2\,1/2}(\theta_{N\Delta}^*) = \frac{1}{3}\left\{ |\vec{P}_N^*|^2 \sin^2\theta_{N\Delta}^* + \frac{4}{M_\Delta^2}\left[E_N^* |\vec{P}_\Delta^*| - E_\Delta |\vec{P}_N^*| \cos\theta_{N\Delta}^*\right]^2 \right\} \tag{6.10}$$

Let us write out the values of $\alpha_{P_R}^{J_R}$ at some values of J_R and P_R [6]

a) $$\alpha_+^{5/2} = \frac{1}{6}\left\{ \frac{2E_\Delta^*}{M_\Delta} + 1 + \frac{2M_R}{M_\Delta} |\vec{P}_\Delta^*|^2 g_+^{5/2} \right\}^2$$

$$\alpha_-^{5/2} = \frac{1}{6}\left\{\frac{2E_\Delta^*}{M_\Delta} - 1 + \frac{2M_R}{M_\Delta}|\vec{P}_\Delta^*|^2 g_-^{5/2}\right\}^2 \tag{6.11}$$

b)
$$\alpha_+^{3/2} = \frac{1}{9}\left\{\frac{2E_\Delta^*}{M_\Delta} - 1 + \frac{2M_R}{M_\Delta}|\vec{P}_\Delta^*|^2 g_+^{3/2}\right\}^2$$

$$\alpha_-^{3/2} = \frac{1}{9}\left\{\frac{2E_\Delta^*}{M_\Delta} + 1 + \frac{2M_R}{M_\Delta}|\vec{P}_\Delta^*|^2 g_-^{3/2}\right\}^2 \tag{6.12}$$

In (6.11) and (6.12) $g_{P_R}^{J_R} = G_2^{R\pi\Delta} / G_1^{R\pi\Delta}$, where the $G_i^{R\pi\Delta}$ are the invariant functions the $R \to \Delta\pi$ decay amplitude depends on.

c) for the case $J^R = 1/2$ $(P_R = \pm)$ it follows from (6.5) that $A_{\lambda_R \to 3/2} = 0$, so only the term with $f_{1/2\,1/2}(\theta_{N\Delta}^*)$ remains in (6.9).

It follows from (6.11) and (6.12) that at J_R = 5/2 and 3/2 the angular distribution depends on the ratio of functions $G_2^{R\pi\Delta}$ and $G_1^{R\pi\Delta}$. Assuming, however, that $g_{P_R}^{J_R}$ are not too large, one can neglect the term with $g_{P_R}^{J_R}$ at $|\vec{P}_\Delta|^2/M_\Delta^2 \ll 1$ and then

$$\alpha_+^{5/2} = \frac{3}{2}\ , \quad \alpha_-^{5/2} = \frac{1}{6}\ ; \quad \alpha_+^{3/2} = \frac{1}{9}\ , \quad \alpha_-^{3/2} = 1 \tag{6.13}$$

Fig. 6.2 demonstrates the theoretical calculations of $W_{P_R}^{J_R}(\cos\theta_{N\Delta}^*)$ carried out at M_R = 1.42 GeV and M_Δ = 1.23 GeV.

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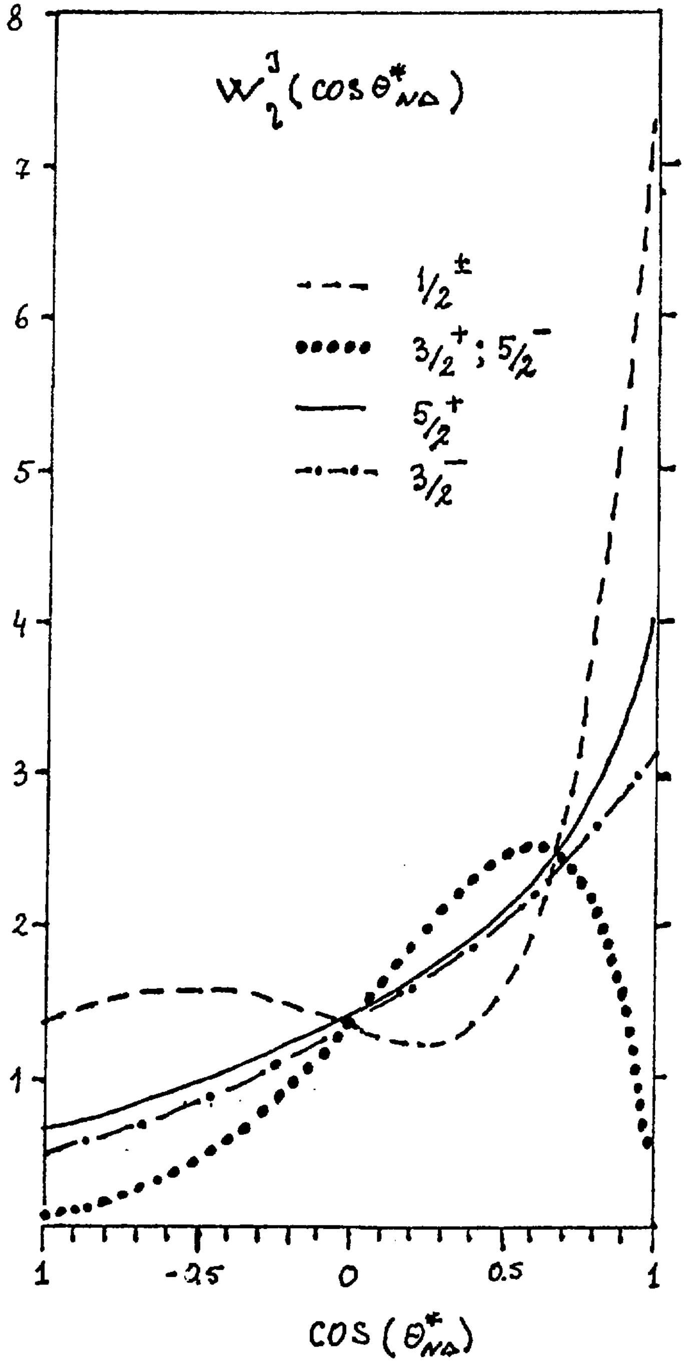

8
7
6
5
4
3
2
1
$W_2^J(\cos\theta^*_{N\Delta})$
1/2±
3/2+ ; 5/2−
5/2+
3/2−
1
-.25
0
0.5
1
COS ($\theta^*_{N\Delta}$)

Fig. 6.2

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А.А.ГРИГОРЯН, Г.Н.ХАЧАТРЯН

ТЕОРЕТИЧЕСКИЕ ПРЕДСКАЗАНИЯ НЕКОТОРЫХ ХАРАКТЕРИСТИК РОЖДЕНИЯ ЭКЗОТИЧЕСКИХ БАРИОНОВ В АДРОННЫХ ПРОЦЕССАХ

(на английском языке, перевод З.Н.Асланян)

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